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MOSAICA: A multi-scale bioeconomic model for the design and ex ante assessment of cropping system mosaics

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4

5 **Title:** MOSAICA: A multi-scale bioeconomic model for the design and *ex ante* assessment of
6 cropping system mosaics

7

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14 **Abstract**

15 To understand the effects of policy changes on organisations and compositions of cropping systems at
16 regional scale and their contribution to the sustainable development of regions, we built a regional,
17 spatially explicit, multi-scale, bioeconomic model called MOSAICA. This model explicitly
18 incorporates information at field, farm, sub-regional and regional scale to provide cropping system
19 mosaics by way of regional optimisation of the sum of individual farmer's utilities under field, farm
20 and territory biophysical and socio-economic constraints. Its generic structure means it can be used in
21 different regions with geographic information on the location of the field and farm, data on cropping
22 system performance, on location factors and on policy schemes. We used the model in Guadeloupe to
23 test the impact of three scenarios of change on the agricultural subsidy regimes. The model produced
24 three cropping system mosaics which reduced the area under banana and sugarcane, turned specialized

25 banana and sugarcane farming systems into breeding systems while improving the overall contribution
26 of agriculture to sustainable development. The spatially explicit results of changes in ecosystem
27 services, and in farming systems with MOSAICA make it an appropriate decision-aid tool for regional
28 planning.

29 **Highlights**

- 30 • We built a multi-scale spatially explicit regional bioeconomic model called MOSAICA
- 31 • MOSAICA combines field, farm, and regional data to produce cropping system mosaics
- 32 • MOSAICA models impacts of policy and novel scenarios on cropping systems mosaics
- 33 • Spatially explicit indicators can help decision-makers to assess different targeted policies
- 34 • MOSAICA can help explore scenarios to improve sustainable development of regions

35

36 **Keywords:** land use change; scenarios; ecosystem services; sustainability indicators; farm typology;
37 agricultural landscapes

38

39 **1. Introduction**

40 Agriculture plays an active role in the provision of ecosystem services by way of ecosystem
41 management. Recent studies have shown that the spatial organisation of cropping systems, which are
42 called cropping system mosaics at the landscape scale, drives the provision of some ecosystem
43 services (Thenail et al., 2011). These cropping system mosaics contribute to the protection of soils
44 (Ronfort et al., 2011), the rational use of water (Bergez et al., 2007) and the conservation of
45 biodiversity (Rusch et al., 2012), among others. The cropping system mosaic is also important for the
46 provision of economic and social services, such as the provision of food and employment. Cropping
47 system mosaics are the results of farmer cropping system choices at the field level (Dury et al., 2011).

48

49 A cropping system choice is driven by a range of parameters that act at the field, farm and regional
50 scale (Aubry et al., 1998). Biophysical drivers (e.g., the slope, the rainfall), social factors (e.g., the age
51 of the farmer), economic factors (e.g., the investment capacity), farm structure and resources (e.g., the
52 farm size, the number of workers), the farmer's objective and risk aversion can strongly drive the
53 choice of cropping system. At the field scale, biophysical factors can constrain the adoption of new
54 cropping systems (Chopin and Blazy, 2013), and the change in the production quota at the farm scale
55 and the personal objectives of farmers affect the choice of farming systems (Bureau et al., 2001). At
56 the regional scale, the implementation of agricultural policies (Flichman et al., 2011) and protected
57 environmental areas drive the choice of crops and agricultural practices. Some of these factors are
58 spatially heterogeneous and can then affect farmer choices in a different way depending on their
59 location in the territory. The location of cropping systems has a direct impact on the values of
60 ecosystem services that are provided by agriculture. Thus, to manage ecosystem service provision at
61 the regional scale, decision-makers should implement well-adapted, multi-scale, spatially explicit
62 policies aimed at organising the landscape to increase the provision of services in the desired direction.

