Designing scenarios for upscaling climate-smart agriculture on a small tropical island

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Title: "Designing Scenarios for Upscaling Climate-Smart Agriculture on a Small Tropical Island"

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Abstract:

CONTEXT: Climate smart agriculture (CSA) is proposed to meet the major challenges of feeding nine billion people by 2050, adapting systems to climate change and mitigating anthropogenic GHG emissions. These challenges are salient in tropical island regions that are particularly vulnerable. While many technical solutions based on agroecology and bioeconomy have been proposed to promote CSA, there is little work on the issue of barriers to the transition towards such systems, which remains slow. There is a need to develop methods to model possible futures to cope with the imposed constraints of climate change and to identify relevant agronomic and policy levers to achieve this goal.

OBJECTIVE: A methodological framework was proposed to design scenarios for upscaling CSA, which was applied in Guadeloupe.

METHODS: The multi-scale and transdisciplinary framework consists of five steps: farm typology building, diagnosis of farming systems from a survey on a sample of farms, design of a prototype of climate-smart farming system, field experimenting, and modeling scenarios to identify levers that can reach the CSA objectives at the regional level under future climate conditions.

RESULTS AND CONCLUSIONS: While new agricultural systems based on agroecology and bioeconomy have the potential to reduce the impacts of climate change, mitigate GHGs, and increase food autonomy, results revealed that many lock-in effects have to be relaxed, increasing workforce availability at the regional scale, reorientating public incentives towards agroecological systems, increasing profitability of CSA products, improving the work efficiency of farmers, and reducing their risk aversion. In the best scenario designed, the potential impact of climate hazards was reduced by 12.5%, the nutritional performance at the regional scale was tripled with 6.0 fed people/ha/yr, the GHG balance switched from net emissions to a sequestration of 0.7 tCO2eq/ha/yr, while the labor productivity rose to $26.5/hr (+14%). Compared to that of the baseline situation, the public cost for mitigating 1 tCO2eq was $432.

SIGNIFICANCE: New ambitious policies targeting farmers' constraints are required to increase CSA. There is a need to develop more stakeholder platforms in which all issues and possible levers are discussed, and transition scenarios are co-designed. The approach proposed herein can be used to feed discussions on such platforms. Research must be continued in the "redesign" field to model transition in a dynamic way, given the uncertainty of many crucial aspects such as climate change scenarios, market evolution, technical progress in agroecology, and farmers' behavior.

Key words: farming system design; climate smart agriculture; scenario; bioeconomic model; Caribbean.

Highlights:

- There is a need to develop methods for upscaling climate-smart agriculture (CSA) in tropical island regions.
- A methodological framework for designing CSA scenarios was proposed, and its application in Guadeloupe was presented.
- Combining agroecology and bioeconomy can lead to CSA; however, this is possible only with a combination of several agro-socio-economic levers.
- Lock-in effects are highlighted, including lack of workforce availability, inadequate public incentives, and lower labor productivity than that in conventional systems.
- New ambitious policies targeting farmers' constraints are required for upscaling CSA

1. Introduction

Global agriculture must meet the major challenge of feeding nine billion people by 2050 while simultaneously adapting to climate change, mitigating anthropogenic greenhouse gas (GHG) emissions, and integrating the principles of sustainable development (Tubiello, 2015). These challenges are particularly salient in tropical and island regions, which are vulnerable to climate change (Petzold and Magnan, 2019). The small island states of the Caribbean face serious challenges in the context of a changing climate such as more severe droughts, temperature increases, sea level rise and saltwater intrusion, increased cyclone intensity, and shifting agricultural seasonality (FAO and CDB, 2019). In a region where the level of malnutrition is high, climate change adaptation and resilience should be a key priority for a sustainable future and agricultural sector development in the medium and long term. The challenges faced by agriculture are threefold: 1) adapting agricultural systems to climate change and mitigating its causes and effects; 2) an improved combination of economic, social, and environmental performance; and 3) increasing the degree of food autonomy of the regions. These objectives are consistent with the emerging concept of climate smart agriculture (CSA), which aims to propose an integrated approach to agriculture to meet the threefold challenge of food security, adaptation, and mitigation of climate change. The goal is to sustainably increase the productivity of agricultural systems while adapting them to strengthen their resilience to climate change and reduce or remove GHG emissions, wherever possible (Lipper et al., 2014; 2018).

To implement CSA, several levers have been investigated, such as the genetic improvement of crops to increase resilience, digital tools, agroecology, and bioeconomy. Agroecology is a method of designing production systems based on the functionalities offered by ecosystems (Gliessman, 2016; Wezel et al., 2009). It amplifies natural processes within agrosystems while aiming to reduce pressure on the environment (e.g., reducing GHG emissions and avoiding the use of synthetic fertilizers and pesticides) and preserving natural resources (water, energy, and mineral elements). Agroecology reintroduces biodiversity into agricultural production systems and restores a diversified landscape mosaic (Altieri and Toledo, 2011). Parallel to agroecology, the emerging concept of bioeconomy aims to propose sustainable development models based on the valorization of bio-sourced products and locally sourced by-products, replacing materials and inputs that consume more fossil energy. For the agricultural sector, the bioeconomy is complementary to agroecology because it can provide new opportunities to increase farm competitiveness while providing sustainable solutions to environmental and societal challenges (Muller et al., 2017). Agroecology can develop a bioeconomy by providing pesticide-free agricultural products for the local market (food, feed, fiber), whereas bioeconomy can support agroecology development through the recycling of local residual organic matter (from industrial or domestic origin) into locally processed bio-inputs (Mousseau, 2015; Valenzuela 2016). Agroecology and bioeconomy are complementary; thus, their synergies are currently being explored in research to develop CSA (Pimbert, 2015).

At the farming system level, prototyping new production systems and system experiments is a tool commonly used to determine the biophysical basis of sustainable and climate smart production (Debaeke et al., 2017). However, beyond the work on the biophysical basis of CSA, agricultural research is questioned regarding its ability to facilitate the transition towards sustainable, climate-smart agricultural systems. Thus, it is challenging to identify pathways for upscaling the CSA (Smith et al., 2021; Westermann et al., 2015). The transition towards such systems remains slow because farmers' adoption rates are low (Long et al., 2016). Farmers often face barriers to adopting agroecological production systems (Magrini et al., 2019; Meynard et al., 2018). Although they can be more profitable, these systems are often perceived as riskier, more time-consuming, and involving more unfamiliar skills than conventional systems. They also face different barriers at the regional scale because of inappropriate supply chains and insufficient policy incentives, which are not oriented towards agroecology and bioeconomy development (Fares et al., 2012; Ponisio and Ehrlich, 2016). The lack of quantitative evidence of cost-benefit is also a barrier to adoption. Thus, although many technical solutions based on agroecology and bioeconomy have been proposed to promote CSA, there is minimal work on the issue of barriers to the transition to appropriate agricultural practices (Lampridi et al., 2019), which is especially true in the Caribbean (FAO, 2019; Saint Ville et al., 2015). There is a need to develop methods to model possible futures to cope with the imposed constraints of climate change and to model the impact of agronomic and policy levers to reach this goal (Thornton at al., 2017). To guide large-scale investment and policy planning to develop CSA, further information is needed regarding the inter-relationships among landscape features, socioecological conditions of farms and markets, external interventions, local institutions, and combined effects on mitigation outcomes. Introducing innovations into agricultural systems requires that they be viewed not just as isolated entities but as part of a nested system where they must meet multiple requirements and constraints at different levels (Ollivier et al., 2018). The scientific challenge is to provide a methodological framework to identify solutions at different scales and define how to combine them in a consistent way to accelerate the adoption of climate smart agricultural systems (Dale et al., 2013; Vervoort et al., 2014).

Scenario analysis can be a useful tool to deal with the complexity of CSA upscaling and identify the practices and policies necessary to achieve the desired futures (Schaafsmaa et al., 2018). Scenarios are defined as coherent descriptions of plausible hypothetical future situations, including uncertain but important socioeconomical, environmental, and technological conditions that may generate that future (Van Notten, 2006). Bioeconomic farm models make it possible to test scenarios aimed at upscaling newly designed agricultural activities, given farm constraints and farmers' risk aversion (van Ittersum et al., 2008). These models prove useful for testing the impacts of new markets and policy conditions. Chopin et al. (2017) proposed a methodological framework for designing exploratory and normative scenarios yielding multi-functional agricultural landscapes with the multi-scale optimization bioeconomic model MOSAICA. Their approach is based on the progressive design and analysis of scenarios to test the ability of new production systems and policies to achieve targeted goals such as CSA objectives.

In this study, the approach of Chopin et al. (2017) was applied to design identification scenarios for the levers that allow the CSA objectives to be reached under future climate conditions with new agroecological systems and adapted policies. We define as "scenario," the context in which farmers choose their cropping systems and the output of the model in terms of a cropping system mosaic at the regional scale and the associated indicators of sustainability. With a multi-scale and transdisciplinary approach based on the combination of farming system experimentation and scenario-based bioeconomic modeling, the aim was to understand how CSA can be successfully upscaled in a small agricultural region of Guadeloupe. The remainder of this paper is organized as follows. First, the methodological framework is presented, as well as how this framework has been implemented in a small agricultural region on the Guadeloupe Island. Section 3 presents the results of the modeling of the five scenarios. Section 4 discusses the implications of the results for policymakers and the limitations and scope of our research.

2. Material and methods

2.1. The modeling framework

2.1.1. Interrelationships across scales

Agricultural systems can be analyzed as nested hierarchical systems (Giller, 2013; Le Gal et al., 2010; Wery, 2015). Reaching sustainability goals at a regional scale requires an adequate combination of innovations at the field scale (agroecological techniques) and adaptation of farm structure organization (integrated farming system, resource allocation), markets, supply chains, and policies. First, to sustainably improve or preserve ecosystem services provided by cropping systems on the landscape scale, biophysical processes must be adapted at the field scale. A cropping system can be defined as a biophysically “controlled” system (Lamanda et al., 2012). Crop management can be determined by the technology and knowledge available at the farm level, or by the field ecosystem aiming at targeted ecosystem services and resources used. Indeed, a technical system in a given field is subject to the decision-making process of the farmer, who manages several fields and agricultural production on their farm. Whole-farm management is conducted with a limited set of resources (such as money, skill, time, and land), with the goal of satisfying the personal objectives of the farmer (Blazy et al., 2011). A farmer’s decision to adopt an innovation is also influenced by personal beliefs, particularly their attitude towards risk and uncertainty, when considering the opportunity to modify their technical systems. The decision-making process behind potential innovation adoption by farmers may also be influenced by opportunities and barriers expressed outside the farm. However, these “external” factors are not controlled by the farmers. Markets, input supply chains, and food systems can create new opportunities or barriers that affect the perceived utility of adopting innovations. Policy incentives such as agroenvironmental schemes may facilitate the adoption of such innovations by compensating for the net losses that occur owing to the required management changes and transaction costs. Finally, designers of new agricultural systems must consider the heterogeneity of fields and farms at a landscape scale.

