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## A framework for designing multi-functional agricultural landscapes: Application to Guadeloupe Island

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6 **Title:** A framework for designing multi-functional agricultural landscapes: Application to Guadeloupe  
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8

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15

16 **Abstract**

17 To improve agriculture faced with regional sustainability issues, agricultural landscapes  
18 providing a diversity and high level of ecosystem services are necessary. We have developed  
19 and tested the MOSAICA-f framework to build innovative multi-functional agricultural  
20 landscapes that can consider explicitly: 1) the performance of cropping systems at the field  
21 scale, 2) farmers' decision processes on the adoption of cropping systems, and 3) possible  
22 scenarios for innovations and policy changes at the regional scale. This framework is based on  
23 a scenario approach that encompasses normative, exploratory and optimized scenarios to  
24 assess the relevance of combinations of new agricultural policies, changes to the external  
25 context (market and regulations) and innovations in cropping systems. The impacts of these  
26 changes on sustainability issues are simulated using the regional bioeconomic model  
27 MOSAICA for farmers' decision processes regarding the adoption of cropping systems at the  
28 field scale throughout a region. Applied in Guadeloupe (French West Indies), the MOSAICA-

29 f framework enabled the design of a scenario increasing agricultural added value, food and  
30 energy self-sufficiency, employment and the quality of water bodies and reducing greenhouse  
31 gas emissions. This sustainable scenario combines new cropping systems tuned to farm types  
32 with a reorientation of subsidies, an increased workforce and banning food crop production on  
33 polluted soils. It can be used to understand the potential contribution of agriculture to  
34 sustainability issues and to help local decision makers define policies that will account for the  
35 spatial diversities of farms and fields in a landscape. Beyond the design of such a win-win  
36 scenario, MOSAICA-f has revealed trade-offs in the provision of services by agriculture.

37  
38 **Highlights:**

- 39 • We propose a modelling framework to aid the design of multi-functional landscapes
- 40 • The framework is based on a scenario approach coupled with an optimization model
- 41 • Normative, optimized, exploratory scenarios with multiple innovations are combined
- 42 • The framework is applied in Guadeloupe to design a sustainable scenario
- 43 • This framework can be used to provide information on possible futures of agriculture

## 44 **1 Introduction**

45 Agricultural landscapes account for one third of the land used by humans worldwide  
46 (FAOSTAT 2008). While agriculture has constantly increased food production, it is  
47 responsible for other positive and negative environmental, economic and social impacts at the  
48 global and local scales (Tilman et al., 2002). Although agriculture can ensure the production  
49 of food, energy, materials and services for society (including the alleviation of poverty),  
50 agriculture faces several sustainability problems, such as climate change and water and soil  
51 pollution. The ability of agriculture to provide multiple services in a sustainable manner is  
52 therefore being questioned (Klapwijk et al., 2014).

53

54 Agronomists have been designing new agricultural systems at the field and farm scales in  
55 order to improve sustainability. However, the design of innovative agricultural systems at  
56 these scales has certain limitations when addressing regional and global issues. For instance,  
57 at the field scale, some cropping systems may fail to respond to sustainability issues defined  
58 at the regional scale because of the low scaling integration and spatial heterogeneity at the  
59 regional scale (Dale et al., 2013). Agronomists must therefore integrate a landscape  
60 perspective when designing new agricultural systems adapted to local regions, and when  
61 addressing sustainability challenges at the regional scale (Dale et al., 2013, Benoit et al.,  
62 2012). The design of such systems at the regional scale will result in new crop compositions  
63 and organizations in landscapes that supply different ecosystem services (Castellazzi et al.,  
64 2010; Benoit et al., 2012; Schaller et al., 2012).

65

66 To determine whether a particular combination of factors such as agricultural policies (e.g.  
67 changes to subsidies, bans on certain inputs), the social context of agriculture (e.g. new  
68 markets) and the characteristics of cropping systems (e.g. new crops, new management, etc.)

69 can drive agricultural change towards sustainability or have unexpected adverse outcomes, a  
70 scenario analysis using an integrated agricultural landscape model is required (Wei et al.,  
71 2009; Carmichael et al., 2004). In this case, an integrated model refers to one that includes  
72 different spatial scales in the decision-making processes of farmers and relative to different  
73 sustainability domains. The "drivers of change" represent potential causes of modifications to  
74 the characteristics of farming systems and their combinations at the landscape level, which  
75 will induce changes to the degree of sustainability that can be assessed using indicators  
76 (Florin et al., 2013).

77

78 Agricultural science has already used scenario analysis coupled with integrated models to  
79 analyse a wide range of sustainability issues relative to agricultural systems (Heckelei and  
80 Britz, 2001; Kropff et al., 2001; Van Ittersum and Donatelli, 2003; Arfini, 2005; Verburg et  
81 al., 2006; Bryan et al., 2011). However, the scenarios implemented in model-based landscape  
82 frameworks tend to focus on a given type of scenario, based either on exploratory "what-if  
83 scenarios" (Therond et al., 2009) or on the optimization of other indicators in the systems  
84 (Hengsdijk and Van ittersum, 2002 ; Groot et al., 2007) in order to determine targeted outputs  
85 for different objectives. These studies do not satisfactorily combine the different types of  
86 scenarios necessary to understand the functioning of agricultural systems and their impacts at  
87 a regional scale.

88

89 Moreover, some of these studies do no account for interactions between scales when trying to  
90 identify the factors driving spatial dynamics (Houet et al., 2014). Several modelling  
91 frameworks do not integrate the regional scale when assessing the services provided by  
92 farming systems (Janssen and van Ittersum, 2007; Riesgo and Gomez-Limon, 2006; Parra-  
93 López et al., 2008) while others take no account of the field scale (Schönhart et al., 2011).

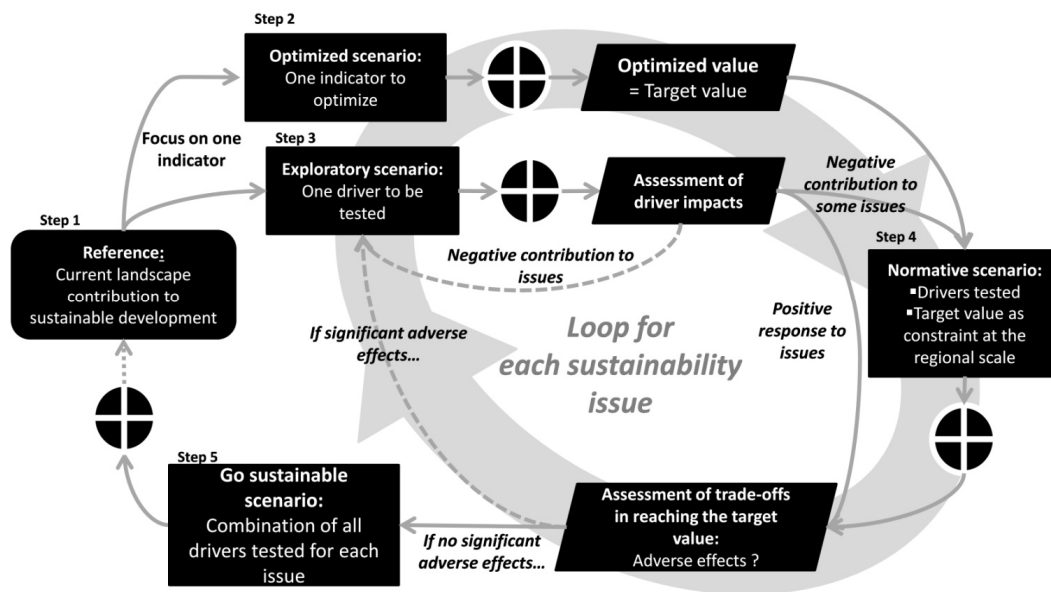
94 Model-based frameworks based on bioeconomic models are seldom spatially explicit with  
95 regards to impact assessments of cropping systems due to a lack of information on field and  
96 farm locations (van Ittersum et al., 2008; Delmotte et al., 2013), and their impact assessments  
97 are not spatially located within an area of study (Meyer, 2007; Veysset et al., 2005; Gafsi et  
98 al., 2006; Van Ittersum et al., 2008; see the SEAMLESS project at [http://www.seamless-  
100 ip.org/](http://www.seamless-<br/>99 ip.org/)).

101 Chopin et al. (2015a) presented the MOSAICA regional bio-economic model and an example  
102 of its application for scenario design in Guadeloupe, based on a preliminary characterization  
103 of the diversity of farming systems (Chopin et al., 2015b). In the present paper, we propose a  
104 methodological framework for the design of scenarios for landscape evolution using this bio-  
105 economic model. This framework, called MOSAICA-f aims to build innovative multi-  
106 functional agricultural landscapes. This enables the representation of agricultural landscape  
107 changes under different drivers and assessment of their contributions to sustainable  
108 development at the regional level. The finality of the framework is to: i) gain step-by-step  
109 knowledge regarding the possible futures of agricultural landscape organization, and ii)  
110 identify the relevant changes to agricultural policies, the social context of agriculture and the  
111 characteristics of cropping systems needed to build multi-functional agricultural landscapes.

112

113

114 **2 The MOSAICA-f framework**



115

116 **Figure 1** The MOSAICA-f framework for designing multi-functional landscapes. Steps are

117 represented by a pre modelling (square), a modelling (circle) and a post modelling phase

118 (parallelogram).

119

120 The framework presented in the paper aims to use the MOSAICA bioeconomic model in an

121 iterative manner in order to aid the building of multi-functional agricultural landscapes. The

122 model is applied in several steps involving different types of scenarios in order to understand

123 the potential for improvements to the landscape in terms of their contribution to regional

124 issues and to identify relevant drivers for change that will optimise their contribution.

125

126

127 **2.1 The MOSAICA-f framework to define a multi-functional scenario**

Variables to optimize	Tested drivers (changes in activity, equations and/or the geographical database)	
	No	Yes
Optimization of the sum of the farmer's utilities (U*)	<b>Step 1: Reference mosaic</b> The reference values of the indicator of interest, $Y_{ref}$ , is obtained => Step 2	<b>Step 3: Exploratory scenario</b> Drivers tested to obtain the value of $Y_{expl}$ <ul style="list-style-type: none"> <li>• If <math>Y_{expl} &lt; Y_{ref}</math> =&gt; Change of driver</li> <li>• if <math>Y_{expl} &gt; Y_{ref}</math> and <math>Y_{expl} &lt; Y^*</math> =&gt; Step 4</li> <li>• If <math>Y_{expl} &gt; Y^*</math> =&gt; Use the Go sustainable scenario</li> </ul>
	<b>Step 2: Optimized scenario</b> Optimization of Y Target value $Y^*$ obtained => Step 3	<b>Step 5: "Go sustainable" scenario</b> Drivers from step 4 are combined here -
Indicator providing information of the response to the sustainability issue of interest (Y)	-	-
Optimization of Z with the value of $Y^*$ to be reached	-	<b>Step 4: Normative scenario</b> If $Y_{norm} = Y^*$ AND $W_{norm}, V_{norm} > 0.8 * W_{ref}, V_{ref}$ => Step 5 Otherwise => step 3

128

129 **Table 1:** Types of scenarios, their relationships within the framework and their  
 130 parameterization within the MOSAICA model. Y,W,V represent the values of different  
 131 indicators across the different phases of the framework:  $_{ref}$ : at step 1 for the reference  
 132 calculation,  $^*$ : at step 2 for optimized scenario,  $_{expl}$ : at step 3 for exploratory scenario and  $_{norm}$ :  
 133 at step 4 for normative scenario.