63

64 Bioeconomic models have been frequently used for *ex ante* assessments of impacts from policy
65 changes on the choice of farmer cropping systems at the farm scale. This type of model links farmer
66 resources and context variables with activities that describe cropping systems (Flichman et al., 2002;
67 Janssen and van Ittersum, 2007). These systems have been widely used in a range of different studies
68 primarily at the farm scale (Dogliotti et al, 2005; Louhichi et al., 2010; Belhouchette et al., 2011; Leite
69 et al., 2014) or from the farm scale to the regional scale (Laborte et al., 2007; van Ittersum et al.,
70 2008).

71

72 However, the interrelationships between the field, farm and regional scales have scarcely been
73 explicitly integrated into bioeconomic models despite their influence on the decision-making process
74 of farmers (Delmotte et al., 2013). Moreover, assessing the consequences of cropping system changes

75 in current bioeconomic models is not spatially explicit, which decreases the usefulness of the
76 assessment for decision-makers, who want to determine the impact of the policy on the cropping
77 system mosaics and the evolution of the contribution from these mosaics to the sustainable
78 development of their region. Some regional models including SOLUS (Schipper et al., 1998) and
79 Landscape IMAGES (Groot et al., 2007) take different spatial scales into account in the design and
80 assessment of policy support for sustainable land-use options. However, SOLUS does not directly
81 account for individual constraints at farm level (Schipper et al., 1998) and IMAGES is mostly used to
82 optimise landscape functions to explore possible trade-offs among these functions with an
83 evolutionary algorithm.

