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

S. Selbonne, L. Guindé, A. Belmadani, C. Bonine, F. L. Causeret, M. Duval,
J. Sierra, J.M. Blazy

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

3
4 **Authors:** Selbonne, S.^a, Guindé, L.^a, Belmadani, A.^b, Bonine, C^c, L. Causeret, F.^a, Duval, M^a,
5 Sierra, J.^a, Blazy, JM^a.

6
7 **Affiliations:**

8 ^a INRAE, UR ASTRO, F-97170, Petit-Bourg, Guadeloupe, France

9 ^b Météo-France, Direction Interrégionale Antilles-Guyane, Fort-de-France, Martinique,
10 France

11 ^c Synergîle, Pôle d’innovation de la Guadeloupe, 97122 Baie-Mahault, Guadeloupe, France

12
13 **Abstract:**

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

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

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

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

34 efficiency of farmers, and reducing their risk aversion. In the best scenario designed, the
35 potential impact of climate hazards was reduced by 12.5%, the nutritional performance at the
36 regional scale was tripled with 6.0 fed people/ha/yr, the GHG balance switched from net
37 emissions to a sequestration of 0.7 tCO₂eq/ha/yr, while the labor productivity rose to \$26.5/hr
38 (+14%). Compared to that of the baseline situation, the public cost for mitigating 1 tCO₂eq
39 was \$432.

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

47

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

50

51

52 **Highlights:**

53

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

63

64 **1. Introduction**

65

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

85 To implement CSA, several levers have been investigated, such as the genetic improvement
86 of crops to increase resilience, digital tools, agroecology, and bioeconomy. Agroecology is a
87 method of designing production systems based on the functionalities offered by ecosystems
88 (Gliessman, 2016; Wezel et al., 2009). It amplifies natural processes within agrosystems
89 while aiming to reduce pressure on the environment (e.g., reducing GHG emissions and
90 avoiding the use of synthetic fertilizers and pesticides) and preserving natural resources
91 (water, energy, and mineral elements). Agroecology reintroduces biodiversity into agricultural
92 production systems and restores a diversified landscape mosaic (Altieri and Toledo, 2011).
93 Parallel to agroecology, the emerging concept of bioeconomy aims to propose sustainable
94 development models based on the valorization of bio-sourced products and locally sourced
95 by-products, replacing materials and inputs that consume more fossil energy. For the
96 agricultural sector, the bioeconomy is complementary to agroecology because it can provide
97 new opportunities to increase farm competitiveness while providing sustainable solutions to

98 environmental and societal challenges (Muller et al., 2017). Agroecology can develop a
99 bioeconomy by providing pesticide-free agricultural products for the local market (food, feed,
100 fiber), whereas bioeconomy can support agroecology development through the recycling of
101 local residual organic matter (from industrial or domestic origin) into locally processed bio-
102 inputs (Mousseau, 2015; Valenzuela 2016). Agroecology and bioeconomy are
103 complementary; thus, their synergies are currently being explored in research to develop CSA
104 (Pimbert, 2015).

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

132 combine them in a consistent way to accelerate the adoption of climate smart agricultural
133 systems (Dale et al., 2013; Vervoort et al., 2014).

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

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

160

161 **2. Material and methods**

162 **2.1. The modeling framework**

163 **2.1.1. Interrelationships across scales**

164 Agricultural systems can be analyzed as nested hierarchical systems (Giller, 2013; Le Gal et
165 al., 2010; Wery, 2015). Reaching sustainability goals at a regional scale requires an adequate

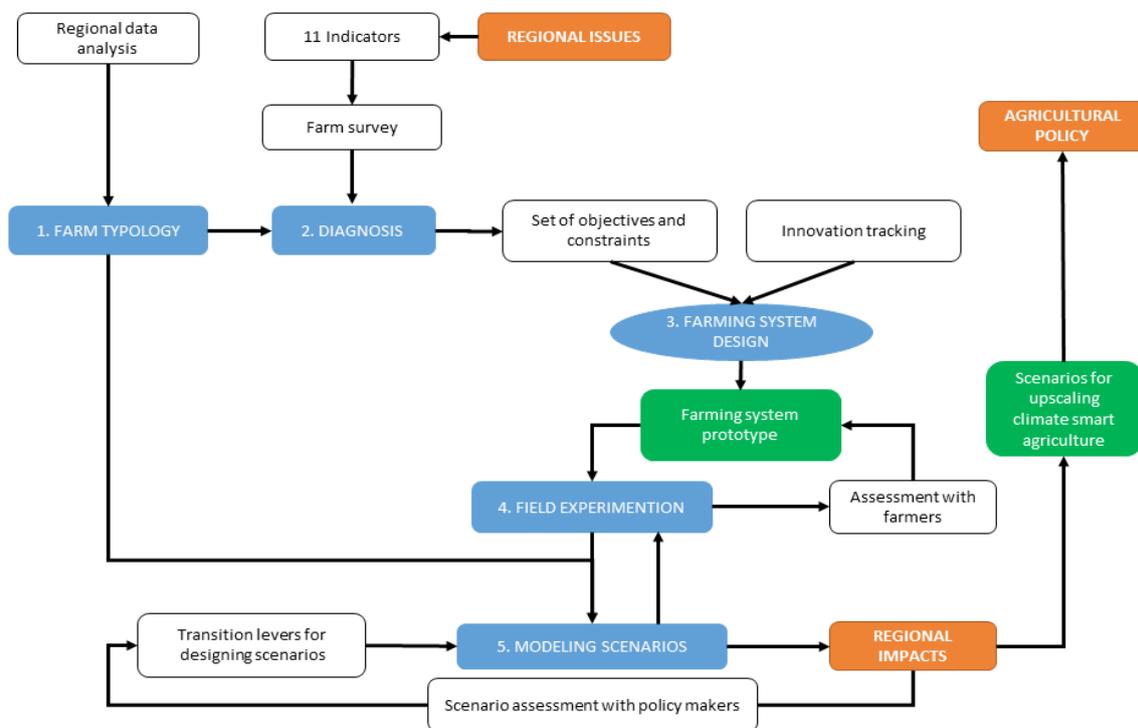
166 combination of innovations at the field scale (agroecological techniques) and adaptation of
167 farm structure organization (integrated farming system, resource allocation), markets, supply
168 chains, and policies. First, to sustainably improve or preserve ecosystem services provided by
169 cropping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

