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

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1 **Title: “Designing Scenarios for Upscaling Climate-Smart Agriculture on a Small Tropical**  
2 **Island”**

3  
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11

12 **Abstract:**

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

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

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

28 **RESULTS AND CONCLUSIONS:** While new agricultural systems based on agroecology and  
29 bioeconomy have the potential to reduce the impacts of climate change, mitigate GHGs, and  
30 increase food autonomy, results revealed that many lock-in effects have to be relaxed,  
31 increasing workforce availability at the regional scale, reorientating public incentives towards  
32 agroecological systems, increasing profitability of CSA products, improving the work  
33 efficiency of farmers, and reducing their risk aversion. In the best scenario designed, the

34 potential impact of climate hazards was reduced by 12.5%, the nutritional performance at the  
35 regional scale was tripled with 6.0 fed people/ha/yr, the GHG balance switched from net  
36 emissions to a sequestration of 0.7 tCO<sub>2</sub>eq/ha/yr, while the labor productivity rose to \$26.5/hr  
37 (+14%). Compared to that of the baseline situation, the public cost for mitigating 1 tCO<sub>2</sub>eq was  
38 \$432.

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

46

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

49

50

51 **Highlights:**

52

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

62

## 63 **1. Introduction**

64

65 Global agriculture must meet the major challenge of feeding nine billion people by 2050 while  
66 simultaneously adapting to climate change, mitigating anthropogenic greenhouse gas (GHG)  
67 emissions, and integrating the principles of sustainable development (Tubiello, 2015). These  
68 challenges are particularly salient in tropical and island regions, which are vulnerable to climate  
69 change (Petzold and Magnan, 2019). The small island states of the Caribbean face serious  
70 challenges in the context of a changing climate such as more severe droughts, temperature  
71 increases, sea level rise and saltwater intrusion, increased cyclone intensity, and shifting  
72 agricultural seasonality (FAO and CDB, 2019). In a region where the level of malnutrition is  
73 high, climate change adaptation and resilience should be a key priority for a sustainable future  
74 and agricultural sector development in the medium and long term. The challenges faced by  
75 agriculture are threefold: 1) adapting agricultural systems to climate change and mitigating its  
76 causes and effects; 2) an improved combination of economic, social, and environmental  
77 performance; and 3) increasing the degree of food autonomy of the regions. These objectives  
78 are consistent with the emerging concept of climate smart agriculture (CSA), which aims to  
79 propose an integrated approach to agriculture to meet the threefold challenge of food security,  
80 adaptation, and mitigation of climate change. The goal is to sustainably increase the  
81 productivity of agricultural systems while adapting them to strengthen their resilience to climate  
82 change and reduce or remove GHG emissions, wherever possible (Lipper et al., 2014; 2018).  
83 To implement CSA, several levers have been investigated, such as the genetic improvement of  
84 crops to increase resilience, digital tools, agroecology, and bioeconomy. Agroecology is a  
85 method of designing production systems based on the functionalities offered by ecosystems  
86 (Gliessman, 2016; Wezel et al., 2009). It amplifies natural processes within agrosystems while  
87 aiming to reduce pressure on the environment (e.g., reducing GHG emissions and avoiding the  
88 use of synthetic fertilizers and pesticides) and preserving natural resources (water, energy, and  
89 mineral elements). Agroecology reintroduces biodiversity into agricultural production systems  
90 and restores a diversified landscape mosaic (Altieri and Toledo, 2011). Parallel to agroecology,  
91 the emerging concept of bioeconomy aims to propose sustainable development models based  
92 on the valorization of bio-sourced products and locally sourced by-products, replacing materials  
93 and inputs that consume more fossil energy. For the agricultural sector, the bioeconomy is  
94 complementary to agroecology because it can provide new opportunities to increase farm  
95 competitiveness while providing sustainable solutions to environmental and societal challenges  
96 (Muller et al., 2017). Agroecology can develop a bioeconomy by providing pesticide-free

97 agricultural products for the local market (food, feed, fiber), whereas bioeconomy can support  
98 agroecology development through the recycling of local residual organic matter (from industrial  
99 or domestic origin) into locally processed bio-inputs (Mousseau, 2015; Valenzuela 2016).  
100 Agroecology and bioeconomy are complementary; thus, their synergies are currently being  
101 explored in research to develop CSA (Pimbert, 2015).

102 At the farming system level, prototyping new production systems and system experiments is a  
103 tool commonly used to determine the biophysical basis of sustainable and climate smart  
104 production (Debaeke et al., 2017). However, beyond the work on the biophysical basis of CSA,  
105 agricultural research is questioned regarding its ability to facilitate the transition towards  
106 sustainable, climate-smart agricultural systems. Thus, it is challenging to identify pathways for  
107 upscaling the CSA (Smith et al., 2021; Westermann et al., 2015). The transition towards such  
108 systems remains slow because farmers' adoption rates are low (Long et al., 2016). Farmers  
109 often face barriers to adopting agroecological production systems (Magrini et al., 2019;  
110 Meynard et al., 2018). Although they can be more profitable, these systems are often perceived  
111 as riskier, more time-consuming, and involving more unfamiliar skills than conventional  
112 systems. They also face different barriers at the regional scale because of inappropriate supply  
113 chains and insufficient policy incentives, which are not oriented towards agroecology and  
114 bioeconomy development (Fares et al., 2012; Ponisio and Ehrlich, 2016). The lack of  
115 quantitative evidence of cost-benefit is also a barrier to adoption. Thus, although many technical  
116 solutions based on agroecology and bioeconomy have been proposed to promote CSA, there is  
117 minimal work on the issue of barriers to the transition to appropriate agricultural practices  
118 (Lampridi et al., 2019), which is especially true in the Caribbean (FAO, 2019; Saint Ville et al.,  
119 2015). There is a need to develop methods to model possible futures to cope with the imposed  
120 constraints of climate change and to model the impact of agronomic and policy levers to reach  
121 this goal (Thornton et al., 2017). To guide large-scale investment and policy planning to  
122 develop CSA, further information is needed regarding the inter-relationships among landscape  
123 features, socioecological conditions of farms and markets, external interventions, local  
124 institutions, and combined effects on mitigation outcomes. Introducing innovations into  
125 agricultural systems requires that they be viewed not just as isolated entities but as part of a  
126 nested system where they must meet multiple requirements and constraints at different levels  
127 (Ollivier et al., 2018). The scientific challenge is to provide a methodological framework to  
128 identify solutions at different scales and define how to combine them in a consistent way to  
129 accelerate the adoption of climate smart agricultural systems (Dale et al., 2013; Vervoort et al.,  
130 2014).