134

135 Our model-based framework consists of five steps (Figure 1), each combining three  
 136 framework components: scenario development, modelling and assessment. The loop between  
 137 steps 2 and 4 is repeated for each sustainability indicator (Table 1).

138 - The first step is calculation of the reference contributions of agriculture to sustainable  
 139 development using a reference mosaic of cropping systems. This mosaic is obtained  
 140 from calibration of the model to the base year in our case study, which is explained in



141 Chopin et al. (2015). Several sustainability issues are selected. To assess the  
142 contribution of the reference mosaic to these issues, several indicators are used in the  
143 assessment (e.g. Y, W and V representing three given sustainability indicators).  
144 Cropping systems are located on each field of the region, and based on these locations,  
145 the assessment is performed by calculating the "reference" values for indicators of the  
146 contribution of agriculture to sustainable development (e.g. Yref, Wref, Vref, etc.).  
147 These references are then used to compare the contributions of mosaics from scenarios  
148 with the base year.

- 149 - The second step involves running optimized scenarios to reveal the potential to adapt  
150 cropping system mosaics in terms of their contribution to a set of sustainability issues.  
151 This potential represents the ability of the landscape to attain sustainability goals and  
152 is thereafter used as the "target value" for each sustainability indicator, such as the Y\*  
153 value for indicator Y.
- 154 -
- 155 - The third step concerns the testing of several drivers of change, encompassing changes  
156 of agricultural policy, the social context and cropping system characteristics, in a  
157 series of exploratory scenarios. In this step, a single driver can be tested under  
158 exploratory scenarios or certain structurally linked drivers (e.g. both an increase in the  
159 price of food crops and limitations on production at a regional scale). In this step, we  
160 test each driver alone (e.g. one model run for the price increase in food crops and one  
161 model run for limitations on production at the regional scale) to identify whether they  
162 have any potential benefits in terms of contributing to targeted issues. Then,  
163 structurally linked drivers tested on the same sustainability issues are combined to  
164 improve the contribution of agriculture to this target issue. Drivers that improve the  
165 values of Yexpl of the Y indicator are compared with the Yref value from the reference

166 mosaic (i.e., if  $Y_{expl} > Y_{ref}$  and  $Y_{expl} \leq Y^*$  in the case of maximization, the drivers  
167 are tested in step 4), while drivers that do not improve the contribution of the mosaic  
168 to the sustainability issue are removed from the analysis. If the  $Y_{expl}$  value obtained is  
169 higher than the optimized  $Y^*$  value, the fourth step is skipped and the drivers are  
170 tested directly during the fifth step. Under these scenarios, the link between a specific  
171 driver and its contribution to the issues is examined, while the combination of several  
172 drivers to different sustainability issues is only addressed in the fifth step.

173

- 174 - The fourth step is to run a series of normative scenarios. For these scenarios, the  
175 different drivers defined for each exploratory scenario, and the target values obtained  
176 under the optimized scenario, are set at the regional level. If reaching the target value  
177 of the indicator of interest is infeasible or adversely affects the contributions of  
178 agriculture to other sustainability issues, then other drivers are sought and the  
179 modellers must return to step 3.
- 180 - The fifth step of the framework concerns testing of the relevant drivers previously  
181 identified and tested in steps 3 and 4 for each sustainability issue, that are here  
182 combined in a "Go sustainable" scenario. The agricultural landscape which best  
183 responds to this scenario is assessed, and indicator values are compared to the  
184 references. If the results are not satisfactory, iteration can be performed to restart the  
185 selection of drivers of change using either new drivers or new values associated with  
186 each driver (e.g. change in the value of prices for local production). If the cropping  
187 system mosaic thus generated is considered to be multi-functional (i.e., simultaneously  
188 reaching several sustainability targets), the results can be further analysed. This  
189 analysis encompasses observations of the spatial heterogeneity of the contribution to  
190 sustainability issues by analysing the indicators at different spatial scales (Figure 2).

## 191 **2.2 Three components for the scenario analysis**

### 192 2.2.1 Scenario development (pre-modelling component)

193 The definition of several scenarios is the pre-modelling component in a model-based  
194 integrated assessment framework (Therond et al., 2009), which implies that the model must  
195 be parameterized using a new set of parameters for each scenario in order to assess the  
196 response of an agricultural landscape and its contribution to sustainability issues at the  
197 regional scale.

198

199 In our framework, the MOSAICA model is used for different types of scenarios to represent  
200 the response to the mosaics of cropping systems (Figure 1). Normative, optimized, or  
201 exploratory approaches can be used to design several types of scenarios. Thus different  
202 declinations of scenarios are used within our framework to compose an itinerary for cropping  
203 system mosaic design.

204

- 205     ▪ Optimized scenarios: This scenario helps to determine the optimal value of a given  
206         indicator, which provides information regarding the contributions of agriculture to a  
207         related sustainability issue. The optimized value represents a "target value", i.e., a  
208         sustainability value to be attained by the cropping system mosaic in order to obtain the  
209         most sustainable state of the system considering this sustainability domain.
- 210     ▪ Exploratory scenarios: The exploratory approach ("what if") is used to explore what  
211         will happen when changes in agricultural policy, the social context and cropping  
212         system characteristics impact the choices of farmers and therefore the cropping  
213         system mosaic (Borjeson et al., 2006; Van Notten et al., 2003). Exploratory "what-if"  
214         scenarios can answer the question "what will happen under certain new conditions?".  
215         They are helpful when selecting a set of new agricultural policies, changes in social

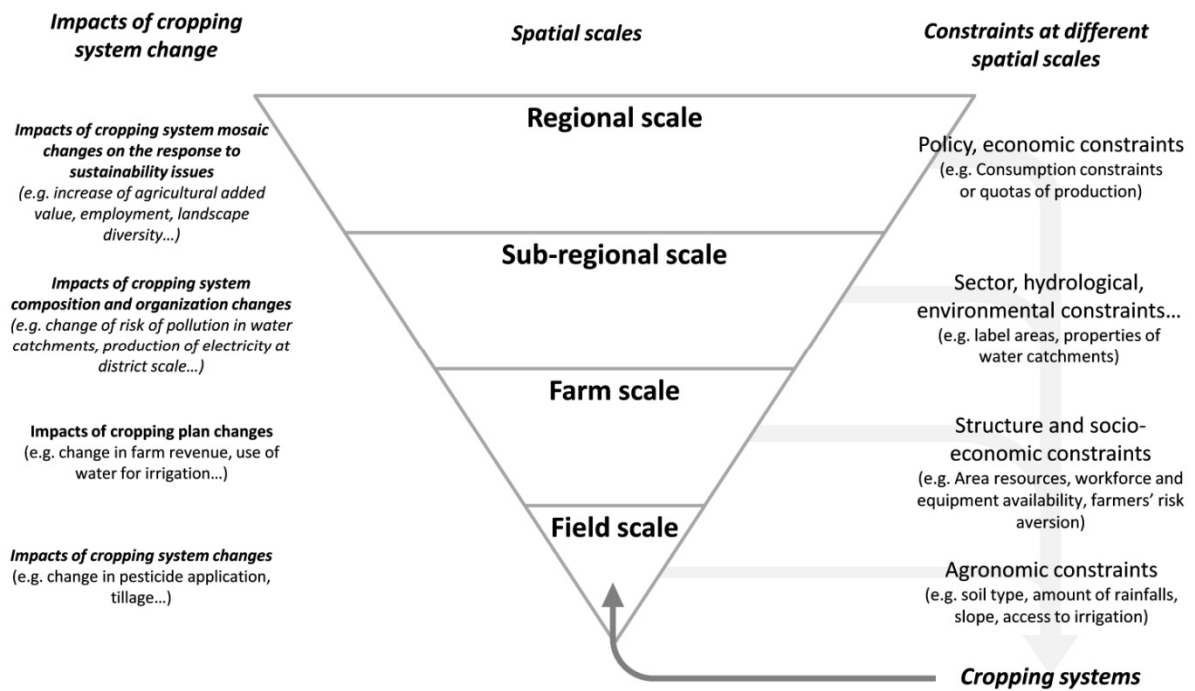
216 context and cropping system characteristics to meet the target values defined  
217 previously, thereby improving the contribution of the cropping system mosaic to  
218 sustainability issues. These changes may be: i) changes at the field level, such as  
219 enabling access to irrigation; ii) the introduction of new cropping systems defined  
220 from experimental trials or expert knowledge; iii) changes to farm resources; iv) the  
221 modification of policy regimes, and v) changes in markets, such as prices and quotas.

- 222 ■ Normative scenarios: The normative approach (“what for”) targets a set of indicator  
223 values to obtain the desired impacts of the cropping system mosaic, and it provides  
224 information regarding the contributions of the mosaics to this set of sustainability  
225 issues. Using the model in a normative way helps to determine whether the change  
226 tested previously with respect to agricultural policy, the social context and cropping  
227 system characteristics can help agriculture to attain its target and to predict the effects  
228 of achieving this target value on other sustainability issues.

229

230

231 2.2.2 Prototyping cropping system mosaics using MOSAICA model: modelling components



232

233 **Figure 2** Inter-relationships of spatial scales in the adoption of cropping systems at the field

234 scale and the impacts of cropping system management at different spatial scales

235

236 The scenarios defined during the pre-modelling component were run using the MOSAICA

237 regional bioeconomic model (Chopin *et al.*, 2015b). This scenario simulates the decision

238 processes of farmers in terms of adopting activities by linking them with a set of bio-

239 economic parameters (frequently referred to as technical coefficients) that drive these

240 decisions (Janssen and van Ittersum, 2007). MOSAICA can be used for the ex ante

241 assessment of the impacts of policies and technological, agronomic or economic changes,

242 amongst others (Janssen and van Ittersum, 2007; Belhouchette *et al.*, 2011; van Ittersum *et al.*,

243 2008; Louhichi *et al.*, 2010). Farmers' choices concern the allocation of one or several

244 activities a, that represent cropping systems, to field p. The simulation of farmers' choices is

245 achieved by optimizing the sum of the farmers' utilities  $U$  (Equation 1) or by optimizing other

246 variables in the agricultural system. The model variable to be optimized is calculated within  
247 the objective function.