2.1.2. Overview of the methodological framework

The proposed framework aims at quantification, spatial integration from the plot to the regional level, and modeling of scenarios for upscaling CSA. The framework (Figure 1) consists of five main steps and combines typology building from a database on farm production systems (step 1); a survey on a sample of farms to diagnose the sustainability of farming systems with a set of indicators (step 2); the design and field experiment of an innovative prototype of the climate smart farming system (steps 3 and 4); and the modeling of scenarios using data from the diagnosis, experiment, and identification of socioeconomic levers to upscale CSA (step 5). Steps 1 and 2 characterize the current farming system within the study area. This consists of building a typology of farming systems to model the diversity of farms in the region, notably in terms of pedoclimatic conditions, nature of farming systems, and farmers' economic endowments. Ideally, the typology is built using census data of farms on crop rotation and area, via a robust statistical clustering method (Blazy et al., 2009; Chopin et al., 2015a). The typology serves as an in situ survey of several farms for each farm type identified. The data collected were then used for the diagnosis of the current regional farming system considered as the "baseline". This diagnosis is based on a set of sustainability indicators, including the potential impacts of climate change (Chopin et al., 2017a). The outputs of these first two steps serve as a basis for the design of prototypes of agroecological crop management systems (step 3), following the method of Blazy et al. (2009). They also serve for the calibration and parameterization of the baseline situation into the bioeconomic model used in step 5 for modeling scenarios.

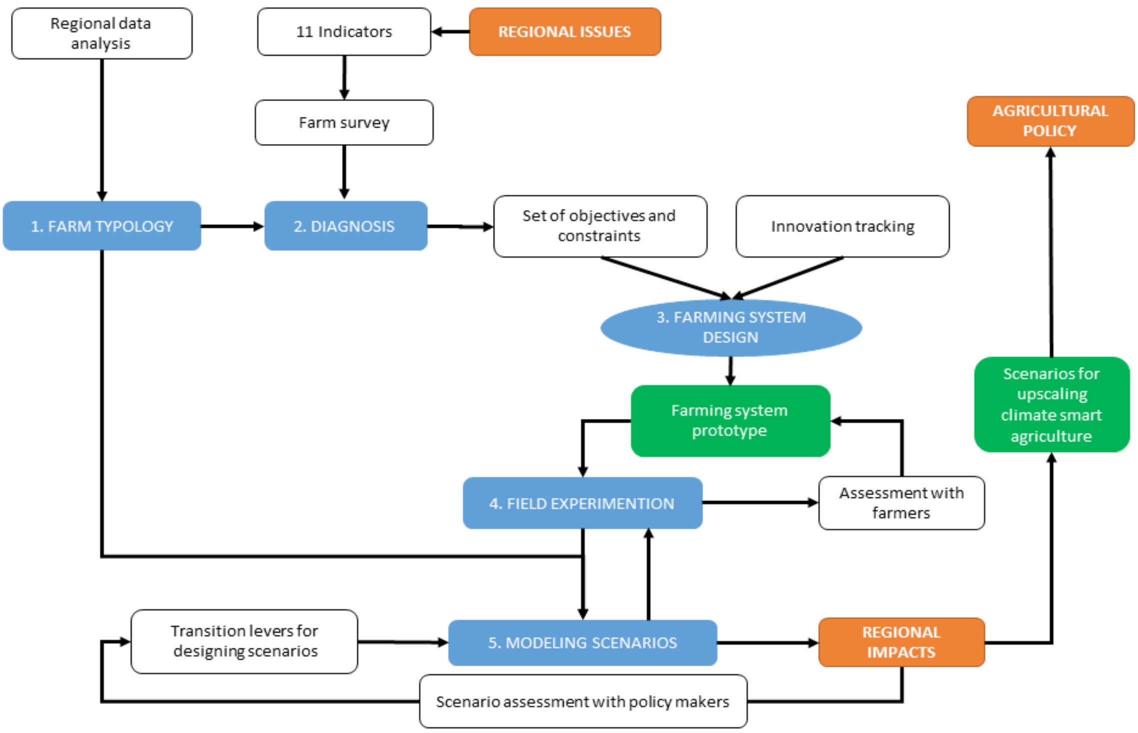

Figure 1. Overview of the methodological framework. The blue boxes correspond to the five main steps of the framework. The green boxes correspond to the main outputs of the framework. The white boxes correspond to the different tools used.

The design of the prototypes of agroecological farming systems is inspired by the regional diversity of issues that farms must address and is exclusively based on agroecological and bioeconomic principles. The design process mobilizes both scientific evidence and farmers' knowledge to propose redesigns of current farming systems, considering farm issues as well as existing opportunities for circular bioeconomy on a regional scale. The output of Step 3 is a co-designed prototype defined as a conceptual model of a farming system that is later experimented on a small-scale pilot farm in Step 4. The purpose of this study is to acquire technical, economic, and environmental references for prototypes of alternative systems. In addition to the parameterization of the model used in Step 5, the role of the experimental microfarm is to provide an interface for discussion and co-evaluation of solutions with stakeholders to adapt farming systems, value chains, and agricultural policies. Subsequently, the resulting data of the experiment in Step 4 are used in Step 5 to evaluate the innovative production system on a regional scale and the design of scenarios using the bioeconomic model MOSAICA (Figure 2).

2.1.3. The modeling approach

MOSAICA simulates mosaics of cropping systems in different agricultural and policy contexts (Chopin et al., 2015b). The model accounts for constraints and opportunities in the field (e.g., soil types and climate), farm (e.g., availability of production factors), and regional levels (e.g., market size). The inputs of MOSAICA are: i) a geographic database of fields that contains information about their biophysical context and their farm structure (e.g., farm size, soil type, and climate); ii) a database of agricultural activities and their technical-economic coefficients describing the cropping systems that can be allocated to fields and entailing the current conventional activities (characterized in step 2) as well as new ones corresponding to the prototype designed in step 3 and assessed in step 4; and iii) the farm typology (step 1) that represents the diversity of farming situations and farmers' risk aversion.

The model is a linear programing model. It optimizes the sum of individual farmers' utilities on a regional scale, which includes revenues and the coefficient of risk aversion towards price and yield variations, which is the calibration parameter. The allocation of cropping systems is modeled through a set of equations modeling the choice of cropping systems by farmers. The objective function of our regional bioeconomic model is a Markowitz-Freund (Mosnier et al., 2009). The optimal acreage at the regional scale is obtained from the maximization of utility, which is the maximum of the sum over the full population of farmers of the total farms' gross margins of activities balanced by the sum of expected positive and negative variations in the gross margin for each activity multiplied by a risk-aversion coefficient at the farm scale (see Chopin et al., 2015a). The risk is then modeled using a linear approach (Mosnier et al., 2009). The coefficients of variability are determined for each activity based on agroeconomic expertise and encompass both agronomic risk (yield variability related to climate conditions, pest attacks, or diseases) and commercial outlet risk (from the variability in selling price during the selling season) aggregated together. The calibration procedure is based on the allocation of several sets of risk-aversion coefficients to farmers according to their farm type. These risk-aversion coefficients at the farm scale help reproduce farmers' cropping plans based on a hypothesis about their level of risk aversion.

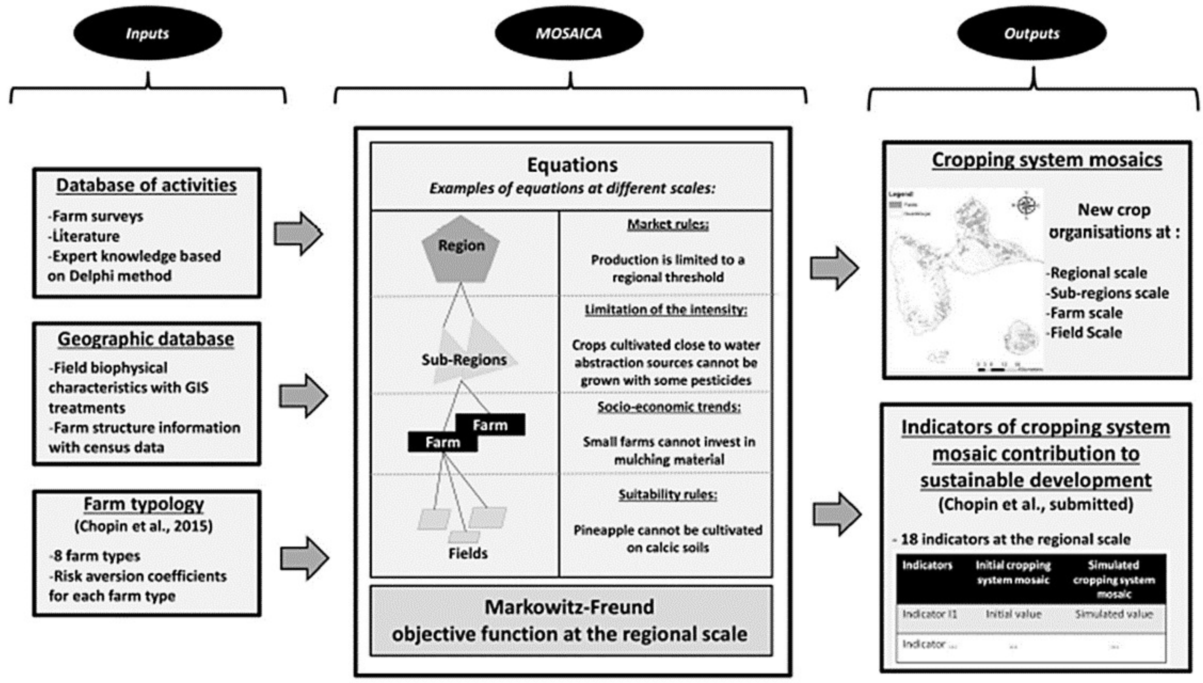

Figure 2. Structure of the bioeconomic model MOSAICA (Chopin et al., 2015b).

The outputs of the model are new agricultural landscapes (called mosaics of cropping systems) and the calculation of sustainability indicators (Chopin et al., 2017a). These indicators were chosen during successive transdisciplinary workshops involving researchers, farmers, and politicians to account for the most important issue in the study area. A description of each indicator used in this study is provided in Supplementary Material 1. These indicators assess the impact of agriculture on society and the environment at the landscape scale by accounting for cropping system externalities at the plot scale and the locations of these cropping systems. The model simulates how introducing new cropping systems and adapting policies could orient farmers towards choosing new cropping systems. This simulated mosaic at the landscape scale was then assessed using the same set of indicators as in the diagnosis (Step 2). Iterative testing of levers in scenarios involving policymakers allows the identification of consistent sets of innovations and policy adaptations, that is, scenarios that satisfy biophysical rules and farmers' socioeconomic constraints (Chopin et al., 2017b).