188

189 **2.1.2. Overview of the methodological framework**

190 The proposed framework aims at quantification, spatial integration from the plot to the
191 regional level, and modeling of scenarios for upscaling CSA. The framework (Figure 1)
192 consists of five main steps and combines typology building from a database on farm
193 production systems (step 1); a survey on a sample of farms to diagnose the sustainability of
194 farming systems with a set of indicators (step 2); the design and field experiment of an
195 innovative prototype of the climate smart farming system (steps 3 and 4); and the modeling of
196 scenarios using data from the diagnosis, experiment, and identification of socioeconomic
197 levers to upscale CSA (step 5). Steps 1 and 2 characterize the current farming system within
198 the study area. This consists of building a typology of farming systems to model the diversity
199 of farms in the region, notably in terms of pedoclimatic conditions, nature of farming systems,

200 and farmers' economic endowments. Ideally, the typology is built using census data of farms
 201 on crop rotation and area, via a robust statistical clustering method (Blazy et al., 2009; Chopin
 202 et al., 2015a). The typology serves as an in situ survey of several farms for each farm type
 203 identified. The data collected were then used for the diagnosis of the current regional farming
 204 system considered as the "baseline". This diagnosis is based on a set of sustainability
 205 indicators, including the potential impacts of climate change (Chopin et al., 2017a). The
 206 outputs of these first two steps serve as a basis for the design of prototypes of agroecological
 207 crop management systems (step 3), following the method of Blazy et al. (2009). They also
 208 serve for the calibration and parameterization of the baseline situation into the bioeconomic
 209 model used in step 5 for modeling scenarios.



210
 211 **Figure 1.** Overview of the methodological framework. The blue boxes correspond to the five
 212 main steps of the framework. The green boxes correspond to the main outputs of the
 213 framework. The white boxes correspond to the different tools used.

214
 215 The design of the prototypes of agroecological farming systems is inspired by the regional
 216 diversity of issues that farms must address and is exclusively based on agroecological and
 217 bioeconomic principles. The design process mobilizes both scientific evidence and farmers'
 218 knowledge to propose redesigns of current farming systems, considering farm issues as well
 219 as existing opportunities for circular bioeconomy on a regional scale. The output of Step 3 is a
 220 co-designed prototype defined as a conceptual model of a farming system that is later

221 experimented on a small-scale pilot farm in Step 4. The purpose of this study is to acquire
222 technical, economic, and environmental references for prototypes of alternative systems. In
223 addition to the parameterization of the model used in Step 5, the role of the experimental
224 microfarm is to provide an interface for discussion and co-evaluation of solutions with
225 stakeholders to adapt farming systems, value chains, and agricultural policies. Subsequently,
226 the resulting data of the experiment in Step 4 are used in Step 5 to evaluate the innovative
227 production system on a regional scale and the design of scenarios using the bioeconomic
228 model MOSAICA (Figure 2).