248

$$249 \quad MAX U = \sum_F (\sum_P \sum_a [X_{a,p} (\bar{m}_a - \phi_F (Z_a^+ + Z_a^-))] \quad (1)$$

250

$$251 \quad \bar{m}_a = (\bar{y}_a pr_a + subsidies_a) - cost_a \quad (2)$$

252

253 Under exploratory and normative scenarios, the objective function is the sum of the farmers'  
254 utilities. These utilities are the sum of the farmers' incomes minus the expected reduction in  
255 income due to variability of the gross margin, this being more or less important depending on  
256 the value of the risk aversion coefficient  $\emptyset$  of farmers, and the positive and negative  
257 variability,  $Z_+$  and  $Z_-$ , respectively, of the gross margin of activity  $a$  (Equation 1). Farmers'  
258 incomes are the sum of field gross margins calculated based on the average gross margin  $m_a$   
259 of each activity  $a$  allocated to each farmer's fields  $p$ . The gross margin  $m_a$  is calculated based  
260 on a mean yield  $y$ , a price  $pr$  and a given level of variable cost "cost" (Equation 2). The levels  
261 of variability depend on the yield and price variability of the crop produced by activity  $a$  in  
262 the market and is determined using agro-economic expertise. The vector of decision variables,  
263 which is the area covered by each activity  $a$  on field  $p$  (farmers can choose one or more  
264 cropping systems for the same field) is indicated by the symbol  $X_{a,p}$ . These activities are  
265 allocated to each field on a farm and, therefore, to all fields in the landscape under this  
266 optimization process. The risk aversion coefficient  $\emptyset$  is used as the calibration parameter and  
267 is attributed to the farm type, which is obtained from the farm typology, depending on current  
268 farming systems and assuming that each type of farmer has a specific aversion to economic  
269 risk depending on the structure of his farm and on the cropping systems he uses. Farmers are  
270 classified within a given type using a classification algorithm that is implemented under

271 MOSAICA. In this algorithm, each farm is considered to remain within the same type or is  
272 moved to another type in the simulated mosaics, depending on the activities selected by the  
273 optimization process (Chopin et al., 2015a).

274

275 The process of assigning activities to fields recorded in a geographical database is driven by  
276 several types of constraints that are implemented at different spatial scales (Figure 2; see also  
277 Chopin et al. 2015a). For instance, at farm level, the amount of workforce available limits the  
278 adoption of labour intensive cropping systems. This information for the process of allocating  
279 activities is determined for each field within the geographical database. The simulated  
280 allocation process is spatially explicit because cropping systems are allocated to a given field  
281 within the map of the territory, based on the sets of equations implemented at different spatial  
282 levels within the model.

283

284 Thus, by modifying the constraints at the different spatial scales, the database of field  
285 characteristics (changes to field parameters; e.g., change of slope due to remodelling), the  
286 nature and technical coefficients of the activities to be allocated to fields and the objective to  
287 optimize can be used to modify the cropping systems chosen by the simulated farmers at the  
288 field scale. These cropping system changes at the field scale reorganize farming systems at the  
289 farm scale and, in fine, the regional cropping system mosaic. Next, modification of the  
290 cropping system mosaics may modify the contribution of mosaics to sustainable development,  
291 which is assessed in the post-modelling component of the framework.

292

293 Under optimized scenarios, the objective function in Equation 1 is replaced by the target  
294 indicator, e.g. the production of energy for the sustainability issue “improving energy self-  
295 sufficiency”. The cropping system mosaics derived from an optimized scenario are obtained

296 by maximization or minimization (depending on the desired direction of change) of the value  
297 of one indicator related to the sustainability issues (Table 1). The only modification of the  
298 model structure is replacement of the sum of the farmers' utilities in the objective function by  
299 the indicator to be optimized. The field characteristics, activities and constraint equations of  
300 the model are not modified in this type of scenario.

301 The cropping system mosaics obtained from exploratory scenarios in step 3 result from  
302 optimizing the sum of the farmers' utilities and from modifying the activities, model  
303 constraint equations and/or field characteristics (Table 1).

304 Normative scenarios are parameterized in step 4 using the same drivers as those used in step 3  
305 of the exploratory scenario and by implementing a constraint equation at the regional scale in  
306 order to reach the "target value" obtained from the optimized scenario.

307

### 308 2.2.3 Assessment of cropping system mosaics: post-modelling component

309 The contributions of cropping system mosaics to the sustainable development of a region  
310 were assessed using a set of indicators at the regional scale and calculated during the post-  
311 modelling component of the framework. Firstly, sustainability issues were selected from a  
312 review of the literature in the area of study. Secondly, interviews were carried out with  
313 decision-makers. In our case study, 13 regional decision-makers completed and validated the  
314 list of issues by means of a web-based survey. Thirdly, based on the sustainability issues  
315 identified at the regional scale, several indicators were used to assess the contribution of  
316 cropping system mosaics to these issues. These indicators could either be reused from  
317 previously published work, could be scale changed from one given scale to another, or could  
318 be newly designed when the issues highlighted are locally contextualized. For instance, some  
319 papers provide a calculation of indicators at the landscape scale (Gerdessen and Pascucci  
320 (2013); Walz (2015)) that can be reused to assess the consequences of agricultural landscape



321 changes (Sepp and Bastian, 2007). Many indicators are available at the cropping system scale  
322 (Sadok et al., 2008; Carof et al., 2013) and may change with a given procedure, such as  
323 aggregation procedures (Ewert et al., 2011). Others are not available because some issues are  
324 specific to our study and need to be built using existing knowledge. This was the case in our  
325 study with respect to the “decrease food contamination due to chlordecone in soils” issue  
326 which has never been assessed using indicators. We therefore had to build an indicator based  
327 on existing knowledge relative to the contamination process of food crops by chlordecone  
328 pesticides.

329

330 These indicators are calculated based on parameters that describe cropping system  
331 externalities and on the characteristics of the fields to which they are allocated. Activities are  
332 described using technical coefficients that represent the externalities of the crop production  
333 process with diverse information, such as yield or pesticide and fertilizer use. Calculating  
334 indicators at the regional scale provides a spatially aggregated value, and the indicators can be  
335 spatialized within the territory to display variations in the contributions of the fields, farms  
336 and sub-regions within a territory in order to improve decision-making.

337

### 338 **3 Application of the MOSAICA-f framework in Guadeloupe**

339

#### 340 **3.1 Characteristics of the study area**

341 The MOSAICA framework was tested in Guadeloupe, an island located in the Caribbean.  
342 This territory presents suitable conditions for implementing the framework for several  
343 reasons. First, due to its insularity, flows of agricultural products are recorded at both entrance  
344 to and exit from the territory (Agreste, 2011; INSEE, 2012). Second, Guadeloupe has to deal  
345 with many local issues that limit the economic, environmental and social sustainability of the

346 territory and may be linked to agriculture. These issues include low food and energy self-  
347 sufficiency, a high level of unemployment and a risk of pollution of water resources by  
348 pesticides (rivers and drinking-water abstractions) used for local consumption (PDRG, 2011).  
349 Another challenge is to “decrease food contamination due to chlordecone in soils”.  
350 Chlordecone is a remnant pesticide that was used between 1965 and 1993 on 15% of  
351 cultivated land in Guadeloupe (Tillieut and Cabidoche, 2006). The regular consumption of  
352 food crops grown on these polluted soils can provoke severe health problems such as prostate  
353 cancer (Multigner et al., 2010). Third, Guadeloupe is a small territory that covers 1600 km<sup>2</sup>  
354 and includes a significant agricultural area of 31,300 hectares. Fourth, geographical data and  
355 statistical information on fields and farms in Guadeloupe, and knowledge regarding cropping  
356 system performances and farm functions, are available. This information describes the  
357 population of farmers and their activities. Finally, the region is heterogeneous, with rainy  
358 mountainous areas on volcanic soils and flat lands on dry calcic soils, which is of interest  
359 when testing the ability of the framework to account for biophysical and socio-economic  
360 variability.

361

### 362 **3.2 Adaptation of the MOSAICA model in Guadeloupe**

363 We explain our adaptation of the MOSAICA model that supports the proposed framework for  
364 Guadeloupe by briefly describing its principal elements for the simulation of multi-functional  
365 agricultural landscapes (Chopin et al., 2015b).

366

- 367 - The database on field characteristics obtained from the Agrigua association that  
368 gathers declarations of farmed land for subsidies, comprised 25,057 fields and  
369 includes biophysical and farm structure information represented by polygons covering

370 27,000 hectares (i.e., 86% of the 31,300 hectares of all agricultural land in  
371 Guadeloupe).

372 - We described 36 activities covering the eight main crops in Guadeloupe: sugar cane,  
373 banana, pasture, orchards, pineapple, plantain, crop-gardening and tubers, with  
374 different management strategies.

375 - Constraint equations were implemented at different spatial scales to constrain the  
376 adoption of activities allocated at the field scale. For instance, we implemented a set of  
377 equations linking the cropping systems to slope, field area, soil type and land tenure at  
378 the field scale. At the farm scale, farm size, agronomic rules for crop rotations,  
379 production quotas and workforce resources were used as the primary constraints for  
380 the adoption of cropping systems. At the sub-regional scale, environmentally protected  
381 zones and geographically protected indications constrain the adoption of cropping  
382 systems. At the regional scale, we defined the maximum thresholds for limiting the  
383 quantities of crops produced (production quotas or overall local consumption from  
384 local production and importation).

385 - The farm typology used was described by Chopin et al. (2015a), in which eight types  
386 of farmers (orchard growers, banana growers, breeders, market gardeners, diversified  
387 cane-growers, diversified, mixed, specialized cane-growers) are defined using a  
388 classification algorithm that allocates each farm to one of the types after new cropping  
389 system mosaics are produced by simulation.

390 - The model was calibrated in Guadeloupe by allocating a risk aversion coefficient to  
391 each farm depending on its type under our farm typology. The model was considered  
392 to be valid because of the crop areas predicted by the reference mosaic, and because  
393 the areas calibrated at the regional, sub-regional, farm and field scales were similar  
394 (Chopin et al., 2015b).