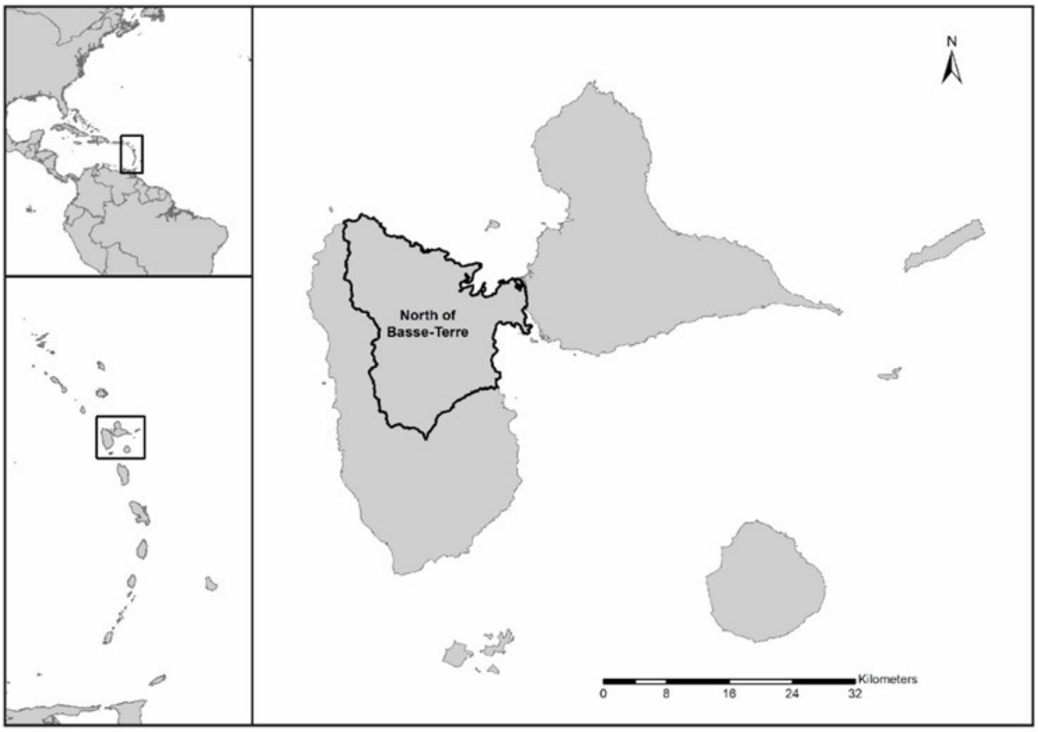

Figure 3. The study site is the north of Basse-Terre (Guadeloupe) covering a surface of 360 km².

2.2. Application of the framework in Guadeloupe

2.2.1 Study area and farming systems context

The framework presented was applied to the North Basse-Terre region of Guadeloupe, a French overseas department in the Caribbean (Figure 3). Guadeloupe is an archipelago (1628 km²) comprising two main islands, Basse-Terre (848 km²) and Grande-Terre (586 km²), with vast ecological contrasts. Sierra et al. (2015) divided the archipelago of Guadeloupe into five agroecological regions. This study focused on the agroecological region of northern Basse-Terre (NBT), characterized by an annual mean temperature and rainfall of 25.4 °C and 2300 mm/yr, respectively, as well as kaolinitic ferralsols developed on aged volcanic ash deposits. The agricultural land area (ALA) represents 5033 ha and 763 farms. In Guadeloupe, agriculture specializes in producing export crops (sugar cane, banana). Intensification over the past three decades has caused widespread environmental damage (e.g., soil and water contamination and biodiversity loss). Farms are poorly diversified, and the local supply of products for the domestic market (especially fresh fruits and vegetables) cannot meet demands (Chopin et al., 2015a). This situation leads to dependence on external supplies, as less than 25% of food needs are met.

A recently conducted GHG inventory analysis indicated that N fertilizers and lime spreading were key causes of GHG emissions (Colomb et al., 2014). Replacement of inorganic fertilizers with organic amendments in agriculture has been explored as a means of managing soil fertility in a more sustainable manner (Blazy et al., 2015; Sierra et al., 2016). This situation is particularly critical, as the combination of climate change and intensive agricultural practices may lead to a decrease in soil organic matter content and thus an increase in CO2 emissions (Sierra et al., 2015). Orienting farmers towards the use of agroecological crop management systems and organic amendments may therefore be a way of reducing the negative environmental impacts of agriculture. It may also be a way to mitigate climate change by storing C in soils and adapting agriculture to climate change by enhancing soil water retention capacity. However, while many climate-smart practices exist, such as enhancing soil organic carbon with agroecology, farmers often face barriers to implementing them (Paul et al., 2017).

2.2.2. Regional diagnosis of farming systems

State census data on the acreage and crop rotations of 763 farms were used as input data to conduct the typology of farming systems in our study area. The data represent 90% of the ALA in the study region. A 4-class typology was obtained following the method detailed by Blazy et al. (2009), combining a principal component analysis with hierarchical clustering (Figure 4).

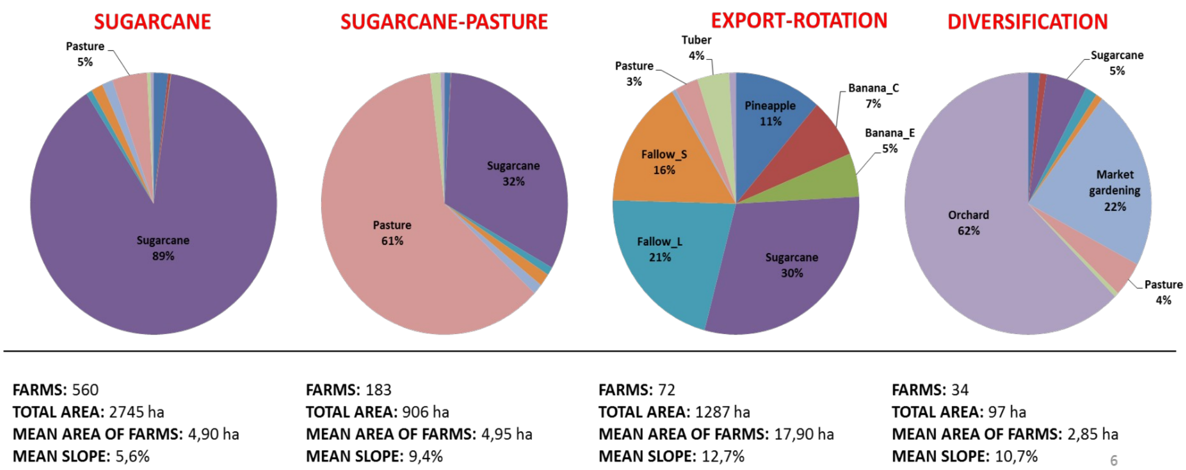

Figure 4. Typology of farms in the North Basse-Terre region (Guadeloupe).

From the typology, three farms in each of the four clusters were randomly selected and surveyed. The diagnosis of the surveyed farms targeted three pillars of CSA: food security, mitigation, and adaptation. These three pillars rely on economic, social, environmental, and agronomic factors. Surveying the 12 farmers provided data on their current agricultural practices. Based on the typology, these data were attributed to each farm in the MOSAICA model for parameterization.

2.2.3. Agroecological farming system design and experiment

The design mobilized the knowledge of eight researchers from diverse scientific disciplines and twelve farmers during several individual and collective meetings. Given the results of the diagnosis, the design of the agroecological prototype of the farming system was based on strong agroecological and circular bioeconomy principles (detailed in Supplementary Material 2) as a means of improving food security, adapting to climate change, and mitigating it in a sustainable way. Agroecological rules and practices relate to (1) soil and nutrient management; (2) flows of solar radiation, air, and water; (3) pest and disease management; (4) species and genetic diversification; and (5) the integration of production within the farm. The "bioeconomy component" of the new agricultural activities relies on the fact that the latter entail only local and bio-sourced inputs, most of them resulting from residual biomass recycling (e.g., massive amendments with industrial compost and mulching with sugarcane by-products). These principles produced a consistent set of practices with high environmental (e.g., no use of synthetic fertilizers and pesticides, intercropping, maximization of biodiversity, valorization of native species and varieties, and valorization of complementarity between crops) and social objectives (e.g., integrating the diversity of currently grown crops, favoring locally available inputs, growing crops for feeding local demand and markets only, facilitating human work, and protecting worker and consumer health). This strategy yielded a prototype of a production system called KARUSMART (Figure 5). The system is structured to stimulate biodiversity and natural regulations and entails a total of more than 60 crops. The list of the main cash crops for each cropping system is detailed in Supplementary Material 3. Surrounded by multi-functional hedges, the system is made of six diversified blocks of sugarcane, banana, tubers, Caribbean crops (e.g., cassava, pineapple, and guava), vegetable crops, and a small livestock system. The implementation of the KARUSMART system began in February 2018 in the form of an experimental microfarm with a surface of 0.7 ha located at the INRAE research institute in Petit-Bourg, the heart of the study region (Figure 5). For this study, the data representing the first three years of the trial were averaged to describe new agricultural activities in the MOSAICA model. Soil analyses were conducted at the beginning of the implementation of the system and were subsequently conducted at least once a year. Data were collected daily the technical management of each block, duration of the work, bio-input uses, purchases, and harvested production. These data were used to calculate the performance of the new activities using a set of indicators and to calculate the technical-economic coefficients for parameterizing the model. Through participatory assessments with farmers, the technical management of AE activities was continuously improved.

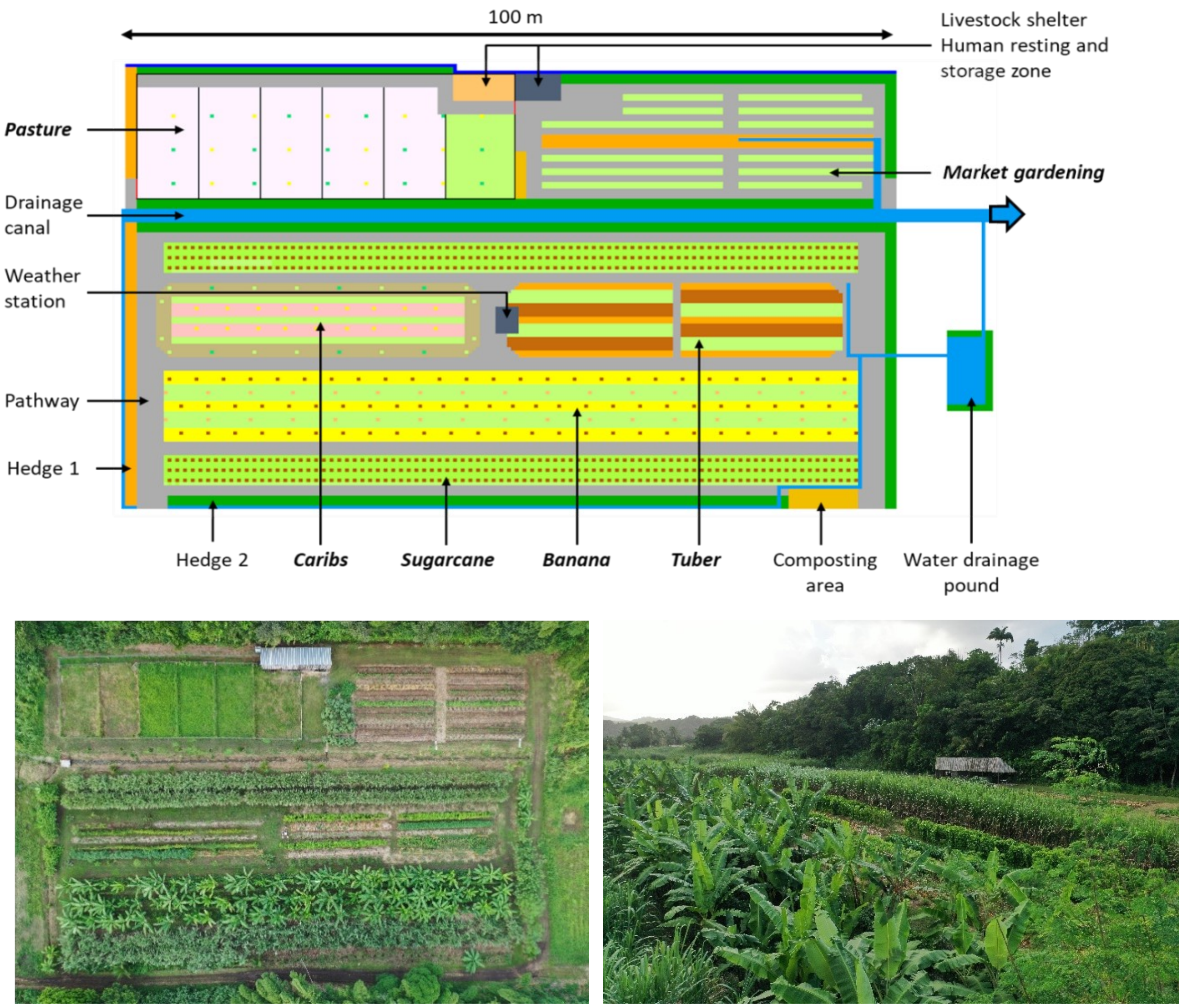

Figure 5. Conceptual model of the structure of the pilot microfarm KARUSMART (above) with aerial photographs of the six highly diverse and interconnected agroecological (AE) activities after 30 months of implementation: Banana AE, Caribs AE, Market gardening AE, Pasture AE, Sugarcane AE, and Tuber AE.