229

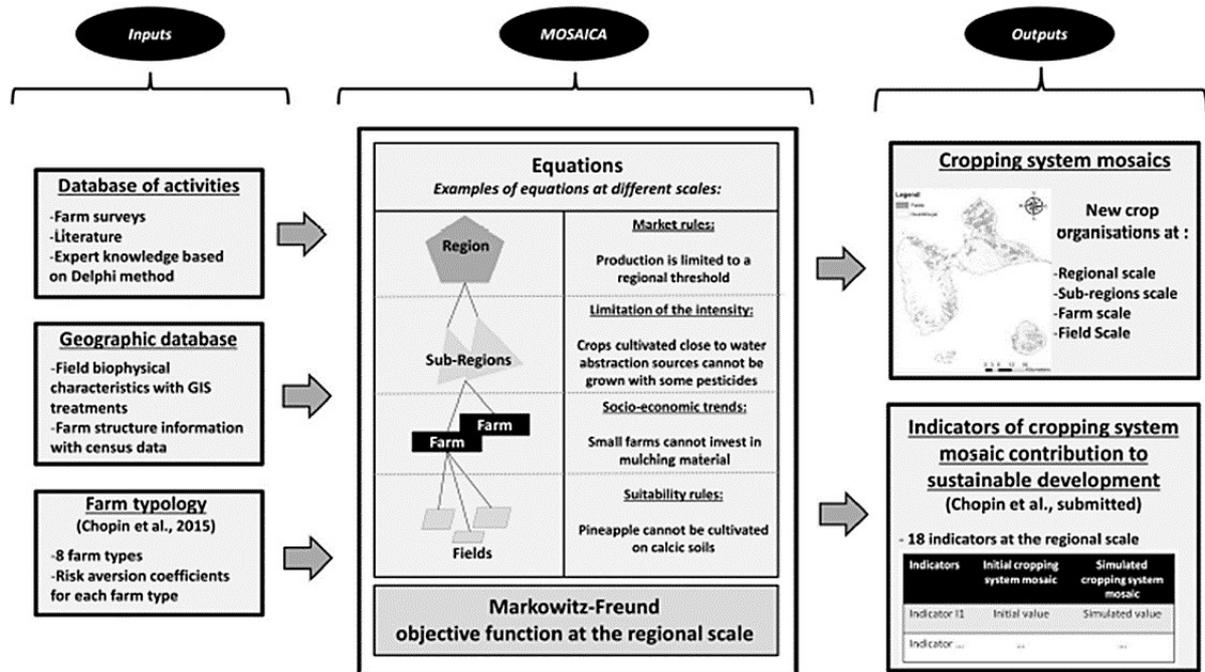
230 **2.1.3. The modeling approach**

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

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

255 allocation of several sets of risk-aversion coefficients to farmers according to their farm type.
 256 These risk-aversion coefficients at the farm scale help reproduce farmers' cropping plans
 257 based on a hypothesis about their level of risk aversion.