		Sustainability goals to be reached							Drivers tested & their combinations				
Targeted objectives	Scenario type	Increasing food self-sufficiency	Increasing energy self-sufficiency	Decreasing the crop contamination by chlordecone	Decreasing the risk of pollution of water resources	Improving the agricultural added value	Increasing employment	Reducing CO <sub>2</sub> emissions	Quotas ↘ of market-gardening variability ↗ workforce availability	Energy cane activity for electricity production (45€·ton <sup>-1</sup> )  Energy cane yield 25% higher than sugarcane  End of subsidies for sugarcane	Cultivation of pasture, market-gardening and tubers forbidden on potentially polluted soils	New market-gardening cropping systems  Taxes of 500€ per pesticide use  Trade payments for organic market-gardening (1000€·ton <sup>-1</sup> )	Decoupling of subsidies from agricultural production
		Agricultural added value of local foodstuff (M€.yr <sup>-1</sup> )	Potential production of electricity (MW)	Area of food products potentially contaminated (ha)	Mean pollution of water resources (score)	Total agricultural added value (M€.yr <sup>-1</sup> )	Workforce needs (persons.yr <sup>-1</sup> )	Quantity of CO <sub>2</sub> emissions (kT CO <sub>2</sub> .yr <sup>-1</sup> )					
	Initial	45	33	592	4.5	96	2905	157	0	0	0	0	0
Increasing food self-sufficiency	Optimized	104*	0	1115	2.7	106	3005	143	0	0	0	0	0
	Exploratory	165	15	1601	3.3	173	3856	184	1	0	0	0	0
	Normative	-	-	-	-	-	-	-	-	-	-	-	-
Increasing energy self-sufficiency	Optimized	6	56*	246	4.3	57	372	44	0	0	0	0	0
	Exploratory	47	52	511	4.5	85	2904	172	0	1	0	0	0
	Normative	46	56°	456	4.8	85	2884	165	0	1	0	0	0
Decreasing the crop contamination by chlordecone	Optimized	22	3	0*	1.9	29	747	5	0	0	0	0	0
	Exploratory	44	34	0	4.9	97	2901	152	0	0	1	0	0
	Normative	-	-	-	-	-	-	-	-	-	-	-	-
Decreasing the risk of pollution in water resources	Optimized	19	2	552	1*	25	652	11	0	0	0	0	0
	Exploratory	45	26	1200	3.4	71	2783	183	0	0	0	1	0
	Normative	90	26	1017	1°	107	2902	141	0	0	0	1	0
Improving the agricultural added value	Optimized	94	45	310	4.7	143*	2997	58	0	0	0	0	0
	Exploratory	90	0	965	2.9	162	2772	135	0	0	0	0	1
	Normative	-	-	-	-	-	-	-	-	-	-	-	-
Go sustainable scenario	Exploratory	120	35	0	4	206	3866	150	1	1	1	1	1

395 **Table 2:** Results from the scenario analysis in terms of the responses to local and global sustainability issues. Numbers with \* are optimized  
396 values.

397 **3.3 Step 1: Diagnosis of the reference contributions of agriculture to sustainable**  
398 **development**

399 The sustainability goals for agriculture in Guadeloupe are to: i) increase crop production for  
400 local markets, ii) increase biomass production for electricity production, iii) decrease the risks  
401 of crop contamination by chlordecone, iv) limit the pollution of water resources, especially  
402 rivers and drinking-water sources, and v) improve the overall added value of agriculture. The  
403 provision of employment for crop management was also assessed because it is an important  
404 parameter of the farm model. However, employment was not included in the scenario analysis  
405 because the workforce cannot increase beyond the limits set for each farm type in the model.  
406 The contribution of agricultural systems to greenhouse gas emissions was also evaluated  
407 because it is a key component in efforts to mitigate climate change. Indicators were first of all  
408 calculated for the reference cropping system mosaics obtained from the calibration (Table 2).

409

410 **3.4 Step 2: Optimized scenarios**

411 Optimizing the current situation regarding the added value of local foodstuffs produced by  
412 agriculture (food self-sufficiency) resulted in a target value of 104 millions € per year. This  
413 value was used as a target value. Under the second optimized scenario for energy self-  
414 sufficiency, we optimized electricity production and obtained a target value of 56 MW.yr<sup>-1</sup>.  
415 This scenario also reduced the number of employees required for crop management from  
416 2905 to 372 persons. The risk of crop contamination by chlordecone reached a negligible  
417 value when local foodstuffs decreased from 45 to 6 million per year and employment  
418 decreased from 2902 to 747 persons. The risk of pollution of water resources was high in the  
419 diagnosis of the reference situation but decreased from 4.5 to 1 unit of the I-PHY indicator.  
420 However, major reductions in the achievements of other sustainability goals, such as  
421 employment, the agricultural added value of local foodstuffs and the potential production of

422 electricity, were observed, with decreases from 2905 to 652 persons, 45 to 19 millions € per  
423 year and 33 MW.yr-1 to 2 MW.yr-1, respectively. The overall agricultural added value  
424 increased from its reference level of 96 to 143 millions € per year, and most sustainability  
425 issues improved, except for the risk of pollution of water resources, which increased from 4.5  
426 to 4.7 units of the I-PHY indicator. These new optimized values were used as target values  
427 under the normative approach (step 4).

428

### 429 **3.5 Step 3: Exploratory scenarios**

430 Different drivers, agricultural policies, contextual social changes and new cropping system  
431 characteristics were all tested under the exploratory approach in step 3 to reach the target  
432 values identified in step 2 and presented in Table 1. The exploratory scenarios tested here  
433 combined several types of possible changes, such as new policies, new biophysical contexts  
434 and agronomic innovations. Based on our knowledge of the region, under one exploratory  
435 scenario we were able to test several drivers for change linked by nature. For instance, in  
436 order to produce more local foodstuffs, education to achieve changes in diet towards more  
437 local food crops is needed (simulated with the deletion of production thresholds), alongside  
438 encouraging local production through agricultural policies such as subsidies. The impacts of  
439 these changes were assessed by running the model with the modifications of these activities,  
440 the geographical database and the equations defined at the different spatial scales.

441 1. The first exploratory scenario consisted of a combination of several changes, including  
442 increased market size at the regional scale (represented with regional thresholds in the  
443 model) for plantain, pineapple, and tubers at the regional scale, reduced variability of  
444 the gross margins of crops due to improved advice for local producers, an increase of  
445 1000 in the workforce available at the regional scale and doubling of the overall  
446 availability of water for irrigation. These changes increased the generation of

447 agricultural added value from local foodstuffs to 165 millions € per year, which is  
448 higher than the previously obtained optimized value of 104 millions. These drivers  
449 were relevant for responding to this issue because they exceeded the objective set by  
450 the target value.

451 2. The second exploratory scenario was a combination of the introduction of energy cane  
452 for electricity production with a price of 45 €/ton-1, a 25% increase in sugar cane yield  
453 potential, and the cessation of subsidies supporting sugar cane cultivation to increase  
454 the production of biomass for electricity production. These changes increased  
455 electricity production from 33 MW.yr-1 in the reference mosaic to 52 MW.yr-1 under  
456 the exploratory scenario, which is below the target value of 56 MW.yr-1. A normative  
457 scenario was therefore necessary in step 4 to understand the possible effects of  
458 reaching the target value on the other sustainability goals.

459 3. The third exploratory scenario consisted of banning vegetable, pasture and tuber  
460 cultivation on soils potentially contaminated by chlordecone in order to decrease the  
461 risk of crop contamination. This ban was spatially targeted on the 3708 of the 25,057  
462 fields in the region where the risk of soil contamination by chlordecone is significant.  
463 This ban was effective because the areas with potential risks of contamination of  
464 foodstuffs dropped from 592 ha in the reference cropping system mosaic to zero under  
465 the exploratory scenario. Banning market gardening and tuber production in highly  
466 chlordecone-contaminated zones was an efficient strategy for completely reducing the  
467 risks of crop contamination by chlordecone while maintaining the values of the others  
468 objectives near the values achieved in the reference state.

469 4. The fourth exploratory scenario consisted in introducing new organic cropping  
470 systems to decrease the risk of pollution of water resources by pesticides. The  
471 technical coefficients of these activities were defined using expert knowledge. The

472 yield decreased by 50%, the workforce requirement increased by 20% and prices rose  
473 by 25%. Yield variability increased when compared with conventional cropping and  
474 market gardening. The cropping and market gardening systems were taxed at a rate of  
475 500 € per point of treatment frequency index (TFI), based on their average TFI.  
476 Subsidies were provided to help commercialize the organic products, with a total of  
477 1000 €.ton-1 of vegetables and fruits from these new organic cropping systems  
478 (POSEI, 2012). The "introduction of organic crop-gardening activities" and "the taxes  
479 on the use of pesticides" points in the exploratory scenario did not make it possible to  
480 reach the target value for the risk of pollution of water resources of approximately 1.  
481 However, the decrease in this value from 4.5 to 3.5 was significant. A normative  
482 scenario also needs to be drawn in step 4 to reach the target value.

483 5. The fifth exploratory scenario was the end of POSEI ("Programme of specific options  
484 for isolation and insularity") payments towards banana and sugar cane and the  
485 decoupling of farm subsidies from agricultural production to improve the added value  
486 of agriculture. This scenario would enhance the agricultural added value of crop  
487 production devoted to the local market. The decoupling of subsidies was relevant  
488 because the agricultural added value increased from 96 millions € per year in the  
489 reference mosaic to 162 millions € per year under the exploratory scenario, which  
490 exceeded the optimized value in step 2 of 143 millions € per year.

491 The drivers used for each scenario are described in Table 2.

492

493

### 494 **3.6 Step 4: Normative scenarios**

495 Normative scenarios were tested in step 4 to assess the potential of the mosaic to attain the  
496 target values for "increasing energy self-sufficiency" and "decreasing the risk of pesticide



497 pollution of water resources" without significantly reducing the contributions of the cropping  
498 system mosaic to other sustainability domains.

499 Regarding energy self-sufficiency, the normative scenario was tested by optimizing the  
500 overall farmers' utilities under the constraint of producing at least 56 MW.yr<sup>-1</sup>. This was  
501 feasible and produced acceptable results for the other sustainability domains when compared  
502 with the reference cropping system mosaic. The area of potentially contaminated products  
503 decreased from 592 to 456 ha. In parallel, the risk of pollution of water resources increased  
504 from 4.5 to 4.8, and the agricultural added value decreased from 96 to 85 millions € per year.

505 Regarding the risk of pollution of water resources, the normative scenario successfully  
506 allowed the crop mosaic to reach the target value of 1, which corresponds to a very low risk of  
507 this pollution. The agricultural added value of local food crops increased from 45 to 90  
508 millions € per year, while the overall agricultural added value increased from 96 to 107  
509 millions € per year. CO<sub>2</sub> emissions decreased from 157 to 141 kt equivalent CO<sub>2</sub>.yr<sup>-1</sup>. In  
510 parallel, the area of food products that was potentially contaminated due to chlordecone in  
511 soils increased from 552 ha to 1017 ha, and potential electricity production fell from 33 to 26  
512 MW.yr<sup>-1</sup>.