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

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

156

## 157 **2. Material and methods**

### 158 **2.1. The modeling framework**

#### 159 **2.1.1. Interrelationships across scales**

160 Agricultural systems can be analyzed as nested hierarchical systems (Giller, 2013; Le Gal et  
161 al., 2010; Wery, 2015). Reaching sustainability goals at a regional scale requires an adequate  
162 combination of innovations at the field scale (agroecological techniques) and adaptation of farm  
163 structure organization (integrated farming system, resource allocation), markets, supply chains,  
164 and policies. First, to sustainably improve or preserve ecosystem services provided by cropping

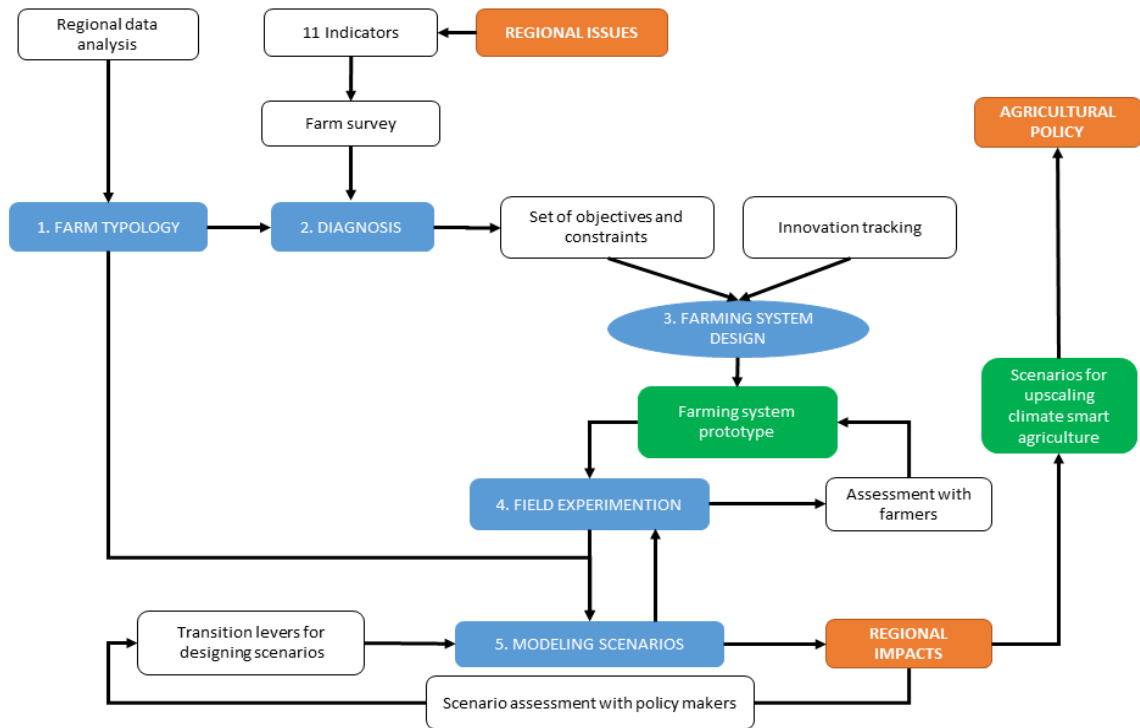
165 systems on the landscape scale, biophysical processes must be adapted at the field scale. A  
166 cropping system can be defined as a biophysically “controlled” system (Lamanda et al., 2012).  
167 Crop management can be determined by the technology and knowledge available at the farm  
168 level, or by the field ecosystem aiming at targeted ecosystem services and resources used.  
169 Indeed, a technical system in a given field is subject to the decision-making process of the  
170 farmer, who manages several fields and agricultural production on their farm. Whole-farm  
171 management is conducted with a limited set of resources (such as money, skill, time, and land),  
172 with the goal of satisfying the personal objectives of the farmer (Blazy et al., 2011). A farmer’s  
173 decision to adopt an innovation is also influenced by personal beliefs, particularly their attitude  
174 towards risk and uncertainty, when considering the opportunity to modify their technical  
175 systems. The decision-making process behind potential innovation adoption by farmers may  
176 also be influenced by opportunities and barriers expressed outside the farm. However, these  
177 “external” factors are not controlled by the farmers. Markets, input supply chains, and food  
178 systems can create new opportunities or barriers that affect the perceived utility of adopting  
179 innovations. Policy incentives such as agroenvironmental schemes may facilitate the adoption  
180 of such innovations by compensating for the net losses that occur owing to the required  
181 management changes and transaction costs. Finally, designers of new agricultural systems must  
182 consider the heterogeneity of fields and farms at a landscape scale.

183

### 184 **2.1.2. Overview of the methodological framework**

185 The proposed framework aims at quantification, spatial integration from the plot to the regional  
186 level, and modeling of scenarios for upscaling CSA. The framework (Figure 1) consists of five  
187 main steps and combines typology building from a database on farm production systems (step  
188 1); a survey on a sample of farms to diagnose the sustainability of farming systems with a set  
189 of indicators (step 2); the design and field experiment of an innovative prototype of the climate  
190 smart farming system (steps 3 and 4); and the modeling of scenarios using data from the  
191 diagnosis, experiment, and identification of socioeconomic levers to upscale CSA (step 5).  
192 Steps 1 and 2 characterize the current farming system within the study area. This consists of  
193 building a typology of farming systems to model the diversity of farms in the region, notably  
194 in terms of pedoclimatic conditions, nature of farming systems, and farmers’ economic  
195 endowments. Ideally, the typology is built using census data of farms on crop rotation and area,  
196 via a robust statistical clustering method (Blazy et al., 2009; Chopin et al., 2015a). The typology  
197 serves as an in situ survey of several farms for each farm type identified. The data collected  
198 were then used for the diagnosis of the current regional farming system considered as the

199 “baseline”. This diagnosis is based on a set of sustainability indicators, including the potential  
 200 impacts of climate change (Chopin et al., 2017a). The outputs of these first two steps serve as  
 201 a basis for the design of prototypes of agroecological crop management systems (step 3),  
 202 following the method of Blazy et al. (2009). They also serve for the calibration and  
 203 parameterization of the baseline situation into the bioeconomic model used in step 5 for  
 204 modeling scenarios.



205  
 206 **Figure 1.** Overview of the methodological framework. The blue boxes correspond to the five  
 207 main steps of the framework. The green boxes correspond to the main outputs of the framework.  
 208 The white boxes correspond to the different tools used.

209  
 210 The design of the prototypes of agroecological farming systems is inspired by the regional  
 211 diversity of issues that farms must address and is exclusively based on agroecological and  
 212 bioeconomic principles. The design process mobilizes both scientific evidence and farmers’  
 213 knowledge to propose redesigns of current farming systems, considering farm issues as well as  
 214 existing opportunities for circular bioeconomy on a regional scale. The output of Step 3 is a co-  
 215 designed prototype defined as a conceptual model of a farming system that is later experimented  
 216 on a small-scale pilot farm in Step 4. The purpose of this study is to acquire technical, economic,  
 217 and environmental references for prototypes of alternative systems. In addition to the  
 218 parameterization of the model used in Step 5, the role of the experimental microfarm is to



219 provide an interface for discussion and co-evaluation of solutions with stakeholders to adapt  
220 farming systems, value chains, and agricultural policies. Subsequently, the resulting data of the  
221 experiment in Step 4 are used in Step 5 to evaluate the innovative production system on a  
222 regional scale and the design of scenarios using the bioeconomic model MOSAICA (Figure 2).