258

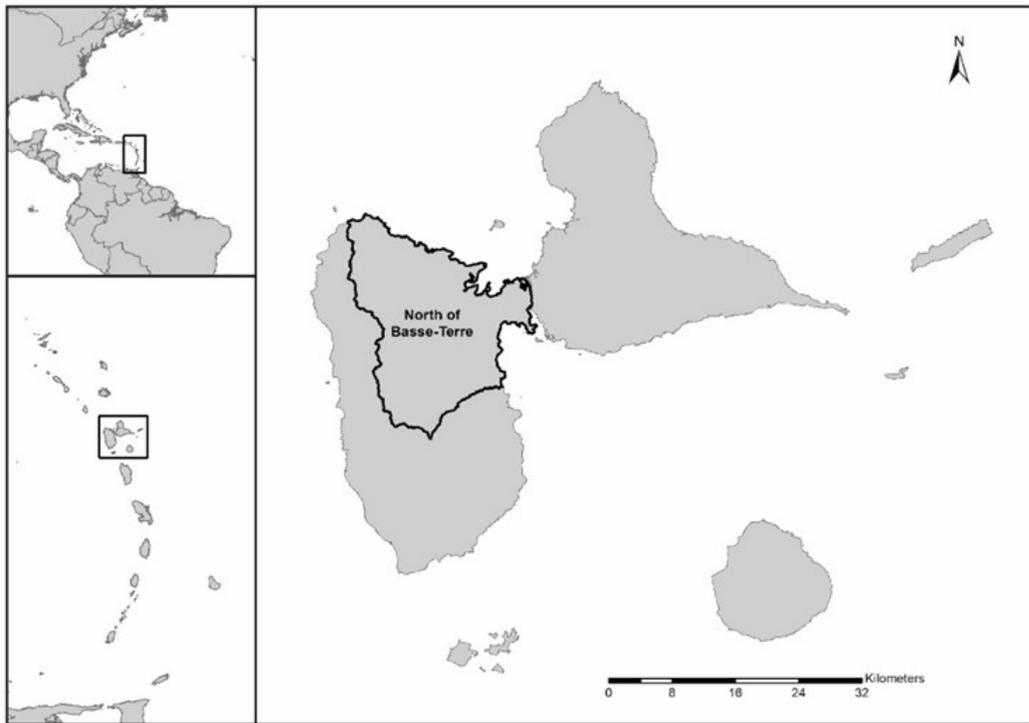


259

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

261

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



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

278

279 **2.2. Application of the framework in Guadeloupe**

280 **2.2.1 Study area and farming systems context**

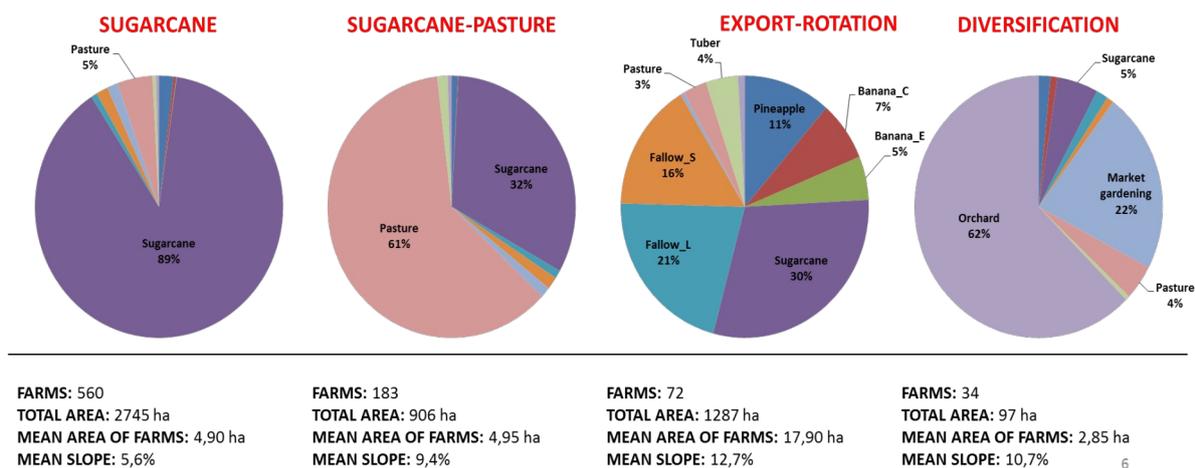
281 The framework presented was applied to the North Basse-Terre region of Guadeloupe, a
 282 French overseas department in the Caribbean (Figure 3). Guadeloupe is an archipelago (1628
 283 km²) comprising two main islands, Basse-Terre (848 km²) and Grande-Terre (586 km²), with
 284 vast ecological contrasts.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

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

308

309 2.2.2. Regional diagnosis of farming systems

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



315

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

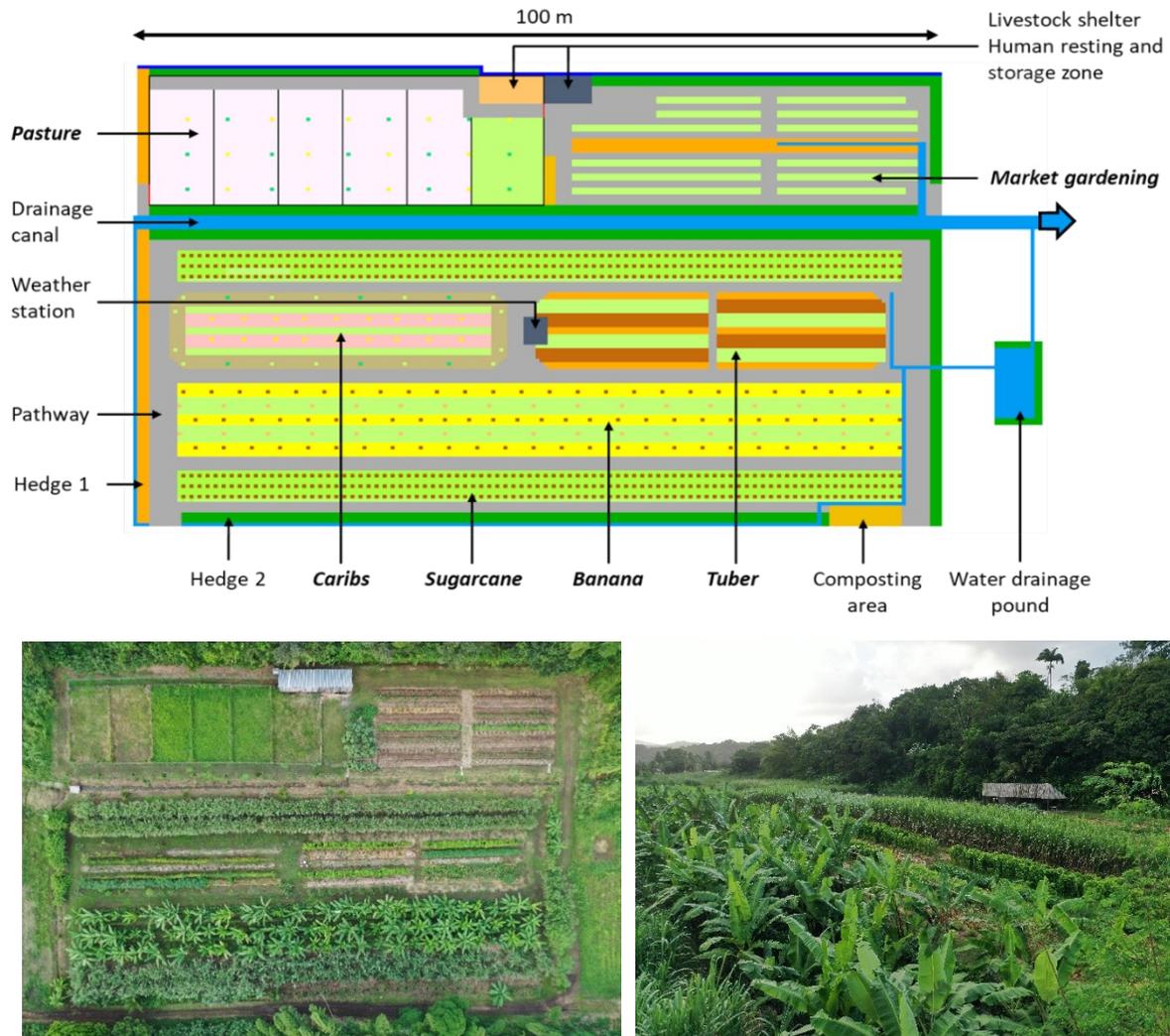
317 From the typology, three farms in each of the four clusters were randomly selected and
 318 surveyed. The diagnosis of the surveyed farms targeted three pillars of CSA: food security,
 319 mitigation, and adaptation. These three pillars rely on economic, social, environmental, and
 320 agronomic factors. Surveying the 12 farmers provided data on their current agricultural

321 practices. Based on the typology, these data were attributed to each farm in the MOSAICA
322 model for parameterization.