513

514 We considered these drivers of change as being effective in reaching the set of target values  
515 when using the optimized scenario in step 2 because the average contribution to other issues  
516 increased by 8% for the "increase energy self-sufficiency" issue and only decreased by 3% for  
517 the "decrease of the risk of pollution of water resources" issue, which was below the 20%  
518 threshold set in the framework (Table 1).

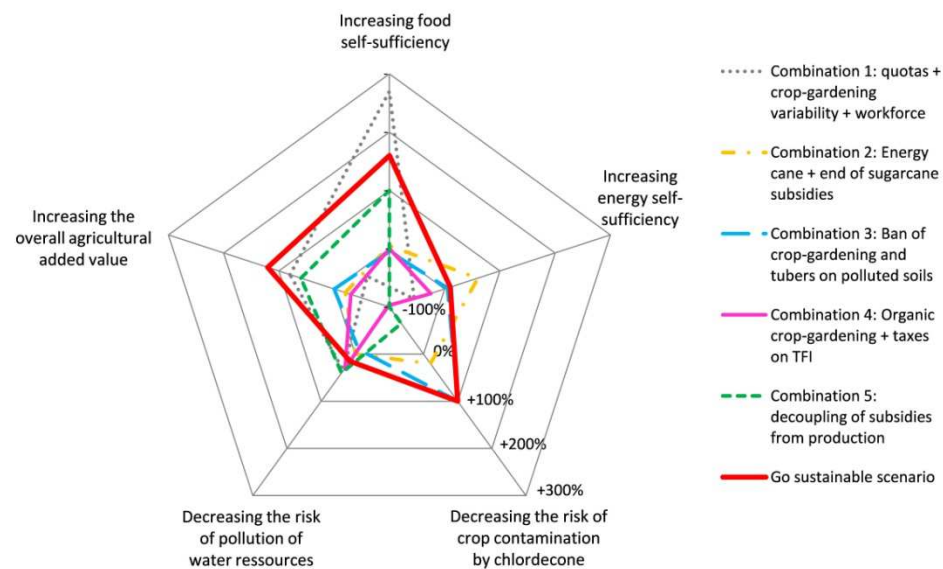
519 All of the drivers tested under the exploratory scenarios helped to reach or exceed the target  
520 values fixed by the optimized scenarios. When the drivers did not reach these values, we  
521 noticed that reaching them under the normative scenarios had no significant negative side

522 effects. Next, these drivers were combined in step 5 under a "Go sustainable" scenario, which  
 523 reflects optimization of the overall farmers' utilities for the selected political, agronomic or  
 524 external drivers of change.

525

### 526 3.8 Step 5: Prototyping a "Go sustainable" scenario

#### 527 3.8.1 Improvements in the contributions of agriculture to sustainable development



528

529 **Figure 3** Evolution of the contributions of each mosaic from exploratory scenarios compared  
 530 to the initial values from the current cropping systems mosaic assessed as deviations from the  
 531 initial values. Positive deviational values are an improvement of the generated mosaic to  
 532 respond to sustainability issues

533

534 This exploratory scenario revealed major improvements due to the contributions of cropping  
 535 system mosaics to all sustainability issues in the analysis when compared to the reference  
 536 situation (Table 2 and Figure 3). The agricultural added value of local production increased  
 537 from 45 to 120 millions € per year, electricity production increased from 33 to 35 MW.yr-1,  
 538 the area at risk of crop contamination decreased from 592 to 0 ha, the risk of pollution of

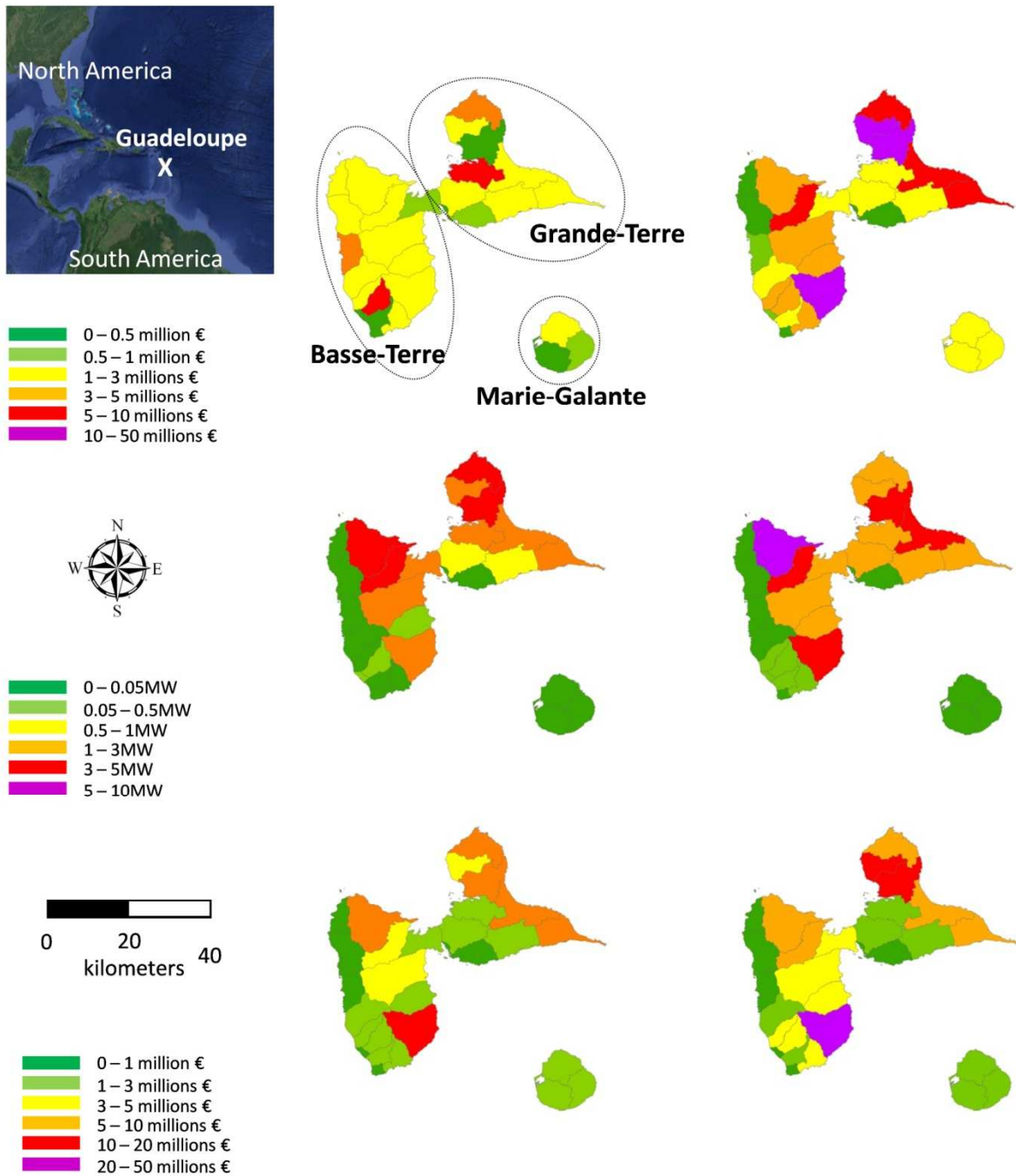
539 water resources decreased from 4.5 to 4, the total agricultural added value increased from 96  
540 to 206 millions € per year, the provision of employment increased from 2905 to 3866 persons  
541 and the CO<sub>2</sub> emissions from agriculture decreased from 157 to 150 Kton-1 of CO<sub>2</sub>  
542 equivalent.yr-1. The impacts were therefore very positive with respect to all sustainability  
543 issues, even if the risk of pollution of water resources remained significant under the “Go  
544 sustainable” scenario.

545

546 The contributions of the different sustainability issues are presented in Figure 3 and can be  
547 used to analyse the relationships between the different sustainability issues. Figure 3 shows  
548 some of these relationships. Increasing food self-sufficiency and overall agricultural added  
549 value and decreasing the risk of pollution of water resources could be achieved  
550 simultaneously but with trade-offs regarding improvements to other issues, namely a decrease  
551 in the risk of crop contamination by chlordecone and improved energy self-sufficiency.

552

553 3.8.2 Spatial heterogeneity of the contributions of cropping system mosaics to sustainable  
554 development in the territory



555

556 **Figure 4** Comparison of the evolution of the contributions of cropping system mosaics to the

557 increasing added value of agricultural from local food stuff (top) to the contributions to

558 electricity production (middle) and the production of added agricultural value (bottom)

559 between the current mosaic (on the left) and the "Go sustainable" scenario (on the right).

560 The contributions of the different cropping systems to sustainability issues can also be

561 analysed spatially. We illustrate this spatial analysis in Figure 4, which shows the changes in

562 the spatial variations of the contributions of sub-regions to food and energy self-sufficiency  
563 and the increases in overall agricultural added value and agricultural added value from local  
564 foodstuffs. Using the same method, the spatial variability of the contributions of cropping  
565 system mosaics to local issues is displayed at the sub-regional and field scales in order to  
566 analyse reductions in risk of pollution of water resources and in the risk of food contamination  
567 (see Supplementary Materials – Figure A).

568

569 At the sub-regional scale, the production of agricultural added value from local foodstuffs  
570 increased in most sub-regions. The greatest increases were observed in the northern and  
571 eastern parts of Grand-Terre and in south-eastern Basse-Terre, due to increases in  
572 conventional and organic crop-gardening (Figure 4). Electricity production increased across  
573 the territory due to the replacement of sugar cane by energy cane, which is more efficient and  
574 more productive. As expected, the increase in overall agricultural added value was higher in  
575 northern Grande-Terre and southern Basse-Terre due to the expansion of market gardening in  
576 these zones.