2.2.4. Parameterization and calibration of the MOSAICA model

The technical-economic coefficients for parameterizing the model for conventional current systems, each of the six retained AE activities, and the entire farming system (considered as an integrated activity) are presented in Supplementary Material 4. The calibration of the model is done by adjusting the risk aversion coefficients per farm type until obtaining 80% of correct allocations of crop areas. In this study, this procedure yielded a satisfactory rate of

96.5% of overall agricultural areas correctly simulated at the regional scale, with 80% of the areas presenting the correct spatial allocation. The diversity of crops was also well simulated at the regional scale, as the same Shannon index of diversity (1.8) was obtained for observed and simulated mosaics of cropping systems. The model was tested at the farm level for its ability to model crop diversity. The ratio between the Shannon index calculated for the modeled initial situation (0.39) considering the weighted average index of the diversity of each farm and the value obtained for the observed situation (0.53) yielded a value of 73%, which indicates that the model tends to reduce the diversity observed within the farms.

2.2.5. Climate projections

Climate projections were obtained using the ARPEGE-Climat model (Chauvin et al., 2020; Cantet et al., 2021) with radiative forcing parameters based on the Representative Concentration Pathway (RCP) 8.5 (Cubasch et al. 2013; Moss et al., 2010). This is the scenario for GHG emissions (IPCC 2021). While pessimistic, it has the advantage of showing policymakers the global and local consequences of human-induced climate change if no action is taken. The atmospheric model is a component of Météo France's (the French meteorological service) coupled general circulation model (CGCM) involved in the IPCC's Coupled Model Intercomparison Project phase 6 (CMIP6, Roehrig et al., 2020; Voldoire et al., 2019). A specific configuration allowed a local horizontal grid spacing of < 15 km over the western tropical northern Atlantic. This enabled representation of Guadeloupe's climate explicitly despite the island's reduced size, unlike CMIP coarse-resolution CGCMs (Cantet et al., 2021), which are critical for island-scale climate projections (Cantet et al., 2014). Although our choice of a specific climate model introduces unquantified uncertainties, to our knowledge, this is the only state-of-the-art model available for the study area with an optimal resolution for our purposes. Furthermore, it has the advantage of allowing a realistic representation of strong hurricane winds and heavy rainfall (Chauvin et al., 2020), which are considered in our modeling framework.

2.2.6 Definition of scenarios for upscaling CSA

Table 1 presents the different contexts of the modeled scenarios (in columns) and the levers applied to each of them (lines). The aim of the scenarios, defined by stakeholders, was to assess the impact of climate change in the long term and the impacts of several agronomic and economic levers to mitigate its consequences on the sustainability of agricultural systems, with all other things being equal." The five scenarios were defined as follows: (1) the choice of a climate change scenario, (2) the identification of levers and their combinations during workshops involving researchers and decision makers, and (3) the modeling and analysis of scenarios. The context of the baseline corresponded to the current situation, that is, the current available activities, socioeconomic context, and climate conditions. The mosaic of cropping systems and values obtained for the eleven indicators in the baseline corresponded to the calibrated model output.

	VARIABLES	**Baseline**	**S1**	**S2**	**S3**	**S4**	**S5**
CLIMATE CHANGE	Yields decrease Mineralization factors	=	2056–2080 climate projections	2056–2080 climate projections	2056–2080 climate projections	2056–2080 climate projections	2056–2080 climate projections
AGROECOLOGICAL SYSTEMS	New agroecological (AE) activities	=	=	7 new AE activities	7 new AE activities	7 new AE activities	7 new AE activities
AGRICULTURAL LABOR INCREASE	Increase of work force availability at the regional scale	=	=	=	+0.5 FTE/Ha	+0.5 FTE/Ha	+0.5 FTE/Ha
PUBLIC POLICIES	Subsidies allocated to AE activities	=	=	=	=	-50% on export crops/+50% on AE activities	-50% on export crops/+50% on AE activities
FARMERS' TRAINING	Risk aversion coefficient	=	=	=	=	=	-25%
ECO-LABEL AND SHORT MARKETING CHANNELS	Selling prices	=	=	=	=	=	+50%
SMALL-SCALE MECHANIZATION	Labour requirements	=	=	=	=	=	-25%
AGRONOMIC PROGRESS	Yields of AE activities	=	=	=	=	=	25%

Table 1. Description of the context of the baseline and the five scenarios made of the different levers explored. AE: agroecological; FTE: full time equivalent work unit; "=": no change

Scenario S1 illustrates a climate change scenario for the period 2056–2080 with a "business as usual" continuation in agricultural systems. The aim of this study was to assess the potential impacts of climate change on agricultural systems in the study area. Scenario S1 was parameterized in the MOSAICA model using two variables: impact on yields and soil organic matter [soil organic carbon (SOC)] mineralization factors. The impact of climate change on

SOC was calculated using empirical relations obtained from historical data (Chopin and Sierra, 2019; Sierra et al., 2015). Impacts on crop yields were calculated by accounting for five climatic hazards (hurricanes, heat waves, drought, flood, and rising sea level) and a measure of the evolution of the cropping system vulnerability (Blazy, 2019). The potential impact index, which combined indicators of exposure to climatic hazards and sensitivity of the cropping systems using the crop ecophysiology, the characteristics of the field, and agricultural practices, was calculated for each field of the study area. The difference between the potential impact index for the current situation and for horizon 2056–2080 was used as a proxy to estimate yield variation. These values are provided in Supplementary Material 5 as potential impacts of climate hazards on agricultural activities. Climate change was included in scenarios S1–S5.

Scenario S2 was built upon Scenario S1 with the introduction of seven new AE activities. This scenario was selected to explore the adoption potential of AE activities without any policies or socioeconomic measures. Scenario S3 corresponded to Scenario S2 with the added assumption of a larger available work force of +0.5 full-time-equivalents/ha on a regional scale. The low adoption of labor-intensive activities due to the lack of available agricultural work force in the study region was addressed in this scenario. Scenario S4 corresponded to S3, with a 50% reallocation of the subsidies given to export crops in favor of AE activities, which corresponds to an extra bonus of $1385/ha for AE activities. The vast differences in the amount of subsidies dedicated to conventional export crops (banana and sugarcane) compared to crops for local markets are often pinpointed as a barrier to the adoption of AE activities.

Scenario S5 was an ambitious one, exploring the impacts of a strong policy in favor of AE transition. It added the four following levers to S4: i) AE yields increase by 25% (progressive improvement of soil characteristics, ecosystem services, and farmers' knowledge); ii) an increase in the price of AE products by 50% (ecolabeling and short marketing channel development); iii) a decrease in farmers' risk aversion (farmers' training and knowledge diffusion with extension services); iv) a reduction in agricultural operation duration of 25% (availability of adapted small machinery and increase in labor efficiency by learning process).

3. Results

3.1. The baseline

Figure 6 shows that conventional sugarcane and pasture activities represented 3248 ha and 649 ha (e.g., 73% and 14%) of the ALA, respectively. The remaining ALA was mainly represented by market gardening (135 ha), pineapple (100 ha), orchard (98 ha), and banana exports (88 ha).

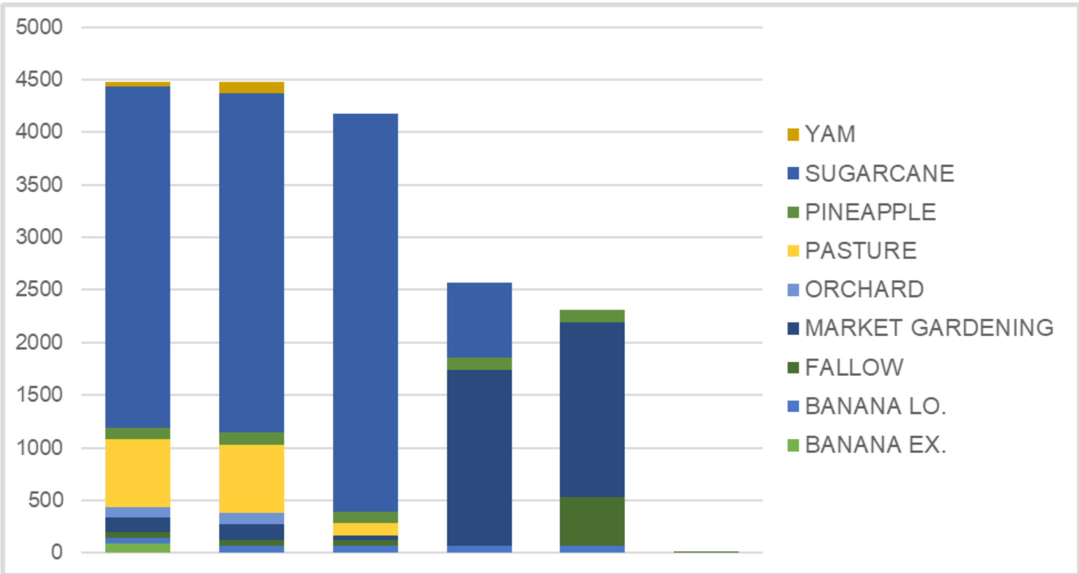

Figure 6. Presentation of the area of agricultural activities (hectares) for the actual situation (baseline) and for the five scenarios simulated in this study. AE = agroecological; LO. = local market ; EX. = export market.

Table 2 shows the average performance of the farming systems in the study region. With 0.1 full-time-equivalent positions per hectare, a gross margin of \$3,300 /ha/yr, and a labor productivity of \$23.3/hr, the farming system of this sub-region contributed to about 450 direct jobs, which is low in relation to the population size (91,000 inhabitants). The average nutritional performance was 3 people fed/ha/yr; thus, this farming system could feed approximately 13,500 people (e.g., 15% of the population of the study area). In terms of adaptation to climate change, the overall potential impact of climate change on the current farming systems reached an average baseline of 28%.