323 **2.2.3. Agroecological farming system design and experiment**

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

355 economic coefficients for parameterizing the model. Through participatory assessments with
 356 farmers, the technical management of AE activities was continuously improved.



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

362

363 **2.2.4. Parameterization and calibration of the MOSAICA model**

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

369 96.5% of overall agricultural areas correctly simulated at the regional scale, with 80% of the
370 areas presenting the correct spatial allocation. The diversity of crops was also well simulated
371 at the regional scale, as the same Shannon index of diversity (1.8) was obtained for observed
372 and simulated mosaics of cropping systems. The model was tested at the farm level for its
373 ability to model crop diversity. The ratio between the Shannon index calculated for the
374 modeled initial situation (0.39) considering the weighted average index of the diversity of
375 each farm and the value obtained for the observed situation (0.53) yielded a value of 73%,
376 which indicates that the model tends to reduce the diversity observed within the farms.

377

378 **2.2.5. Climate projections**

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

396

397 **2.2.6 Definition of scenarios for upscaling CSA**

398 Table 1 presents the different contexts of the modeled scenarios (in columns) and the levers
399 applied to each of them (lines). The aim of the scenarios, defined by stakeholders, was to
400 assess the impact of climate change in the long term and the impacts of several agronomic and
401 economic levers to mitigate its consequences on the sustainability of agricultural systems,
402 with all other things being equal." The five scenarios were defined as follows: (1) the choice

403 of a climate change scenario, (2) the identification of levers and their combinations during
 404 workshops involving researchers and decision makers, and (3) the modeling and analysis of
 405 scenarios. The context of the baseline corresponded to the current situation, that is, the current
 406 available activities, socioeconomic context, and climate conditions. The mosaic of cropping
 407 systems and values obtained for the eleven indicators in the baseline corresponded to the
 408 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 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%

409 **Table 1.** Description of the context of the baseline and the five scenarios made of the different
 410 levers explored. AE: agroecological; FTE: full time equivalent work unit; “=”: no change
 411

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

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

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

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

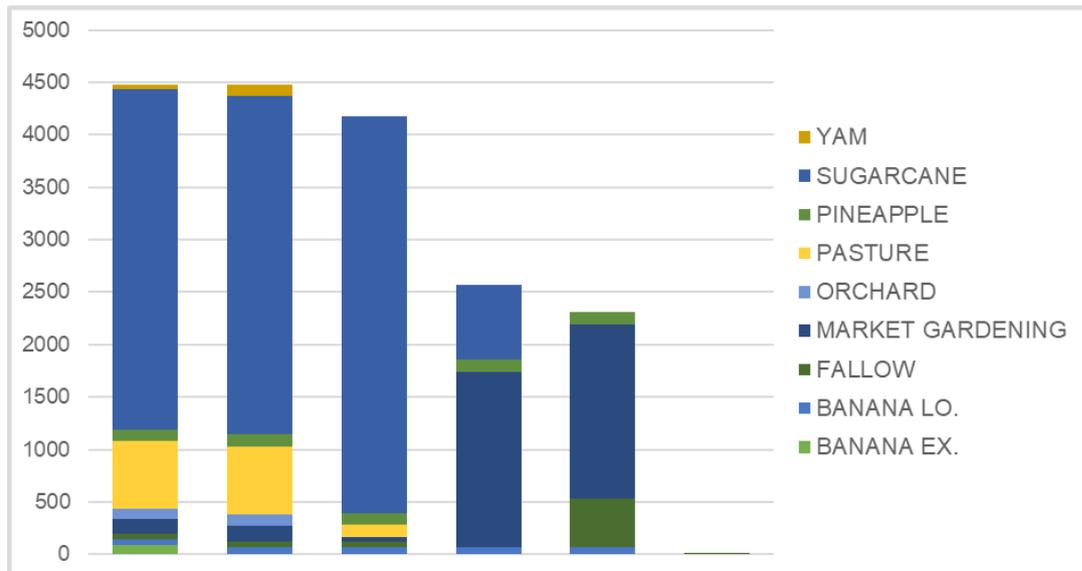
445

446 **3. Results**

447 **3.1. The baseline**

448 Figure 6 shows that conventional sugarcane and pasture activities represented 3248 ha and
449 649 ha (e.g., 73% and 14%) of the ALA, respectively. The remaining ALA was mainly
450 represented by market gardening (135 ha), pineapple (100 ha), orchard (98 ha), and banana
451 exports (88 ha).