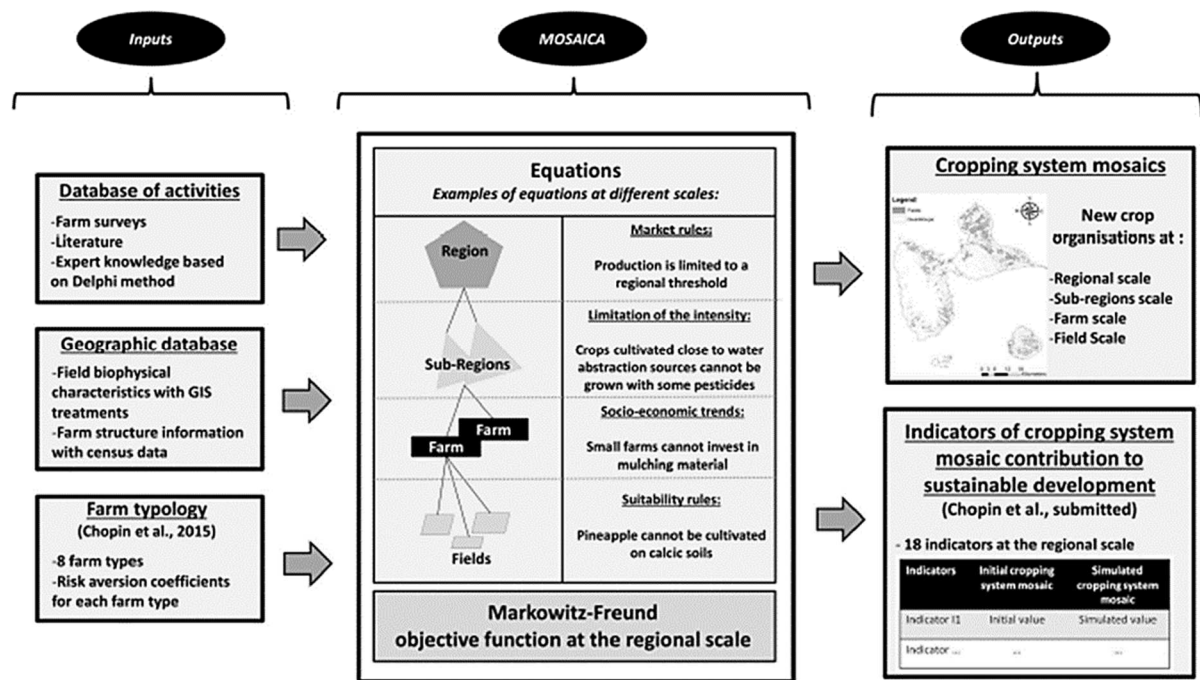
223

### 224 **2.1.3. The modeling approach**

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

235 The model is a linear programming model. It optimizes the sum of individual farmers' utilities  
236 on a regional scale, which includes revenues and the coefficient of risk aversion towards price  
237 and yield variations, which is the calibration parameter. The allocation of cropping systems is  
238 modeled through a set of equations modeling the choice of cropping systems by farmers. The  
239 objective function of our regional bioeconomic model is a Markowitz-Freund (Mosnier et al.,  
240 2009). The optimal acreage at the regional scale is obtained from the maximization of utility,  
241 which is the maximum of the sum over the full population of farmers of the total farms' gross  
242 margins of activities balanced by the sum of expected positive and negative variations in the  
243 gross margin for each activity multiplied by a risk-aversion coefficient at the farm scale (see  
244 Chopin et al., 2015a). The risk is then modeled using a linear approach (Mosnier et al., 2009).  
245 The coefficients of variability are determined for each activity based on agro-economic expertise  
246 and encompass both agronomic risk (yield variability related to climate conditions, pest attacks,  
247 or diseases) and commercial outlet risk (from the variability in selling price during the selling  
248 season) aggregated together. The calibration procedure is based on the allocation of several sets  
249 of risk-aversion coefficients to farmers according to their farm type. These risk-aversion  
250 coefficients at the farm scale help reproduce farmers' cropping plans based on a hypothesis  
251 about their level of risk aversion.

252



253

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

255

256 The outputs of the model are new agricultural landscapes (called mosaics of cropping systems)

257 and the calculation of sustainability indicators (Chopin et al., 2017a). These indicators were

258 chosen during successive transdisciplinary workshops involving researchers, farmers, and

259 politicians to account for the most important issue in the study area. A description of each

260 indicator used in this study is provided in Supplementary Material 1. These indicators assess

261 the impact of agriculture on society and the environment at the landscape scale by accounting

262 for cropping system externalities at the plot scale and the locations of these cropping systems.

263 The model simulates how introducing new cropping systems and adapting policies could orient

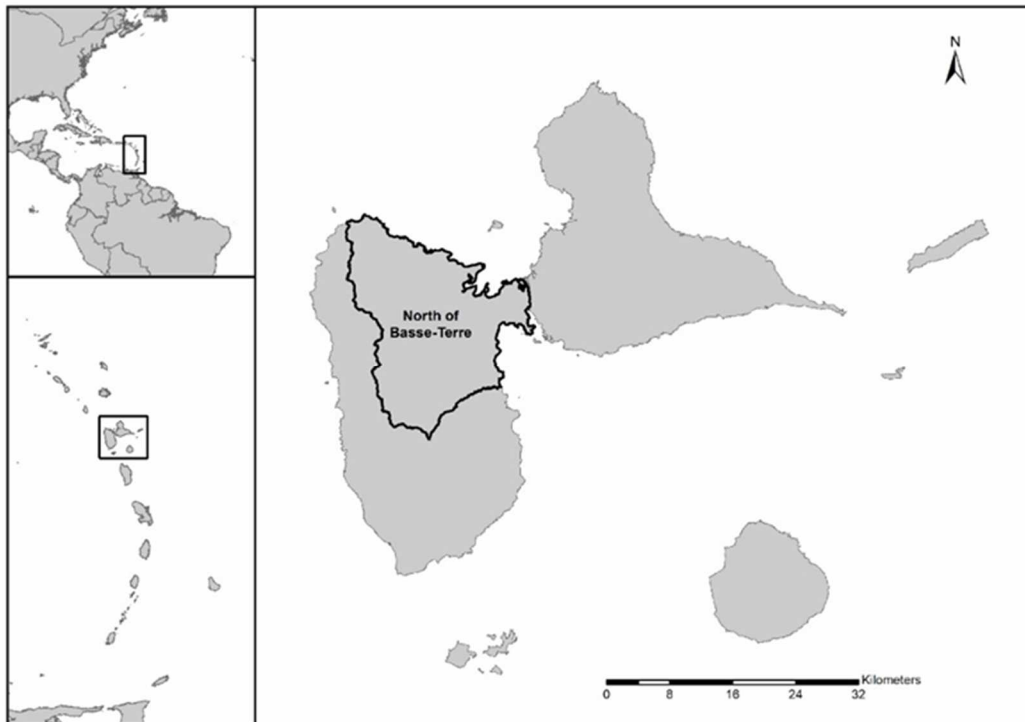
264 farmers towards choosing new cropping systems. This simulated mosaic at the landscape scale

265 was then assessed using the same set of indicators as in the diagnosis (Step 2). Iterative testing

266 of levers in scenarios involving policymakers allows the identification of consistent sets of

267 innovations and policy adaptations, that is, scenarios that satisfy biophysical rules and farmers'

268 socioeconomic constraints (Chopin et al., 2017b).



269 **Figure 3.** The study site is the north of Basse-Terre (Guadeloupe) covering a surface of 360  
 270 km<sup>2</sup>.