According to the calculation method, this value means that the current climate context has a 28% chance of inducing significant impacts on farm production. The farms in the study region relied on 4.4 kg/ha/yr of active pesticide ingredients and 70 kg/ha/yr of inorganic N. In terms of mitigation potential, GHG emissions were on average 1.9 tCO2eq/ha/yr. However, the SOC variation was -0.5 tCO2eq/ha/yr; thus, the average regional GHG balance was an emission of +2.4 tCO2eq/ha/yr in the baseline scenario. Therefore, the farming system emitted 0.8 tCO2eq/yr per nourished person. The last indicator revealed that an average of 1.2 tillages per year were performed in each field.

	INDICATORS	UNITS	Baseline	S1	S2	S3	S4	S5
FOOD SECURITY	Gross margin	\$/ha/yr	3.3E+03	2.7E+03	3.1E+03	10.2E+03	10.3E+03	22.6E+03
	Labor requirement	Person/ha/yr	0.1	0.1	0.1	0.6	0.6	0.6
	Labor productivity	\$/hr	23.3	19.3	20.6	11.2	11.5	25.0
	Average nutri. perf.	Fed person/ha/yr	3.0	2.1	2.0	6.7	6.9	6.0
ADAPTATION	Climate potential impact	%	28	32	32	34	32	28
	Pesticides active ingredients	Kg/ha/yr	4.4	4.4	4.8	2.2	1.4	0.0
	Inorg. nitrogen	Kg/ha/yr	70	66	68	34	22	0
MITIGATION	GHG emissions	tCO2eq/ha/yr	1.9	1.8	1.4	1.5	1.9	3.3
	SOC change	tCO2eq /ha/yr	-0.5	-0.9	-0.3	+0.3	+1.1	+4.0
	GHG balance	tCO2eq/ha/yr	2.4	2.7	1.7	1.2	0.8	-0.7
	Ploughing intensity	Passage/ ha/yr	1.2	1.2	1.2	2.6	2.3	0.7
TOTAL PUBLIC INCENTIVE		\$/ha/yr	3125	2679	3125	1853	2188	4464

Table 2. Results of the 11 indicators selected for the actual situation (baseline) and for the five scenarios explored in the study for the studied region (4480 ha, 763 farms).

3.2 Scenario S1: "Climate change"

The simulation of the climate change impact for 2056–2080 did not produce significant changes in the two dominant activities. Sugarcane and pasture area shifted from 3248 ha to 3,229 ha (-1%) and from 649 ha to 645 ha (-1%), respectively (Figure 6). However, the remaining ALA showed significant changes in market gardening (+9%), pineapple (+15%), orchards (+16%), and yams (+130%). Moreover, banana exports almost disappeared, while the area of bananas cultivated for the local market rose slightly, from 58 ha to 66 ha. One can observe, however, an important decrease in the average gross margin from \$3,300/ha/yr to \$2700/ha/yr (-18%) and labor productivity (-17%). Equally, the nutritional performance showed an important decline of -30% from 3.0 to 2.1 fed people/ha/yr corresponding to a potential for feeding 9,400 people (10% of the population). On a regional scale, the adaptation indicators showed that the overall potential impact of climate change increased by 14% and reached an average value of 32% for 2056–2080. The model simulation showed a slight decrease in inorganic N use (-6%), however, a constant application of pesticide active ingredients. For the mitigation potential, the GHG emissions displayed a 5% decrease from 1.9 tCO2eq/ha/yr to 1.8 tCO2eq/ha/yr, while the SOC reduction almost doubled with an 80% increase in emissions from -0.5 tCO2eq/ha/yr to -0.9 tCO2eq/ha/yr, corresponding to a global GHG balance of +2.7 tCO2eq/ha/yr. These changes will lead to 1.3 tCO2eq emission per nourished person (+62%). The annual number of ploughings per hectare remained the same in this scenario. This simulation shows that climate change could have detrimental impacts on food security if no changes are made to the farming systems.

3.3. Scenario S2: "New agroecological activities"

This scenario corresponds to S1 with the introduction of the seven new AE activities previously designed. In S2, sugarcane activities increased to 3,784 ha (+16%), whereas pasture activities showed an notable reduction of 112 ha (-83%). The activities of both bananas for export and local markets showed the same tendency as that of S1 (Figure 6). Furthermore, both yam and orchard activities were no longer represented, while market gardening showed an important decrease of -68%. Interestingly, one can see that the introduction of the new AE activities in the actual socioeconomic context included the adoption of 114 ha of "AE pasture" and 186 ha of "AE tuber", corresponding to 7% of the ALA devoted to AE activities. With a gross margin of \$3,100/ha/yr (-6% compared to that of the baseline) and a labor productivity of \$206/hr (-12%), this scenario presented higher economic performance than S1. However, the nutritional performance presented the same significant decrease with 2.0 fed people/ha/yr (-33%). For the adaptation indicators, the climate potential impact showed the same increase as S1 (+14%). Owing to the increase in conventional sugarcane (+536 ha) area and the decrease in livestock area (-537 ha), the application of pesticides' active ingredients showed an increase of +9% with 4.8 kg/ha/yr. The use of inorganic N was slightly reduced to 68 kg/ha/y. The GHG emissions decreased to a value of 1.4 tCO2eq/ha/yr (-26%), with SOC change decreasing by -40% from -0.5 tCO2eq/ha/yr to -0.3 tCO2eq/ha/yr. These values correspond to a -29% decrease in global GHG balance with +1.7 tCO2eq/ha/yr with an equal value of 0.8 tCO2eq emitted per nourished person. The last indicator of mitigation potential indicates no change in the plowing intensity in the new mosaic of activities. This scenario shows that with no changes in the socioeconomic environment of farming systems, the adoption of the newly designed AE activities is relatively low.

3.4. Scenario S3: "Increase of work force availability"

The availability of an additional 0.5 full-time equivalent (FTE) work force units per hectare in scenario S3 led to important changes in the farming system structure at the regional scale. Sugarcane area showed a significant reduction of -78% (715 ha), while pasture was no longer represented. Notably, market gardening became the dominant activity and represented 1,672 ha (37% of the ALA). The projections of the other conventional activities presented the same tendencies as S2, except for fallow, which was no longer present. The new AE activities were more readily adopted than in S2, with AE sugarcane representing the second most important activity at 1,160 ha of area. Moreover, AE pasture and tuber activities took third and fourth positions (just behind conventional sugarcane) at 384 ha and 367 ha of area, respectively. Globally, 43% of the ALA was devoted to AE activity in S3. These changes led to an increase in the average gross margin from $3,300/ha/yr to $10,200/ha/yr (+209%), even if the working productivity showed a decrease of -52%. This situation was due to larger production values with a -42% decrease in government subsidies allocated. Another interesting result was the +123% increase in nutritional performance with 6.7 fed people/ha/yr, corresponding to a potential for feeding 30,000 people (i.e., 33% of the population), more than double the actual (baseline) score. This increase was due to a notable increase in conventional market gardening activity at the expense of conventional sugarcane activity. All the other indicators showed a net improvement: inorganic N (-51%), pesticide active ingredients (-50%), and ploughing (-15%). GHG emissions were forecast at an average value of 1.5 tCO2eq/ha (-21%), and the SOC change became positive with an average value of +0.3 tCO2eq/ha/yr. These values correspond to a -50% decrease in global GHG balance with the emission of +1.2 tCO2eq/ha/yr, leading to a value of 0.2 tCO2eq per nourished person, which is four times lower than that in the current situation. However, among the three indicators of adaptation, the global potential impact of climate change on the new mosaic of the cropping system is approximately 21% higher than that in the current situation without climate change (Table 3). This was mainly due to the replacement of sugarcane by market gardening crops that are more sensitive to climate change, particularly to heat and drought waves. Moreover, this large adoption of conventional market gardening activities led to more than double the average number of ploughings with 2.6 per year. This scenario clearly shows the key role of increasing the availability of the agricultural workforce to increase food autonomy in Guadeloupe.

3.5. Scenario S4: "50% of subsidy reallocation to local crops"

In scenario S4, market gardening with 1,661 ha (37% of the ALA) and fallowing with 465 ha (about 10% of the ALA) were the dominant conventional activities. For other conventional activities, only local banana (66 ha) and pineapple (115 ha) production was still present in the ALA. In this scenario, there was a significant adoption of the AE activities, representing almost 50% of the regional ALA. The AE pasture was dominant (1,423 ha), followed by AE sugarcane (384 ha), and AE tuber (367 ha). Similarly in S3, the average nutritional performance in S4 was high, with 6.9 fed people/ha. The potential impact of climate change presented the same +14% increase as in S1, while the two other indicators of adaptation showed improvement with a -68% decrease in pesticide active ingredient application (14 kg/ha/yr) and -69% decrease in inorganic N use (22 kg/ha/yr). For the mitigation potential, the GHG emissions were 1.9 tCO2eq/ha/yr in this scenario, which matches the baseline amount. However, the SOC change switched from emissions (-0.5 tCO2eq/ha/yr at baseline) to sequestration with +1.1 tCO2eq/ha/yr. This value corresponds to a -67% (0.8 tCO2eq/ha/yr) decrease in global GHG balance in S4. Therefore, the new mosaic of activities led to a value of about 0.1 tCO2eq emitted per nourished person, which is 13 times lower than that in scenario S1. Finally, the mitigation potential indicator "number of ploughing operations" showed a significant increase from 1.2 to 2.3 operations per hectare and per year (e.g., +90% as compared to that of the baseline) (Table 3). This scenario clearly demonstrates the key role of adapting subsidies to orient farmers' choices towards AE activities. However, conventional market gardening activities remain very attractive relative to AE options, mainly because of their higher gross margins.

3.6. Scenario S5: "multi-levers"

In this scenario, the model simulated a complete transition of farming systems towards AE activities (Figure 6). AE pasture was strongly adopted with an area of 3,729 ha (83% of the ALA), followed by AE Caribs, AE tubers, and AE bananas with 399 ha (9%), 294 ha (7%), and 46 ha (1%), respectively. This complete change in the regional farming structure was viewed alongside the best improvement in the average farm performance (Table 3). The average gross margin and labor productivity rose to $22,600/ha/yr and $25/hr, respectively. The nutritional performance was doubled compared to that of the baseline (6.0 fed people/ha/yr) and tripled compared to that of S1. This scenario simulated the use of inorganic N and pesticides in the study region. Moreover, plowing practice significantly decreased, with an average value of 0.7 operations per year (-42%). This low value was mainly due to the strong adoption of AE pastures. Because of livestock development, this mosaic of activities also induced a significant increase in GHG emissions with 3.3 tCO2eq/ha/yr, due to enteric fermentation of ruminants. However, SOC change reached a value of +4.0 tCO2eq/ha/yr, leading to a positive global GHG balance of -0.7 tCO2eq sequestered per hectare per year (Table 3). The additional cost ($525) for mitigating 1 tCO2eq in this scenario was determined by dividing the difference in GHG between S1 and S5 by the difference in public incentives: (-0.7) - 2.7 = -3.4 / ($4464 - $2679) = $525 $tCO2eq^{-1}$. This calculation was also used to compare S5 and baseline, resulting in $432.Food production corresponded to the sequestration of 0.1 tCO2eq/ha/yr per fed person. Finally, the potential impact of climate change on this new mosaic of farming systems was assessed, resulting in an average value of 28%, which is 12.5% less than that in S1; thus, there was a decrease in vulnerability.