452



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

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

464 According to the calculation method, this value means that the current climate context has a
 465 28% chance of inducing significant impacts on farm production. The farms in the study region
 466 relied on 4.4 kg/ha/yr of active pesticide ingredients and 70 kg/ha/yr of inorganic N. In terms
 467 of mitigation potential, GHG emissions were on average 1.9 tCO₂eq/ha/yr. However, the
 468 SOC variation was -0.5 tCO₂eq/ha/yr; thus, the average regional GHG balance was an
 469 emission of +2.4 tCO₂eq/ha/yr in the baseline scenario. Therefore, the farming system
 470 emitted 0.8 tCO₂eq/yr per nourished person. The last indicator revealed that an average of 1.2
 471 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.Fed perf.	nutri.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 ₂ eq/ha/yr	1.9	1.8	1.4	1.5	1.9	3.3
	SOC change	tCO ₂ eq /ha/yr	-0.5	-0.9	-0.3	+0.3	+1.1	+4.0
	GHG balance	tCO ₂ 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 INCENTIVE	PUBLIC \$/ha/yr	3125	2679	3125	1853	2188	4464	

472

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

475 **3.2 Scenario S1: “Climate change”**

476 The simulation of the climate change impact for 2056–2080 did not produce significant
477 changes in the two dominant activities. Sugarcane and pasture area shifted from 3248 ha to
478 3,229 ha (-1%) and from 649 ha to 645 ha (-1%), respectively (Figure 6). However, the
479 remaining ALA showed significant changes in market gardening (+9%), pineapple (+15%),
480 orchards (+16%), and yams (+130%). Moreover, banana exports almost disappeared, while
481 the area of bananas cultivated for the local market rose slightly, from 58 ha to 66 ha. One can
482 observe, however, an important decrease in the average gross margin from \$3,300/ha/yr to
483 \$2700/ha/yr (-18%) and labor productivity (-17%). Equally, the nutritional performance
484 showed an important decline of -30% from 3.0 to 2.1 fed people/ha/yr corresponding to a
485 potential for feeding 9,400 people (10% of the population). On a regional scale, the adaptation
486 indicators showed that the overall potential impact of climate change increased by 14% and
487 reached an average value of 32% for 2056–2080. The model simulation showed a slight
488 decrease in inorganic N use (-6%), however, a constant application of pesticide active
489 ingredients. For the mitigation potential, the GHG emissions displayed a 5% decrease from
490 1.9 tCO₂eq/ha/yr to 1.8 tCO₂eq/ha/yr, while the SOC reduction almost doubled with an 80%
491 increase in emissions from -0.5 tCO₂eq/ha/yr to -0.9 tCO₂eq/ha/yr, corresponding to a global
492 GHG balance of +2.7 tCO₂eq/ha/yr. These changes will lead to 1.3 tCO₂eq emission per
493 nourished person (+62%). The annual number of ploughings per hectare remained the same in
494 this scenario. This simulation shows that climate change could have detrimental impacts on
495 food security if no changes are made to the farming systems.

496

497 **3.3. Scenario S2: “New agroecological activities”**

498 This scenario corresponds to S1 with the introduction of the seven new AE activities
499 previously designed. In S2, sugarcane activities increased to 3,784 ha (+16%), whereas
500 pasture activities showed a notable reduction of 112 ha (-83%). The activities of both
501 bananas for export and local markets showed the same tendency as that of S1 (Figure 6).
502 Furthermore, both yam and orchard activities were no longer represented, while market
503 gardening showed an important decrease of -68%. Interestingly, one can see that the
504 introduction of the new AE activities in the actual socioeconomic context included the
505 adoption of 114 ha of “AE pasture” and 186 ha of “AE tuber”, corresponding to 7% of the
506 ALA devoted to AE activities. With a gross margin of \$3,100/ha/yr (-6% compared to that of
507 the baseline) and a labor productivity of \$206/hr (-12%), this scenario presented higher
508 economic performance than S1. However, the nutritional performance presented the same

509 significant decrease with 2.0 fed people/ha/yr (-33%). For the adaptation indicators, the
510 climate potential impact showed the same increase as S1 (+14%). Owing to the increase in
511 conventional sugarcane (+536 ha) area and the decrease in livestock area (-537 ha), the
512 application of pesticides' active ingredients showed an increase of +9% with 4.8 kg/ha/yr.
513 The use of inorganic N was slightly reduced to 68 kg/ha/y. The GHG emissions decreased to a
514 value of 1.4 tCO₂eq/ha/yr (-26%), with SOC change decreasing by -40% from -0.5
515 tCO₂eq/ha/yr to -0.3 tCO₂eq/ha/yr. These values correspond to a -29% decrease in global
516 GHG balance with +1.7 tCO₂eq/ha/yr with an equal value of 0.8 tCO₂eq emitted per
517 nourished person. The last indicator of mitigation potential indicates no change in the plowing
518 intensity in the new mosaic of activities. This scenario shows that with no changes in the
519 socioeconomic environment of farming systems, the adoption of the newly designed AE
520 activities is relatively low.