271

## 272 **2.2. Application of the framework in Guadeloupe**

### 273 **2.2.1 Study area and farming systems context**

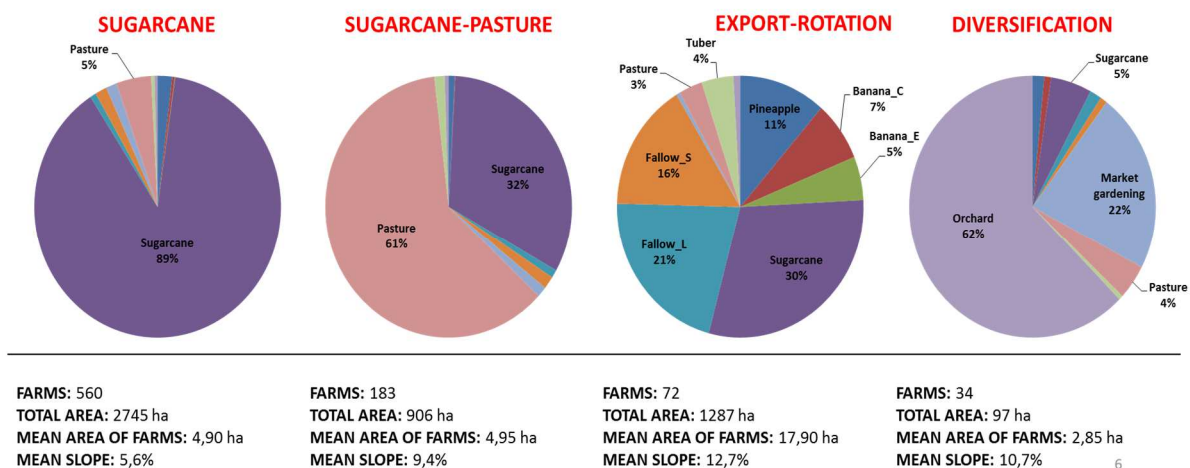
274 The framework presented was applied to the North Basse-Terre region of Guadeloupe, a French  
 275 overseas department in the Caribbean (Figure 3). Guadeloupe is an archipelago (1628 km<sup>2</sup>)  
 276 comprising two main islands, Basse-Terre (848 km<sup>2</sup>) and Grande-Terre (586 km<sup>2</sup>), with vast  
 277 ecological contrasts. Sierra et al. (2015) divided the archipelago of Guadeloupe into five  
 278 agroecological regions. This study focused on the agroecological region of northern Basse-  
 279 Terre (NBT), characterized by an annual mean temperature and rainfall of 25.4 °C and 2300  
 280 mm/yr, respectively, as well as kaolinitic ferralsols developed on aged volcanic ash deposits.  
 281 The agricultural land area (ALA) represents 5033 ha and 763 farms. In Guadeloupe, agriculture  
 282 specializes in producing export crops (sugar cane, banana). Intensification over the past three  
 283 decades has caused widespread environmental damage (e.g., soil and water contamination and  
 284 biodiversity loss). Farms are poorly diversified, and the local supply of products for the  
 285 domestic market (especially fresh fruits and vegetables) cannot meet demands (Chopin et al.,  
 286 2015a). This situation leads to dependence on external supplies, as less than 25% of food needs  
 287 are met.

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

300

### 301 2.2.2. Regional diagnosis of farming systems

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



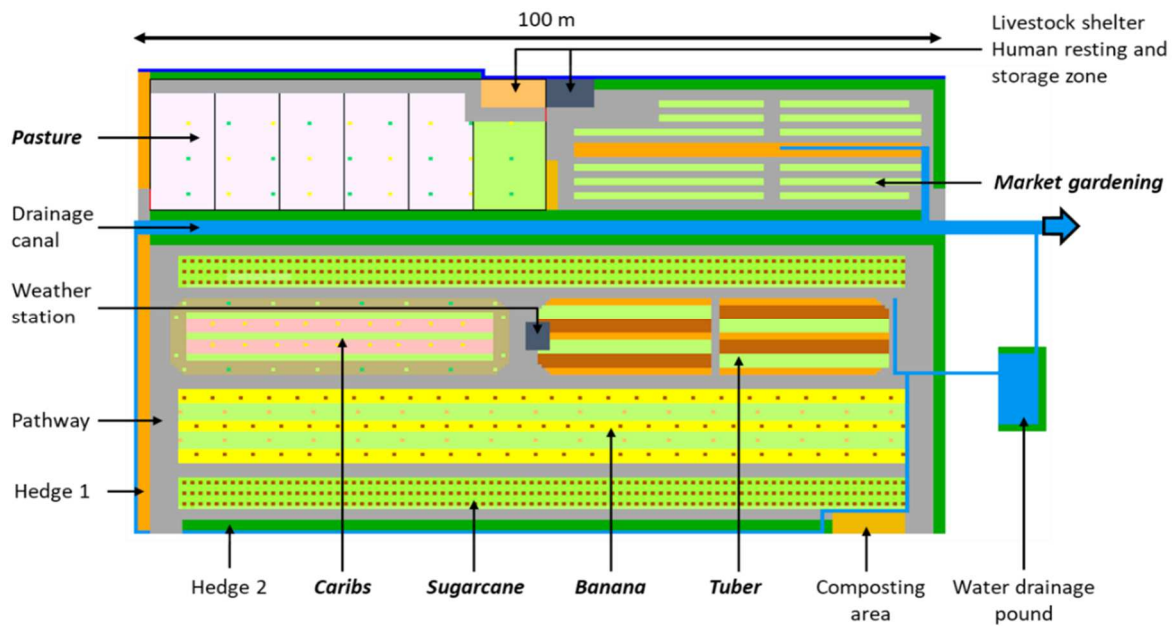
306

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

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

### 314 **2.2.3. Agroecological farming system design and experiment**

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



348

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

353

#### 354 **2.2.4. Parameterization and calibration of the MOSAICA model**

355 The technical-economic coefficients for parameterizing the model for conventional current  
 356 systems, each of the six retained AE activities, and the entire farming system (considered as an  
 357 integrated activity) are presented in Supplementary Material 4. The calibration of the model is  
 358 done by adjusting the risk aversion coefficients per farm type until obtaining 80% of correct  
 359 allocations of crop areas. In this study, this procedure yielded a satisfactory rate of 96.5% of  
 360 overall agricultural areas correctly simulated at the regional scale, with 80% of the areas  
 361 presenting the correct spatial allocation. The diversity of crops was also well simulated at the  
 362 regional scale, as the same Shannon index of diversity (1.8) was obtained for observed and

363 simulated mosaics of cropping systems. The model was tested at the farm level for its ability to  
364 model crop diversity. The ratio between the Shannon index calculated for the modeled initial  
365 situation (0.39) considering the weighted average index of the diversity of each farm and the  
366 value obtained for the observed situation (0.53) yielded a value of 73%, which indicates that  
367 the model tends to reduce the diversity observed within the farms.

368

### 369 **2.2.5. Climate projections**

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

387

### 388 **2.2.6 Definition of scenarios for upscaling CSA**

389 Table 1 presents the different contexts of the modeled scenarios (in columns) and the levers  
390 applied to each of them (lines). The aim of the scenarios, defined by stakeholders, was to assess  
391 the impact of climate change in the long term and the impacts of several agronomic and  
392 economic levers to mitigate its consequences on the sustainability of agricultural systems, with  
393 all other things being equal." The five scenarios were defined as follows: (1) the choice of a  
394 climate change scenario, (2) the identification of levers and their combinations during  
395 workshops involving researchers and decision makers, and (3) the modeling and analysis of  
396 scenarios. The context of the baseline corresponded to the current situation, that is, the current



397 available activities, socioeconomic context, and climate conditions. The mosaic of cropping  
 398 systems and values obtained for the eleven indicators in the baseline corresponded to the  
 399 calibrated model output.