84

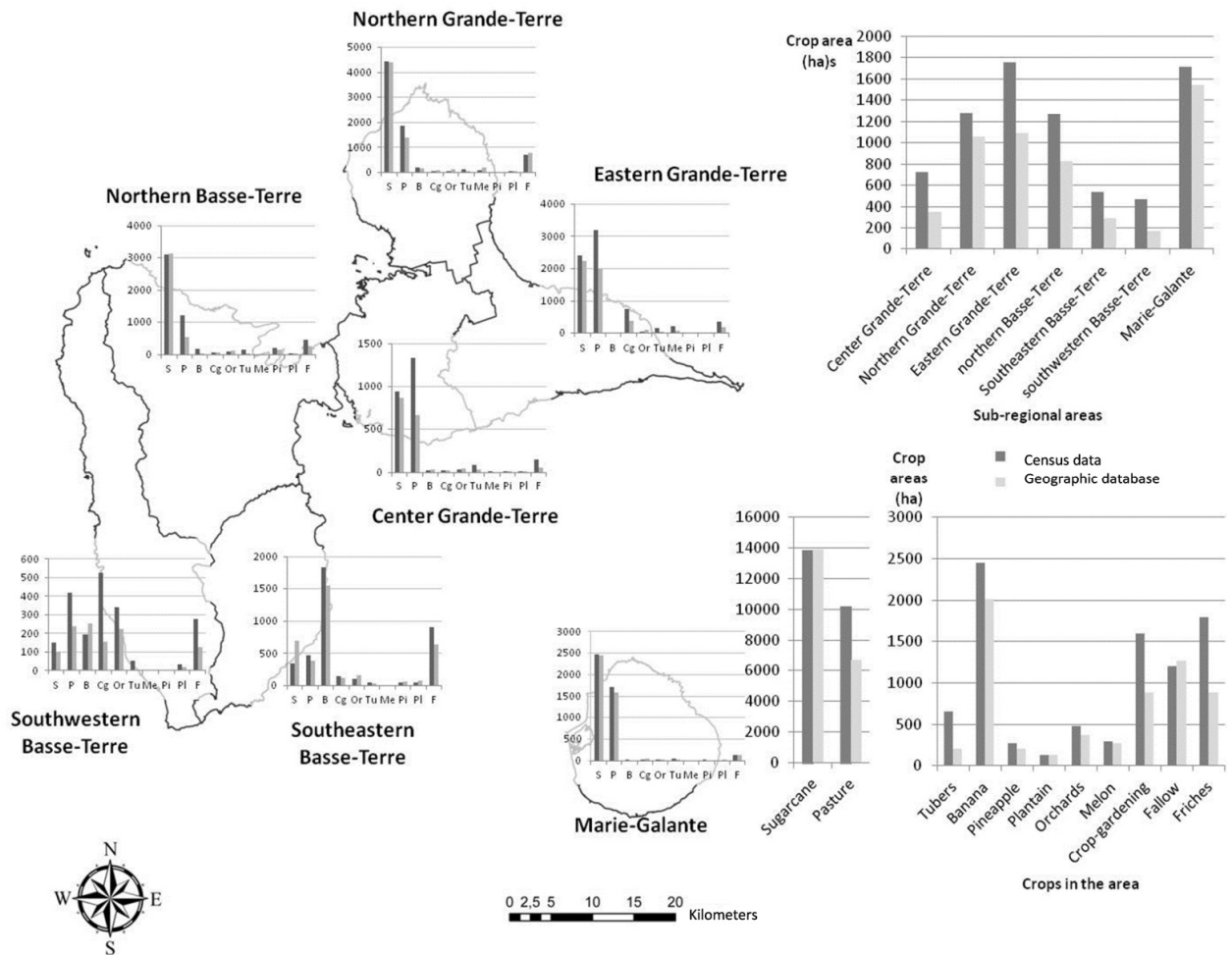
85 To assess the effects of policies on the contribution of cropping systems to sustainable development at
86 a regional scale, we built a regional, spatially explicit, multi-scale bioeconomic model of farmers'
87 choice of cropping systems at the field scale. The economic component is embedded in the decision
88 model, which is based on the optimisation of the overall gross margin with a risk coefficient under
89 farm resources constraints such as farm size or workforce. The biophysical part of MOSAICA relies
90 on (i) an algorithm of cropping system allocation, which is under the conjoint influence of the
91 biophysical context of the fields and the biophysical performance of the cropping systems, and (ii) the
92 biophysical process behind the equations used to calculate the indicators, which provide information
93 on the pressure of the cropping system mosaic on the ecosystems. This model can optimise the
94 allocation of cropping systems regionally at the field scale by accounting for the constraints and
95 opportunities at the field level, the availability of production factors at the farm scale, farmers'
96 attitudes to risk, the policy implemented and the availability of resources (e.g., water for irrigation) at
97 the regional scale.

98 We first present the area of implementation and then the bioeconomic model for a scenario analysis at
99 the regional scale with an application in Guadeloupe, a French Outermost Region, with three
100 scenarios.