521

522 **3.4. Scenario S3: “Increase of work force availability”**

523 The availability of an additional 0.5 full-time equivalent (FTE) work force units per hectare in
524 scenario S3 led to important changes in the farming system structure at the regional scale.
525 Sugarcane area showed a significant reduction of -78% (715 ha), while pasture was no longer
526 represented. Notably, market gardening became the dominant activity and represented 1,672
527 ha (37% of the ALA). The projections of the other conventional activities presented the same
528 tendencies as S2, except for fallow, which was no longer present. The new AE activities were
529 more readily adopted than in S2, with AE sugarcane representing the second most important
530 activity at 1,160 ha of area. Moreover, AE pasture and tuber activities took third and fourth
531 positions (just behind conventional sugarcane) at 384 ha and 367 ha of area, respectively.
532 Globally, 43% of the ALA was devoted to AE activity in S3. These changes led to an increase
533 in the average gross margin from \$3,300/ha/yr to \$10,200/ha/yr (+209%), even if the working
534 productivity showed a decrease of -52%. This situation was due to larger production values
535 with a -42% decrease in government subsidies allocated. Another interesting result was the
536 +123% increase in nutritional performance with 6.7 fed people/ha/yr, corresponding to a
537 potential for feeding 30,000 people (i.e., 33% of the population), more than double the actual
538 (baseline) score. This increase was due to a notable increase in conventional market gardening
539 activity at the expense of conventional sugarcane activity. All the other indicators showed a
540 net improvement: inorganic N (-51%), pesticide active ingredients (-50%), and ploughing (-
541 15%). GHG emissions were forecast at an average value of 1.5 tCO₂eq/ha (-21%), and the
542 SOC change became positive with an average value of +0.3 tCO₂eq/ha/yr. These values

543 correspond to a -50% decrease in global GHG balance with the emission of +1.2
544 tCO₂eq/ha/yr, leading to a value of 0.2 tCO₂eq per nourished person, which is four times
545 lower than that in the current situation. However, among the three indicators of adaptation, the
546 global potential impact of climate change on the new mosaic of the cropping system is
547 approximately 21% higher than that in the current situation without climate change (Table 3).
548 This was mainly due to the replacement of sugarcane by market gardening crops that are more
549 sensitive to climate change, particularly to heat and drought waves. Moreover, this large
550 adoption of conventional market gardening activities led to more than double the average
551 number of ploughings with 2.6 per year. This scenario clearly shows the key role of
552 increasing the availability of the agricultural workforce to increase food autonomy in
553 Guadeloupe.

554

555 **3.5. Scenario S4: “50% of subsidy reallocation to local crops”**

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

577 **3.6. Scenario S5: “multi-levers”**

578 In this scenario, the model simulated a complete transition of farming systems towards AE
579 activities (Figure 6). AE pasture was strongly adopted with an area of 3,729 ha (83% of the
580 ALA), followed by AE Caribs, AE tubers, and AE bananas with 399 ha (9%), 294 ha (7%),
581 and 46 ha (1%), respectively. This complete change in the regional farming structure was
582 viewed alongside the best improvement in the average farm performance (Table 3). The
583 average gross margin and labor productivity rose to \$22,600/ha/yr and \$25/hr, respectively.
584 The nutritional performance was doubled compared to that of the baseline (6.0 fed
585 people/ha/yr) and tripled compared to that of S1. This scenario simulated the use of inorganic
586 N and pesticides in the study region. Moreover, plowing practice significantly decreased, with
587 an average value of 0.7 operations per year (-42%). This low value was mainly due to the
588 strong adoption of AE pastures. Because of livestock development, this mosaic of activities
589 also induced a significant increase in GHG emissions with 3.3 tCO₂eq/ha/yr, due to enteric
590 fermentation of ruminants. However, SOC change reached a value of +4.0 tCO₂eq/ha/yr,
591 leading to a positive global GHG balance of -0.7 tCO₂eq sequestered per hectare per year
592 (Table 3). The additional cost (\$525) for mitigating 1 tCO₂eq in this scenario was determined
593 by dividing the difference in GHG between S1 and S5 by the difference in public incentives:
594 $(-0.7) - 2.7 = -3.4 / (\$4464 - \$2679) = \$525 \text{ tCO}_2\text{eq}^{-1}$. This calculation was also used to
595 compare S5 and baseline, resulting in \$432. Food production corresponded to the sequestration
596 of 0.1 tCO₂eq/ha/yr per fed person. Finally, the potential impact of climate change on this
597 new mosaic of farming systems was assessed, resulting in an average value of 28%, which is
598 12.5% less than that in S1; thus, there was a decrease in vulnerability.

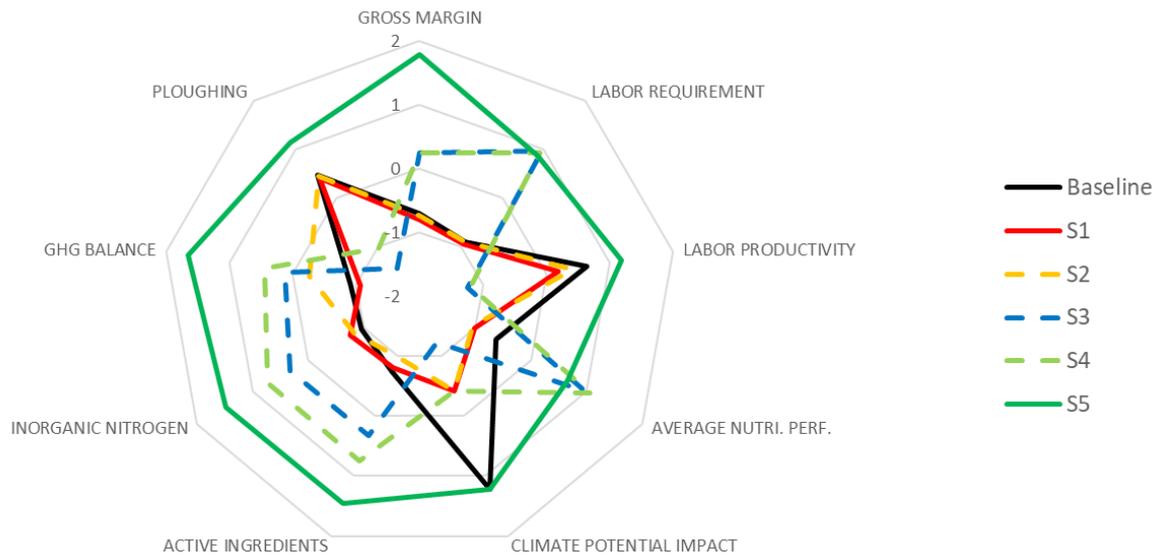
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600 **4. Discussion**