	VARIABLES	Baseline	S1	S2	S3	S4	S5
CLIMATE CHANGE	Yields decrease Mineralization factors	=	2056– 2080 climate projectio ns	2056– 2080 climate projectio ns	2056– 2080 climate projectio ns	2056– 2080 climate projectio ns	2056– 2080 climate projectio ns
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/+5 0% on AE activities	-50% on export crops/+5 0% 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%

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

402  
 403 Scenario S1 illustrates a climate change scenario for the period 2056–2080 with a “business as  
 404 usual” continuation in agricultural systems. The aim of this study was to assess the potential  
 405 impacts of climate change on agricultural systems in the study area. Scenario S1 was  
 406 parameterized in the MOSAICA model using two variables: impact on yields and soil organic  
 407 matter [soil organic carbon (SOC)] mineralization factors. The impact of climate change on  
 408 SOC was calculated using empirical relations obtained from historical data (Chopin and Sierra,

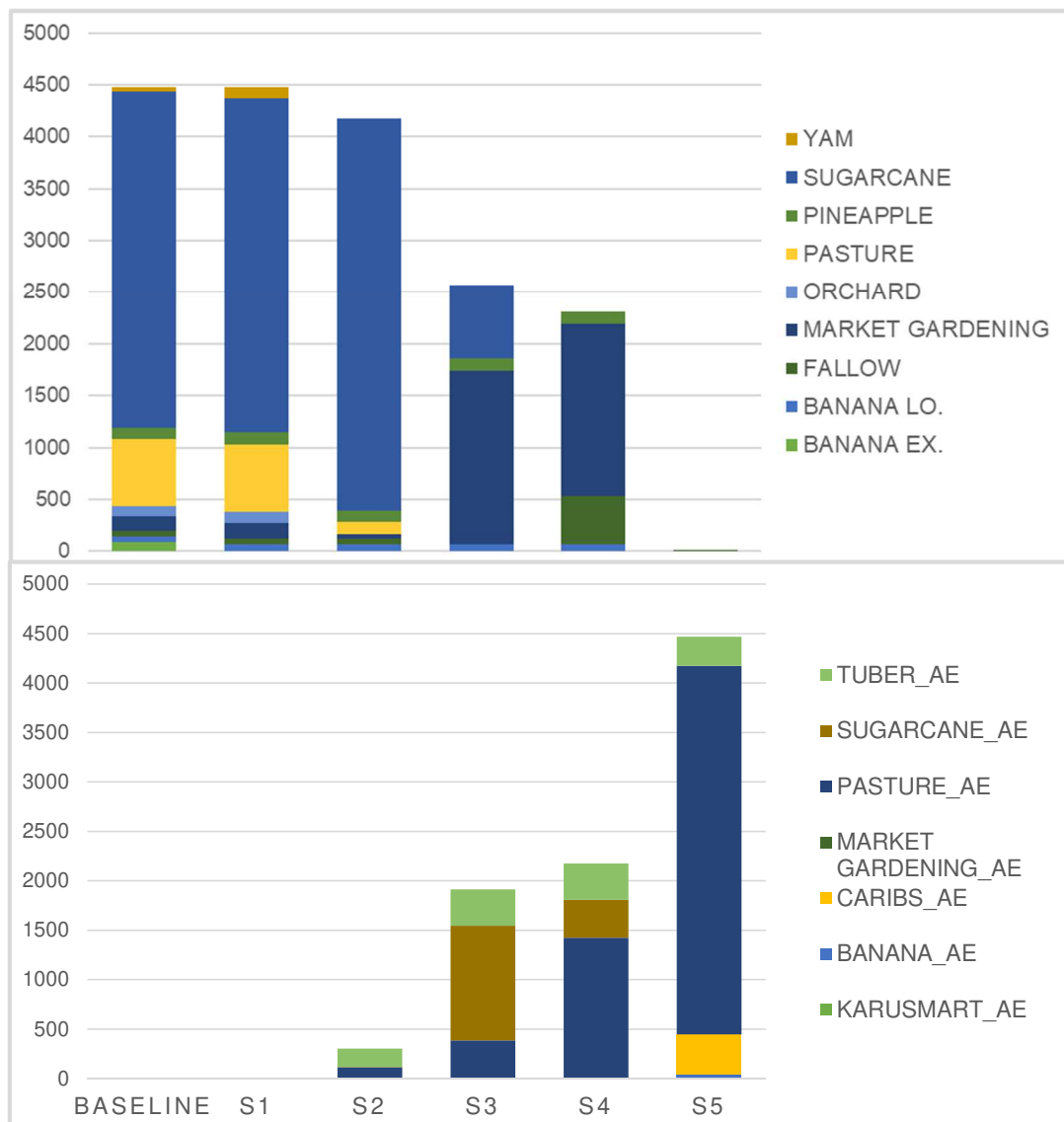


409 2019; Sierra et al., 2015). Impacts on crop yields were calculated by accounting for five climatic  
410 hazards (hurricanes, heat waves, drought, flood, and rising sea level) and a measure of the  
411 evolution of the cropping system vulnerability (Blazy, 2019). The potential impact index, which  
412 combined indicators of exposure to climatic hazards and sensitivity of the cropping systems  
413 using the crop ecophysiology, the characteristics of the field, and agricultural practices, was  
414 calculated for each field of the study area. The difference between the potential impact index  
415 for the current situation and for horizon 2056–2080 was used as a proxy to estimate yield  
416 variation. These values are provided in Supplementary Material 5 as potential impacts of  
417 climate hazards on agricultural activities. Climate change was included in scenarios S1–S5.  
418 Scenario S2 was built upon Scenario S1 with the introduction of seven new AE activities. This  
419 scenario was selected to explore the adoption potential of AE activities without any policies or  
420 socioeconomic measures. Scenario S3 corresponded to Scenario S2 with the added assumption  
421 of a larger available work force of +0.5 full-time-equivalents/ha on a regional scale. The low  
422 adoption of labor-intensive activities due to the lack of available agricultural work force in the  
423 study region was addressed in this scenario. Scenario S4 corresponded to S3, with a 50%  
424 reallocation of the subsidies given to export crops in favor of AE activities, which corresponds  
425 to an extra bonus of \$1385/ha for AE activities. The vast differences in the amount of subsidies  
426 dedicated to conventional export crops (banana and sugarcane) compared to crops for local  
427 markets are often pinpointed as a barrier to the adoption of AE activities.  
428 Scenario S5 was an ambitious one, exploring the impacts of a strong policy in favor of AE  
429 transition. It added the four following levers to S4: i) AE yields increase by 25% (progressive  
430 improvement of soil characteristics, ecosystem services, and farmers' knowledge); ii) an  
431 increase in the price of AE products by 50% (ecolabeling and short marketing channel  
432 development); iii) a decrease in farmers' risk aversion (farmers' training and knowledge  
433 diffusion with extension services); iv) a reduction in agricultural operation duration of 25%  
434 (availability of adapted small machinery and increase in labor efficiency by learning process).  
435

436 **3. Results**

437 **3.1. The baseline**

438 Figure 6 shows that conventional sugarcane and pasture activities represented 3248 ha and 649  
 439 ha (e.g., 73% and 14%) of the ALA, respectively. The remaining ALA was mainly represented  
 440 by market gardening (135 ha), pineapple (100 ha), orchard (98 ha), and banana exports (88 ha).  
 441



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

445 Table 2 shows the average performance of the farming systems in the study region. With 0.1  
 446 full-time-equivalent positions per hectare, a gross margin of \$3,300 /ha/yr, and a labor  
 447 productivity of \$23.3/hr, the farming system of this sub-region contributed to about 450 direct