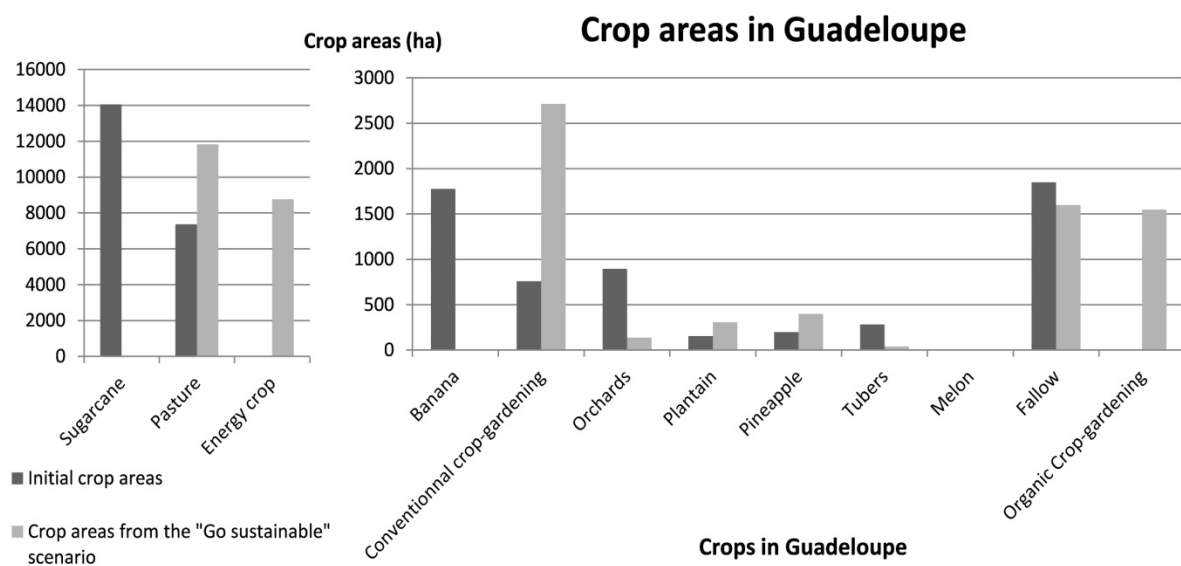
577 As for decreasing the risk of pollution of water resources, we observed an evolution of the  
578 effects of pesticide application in rivers and drinking-water abstractions (Supplementary  
579 materials). In the reference cropping system mosaic, most rivers in south-western Basse-Terre  
580 are potentially polluted by the pesticides used for banana cultivation and intensive market  
581 crop-gardening/orchard production. The reduction in the risk of pollution of water resources  
582 in the scenario in southern Basse-Terre was important when banana and market crop-  
583 gardening were replaced by less intensive cropping systems. The targeted reduction in the risk  
584 of crop contamination by chlordecone was attained, with all the area potentially  
585 contaminating crops in southern Basse-Terre being transformed into an area free of risk of  
586 contamination. This was due to the change from pasture in this zone to non-contaminating

587 crop-gardening, including for instance tomatoes and cauliflowers (and not cucurbitaceae that  
 588 are highly contaminated by chlordecone) or plantain (Cabidoche and Lesueur-Jannoyer,  
 589 2012).

590

591 **3.9 Analysis of modifications to the agricultural system under the "Go sustainable"**  
 592 **scenario**

593 3.9.1 Cropping system changes



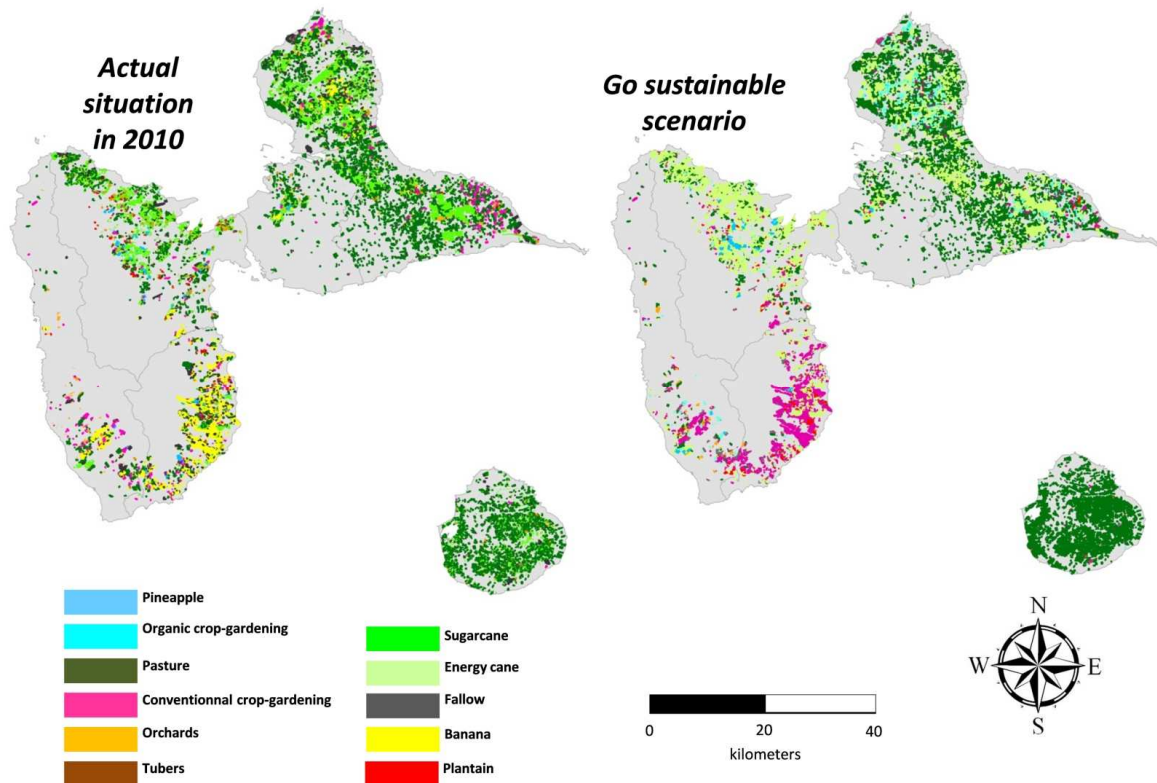
594

595 **Figure 5** Evolution of the crop areas at the regional scale between the initial situation and the  
 596 cropping system mosaics obtained in the "Go sustainable" scenario

597

598 The main trend for change was the disappearance of sugar cane and banana and an increase in  
 599 crop-gardening and pasture and energy cane for electricity production (Figure 5).

600



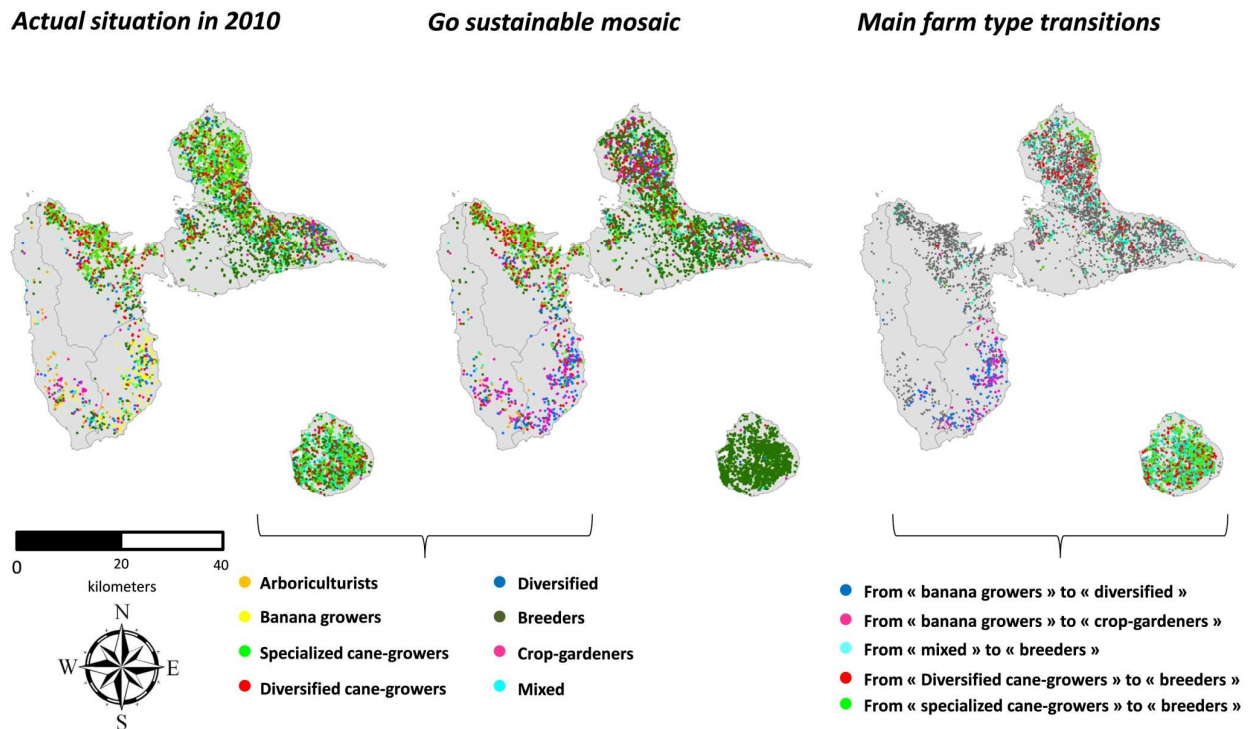
601

602 **Figure 6** Evolution of the crop arrangement in Guadeloupe at the regional scale between the  
 603 initial situation and the cropping system mosaics from the "Go sustainable" scenario

604

605 The spatial arrangement of cropping systems changed within the territory as a result of the  
 606 crop changes on farms (see Figure 6). This change mainly occurred in northern Grande-Terre  
 607 with the emergence of organic crop gardening and in south-eastern Basse-Terre with the  
 608 development of crop-gardening and plantain. The eastern part of Grande-Terre remained  
 609 cultivated with conventional crop-gardening, but organic crop- gardening appeared in this  
 610 zone, as did the cultivation of energy cane. In northern Basse-Terre, a high proportion of sugar  
 611 cane was mainly replaced by energy cane, and the area of pineapple and conventional crop-  
 612 gardening at the border with south-eastern Basse-Terre increased. The south-western part of  
 613 the island was turned into a sub region with more crop-gardening and plantain in replacement  
 614 of banana for export.

615



617 **Figure 7** Evolution of the farm types in Guadeloupe at the regional scale between the initial  
 618 situation and the cropping system mosaics from the "Go sustainable" scenario

619

620

621 The changes in farm types are shown in Figure 7, and the trajectories of change are shown in

622 Table 3 (see Supplementary materials – Figure B). The main trend was a change from mixed

623 and specialized cane-growers towards livestock breeders. This was especially true in the

624 Marie-Galante island, where under this scenario there is no industry for the production of

625 electricity with energy cane (See Figure 7). However, a small proportion of cane-growers

626 changed to crop-gardeners and to diversified cane-growers type, especially in northern and

627 eastern Grande-Terre.