4. Discussion

4.1. Lessons for policy makers and practical recommendations for upscaling CSA

Based on the scenario analysis in Guadeloupe, our study provided some evidence regarding levers to be mobilized for upscaling CSA from the field to the regional scale. Because it leads to an increase in food autonomy and a strong improvement in the balance of GHG of local agricultural systems and adapts farming systems to climate change while maintaining productive capacities, the "multi-levers" scenario S5 makes reaching the CSA objectives an attainable prospect (Figure 7). In S5, all sustainability criteria were indeed improved, which made it possible to increase food security twofold, while contributing to climate change mitigation (sequestration of 0.7 t/ha/yr) and drastically reducing the negative environmental impact of agricultural systems. The additional public cost of this scenario was $1339 per hectare, which is low given the social and environmental benefits it provides, such as employment increase, reduction in pesticide use, and increase in food autonomy.

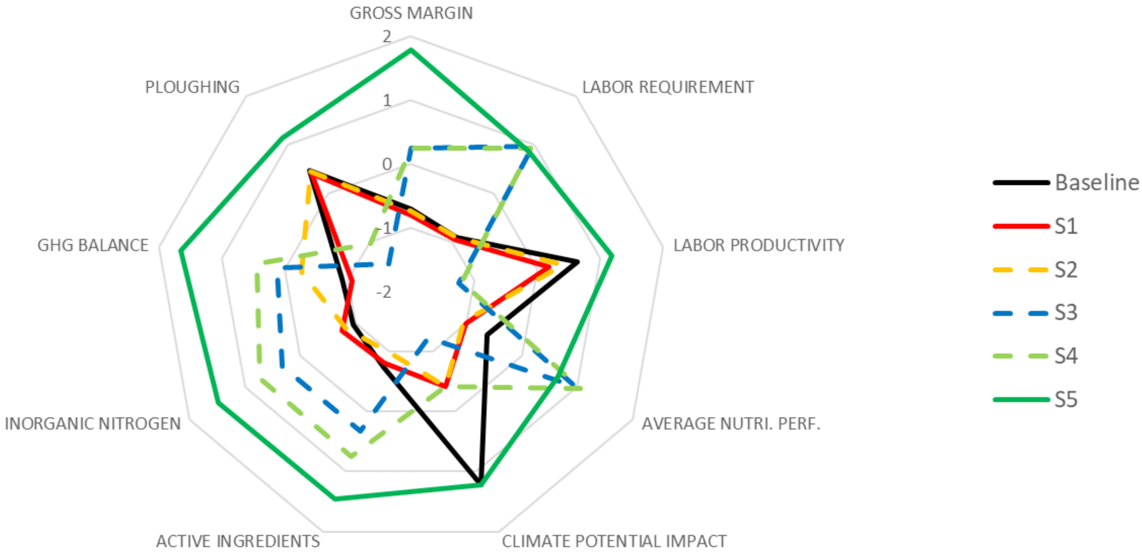

Figure 7. Radar charts of the relative scores of nine indicators for the five explored scenarios and the baseline. Note: after mean-centering the scores, the values of indicators that should have decreased were multiplied (Climate potential impact, Active ingredients, Inorganic N, GHG Balance, and Ploughing) by -1 in order to have the same reading. Higher values correspond to better performances. GHG Balance = GHG emissions - SOC changes.

If new crop management systems based on agroecology and bioeconomy have the potential to reach the goals of CSA, the results obtained in this study confirm that a set of new policies targeting farmers' constraints are required to upscale CSA (Ollivier et al., 2018; Meynard et al., 2018; Thornton et al., 2017; Westermann et al., 2015). Indeed, comparing scenarios S2 and S5 shows that the introduction of the new AE activities alone is not sufficient if no other policy measures are undertaken, owing to the limited adoption rate (7% of the ALA). First, the lack of an agricultural workforce constrains the adoption of new systems that are more labor-intensive. Increasing agricultural labor availability from 0.1 people/ha/yr to 0.6 people/ha/yr led to an increase in adoption rate of AE activities (from 7% to a 43%). Practically, this constraint could be remedied by the development of training courses for agricultural workers in agroecology, the development of temporary employment agencies specialized in agricultural work, and by massive communication aimed at making the farming profession more attractive, especially to young people.

The second constraint to be rectified is the actual orientation of 80% of subsidies for conventional export crops like bananas and sugarcane. The reallocation of 50% of subsidies from these two conventional activities to AE activities in S4 induced noticeable changes in the mosaic of activities in comparison to S3. This confirms that adapting policies in a consistent way is required to orient agricultural systems towards CSA (Lipper et al., 2018; Markard et al., 2012). Third, reducing farmers' risk aversion is crucial to completely influence farmers to adopt AE activities (Hill, 2014). As most farmers are currently involved in simplified agricultural systems, they can be reluctant to engage in more complex and risky systems, where they have to manage many more crops and cannot access chemical inputs (Chèze et al., 2020; Moss 2019). Therefore, training farmers in the technical and economic management of AE systems could be a key factor in a successful transition. This lever could take place in training centers comprising of "pilot" AE microfarms in which climate smart systems are demonstrated, allowing farmers to increase their technical skills. These centers could accompany farmers, helping them redesign a system that is both technically and economically viable for their own context. Finally, the cross-sectional analysis of all scenarios confirmed that labor productivity is a key. Three policy levers could be mobilized to increase the current level of labor productivity in the context of entirely agroecology-based agriculture. First, the increase in the sales prices of AE products seems essential to valorize their social and environmental benefits. This can be implemented practically in different manners, particularly through the valorization of AE production with eco-labels, agro-transformation (e.g., to market "ready to eat" food), and development of short marketing channels for the local market. An increase in work efficiency could also be achieved through adapted small mechanization to increase the competitiveness of AE crop management systems. Policymakers could promote better availability of adapted micro-machinery, for example, through the establishment of cooperatives for specific materials for agricultural microfarms (Thornton et al., 2019). Finally, an increase in agronomic yields in AE systems could increase the economic efficiency of these systems. An increase in yield is often observed after several years of transition to an AE system. This could be due to the progressive setting up of ecosystem services and their positive effects on the function of an agro-ecosystem. Another result of our study is that AE livestock systems can contribute to mitigating climate change and increasing food security and resilience. However, converting arable lands to livestock systems with high grassland shares will require many transformations in farm structure and farmers' skills, and such a conversion would also require much policy support from the perspective of a successful transition.

Such a study combining tools and knowledge from different scientific disciplines and aimed at designing scenarios for upscaling CSA on a regional level is useful for helping policy makers define strategic orientation for agricultural development and adaptation to climate change. The results presented in this study are currently feeding a multitude of discussions between agricultural stakeholders in Guadeloupe and have recently influenced policy measures as of November 2020. The regional council of Guadeloupe designed and laid out an "agro-ecological transition plan" for Guadeloupe based on some of the recommendations presented in this study.

4.2. Limitations of the study and scientific challenges

The methodological approach proposed in this study relies on a combination of tools and analyses. This study has three main limitations that need to be addressed. First, the indicators used have important weights in the orientation and evaluation of the scenarios. Therefore, the choice of their nature is particularly important. In our case, we chose to retain a diversity of indicators, already existing, to cover the diversity of issues of interest to stakeholders. These chosen indicators are relatively simple and accessible for their parameterization and understanding. Some key indicators should be made more complex to better discriminate between scenarios. These are, in particular, indicators of the potential impact of climate change and nutritional performance, especially for addressing variations among experts' perceptions and for compensation between components. Second, the choice of data used to parameterize the MOSAICA model also plays an important role. As far as experimental data are concerned, we have based ourselves on the first three years of the system's implementation. It will be necessary to re-evaluate the scenarios as we obtain consolidated data and as the system prototypes evolve through progressive adaptations. Another important aspect of model parameterization is the assumption of the stability of certain coefficients, such as farmers' risk aversion, which is likely to evolve progressively as the effects of climate change are felt (Bartkowski et al., 2018; Marvuglia et al., 2022). In order to go further, it would be useful to analyze transition pathways with dynamic modeling of scenarios. Bioeconomic models can also be used to develop scenarios for the near future, thereby contributing to the transition process (Castroa and Lechthaler, 2022). The research must be continued by analyzing the dynamics involved in the implementation of the scenarios. The first step is to analyze the scenarios developed by evaluating how the indicators would evolve over time during the transition. The resilience capacities of agricultural systems should be analyzed by simulating different shocks (climatic, economic, and health) and their impacts.

To this end, methodological frameworks can be used to assess the resilience of farming systems while considering different resilience capacities (robustness, adaptability, and transformability) and nested levels of farming, such as those proposed by Meuwissen et al. (2019) and Zampieri et al. (2020). Another axis of research is to perform sensitivity analyses on the key parameters of transition (e.g., climate change scenario, adaptation of society food habits, and evolution of markets) or those parameters containing uncertainty (e.g., the levels of levers mobilized in the scenarios, the intensity of effects of climate change, the performance of AE systems).

4.3. A contribution to the "redesign approach" of agricultural systems

While climate change is accelerating and environmental concerns about the negative impacts of agriculture are growing, agricultural research is called upon more than ever to propose methods that define how to achieve a transition towards sustainable agriculture and food systems (Duru et al., 2015). It is no longer just a question of generating analytical knowledge on the processes underlying sustainability but also a question of proposing methods for designing, evaluating, and implementing transitions (Markard et al., 2012; Martin et al., 2018; Notenbaert 2017). One vital step in implementing the transition is to define where agricultural systems should go and what the barriers to this pathway are (Long et al., 2016). This study proposes a method to test scenarios made of a combination of agronomic and socioeconomic levers to upscale CSA. If regional data on agricultural systems are available, it provides a rapid assessment of transition possibilities (three years for the five steps), highlighting barriers to be removed and levers to be mobilized to define the long-term strategic orientations of transition policies. The proposed approach contributes to research prioritizing climate-smart agricultural interventions at different scales (Thornton et al., 2017).

The methodological framework proposed in this paper is a contribution to the "redesign" approach. Strategies for improving sustainability of agricultural systems rely on three research axes that constitute the three levels of the AE transition framework called "ESR": (1) "Efficiency," improving the efficiency of natural and economic resource use; (2) "Substitution," developing bio-technologies and bio-inputs and (3) "Redesign," developing integration of ecosystem services (Hill and MacRae, 1996; Rosset and Altieri, 1997). One needs to explore the "redesign" approach in order to measure the efficiency of "breaking away" production systems and, thus, cultivate more references on the performance of these systems (Padel et al., 2020). One also needs to measure its effectiveness in mitigating lock-in effects in an AE-based bioeconomy responding to the urgency of global issues (Hill, 2014; Pissonnier et al., 2019; Pretty, 2018).

The use of a combination of diverse tools is required to implement the framework: farm surveys and regional data analysis, prototyping of new crop management systems through system experiments, climate change models, mathematical optimization models, sustainability indicators, and a variety of workshop types with stakeholders. These tools are now being developed in many parts of the world, including developed and emerging countries. An important capital of knowledge and tools for adapting it to a diverse range of contexts exists. The advantage of coupling these tools and integrating them through bioeconomic modeling is that aggregating disciplinary knowledge in a system approach highlights the emerging properties of increasingly complex agricultural systems. In the implementation of these approaches, it is important to involve stakeholders in exploring a wide range of options and finding transition scenarios that are feasible and socially acceptable (Dupré et al., 2021; Salvini et al., 2016).