601 **4.1. Lessons for policy makers and practical recommendations for upscaling CSA**

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

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



613
 614 **Figure 7.** Radar charts of the relative scores of nine indicators for the five explored scenarios
 615 and the baseline. Note: after mean-centering the scores, the values of indicators that should
 616 have decreased were multiplied (Climate potential impact, Active ingredients, Inorganic N,
 617 GHG Balance, and Ploughing) by -1 in order to have the same reading. Higher values
 618 correspond to better performances. GHG Balance = GHG emissions - SOC changes.

619
 620 If new crop management systems based on agroecology and bioeconomy have the potential to
 621 reach the goals of CSA, the results obtained in this study confirm that a set of new policies
 622 targeting farmers' constraints are required to upscale CSA (Ollivier et al., 2018; Meynard et
 623 al., 2018; Thornton et al., 2017; Westermann et al., 2015). Indeed, comparing scenarios S2
 624 and S5 shows that the introduction of the new AE activities alone is not sufficient if no other
 625 policy measures are undertaken, owing to the limited adoption rate (7% of the ALA). First,
 626 the lack of an agricultural workforce constrains the adoption of new systems that are more
 627 labor-intensive. Increasing agricultural labor availability from 0.1 people/ha/yr to 0.6
 628 people/ha/yr led to an increase in adoption rate of AE activities (from 7% to a 43%).
 629 Practically, this constraint could be remedied by the development of training courses for
 630 agricultural workers in agroecology, the development of temporary employment agencies
 631 specialized in agricultural work, and by massive communication aimed at making the farming
 632 profession more attractive, especially to young people.

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

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

675

676 **4.2. Limitations of the study and scientific challenges**

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

701 To this end, methodological frameworks can be used to assess the resilience of farming
702 systems while considering different resilience capacities (robustness, adaptability, and
703 transformability) and nested levels of farming, such as those proposed by Meuwissen et al.
704 (2019) and Zampieri et al. (2020). Another axis of research is to perform sensitivity analyses
705 on the key parameters of transition (e.g., climate change scenario, adaptation of society food
706 habits, and evolution of markets) or those parameters containing uncertainty (e.g., the levels
707 of levers mobilized in the scenarios, the intensity of effects of climate change, the
708 performance of AE systems).

709

710 **4.3. A contribution to the “redesign approach” of agricultural systems**

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

725 The methodological framework proposed in this paper is a contribution to the "redesign"
726 approach. Strategies for improving sustainability of agricultural systems rely on three research
727 axes that constitute the three levels of the AE transition framework called “ESR”: (1)
728 “Efficiency,” improving the efficiency of natural and economic resource use; (2)
729 “Substitution,” developing bio-technologies and bio-inputs and (3) “Redesign,” developing
730 integration of ecosystem services (Hill and MacRae, 1996; Rosset and Altieri, 1997). One
731 needs to explore the “redesign” approach in order to measure the efficiency of “breaking
732 away” production systems and, thus, cultivate more references on the performance of these
733 systems (Padel et al., 2020). One also needs to measure its effectiveness in mitigating lock-in

734 effects in an AE-based bioeconomy responding to the urgency of global issues (Hill, 2014;
735 Pisonnier et al., 2019; Pretty, 2018).

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

748

749 **5. Conclusions**

750 In this paper, a methodological framework combining farm regional diagnosis, system
751 experiments, and bioeconomic modeling is proposed to design scenarios for upscaling CSA.
752 When applied to Guadeloupe, our results show that new agricultural production systems based
753 on agroecology and bioeconomy principles have the potential to achieve the objectives of
754 CSA at the regional scale. In the best scenario designed, the potential impact of climate
755 change on production was reduced by 12.5%, the nutritional performance at the regional scale
756 were tripled with 6.0 fed people/ha/yr on average, the GHG balance switched from net
757 emissions to a sequestration of 0.7 tCO₂eq/ha/yr, and the labor productivity rose to \$26.5/hr
758 (+14%). Compared to that in the baseline situation, the public cost for mitigating 1 tCO₂eq
759 was \$432.

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

766 Therefore, new ambitious policies targeting farmers' constraints are required to upscale CSA.
767 There is a need to develop more stakeholder platforms in which all issues and possible levers

768 are discussed and scenarios are co-designed to define successful transition of agricultural
769 systems. The approach proposed herein can be used to feed discussions on such platforms.
770 Research has to be continued in the “redesign” field to model the transition of agricultural
771 systems in a dynamic way, given the uncertainty of many crucial aspects such as climate
772 change scenarios, market evolution, technical progress in agroecology, and farmers’ behavior.

773

774

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