448 jobs, which is low in relation to the population size (91,000 inhabitants). The average nutritional  
 449 performance was 3 people fed/ha/yr; thus, this farming system could feed approximately 13,500  
 450 people (e.g., 15% of the population of the study area). In terms of adaptation to climate change,  
 451 the overall potential impact of climate change on the current farming systems reached an  
 452 average baseline of 28%.  
 453 According to the calculation method, this value means that the current climate context has a  
 454 28% chance of inducing significant impacts on farm production. The farms in the study region  
 455 relied on 4.4 kg/ha/yr of active pesticide ingredients and 70 kg/ha/yr of inorganic N. In terms  
 456 of mitigation potential, GHG emissions were on average 1.9 tCO<sub>2</sub>eq/ha/yr. However, the SOC  
 457 variation was -0.5 tCO<sub>2</sub>eq/ha/yr; thus, the average regional GHG balance was an emission of  
 458 +2.4 tCO<sub>2</sub>eq/ha/yr in the baseline scenario. Therefore, the farming system emitted 0.8  
 459 tCO<sub>2</sub>eq/yr per nourished person. The last indicator revealed that an average of 1.2 tillages per  
 460 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	tCO <sub>2</sub> eq/ha/yr	1.9	1.8	1.4	1.5	1.9	3.3
	SOC change	tCO <sub>2</sub> eq/ha/yr	-0.5	-0.9	-0.3	+0.3	+1.1	+4.0
	GHG balance	tCO <sub>2</sub> eq/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	

461  
 462 **Table 2.** Results of the 11 indicators selected for the actual situation (baseline) and for the five  
 463 scenarios explored in the study for the studied region (4480 ha, 763 farms).

### 464 **3.2 Scenario S1: “Climate change”**

465 The simulation of the climate change impact for 2056–2080 did not produce significant changes  
466 in the two dominant activities. Sugarcane and pasture area shifted from 3248 ha to 3,229 ha (-  
467 1%) and from 649 ha to 645 ha (-1%), respectively (Figure 6). However, the remaining ALA  
468 showed significant changes in market gardening (+9%), pineapple (+15%), orchards (+16%),  
469 and yams (+130%). Moreover, banana exports almost disappeared, while the area of bananas  
470 cultivated for the local market rose slightly, from 58 ha to 66 ha. One can observe, however, an  
471 important decrease in the average gross margin from \$3,300/ha/yr to \$2700/ha/yr (-18%) and  
472 labor productivity (-17%). Equally, the nutritional performance showed an important decline  
473 of -30% from 3.0 to 2.1 fed people/ha/yr corresponding to a potential for feeding 9,400 people  
474 (10% of the population). On a regional scale, the adaptation indicators showed that the overall  
475 potential impact of climate change increased by 14% and reached an average value of 32% for  
476 2056–2080. The model simulation showed a slight decrease in inorganic N use (-6%), however,  
477 a constant application of pesticide active ingredients. For the mitigation potential, the GHG  
478 emissions displayed a 5% decrease from 1.9 tCO<sub>2</sub>eq/ha/yr to 1.8 tCO<sub>2</sub>eq/ha/yr, while the SOC  
479 reduction almost doubled with an 80% increase in emissions from -0.5 tCO<sub>2</sub>eq/ha/yr to -0.9  
480 tCO<sub>2</sub>eq/ha/yr, corresponding to a global GHG balance of +2.7 tCO<sub>2</sub>eq/ha/yr. These changes  
481 will lead to 1.3 tCO<sub>2</sub>eq emission per nourished person (+62%). The annual number of  
482 ploughings per hectare remained the same in this scenario. This simulation shows that climate  
483 change could have detrimental impacts on food security if no changes are made to the farming  
484 systems.

485

### 486 **3.3. Scenario S2: “New agroecological activities”**

487 This scenario corresponds to S1 with the introduction of the seven new AE activities previously  
488 designed. In S2, sugarcane activities increased to 3,784 ha (+16%), whereas pasture activities  
489 showed a notable reduction of 112 ha (-83%). The activities of both bananas for export and  
490 local markets showed the same tendency as that of S1 (Figure 6). Furthermore, both yam and  
491 orchard activities were no longer represented, while market gardening showed an important  
492 decrease of -68%. Interestingly, one can see that the introduction of the new AE activities in  
493 the actual socioeconomic context included the adoption of 114 ha of “AE pasture” and 186 ha  
494 of “AE tuber”, corresponding to 7% of the ALA devoted to AE activities. With a gross margin  
495 of \$3,100/ha/yr (-6% compared to that of the baseline) and a labor productivity of \$206/hr (-  
496 12%), this scenario presented higher economic performance than S1. However, the nutritional  
497 performance presented the same significant decrease with 2.0 fed people/ha/yr (-33%). For the

498 adaptation indicators, the climate potential impact showed the same increase as S1 (+14%).  
499 Owing to the increase in conventional sugarcane (+536 ha) area and the decrease in livestock  
500 area (-537 ha), the application of pesticides' active ingredients showed an increase of +9% with  
501 4.8 kg/ha/yr. The use of inorganic N was slightly reduced to 68 kg/ha/y. The GHG emissions  
502 decreased to a value of 1.4 tCO<sub>2</sub>eq/ha/yr (-26%), with SOC change decreasing by -40% from -  
503 0.5 tCO<sub>2</sub>eq/ha/yr to -0.3 tCO<sub>2</sub>eq/ha/yr. These values correspond to a -29% decrease in global  
504 GHG balance with +1.7 tCO<sub>2</sub>eq/ha/yr with an equal value of 0.8 tCO<sub>2</sub>eq emitted per nourished  
505 person. The last indicator of mitigation potential indicates no change in the plowing intensity  
506 in the new mosaic of activities. This scenario shows that with no changes in the socioeconomic  
507 environment of farming systems, the adoption of the newly designed AE activities is relatively  
508 low.

509

### 510 **3.4. Scenario S3: “Increase of work force availability”**

511 The availability of an additional 0.5 full-time equivalent (FTE) work force units per hectare in  
512 scenario S3 led to important changes in the farming system structure at the regional scale.  
513 Sugarcane area showed a significant reduction of -78% (715 ha), while pasture was no longer  
514 represented. Notably, market gardening became the dominant activity and represented 1,672 ha  
515 (37% of the ALA). The projections of the other conventional activities presented the same  
516 tendencies as S2, except for fallow, which was no longer present. The new AE activities were  
517 more readily adopted than in S2, with AE sugarcane representing the second most important  
518 activity at 1,160 ha of area. Moreover, AE pasture and tuber activities took third and fourth  
519 positions (just behind conventional sugarcane) at 384 ha and 367 ha of area, respectively.  
520 Globally, 43% of the ALA was devoted to AE activity in S3. These changes led to an increase  
521 in the average gross margin from \$3,300/ha/yr to \$10,200/ha/yr (+209%), even if the working  
522 productivity showed a decrease of -52%. This situation was due to larger production values  
523 with a -42% decrease in government subsidies allocated. Another interesting result was the  
524 +123% increase in nutritional performance with 6.7 fed people/ha/yr, corresponding to a  
525 potential for feeding 30,000 people (i.e., 33% of the population), more than double the actual  
526 (baseline) score. This increase was due to a notable increase in conventional market gardening  
527 activity at the expense of conventional sugarcane activity. All the other indicators showed a net  
528 improvement: inorganic N (-51%), pesticide active ingredients (-50%), and ploughing (-15%).  
529 GHG emissions were forecast at an average value of 1.5 tCO<sub>2</sub>eq/ha (-21%), and the SOC  
530 change became positive with an average value of +0.3 tCO<sub>2</sub>eq/ha/yr. These values correspond  
531 to a -50% decrease in global GHG balance with the emission of +1.2 tCO<sub>2</sub>eq/ha/yr, leading to

532 a value of 0.2 tCO<sub>2</sub>eq per nourished person, which is four times lower than that in the current  
533 situation. However, among the three indicators of adaptation, the global potential impact of  
534 climate change on the new mosaic of the cropping system is approximately 21% higher than  
535 that in the current situation without climate change (Table 3). This was mainly due to the  
536 replacement of sugarcane by market gardening crops that are more sensitive to climate change,  
537 particularly to heat and drought waves. Moreover, this large adoption of conventional market  
538 gardening activities led to more than double the average number of ploughings with 2.6 per  
539 year. This scenario clearly shows the key role of increasing the availability of the agricultural  
540 workforce to increase food autonomy in Guadeloupe.