5. Conclusions

In this paper, a methodological framework combining farm regional diagnosis, system experiments, and bioeconomic modeling is proposed to design scenarios for upscaling CSA. When applied to Guadeloupe, our results show that new agricultural production systems based on agroecology and bioeconomy principles have the potential to achieve the objectives of CSA at the regional scale. In the best scenario designed, the potential impact of climate change on production was reduced by 12.5%, the nutritional performance at the regional scale were tripled with 6.0 fed people/ha/yr on average, the GHG balance switched from net emissions to a sequestration of 0.7 tCO2eq/ha/yr, and the labor productivity rose to $26.5/hr (+14%). Compared to that in the baseline situation, the public cost for mitigating 1 tCO2eq was $432.

While the new agricultural systems have the potential to meet the objectives of CSA, our study showed that their large uptake at the regional scale implies that many lock-ins to their adoption must be relaxed. To this end, we identified the following levers: increasing workforce availability at the regional scale, reorientating public incentives towards AE systems, increasing the profitability of CSA products with eco-labels, improving the work efficiency of farmers, and reducing their risk aversion.

Therefore, new ambitious policies targeting farmers' constraints are required to upscale CSA. There is a need to develop more stakeholder platforms in which all issues and possible levers are discussed and scenarios are co-designed to define successful transition of agricultural systems. The approach proposed herein can be used to feed discussions on such platforms. Research has to be continued in the "redesign" field to model the transition of agricultural systems in a dynamic way, given the uncertainty of many crucial aspects such as climate change scenarios, market evolution, technical progress in agroecology, and farmers' behavior.

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References

Altieri, MA. et Toledo, VM., 2011. The Agroecological Revolution in Latin America: Rescuing Nature, Ensuring Food Sovereignty and Empowering Peasants. Journal of Peasant Studies 38 (3): 587-612. https://doi.org/10.1080/03066150.2011.582947

Bartkowski B, Bartke S. Leverage Points for Governing Agricultural Soils: A Review of Empirical Studies of European Farmers' Decision-Making. Sustainability. 2018; 10(9):3179. https://doi.org/10.3390/su10093179

Belmadani, A., Chauvin, F., Cantet, P., Dutrieux, PC., Decourcelle, C., Dalphinet, A., Palany, P., 2020. Future Climate Projections in the French West Indies: Regional Climate, Tropical Cyclones, and Storm Waves. Oral presentation given at the 100th American Meteorological Society Annual Meeting, 33rd Conference on Climate Variability and Change, paper J41.1, Boston, MA, January 15 2020.

Blazy, J-M., Ozier-Lafontaine, H., Doré, T., Thomas, A., Wery, J., 2009. A methodological framework that accounts for farm diversity in the prototyping of crop management systems. Application to banana-based systems in Guadeloupe. Agricultural Systems 101, 30-41.

Blazy, J.-M., Carpentier, A., Thomas, A., 2011. The willingness to adopt agro-ecological innovations: Application of choice modelling to Caribbean banana planters. Ecological Economics 72, 140-150. doi: 10.1016/j.ecolecon.2011.09.021

Blazy, J-M., Barlagne, C., Sierra, J., 2015. Environmental and economic impacts of Agri-Environmental Schemes designed in French West Indies to enhance soil C sequestration and reduce pollution risks. A modeling approach. Agricultural Systems 140, 11-18.

Blazy, JM., 2019. Climate-smart agriculture, a solution to tackle the effects of climate change in South America. Oral presentation given at « Premières Assises franco-colombiennes de l'enseignement supérieur de la recherche et de l'innovation - Colifri 2019 ». Lanzamiento del programa CLIMAT AmSud, 12-13 june 2019, Medellin, Colombia.

Cantet, P., Belmadani, A., Chauvin, F., Palany, P., 2021. Projections of tropical cyclone rainfall over land with an Eulerian approach: Case study of three islands in the West Indies. International Journal of Climatology;41 (Suppl. 1), E1164-E1179. https://doi.org/10.1002/joc.6760

Cantet, P., Déqué, M., Palany, P., Maridet, J.-L., 2014. The importance of using a high-resolution model to study the climate change on small islands: the Lesser Antilles case. Tellus A: Dynamic Meteorology and Oceanography, 66(1), 24065. https://doi.org/10.3402/tellusa.v66.24065

Castroa LM., Lechthaler, F., 2022. The contribution of bio-economic assessments to better informed land-use decision making: An overview. Ecological Engineering 174, 106449.

Chauvin, F., Pilon, R., Palany, P., Belmadani, A., 2020. Future changes in Atlantic hurricanes with the rotated-stretched ARPEGE-Climat at very high resolution. Climate Dynamics 54, 947–972. https://doi.org/10.1007/s00382-019-05040-4

Chèze, B., David, M., Martinet, V., 2020. Understanding farmers' reluctance to reduce pesticide use: A choice experiment. Ecological Economics 167, January 2020, 106349. https://doi.org/10.1016/j.ecolecon.2019.06.004

Chopin, P., Blazy, J-M., Doré, T., 2015a. A new method to assess farming system evolution at the landscape scale. Agronomy for Sustainable Development 35, 325-337.

Chopin, P., Guindé, L., Doré, T., Blazy, J-M., 2015b. MOSAICA: A multi-scale bioeconomic model for the design and ex ante assessment of cropping system mosaics. Agricultural Systems 140, 26-39.

Chopin, P., Blazy, JM., Guindé, L., Tournebize, R., Doré, T., 2017a. A novel approach for assessing the contribution of agricultural systems to the sustainable development of regions with multi-scale indicators: Application to Guadeloupe. Land Use Policy 62, 132–142.

Chopin, P., Blazy, JM., Guindé, L., Wery, J., Doré, T., 2017b. A framework for designing multi-functional agricultural landscapes: Application to Guadeloupe Island. Agricultural Systems 157, 316–329

Chopin, P. and Sierra, J., 2019. Reduced tillage and organic amendments can offset the negative impact of climate change on soil carbon: A regional modelling study in the Caribbean. Soil and Tillage Research 192, 113-120

Colomb, V., Martel, M., Bockel, L., Martin, S., Chotte, J.L., Bernoux, M., 2014. Promoting GHG mitigation policies for agriculture and forestry: a case study in Guadeloupe, French West Indies. Land Use Policy 39, 1–11.

Cubasch, U., Wuebbles, D., Chen, D., Facchini, M.C., Frame, D., Mahowald, N., Winther, J.-G., 2013: Introduction. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Dale, V., Kline, K., Kaffka, S. & Langeveld, J.W.A., 2013. A landscape perspective on sustainability of agricultural systems. Landscape Ecology 23, 1111-1123.

Debaeke, P., Pellerin, S., Scopel, E., 2017. Climate-smart cropping systems for temperate and tropical agriculture: mitigation, adaptation and trade-offs. Cahiers Agricultures, EDP Sciences, 2017, 26 (3), pp.1-12.

Dupré M., Blazy J.-M., Michels T., Le Gal P.-Y., 2021 Supporting policymakers in designing agricultural policy instruments: a participatory approach with a regional bioeconomic model in La Réunion (France). Land Use Policy 100, 105128.

Duru, M., Therond, O., Fares, M., 2015. Designing agroecological transitions; A review. Agronomy for Sustainable Development 35:1237–1257.

FAO. 2019. Current Status of agriculture in the Caribbean and implications for Agriculture Policy and Strategy. 2030 - Food, Agriculture and rural development in Latin America and the Caribbean, Nº14. Santiago de Chile. FAO. 28p

FAO and CDB. 2019. Study on the State of Agriculture in the Caribbean. Rome, 212 pp.

Fares, M., Magrini, MB. et Triboulet, P., 2012. Agroecological transition, innovation and lock-in effects: The impact of the organizational design of supply chains. Cahiers Agricultures 21 (1): 34-45. https://doi.org/10.1684/agr.2012.0539

Giller, K., 2013. Can we define the term ‘farming systems’? A question of scale. Outlook on Agriculture 42: 149-153.

Gliessman, SR., 2016. Agroecology and Agroecosystems. In Agronomy Monographs, edited by Rickerl Diane et Charles Francis, 19-29. Madison, WI, USA: American Society of

Agronomy, Crop Science Society of America, Soil Science Society of America. https://doi.org/10.2134/agronmonogr43.c2

Hill, SB., 2014. Considerations for Enabling the Ecological Redesign of Organic and Conventional Agriculture: A Social Ecology and Psychosocial Perspective. In Organic Farming, Prototype for Sustainable Agricultures, edited by Bellon, S. et Penvern, s. Pages 401-22. Dordrecht: Springer Netherlands. https://doi.org/10.1007/978-94-007-7927-3_22

Hill, SB. et MacRae, RJ., 1996. Conceptual Framework for the Transition from Conventional to Sustainable Agriculture. Journal of Sustainable Agriculture 7 (1): 81-87. https://doi.org/10.1300/J064v07n01_07

IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change[Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu,and B. Zhou (eds.)]. Cambridge University Press. In Press.

Kershen, DL., 2012. The contested vision for agriculture's future: Sustainable Intensive Agriculture and Agroecology. Creighton L. Rev. 46: 591.

Lamanda N., Roux S., Delmotte S., Merot A., Rapidel B., Adam M., Wery J., 2012. A protocol for the conceptualisation of an agro-ecosystem to guide data acquisition and analysis and expert knowledge integration. European Journal of Agronomy 38:104-116.

Lampridi, MG., Sørensen, CG., Bochtis, D., 2019. Agricultural Sustainability: A Review of Concepts and Methods. Sustainability 2019, 11, 5120; https://doi:10.3390/su11185120

Le Gal, P.Y., Merot, A., Moulin, C.H., Navarrete, M., Wery, J., 2010. A modelling framework to support farmers in designing agricultural production systems. Environmental Modelling & Software 25: 258-268.

Levidow, L., Birch, K. et Papaioannou, T., 2013. Divergent Paradigms of European Agro-Food Innovation: The Knowledge-Based Bioeconomy (KBBE) as an R&D Agenda. Science, Technology, & Human Values 38 (1): 94-125. https://doi.org/10.1177/0162243912438143

Levidow, L., Nieddu, M., Vivien, FD., Béfort, N., 2019. Transitions towards a European Bioeconomy: Life Sciences versus Agroecology Trajectories. In "Ecology, Capitalism and the New Agricultural Economy. The Second Great Transformation." Taylor and Francis. Edited By Allaire, G. and Daviron, B., book chapter 9, 24p.

Lipper, L., Thornton, P., Campbell, B.M., Baedeker, T., Braimoh, A., Bwalya, M., Caron, P., Cattaneo, A., Garrity, D., Henry, K., Hottle, R., Jackson, L., Jarvis, A., Kossam, F., Mann, W., McCarthy, N., Meybeck, A., Neufeldt, H., Remington, T., Sen, P.T., Sessa, R., Shula, R., Tibu, A., Torquebiau, E.F., 2014. Climate-smart agriculture for food security. Nature Climate Change 4, 1068–1072.

Lipper, L., McCarthy, N., Zilberman, D., Asfaw, S. et Giacomo Branca, 2018. Climate Smart Agriculture: Building Resilience to Climate Change. Vol. 52. Natural Resource Management and Policy. Springer International Publishing. https://doi.org/10.1007/978-3-319-61194-5

Long TB., Blok V., Coninx I., 2016. Barriers to the adoption and diffusion of technological innovations for climate-smart agriculture in Europe: evidence from the Netherlands, France, Switzerland and Italy. Journal of Cleaner Production 112, 9-21.