628



Initial farm type / farm types after the "Go sustainable" scenario	Arboriculturists	Banana growers	Specialized cane- growers	Diversified cane- growers	Diversified	Breeders	Crop- gardeners	Mixed	Initial number of farms
Arboriculturists	10 8%	0 0%	0 0%	30 25%	31 26%	35 29%	2 2%	13 11%	121
Banana growers	1 0%	0 0%	0 0%	3 1%	<b>80</b> <b>39%</b>	5 2%	<b>106</b> <b>52%</b>	10 5%	205
Specialized cane- growers	0 0%	0 0%	546 35%	140 9%	79 5%	<b>630</b> <b>40%</b>	156 10%	26 2%	1577
Diversified cane- growers	0 0%	0 0%	110 10%	345 33%	7 1%	<b>524</b> <b>50%</b>	0 0%	64 6%	1050
Diversified	0 0%	0 0%	5 2%	49 17%	101 35%	78 27%	29 10%	24 8%	286
Breeders	6 1%	0 0%	12 1%	14 1%	10 1%	1044 96%	0 0%	3 0%	1089
Crop-gardeners	0 0%	0 0%	0 0%	0 0%	4 3%	0 0%	150 97%	0 0%	154
Mixed	3 0%	0 0%	3 0%	8 1%	8 1%	<b>654</b> <b>77%</b>	0 0%	178 21%	854
Number of farms after the "Go sustainable" scenario	20	0	676	589	320	2970	443	318	5336

630

631 **Table 3:** Evolution of the number of farms based on type, the proportion of farm type change  
632 and their trajectories of change from the initial cropping system mosaic to the mosaic  
633 obtained from the "Go sustainable" scenario. The changes in bold are spatialized in Figure 7.

634

635 Most farmers growing banana turned their banana farming systems into crop-gardening  
636 systems and became either crop-gardeners or diversified farmers. However, specialized cane-  
637 growers remained cane-growers throughout Guadeloupe because the energy cane was used for  
638 electricity production. The population of orchard growers that changed their specialization in  
639 south-western Basse-Terre turned towards livestock breeding. Farming systems in northern  
640 Basse-Terre remained almost identical.

641

## 642 **4 Discussion**

### 643 **4.1 A framework to guide the scenario-based integrated analysis of agricultural systems**

644 The MOSAICA-f framework can help to parameterize a multi-functional scenario to improve  
645 the contributions of agricultural systems at a regional level to several sustainability issues. To  
646 achieve this and attain one or several goals, the framework can design scenarios made up of  
647 changes to drivers that can optimally modify the agricultural landscapes. Most current  
648 scenario analyses only compare business-as-usual scenarios with highly contrasted  
649 exploratory scenarios (Kok et al., 2011; Milestad et al., 2014; Vervoort et al., 2014; Gutzler et  
650 al., 2015). The set of scenarios produced by these approaches are useful in that they can  
651 provide decision-makers with contrasting views regarding the development potentials of the  
652 system being modelled (Herrero et al., 2014). However, in the past, we lacked a modelling  
653 framework for the iterative design of a multi-functional scenario, achieved through the  
654 simultaneous modification of several drivers of change. We propose such a framework based  
655 on the development of multi-functional scenarios and achieved by combining exploratory,  
656 normative and optimized scenarios across our 5-step method. The exploratory approach used  
657 (step 3) after the optimized approach (step 2) mimics the backward approach used in scenario  
658 analysis (van Vliet et al., 2012; Borjeson et al., 2006, Quist et al., 2011; Kok et al., 2011) to  
659 show how visions of the future and goals that are generated under an optimized scenario could  
660 be met (Ramos, 2010). Normative scenarios (step 4) indicate whether the agricultural systems  
661 can or cannot achieve these regional goals, and exploratory scenarios are helpful when  
662 selecting a set of drivers to meet these goals. For each goal, the targets defined with the  
663 optimized scenarios can provide information on the structural gap between the reference  
664 cropping system mosaic and the optimal cropping system mosaic for a given sustainability  
665 issue (Acosta-Alba et al., 2012; Bryan et al., 2011). Targets are often thresholds that must be  
666 attained and their definition is based on expert knowledge when this is available. In our test

667 case, targets were not available for each domain; thus, the optimized scenario was used to  
668 provide information regarding potential development of the reference landscape mosaic. This  
669 combination of scenarios is possible at the regional scale because the MOSAICA model  
670 allows for the optimisation of indicators and the change of constraints at the regional scale.  
671 This is not possible using regional approaches where models are run at the farm scale and the  
672 results are then up-scaled to the regional level.

673

674 In step 5 of the framework, the combination of drivers aims to design a scenario that can  
675 make use of the potential synergies between drivers, meaning that the combined impact will  
676 exceed the sum of their individual impacts. Use of the framework with a single driver was  
677 implemented first of all in order to identify drivers of interest, and then combine them to  
678 identify potential coherence among drivers of change. We have focused here on designing  
679 scenarios under which we can account for interactions between drivers in order to maximise  
680 their ability to improve their contribution to issues. This type of framework is similar to that  
681 used in multi-objective studies, in which several system variables are optimized to assess the  
682 potential contribution of the model to several sustainability issues (Acosta-alba et al., 2012,  
683 Groot et al., 2012). However, the objectives need to be prioritized when using this type of  
684 approach, which introduces subjectivity when analysing impacts. Lastly, the results of our  
685 framework could be improved by modifying the MOSAICA model to become a dynamic (e.g.  
686 recursive) model that could operate the transition from a reference agricultural landscape to  
687 one generated under the “go sustainable” scenario (Janssen and van Ittersum, 2007).

688

#### 689 **4.2 Spatially explicit multi-scale analysis**

690 One specific feature of the MOSAICA-f framework is that it can be used to test a broad range  
691 of drivers at different spatial scales with spatially explicit drivers and outcomes. The drivers

692 thus tested are new agricultural policies (e.g. change of subsidies), change of social context  
693 (e.g. changes of diet, with more consumption of local agricultural products) and new cropping  
694 system characteristics (e.g. organic cropping systems). Others drivers could have been  
695 selected, such as biophysical (e.g. remodelling of field slope), environmental (e.g. zones with  
696 a restricted use of pesticides), or social (e.g. change in land tenure) drivers. They could have  
697 been implemented at the field, farm, sub-regional and regional scales, and specifically  
698 targeted certain fields, farms or sub-regions. Thus, in our pathway for scenario building, we  
699 mixed different drivers (such as new cropping system characteristics) with either new  
700 cropping systems (e.g., organic crop-gardening and energy crops) or improved cropping  
701 systems (e.g., crop-gardening with reduced gross margin variability) at the field scale, social  
702 context changes at the regional scale (e.g., increased availability of labour), new agricultural  
703 policies (changes of market size thresholds based on local consumption), new agricultural  
704 policies at the sub-regional scale (e.g., banning the cultivation of food crops on polluted soils)  
705 or the regional scale (e.g., cessation of subsidies for sugar production). This type of multi-  
706 scale and spatially targeted strategy is relevant when responding to local and global issues  
707 (e.g., food self-sufficiency (Spiertz et al., 2012), biodiversity (Cunningham et al., 2013) and  
708 climate change (Lyle, 2015)). Hence MOSAICA can be of use when trying to find solutions to  
709 global and local challenges related to agriculture.

710

711 This framework may be of particular use to inform regional planning because it generates  
712 optimal outcomes at the regional scale and provides information on the spatial organization of  
713 crops and its impacts at different spatial scales. Building multi-functional agricultural  
714 landscapes implies significant changes to agricultural systems across several scales, driving  
715 transitions in cropping and farming systems (Seppelt et al., 2013). Such agricultural system  
716 transitions must be accompanied by several political, technical and agronomic prerequisites.

717 Agricultural policies can provide subsidies that enable changes to farming systems. Changes  
718 to farming practices require financial and technical support for farmers, including the supply  
719 of new equipment (e.g., for irrigation or mechanical tillage) and training so that farmers can  
720 manage more complex cropping systems. Increases in local food consumption are linked with  
721 education policies and local consumers' willingness to pay for local food crops (Barlagne et  
722 al., 2015). This spatially explicit information on changes to agriculture impacts, displayed in  
723 the form of maps, can guide decision-makers when implementing spatially targeted measures  
724 that are likely to be more efficient than regional policies. We therefore hypothesize that the  
725 MOSAICA-f framework could be a useful tool for policy analysis and design at the regional  
726 level if it is properly used in interaction with decision-makers (Delmotte et al., 2016),  
727 although that is beyond the scope of our work.

728

#### 729 **4.3 Framework implementation with decision-makers**

730 The MOSAICA-f framework could help decision makers by providing knowledge on drivers  
731 towards a better contribution to the sustainable development of a region. However, the  
732 MOSAICA framework requires a well-adapted interaction between modellers and  
733 stakeholders, including decision-makers, to fulfil these sustainability objectives. Participatory  
734 modelling with optimization tools requires particular attention because parameterization of  
735 the different scenarios within the model, and simulation, require large amounts of time  
736 (Delmotte et al., 2016). Because of this time requirement, decision-makers and modellers  
737 need to manage the framework together. Nevertheless the scientific and modelling skills  
738 required to ensure appropriate use of the MOSAICA model for scenario simulation implies  
739 that both the modelling component and the overall 5-step approach are managed by a  
740 multidisciplinary group of scientists. This group should i) have wide-ranging knowledge of  
741 cropping system performance, farm function and impact assessment and ii) have the

742 programming skills required to modify the MOSAICA model for each type of scenario.  
743 Decision-makers need to participate actively in scenario design and the diagnosis and  
744 definition of the issues they want to address (Walz et al., 2007). Co-designing or co-selecting  
745 sustainability issues and/or indicators for the contribution of agriculture to sustainable  
746 development (Mascarenhas et al., 2015), while considering the variables used and produced  
747 by the model; are also important to successful participatory approaches (Therond et al., 2009).  
748 Meetings with decision-makers should be organized by the modelling team and local experts  
749 in order to exchange possible drivers of local agriculture changes so as to target relevant  
750 drivers of changes to farming systems. A range of values to be tested for each driver needs to  
751 be defined. The modellers should then run the simulation of the different scenarios and  
752 present their results to decision-makers. Feedback from decision-makers should integrate the  
753 new drivers that emerged from group thinking (e.g. brainstorming) with the range of values to  
754 be tested. This loop between decision-makers and modellers could operate continuously as the  
755 model integrates new sustainability issues (e.g., crop diseases) and indicators with a broader  
756 diversity of cropping systems or the addition of new fields within the field characteristics  
757 database.

758

759 An analysis of the sensitivity of model outputs to model inputs or the drivers tested under the  
760 exploratory scenarios would also be important prerequisites for stakeholder discussions on the  
761 scenarios presented in this paper. Sensitivity analysis could be used in two ways: i) to assess  
762 the impacts of input variable uncertainty on the framework outputs, and ii) to refine the  
763 analysis of a given scenario by assessing the impacts of driver values on scenario outcomes.  
764 The former specifically targets the uncertainty in the model inputs from calibration of the  
765 model, such as the technical coefficients that define cropping systems. The outcomes of this  
766 use regarding the uncertainty of indicator values must be discussed with decision makers in

767 order to determine whether it can fit into their decision process or to convince them to invest  
768 in data acquisition and/or model development so as to reduce uncertainty. The latter use  
769 would focus on how, and to what extent, a particular driver can help to attain a target value  
770 and improve the contribution of agriculture to sustainable development. Different driver  
771 values should be tested step by step to identify which has the best potential effect in terms of  
772 multi-functionality in the post-modelling components. The Morris method could be used for  
773 this sensitivity analysis because it i) is a reliable technique to identify and rank important  
774 variables in terms of their impacts on the output variability of a modelled system (DeJonge et  
775 al., 2012; Drouet et al., 2011), and ii) is well-adapted to analyze a combination of variables,  
776 such as the combination of drivers tested within our framework.