101

102 **2. Material and methods**

103 **2.1. Area of implementation**



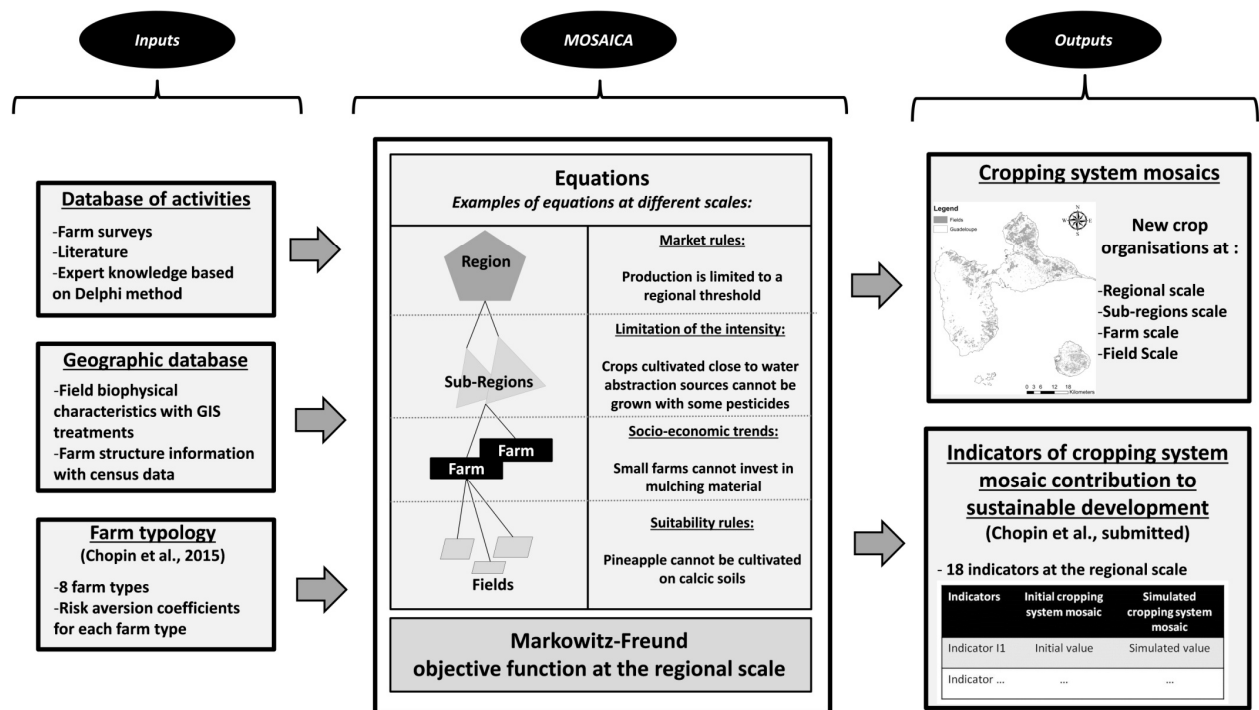
104

105 Figure 1: Crop organisation at the district scale and comparison of the census data in 2010 with the
106 geographic database used in the study. On the map, S stands for sugarcane, P for pasture, B for
107 banana, Cg for crop-gardening, Or for orchards, Tu for tubers, Me for melon, Pi for pineapple, PI for
108 plantain and F for fallow

109 We implemented our generic bioeconomic model in Guadeloupe as an example. Guadeloupe is a
110 French archipelago located in the Caribbean. In this area, the climate is tropical, rainfall is positively
111 correlated with relief, and ranges from 1,000 to 5,000 mm yr⁻¹. Soils in the mountain areas are acid,
112 Andosols, Nitosols, Ferralsols and vertic soils, while flat lands have Calcisols and Vertisols. The total

113 cultivated area of the archipelago, which is composed of the Grande-Terre, Basse-Terre and Marie-
 114 Galante islands, is 32,948 hectares (PDRG, 2011), the different cropped areas and their spatial
 115 arrangement within the territory, is shown in Figure 1. There are 7749 farms in Guadeloupe, and their
 116 sizes range from less than one hectare to more than one hundred hectares, with an average of four
 117 hectares (Agreste, 2010). This variability in the socioeconomic and biophysical context and farm
 118 resources is responsible for the variability of the cropping systems, described through typologies such
 119 as that of Blazy et al. (2009) for banana farms and Chopin et al. (2015) for farming systems.

120 **2.2. Overview of the bioeconomic model MOSAICA**



121

122 Figure 2: Presentation of Multi-scale model of the crOpping Systems Arrangement and Its
 123 Contribution to sustAinable development (MOSAICA)

124 The modelling framework with the inputs and outputs of the Multi-scale model of the crOpping
 125 Systems Arrangement and Its Contribution to sustAinable development (MOSAICA) is shown in
 126 Figure 2. The inputs of the model are i) the geographic database of fields that contain information
 127 about the biophysical context and the farm structure, e.g., the farm size and the land tenure, ii) the
 128 database of activities that describe the cropping systems and technical-economic coefficients that can