Magrini, MB., Martin, G., Magne, MA., Duru, M., Couix, N., Hazard, L. et Plumecocq, G., 2019. Agroecological Transition from Farms to Territorialised Agri-Food Systems: Issues and Drivers. In Agroecological Transitions: From Theory to Practice in Local Participatory Design, edited by Bergez, Audouin, and Therond, 69-98. Springer International Publishing. https://doi.org/10.1007/978-3-030-01953-2_5

Markard, J., Raven, R., Truffer, B., 2012. Sustainability transitions: An emerging field of research and its prospects. Research Policy 41 (6), 955-967

Martin G., Allain S. Bergez JE., Burger-Leenhardt D., Constantin J., Duru M., Hazard L., Lacombe C., Magda D., Magne MA., Ryschawy J., Thénard V., Tribouillois H., Willaume M., 2018. Sustainability 10, 2083.

Marvuglia, A., Bayram, A., Baustert, P., Navarrete Gutiérrez, T., Igos, E., 2022. Agent-based modelling to simulate farmers' sustainable decisions: Farmers' interaction and resulting green consciousness evolution. Journal of Cleaner Production (332), 129847, https://doi.org/10.1016/j.jclepro.2021.129847.

Meuwissen, MPM., Feindt, PH., Spiegel, A., et al. 2019. A framework to assess the resilience of farming systems. Agricultural Systems 176, 102656.

Meynard, JM., Charrier, F., Fares, M., Le Bail, M., Magrini, MB., Charlier, A. et Messéan, A., 2018. Socio-Technical Lock-in Hinders Crop Diversification in France. Agronomy for Sustainable Development 38 (5): 54. https://doi.org/10.1007/s13593-018-0535-1

Mosnier, C., Ridier, A., Képhaliacos, C., Carpy-Goulard, F., 2009. Economic and environmental impact of the CAP mid-term review on arable crop farming in Southwestern France. Ecol. Econ. 68, 1408–1416.

Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S.K., van Vuuren, D.P., Carter, T.R., Emori, S., Kainuma, M., Kram, T., Meehl, G.A., Mitchell, J.F.B., Nakicenovic, N., Riahi, K., Smith, S.J., Stouffer, R.J., Thomson, A.M., Weyant, J.P., Wilbanks, T.J., 2010. The next generation of scenarios for climate change research and assessment. Nature 463, 747–756.

Moss, S., 2019. Integrated weed management (IWM): why are farmers reluctant to adopt non-chemical alternatives to herbicides? Pest Management Science 75 (5), 1205-1211. https://doi.org/10.1002/ps.5267

Mousseau, F., 2015. The Untold Success Story of Agroecology in Africa. Development 58 (2-3): 341-45. https://doi.org/10.1057/s41301-016-0026-0

Muller, A., Schader, C., El-Hage Scialabba, N., Brüggemann, J., Isensee, A., Erb, KH., Smith, P., Klocke, P., Leiber, F., Stolze, M., Niggli, U., 2017. Strategies for Feeding the World More Sustainably with Organic Agriculture. Nature Communications 8 (1): 1290. https://doi.org/10.1038/s41467-017-01410-w

Notenbaert A., Pfeifer C., Silvestri S., Herrero, M., 2017. Targeting, out-scaling and prioritising climate-smart interventions in agricultural systems: Lessons from applying a generic framework to the livestock sector in sub-Saharan Africa. Agricultural Systems 151, 153-162.

Ollivier, G., D. Magda, A. Mazé, G. Plumecocq, and C. Lamine. 2018. Agroecological transitions: What can sustainability transition frameworks teach us? An ontological and empirical analysis. Ecology and Society 23(2):5

Padel, S., Levidow, L. et Pearce, B., 2020. UK Farmers' Transition Pathways towards Agroecological Farm Redesign: Evaluating Explanatory Models. Agroecology and sustainable Food Systems 44 (2)? 139-63. https://doi.org/10.1080/21683565.2019.1631936

Paul, J., Sierra, J., Causeret, F., Guindé, L., Blazy, JM., 2017. Factors affecting the adoption of compost use by farmers in small tropical Caribbean islands. Journal of Cleaner Production 142, 2017. 1387-1396

Petzold, J., Magnan, AK., 2019. Climate change: thinking small islands beyond Small Island Developing States (SIDS). Climatic Change 152, 145–165.

Pimbert, M., 2015. Agroecology as an Alternative Vision to Conventional Development and Climate-Smart Agriculture. Development 58 (2-3): 286-98. https://doi.org/10.1057/s41301-016-0013-5

Pissonnier, S., Dufils, A. et Le Gal, PY., 2019. A Methodology for Redesigning Agroecological Radical Production Systems at the Farm Level. Agricultural Systems 173, 161-71. https://doi.org/10.1016/j.agsy.2019.02.018

Ponisio, L. et Ehrlich, P., 2016. Diversification, Yield and a New Agricultural Revolution: Problems and Prospects. Sustainability 8 (11): 1118. https://doi.org/10.3390/su8111118

Pretty, J., 2018. Intensification for Redesigned and Sustainable Agricultural Systems. Science 362 (6417): eaav0294. https://doi.org/10.1126/science.aav0294

Roehrig, R., Beau, I., Saint-Martin, D., Alias, A., Decharme, B., Guérémy, J.-F., Voldoire, A., Abdel-Lathif, A.Y., Bazile, E., Belamari, S., Blein, S., Bouniol, D., Bouteloup, Y., Cattiaux, J., Chauvin, F., Chevallier, M., Colin, J., Douville, H., Marquet, P., Michou, M., Nabat, P., Oudar, T., Peyrillé, P., Piriou, J.-M., Salas y Mélia, D., Séférian, R., Sénési, S. 2020. The CNRM global atmosphere model ARPEGE-Climat 6.3 : description and evaluation. Journal of Advances in Modeling Earth Systems 12, e2020MS002075. https://doi.org/10.1029/2020MS002075

Rosset, PM. et Altieri, MA., 1997. Agroecology versus Input Substitution: A Fundamental Contradiction of Sustainable Agriculture. Society & Natural Resources 10 (3): 283-95. https://doi.org/10.1080/08941929709381027

Saint Ville AS., Hickey GM., Phillip LE., 2015. Addressing food and nutrition insecurity in the Caribbean through domestic smallholder farming system innovation. Regional Environmental Change 15:1325–1339.

Salvini G., van Paassen A., Ligtenberg A., Carrero GC., Bregt AK., 2016. A role-playing game as a tool to facilitate social learning and collective action towards Climate Smart Agriculture: Lessons learned from Apuí, Brazil. Environmental Science & Policy 63, 113-121.

Schaafsmaa M., Utilac H., Hironsd MA., 2018. Understanding trade-offs in upscaling and integrating climate-smart agriculture and sustainable river basin management in Malawi. Environmental Science and Policy 80, 117–124.

Sierra, J., Causeret, F., Diman, J-L., Publicol, M., Desfontaines, L., Cavalier, A., Chopin, P., 2015. Observed and predicted changes in soil carbon stocks under export and diversified agriculture in the Caribbean. The case study of Guadeloupe. Agriculture, Ecosystems & Environment 213, 252-264.

Sierra, J., Chopart, JL., Guindé, L., Blazy, JM., 2016. Optimisation of biomass and compost management to sustain soil organic matter in energy cane cropping systems in a tropical polluted soil: a modelling study. Bioenergy research 9 (3), 798–808.

Smith HE., Sallu SM., Whitfield S., Gaworek-Michalczenia, MF., Recha JW., Sayula GJ., Mziray S., 2021. Innovation systems and affordances in climate smart agriculture. Journal of Rural Studies 87,199-212.

Thornton P., Aggarwal P., Parsons D., 2017. Prioritising climate-smart agricultural interventions at different scales. Agricultural Systems 151, 149-152.

Thornton PK, Loboguerrero AM, Campbell BM, Kavikumar KS, Mercado L, Shackleton S. 2019. Rural livelihoods, food security and rural transformation under climate change. Rotterdam and Washington, DC: Global Commission on Adaptation.

Tubiello F.N., Salvatore M., Ferrara A., House J. , Federici, S., Rossi S., Biancalani R., Golec, R.D.C., Jacobs H., Flamini A., Prosperi, P., Cardenas-Galindo, P., Schmidhuber, J., Sanchez, M.J.S., Srivastava, N., Smith, P., 2015. The contribution of agriculture, forestry and other land use activities to global warming, 1990-2012. Global Change Biology. (21): 2655-2660.

Van Notten, P., 2006. Scenario development: a typology of approaches. Think Scenario, Rethink Education. OECD Publishing, Paris, pp. 69–84.

Valenzuela, H., 2016. Agroecology: A Global Paradigm to Challenge Mainstream Industrial Agriculture. Horticulturae 2 (1): 2. https://doi.org/10.3390/horticulturae2010002

Vervoort, J.M., Thornton, P.K., Kristjanson, P., Förch, W., Ericksen, P.J., Kok, K., Ingram, J.S., Herrero, M., Palazzo, A., Helfgott, A.E., Wilkinson, A., 2014. Challenges to scenario-guided adaptive action on food security under climate change. Global Environ. Change 28, 383–394.

Voldoire, A., E. Sanchez-Gomez, D. Salas y Mélia, B. Decharme, C. Cassou, S. Sénési, S. Valcke, et al. 2013. The CNRM-CM5.1 Global Climate Model: Description and Basic Evaluation. Climate Dynamics 40, 2091-2121.

Voldoire, A., D. Saint-Martin, S. Sénési, B. Decharme, A. Alias, M. Chevallier, J. Colin, J.-F. Guérémy, M. Michou, M.-P. Moine, P. Nabat, R. Roehrig, D. Salas y Mélia, R. Séférian, S. Valcke, I. Beau, S. Belamari, S. Berthet, C. Cassou, J. Cattiaux, J. Deshayes, H. Douville, C. Ethé, L. Franchisteguy, O. Geoffroy, C. Lévy, G. Madec, Y. Meurdesoif, R. Msadek, A. Ribes, E. Sanchez-Gomez, L. Terray, R. Waldman, 2019, Evaluation of CMIP6 DECK experiments with CNRM-CM6-1, J. Adv. Model. Earth Syst., 11(7), 2177-2213, DOI:10.1029/2019MS001683.

Wery, J., 2015. Systems Analysis for management and design in Agriculture: can we do it with only two concepts ? Proceedings of the Farming System Design 2015 congress, Montpellier 7-10 september 2015, pp. 3-4.

Westermann O, Thornton P, Förch W., 2015. Reaching more farmers – innovative approaches to scaling up climate smart agriculture. CCAFS Working Paper no. 135. Copenhagen, Denmark: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS).

Wezel, A., S. Bellon, T. Doré, C. Francis, D. Vallod, et C. David. 2009. Agroecology as a Science, a Movement and a Practice. A Review. Agronomy for Sustainable Development 29 (4): 503-15. https://doi.org/10.1051/agro/2009004

Zampieri, M., Weissteiner, CJ., Grizzetti, B., Toreti, A., van den Berg, M., Dentener, F., 2020. Estimating resilience of crop production systems: From theory to practice. Science of the Total Environment 735, 139378