777

## 778 **5 Conclusions**

779 In this paper, we have proposed and tested a model-based framework for the design and  
780 assessment of multi-functional agricultural landscapes. This framework is based on five steps  
781 that enable the construction of sustainable cropping system mosaics using a bioeconomic  
782 model. This framework combines optimized, normative and exploratory scenarios to provide  
783 knowledge to decision-makers regarding the potential drivers of change that could be used to  
784 attain multiple local and global sustainability goals. This holistic approach offers an analysis  
785 of the changes and impacts that could or should occur at the regional, farm and field scales,  
786 and highlights the spatial externalities of cropping system mosaics. This framework could be  
787 used to study potential spatial trade-offs between the provision of services by agriculture to  
788 society by means of spatialized indicators, as was done by Tian et al. (2015) at a watershed  
789 scale. In addition, the results of this study show that it is important to account for spatial  
790 heterogeneity in regional studies, and also to consider multiple drivers when the aim is to  
791 achieve multi-functional agriculture. This proposed framework could help decision makers,

792 farmers and society understand the pathways needed to achieve transition towards a more  
793 sustainable future in regions where significant investments are made in data acquisition at the  
794 field, farm and regional scales.

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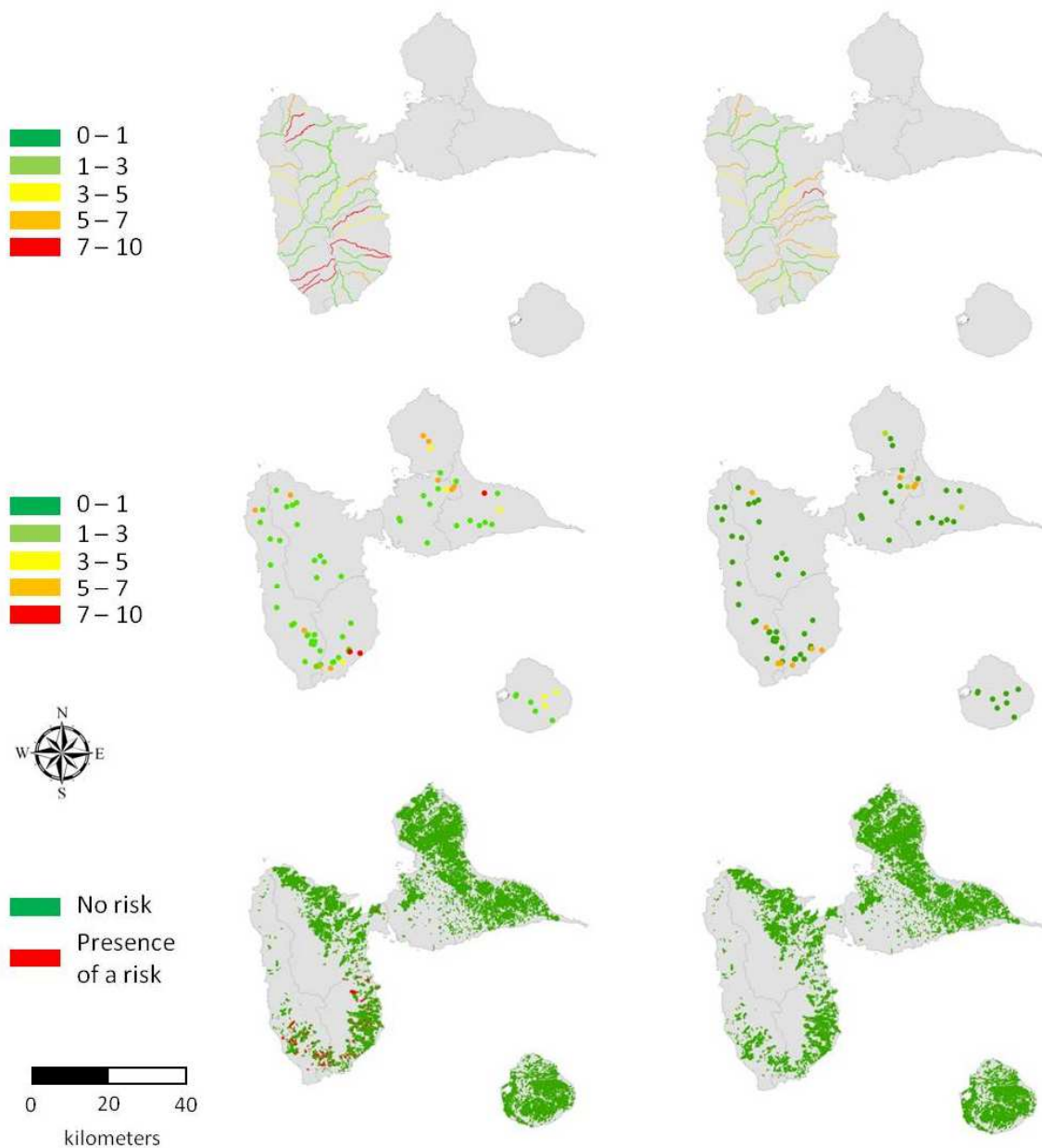
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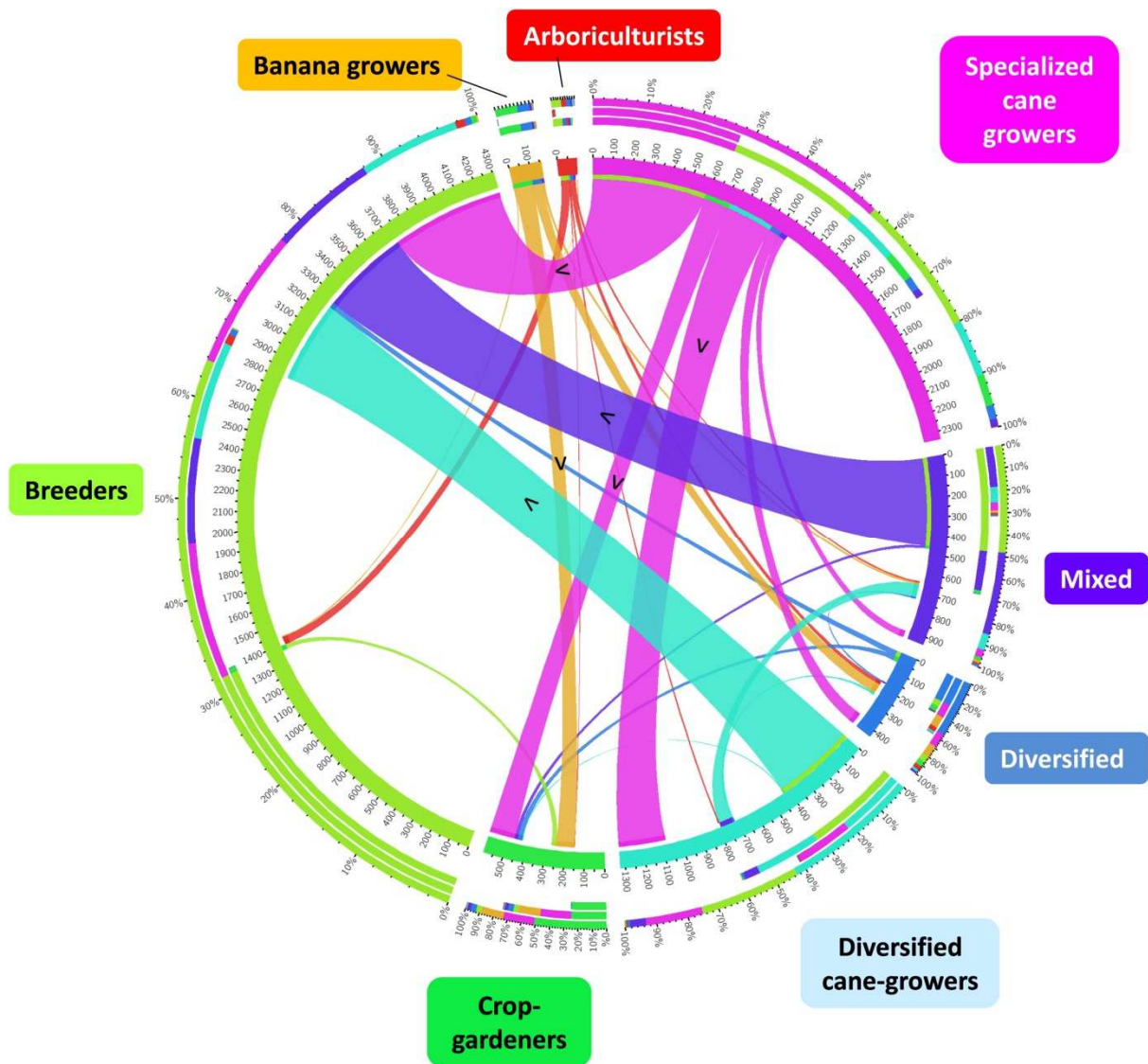
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 1094 **Figure A:** Comparison of the evolution of the contribution of cropping system mosaics to the  
 1095 decrease of pollution in rivers (top), drinking-water abstraction (middle) and to the decrease  
 1096 of the area of risk of contamination of crops by chlordecone (bottom) between the current  
 1097 mosaic (left) and the one from the "Go sustainable" scenario (right).



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1100 **Figure B: Trajectories of farming system changes within the territory.** Arrows represent  
 1101 the directions of farming system changes from the initial to the "Go sustainable" mosaic.  
 1102 Ribbons between types represent the transition of farms from a given type in the initial  
 1103 cropping system mosaic to another one in the mosaic obtained with the "Go sustainable"  
 1104 scenario. Ribbon width represents the number of farms in transition. The angular sizes of  
 1105 circularly arranged segments represent the population of each type and are proportional to the  
 1106 size of farm types in the initial cropping system mosaic. The four circularly arranged stake  
 1107 bars, from the center of the figure to the edges, represent respectively, the relative contribution

1108 of outgoing ribbons from each farm type in number of farms, in percentage, the relative  
1109 contribution of ingoing ribbons to each farm type in percentage and the proportion of ingoing  
1110 and outgoing ribbons in the total population.  
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