129 be allocated to fields and iii) the farm typology and the classification algorithm for the eight farm
130 types. The model optimizes the sum of individual farmer's utilities at the regional scale, which
131 includes expected farm revenue and the risk aversion towards price and yield variations. The
132 allocation of cropping systems is modelled through a set of equations that model the choice of
133 cropping systems by farmers at different scales, namely the field, farm, sub-regional and regional
134 scales. Optimisation is performed at the regional scale because equations are implemented at this scale
135 to constrain the overall quantity of production for some crops within the entire area of study (because
136 of market sizes or production quotas). The outputs of the model are the cropping system mosaics and
137 the calculation of a range of sustainability indicators.

138

139 **2.3. Model inputs**

140 **2.3.1. Building the geographic databases**

141 First, a geographic database of fields is needed to calibrate the model and to design and assess
142 cropping system mosaics. Second, a shapefile of farms is built with the information obtained on the
143 farm locations. Third, the reliability of these databases must be checked before the scenario analysis at
144 the regional scale, e.g., by comparison of the crop areas with regional public statistics. Fourth, the
145 farm and field databases are completed with allocation factors that are biophysical and structural
146 context variables.

147 In our case study in Guadeloupe, we worked with a geodatabase of fields that was provided by the
148 local agency that helps farmers with their subsidy applications. The initial geographic database
149 gathered 25 057 fields, owned by 5336 farmers, and the crops grown on them in 2010. The reliability
150 of the farm and field databases is checked by comparing the area of each crop in the database with the
151 agricultural census data in 2010 (Agreste, 2010). We can see that the total number of farms in the
152 database is smaller than the actual number, 5336 farms compared with the initial 7749 farms, from the
153 statistics. This discrepancy in the database is quite homogeneously spread among the sub-regional
154 areas, but the Marie-Galante area is better represented than the eastern Grande-Terre and the

155 southwestern Basse-Terre. The crop areas follow trends that are linked to the number of farms. Except
156 for the lack of data on crop-gardening and pastures, a gap that prevents us from generalising some of
157 the trends in changes observed in these crops (Figure 1), the database is satisfactory because it
158 represents 80% of the agricultural area.

159

160 The field areas were then calculated and aggregated to obtain the size of each farm. Rainfall quantities
161 were calculated based on the mean rainfall levels for 30 years. Inter-annual rainfall was assessed based
162 on monthly rainfall determined from data from meteorological stations interpolated using the kriging
163 tool in ArcGIS 9.3 (ESRI, 2009). The soil types were added based on an intersection with the soil
164 shapefiles from a soil map (Colmet-Daage, 1969). In Guadeloupe, 20% of the fields are contaminated
165 by chlordecone (Cabidoche et al., 2009), which can be up taken by some crops. The contamination
166 rate depends on the soil chlordecone content, plant anatomy and physical-chemical properties of the
167 soil (Cabidoche and Lesueur-Jannoyer, 2012). Consumption of contaminated crops has been shown to
168 have harmful effects on humans (Multigner et al., 2015). The risk map for chlordecone contents was
169 used to generate the chlordecone risk in the plots (Tillieut and Cabidoche, 2006). Irrigation schemes
170 were intersected with fields to provide information on access to irrigation. The altitude was calculated
171 from a 15-metre digital elevation model (DEM). The slope raster was determined from this DEM by
172 using the slope tool. The fields were spatially intersected with sub-regions and determined based on
173 the similarity of their soil and climate conditions. This biophysical information is used in two ways:
174 (1) as constraints for the allocation of an activity to fields (for example, when rainfall is insufficient
175 and irrigation is impossible, the activity cannot be adopted) and (2) as input parameters for the
176 calculation of certain indicators (mainly environmental indicators).