541

### 542 **3.5. Scenario S4: “50% of subsidy reallocation to local crops”**

543 In scenario S4, market gardening with 1,661 ha (37% of the ALA) and fallowing with 465 ha  
544 (about 10% of the ALA) were the dominant conventional activities. For other conventional  
545 activities, only local banana (66 ha) and pineapple (115 ha) production was still present in the  
546 ALA. In this scenario, there was a significant adoption of the AE activities, representing almost  
547 50% of the regional ALA. The AE pasture was dominant (1,423 ha), followed by AE sugarcane  
548 (384 ha), and AE tuber (367 ha). Similarly in S3, the average nutritional performance in S4 was  
549 high, with 6.9 fed people/ha. The potential impact of climate change presented the same +14%  
550 increase as in S1, while the two other indicators of adaptation showed improvement with a -  
551 68% decrease in pesticide active ingredient application (14 kg/ha/yr) and -69% decrease in  
552 inorganic N use (22 kg/ha/yr). For the mitigation potential, the GHG emissions were 1.9  
553 tCO<sub>2</sub>eq/ha/yr in this scenario, which matches the baseline amount. However, the SOC change  
554 switched from emissions (-0.5 tCO<sub>2</sub>eq/ha/yr at baseline) to sequestration with +1.1  
555 tCO<sub>2</sub>eq/ha/yr. This value corresponds to a -67% (0.8 tCO<sub>2</sub>eq/ha/yr) decrease in global GHG  
556 balance in S4. Therefore, the new mosaic of activities led to a value of about 0.1 tCO<sub>2</sub>eq emitted  
557 per nourished person, which is 13 times lower than that in scenario S1. Finally, the mitigation  
558 potential indicator "number of ploughing operations" showed a significant increase from 1.2 to  
559 2.3 operations per hectare and per year (e.g., +90% as compared to that of the baseline) (Table  
560 3). This scenario clearly demonstrates the key role of adapting subsidies to orient farmers'  
561 choices towards AE activities. However, conventional market gardening activities remain very  
562 attractive relative to AE options, mainly because of their higher gross margins.

### 563 **3.6. Scenario S5: “multi-levers”**

564 In this scenario, the model simulated a complete transition of farming systems towards AE  
565 activities (Figure 6). AE pasture was strongly adopted with an area of 3,729 ha (83% of the  
566 ALA), followed by AE Caribs, AE tubers, and AE bananas with 399 ha (9%), 294 ha (7%), and  
567 46 ha (1%), respectively. This complete change in the regional farming structure was viewed  
568 alongside the best improvement in the average farm performance (Table 3). The average gross  
569 margin and labor productivity rose to \$22,600/ha/yr and \$25/hr, respectively. The nutritional  
570 performance was doubled compared to that of the baseline (6.0 fed people/ha/yr) and tripled  
571 compared to that of S1. This scenario simulated the use of inorganic N and pesticides in the  
572 study region. Moreover, plowing practice significantly decreased, with an average value of 0.7  
573 operations per year (-42%). This low value was mainly due to the strong adoption of AE  
574 pastures. Because of livestock development, this mosaic of activities also induced a significant  
575 increase in GHG emissions with 3.3 tCO<sub>2</sub>eq/ha/yr, due to enteric fermentation of ruminants.  
576 However, SOC change reached a value of +4.0 tCO<sub>2</sub>eq/ha/yr, leading to a positive global GHG  
577 balance of -0.7 tCO<sub>2</sub>eq sequestered per hectare per year (Table 3). The additional cost (\$525)  
578 for mitigating 1 tCO<sub>2</sub>eq in this scenario was determined by dividing the difference in GHG  
579 between S1 and S5 by the difference in public incentives:  $(-0.7) - 2.7 = -3.4 / (\$4464 - \$2679)$   
580  $= \$525 \text{ tCO}_2\text{eq}^{-1}$ . This calculation was also used to compare S5 and baseline, resulting in  
581 \$432. Food production corresponded to the sequestration of 0.1 tCO<sub>2</sub>eq/ha/yr per fed person.  
582 Finally, the potential impact of climate change on this new mosaic of farming systems was  
583 assessed, resulting in an average value of 28%, which is 12.5% less than that in S1; thus, there  
584 was a decrease in vulnerability.

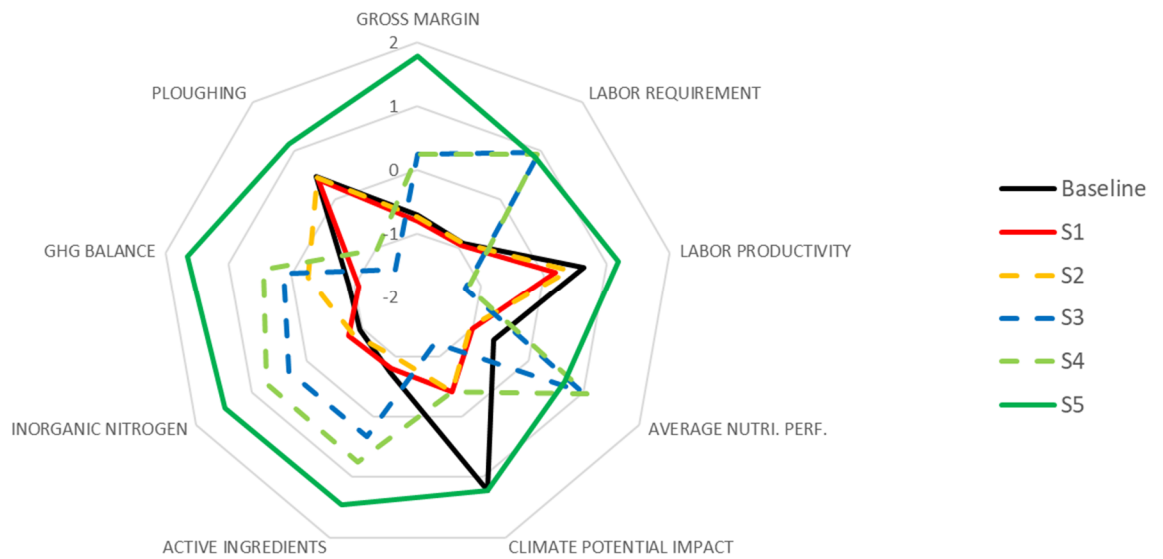
585

## 586 **4. Discussion**

### 587 **4.1. Lessons for policy makers and practical recommendations for upscaling CSA**

588 Based on the scenario analysis in Guadeloupe, our study provided some evidence regarding  
589 levers to be mobilized for upscaling CSA from the field to the regional scale. Because it leads  
590 to an increase in food autonomy and a strong improvement in the balance of GHG of local  
591 agricultural systems and adapts farming systems to climate change while maintaining  
592 productive capacities, the “multi-levers” scenario S5 makes reaching the CSA objectives an  
593 attainable prospect (Figure 7). In S5, all sustainability criteria were indeed improved, which  
594 made it possible to increase food security twofold, while contributing to climate change  
595 mitigation (sequestration of 0.7 t/ha/yr) and drastically reducing the negative environmental

596 impact of agricultural systems. The additional public cost of this scenario was \$1339 per  
 597 hectare, which is low given the social and environmental benefits it provides, such as  
 598 employment increase, reduction in pesticide use, and increase in food autonomy.



599  
 600 **Figure 7.** Radar charts of the relative scores of nine indicators for the five explored scenarios  
 601 and the baseline. Note: after mean-centering the scores, the values of indicators that should  
 602 have decreased were multiplied (Climate potential impact, Active ingredients, Inorganic N,  
 603 GHG Balance, and Ploughing) by -1 in order to have the same reading. Higher values  
 604 correspond to better performances. GHG Balance = GHG emissions - SOC changes.

605  
 606 If new crop management systems based on agroecology and bioeconomy have the potential to  
 607 reach the goals of CSA, the results obtained in this study confirm that a set of new policies  
 608 targeting farmers' constraints are required to upscale CSA (Ollivier et al., 2018; Meynard et al.,  
 609 2018; Thornton et al., 2017; Westermann et al., 2015). Indeed, comparing scenarios S2 and S5  
 610 shows that the introduction of the new AE activities alone is not sufficient if no other policy  
 611 measures are undertaken, owing to the limited adoption rate (7% of the ALA). First, the lack of  
 612 an agricultural workforce constrains the adoption of new systems that are more labor-intensive.  
 613 Increasing agricultural labor availability from 0.1 people/ha/yr to 0.6 people/ha/yr led to an  
 614 increase in adoption rate of AE activities (from 7% to a 43%). Practically, this constraint could  
 615 be remedied by the development of training courses for agricultural workers in agroecology,  
 616 the development of temporary employment agencies specialized in agricultural work, and by  
 617 massive communication aimed at making the farming profession more attractive, especially to  
 618 young people.



619 The second constraint to be rectified is the actual orientation of 80% of subsidies for  
620 conventional export crops like bananas and sugarcane. The reallocation of 50% of subsidies  
621 from these two conventional activities to AE activities in S4 induced noticeable changes in the  
622 mosaic of activities in comparison to S3. This confirms that adapting policies in a consistent  
623 way is required to orient agricultural systems towards CSA (Lipper et al., 2018; Markard et al.,  
624 2012). Third, reducing farmers' risk aversion is crucial to completely influence farmers to adopt  
625 AE activities (Hill, 2014). As most farmers are currently involved in simplified agricultural  
626 systems, they can be reluctant to engage in more complex and risky systems, where they have  
627 to manage many more crops and cannot access chemical inputs (Chèze et al., 2020; Moss 2019).  
628 Therefore, training farmers in the technical and economic management of AE systems could be  
629 a key factor in a successful transition. This lever could take place in training centers comprising  
630 of "pilot" AE microfarms in which climate smart systems are demonstrated, allowing farmers  
631 to increase their technical skills. These centers could accompany farmers, helping them  
632 redesign a system that is both technically and economically viable for their own context.  
633 Finally, the cross-sectional analysis of all scenarios confirmed that labor productivity is a key.  
634 Three policy levers could be mobilized to increase the current level of labor productivity in the  
635 context of entirely agroecology-based agriculture. First, the increase in the sales prices of AE  
636 products seems essential to valorize their social and environmental benefits. This can be  
637 implemented practically in different manners, particularly through the valorization of AE  
638 production with eco-labels, agro-transformation (e.g., to market "ready to eat" food), and  
639 development of short marketing channels for the local market. An increase in work efficiency  
640 could also be achieved through adapted small mechanization to increase the competitiveness of  
641 AE crop management systems. Policymakers could promote better availability of adapted  
642 micro-machinery, for example, through the establishment of cooperatives for specific materials  
643 for agricultural microfarms (Thornton et al., 2019). Finally, an increase in agronomic yields in  
644 AE systems could increase the economic efficiency of these systems. An increase in yield is  
645 often observed after several years of transition to an AE system. This could be due to the  
646 progressive setting up of ecosystem services and their positive effects on the function of an  
647 agro-ecosystem. Another result of our study is that AE livestock systems can contribute to  
648 mitigating climate change and increasing food security and resilience. However, converting  
649 arable lands to livestock systems with high grassland shares will require many transformations  
650 in farm structure and farmers' skills, and such a conversion would also require much policy  
651 support from the perspective of a successful transition.

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

659

#### 660 **4.2. Limitations of the study and scientific challenges**

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

686 capacities (robustness, adaptability, and transformability) and nested levels of farming, such as  
687 those proposed by Meuwissen et al. (2019) and Zampieri et al. (2020). Another axis of research  
688 is to perform sensitivity analyses on the key parameters of transition (e.g., climate change  
689 scenario, adaptation of society food habits, and evolution of markets) or those parameters  
690 containing uncertainty (e.g., the levels of levers mobilized in the scenarios, the intensity of  
691 effects of climate change, the performance of AE systems).

692

### 693 **4.3. A contribution to the “redesign approach” of agricultural systems**

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

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

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

731

## 732 **5. Conclusions**

733 In this paper, a methodological framework combining farm regional diagnosis, system  
734 experiments, and bioeconomic modeling is proposed to design scenarios for upscaling CSA.  
735 When applied to Guadeloupe, our results show that new agricultural production systems based  
736 on agroecology and bioeconomy principles have the potential to achieve the objectives of CSA  
737 at the regional scale. In the best scenario designed, the potential impact of climate change on  
738 production was reduced by 12.5%, the nutritional performance at the regional scale were tripled  
739 with 6.0 fed people/ha/yr on average, the GHG balance switched from net emissions to a  
740 sequestration of 0.7 tCO<sub>2</sub>eq/ha/yr, and the labor productivity rose to \$26.5/hr (+14%).  
741 Compared to that in the baseline situation, the public cost for mitigating 1 tCO<sub>2</sub>eq was \$432.  
742 While the new agricultural systems have the potential to meet the objectives of CSA, our study  
743 showed that their large uptake at the regional scale implies that many lock-ins to their adoption  
744 must be relaxed. To this end, we identified the following levers: increasing workforce  
745 availability at the regional scale, reorientating public incentives towards AE systems, increasing  
746 the profitability of CSA products with eco-labels, improving the work efficiency of farmers,  
747 and reducing their risk aversion.

748 Therefore, new ambitious policies targeting farmers' constraints are required to upscale CSA.  
749 There is a need to develop more stakeholder platforms in which all issues and possible levers  
750 are discussed and scenarios are co-designed to define successful transition of agricultural  
751 systems. The approach proposed herein can be used to feed discussions on such platforms.  
752 Research has to be continued in the "redesign" field to model the transition of agricultural

753 systems in a dynamic way, given the uncertainty of many crucial aspects such as climate change  
754 scenarios, market evolution, technical progress in agroecology, and farmers' behavior.

755

756

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764

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