177

178

179 **2.3.2. Building the database of activities**

Example of cropping systems/ Examples of technical coefficients	Intensive banana cropping system in plain	Traditional beef production on pasture	Staked yam based cropping system	Mechanized sugarcane in the northern Basse-Terre	Plantain cropping system in Basse-Terre	Pineapple cropping system with plastic mulch
Mean yield (tons.ha ⁻¹ .yr ⁻¹)	44	0.66	15	74	26	23.3
Price of sell (€.t ⁻¹)	540	5400	2000	11.2	800	1100
Income (€.ha ⁻¹ .yr ⁻¹)	42957	3564	30000	4852	20800	38500
Mean variable costs (€.ha ⁻¹ .yr ⁻¹)	32540	1974	20939	2212	9414	9303
Gross margin (€.ha ⁻¹ .yr ⁻¹)	10417	1590	9061	2640	11386	16327
Use of pesticides (number of doses.yr ⁻¹ .ha ⁻¹)	8	0	2	1	3	10
Workforce needs (hours.ha ⁻¹ .yr ⁻¹)	1560	70	990	15	620	450

180

181 Table 1: Description of some cropping systems in the database of activities

182 The central element of the bioeconomic modelling approach is the simulated production process

183 (Hazell and Norton, 1986), which is performed through the production activity choices of farmers

184 (Flichman et al., 2011). One activity is defined by the technical coefficients that represent the use of

185 inputs needed to produce different outputs. The description of the cropping systems depends on the

186 nature of data required for the optimisation process and on the calculation of the indicators (e.g., the

187 average gross margin, cost of production, yield, working demand, sale price, etc.).

188 In our case study, we described 36 cropping systems currently used by farmers based on (i) previously

189 published work, (ii) expert knowledge and (iii) on-farm surveys. The model is static and does not

190 account for variations in cropping systems over time since its main aim is to perform a strategic

191 analysis of agricultural systems under new conditions in a what-if scenario framework. We then

192 describe multi-annual cropping system (such as banana, sugarcane or orchards), as an average of

193 practices and performances over the full life cycle of crops without a discount rate. The possible

194 decrease in the gross margin of multi-annual cropping systems is taken into account in the positive and

195 negative variations in the gross margin Z^+ and Z^- defined for each activity a . Some of the activities
196 with their technical coefficients are presented in Table 1. Livestock activities are included in pasture
197 activities, which describe outputs from grazing livestock productions. Previously published works
198 include scientific publications, such as Blazy et al. (2009) for banana production and technical guides
199 published by local agricultural institutes and agricultural cooperatives. In total, 25 experts were first
200 interviewed individually and then gathered together to come to an agreement on the characteristics of
201 cropping systems by following the principle of the Delphi method (Harold and Murray, 2002). Ten
202 further on-farm surveys were conducted to complete lacking data. Alternative activities could have
203 been described but we chose not to do so in this study, since the aim of the scenarios was to assess the
204 impacts of changes in the subsidies regime on existing farming systems. However with MOSAICA, it
205 is possible to assess the potential contribution of new cropping systems to regional sustainability by
206 defining new activities.

207

208 **2.3.3. Farm typology**

209 Statistical analyses were performed on the farm database to cluster farmers based on their decision
210 processes.. Because crop acreages are the results of the farmer decision process (Aubry et al., 1998;
211 Dury et al., 2011), these variables should be included in the statistical analysis, which may also
212 include biophysical variables, farm structure or socio-economic variables (Andersen et al., 2007).

213 In our case study, we used a farming system typology and a classification algorithm that were realised
214 on Guadeloupian farmers categorised into the following eight farm types: "arboriculturists", "banana
215 growers", "specialised cane growers", "diversified cane growers", "diversified", "breeders", "crop-
216 gardeners" and "mixed cane growers-breeders"(Chopin et al., 2015). These are mainly the percentages
217 of the acreages of the different crops grown on a given farm. As a cropping plan is the result of the
218 farmer's decision process, the farm typology groups farms with similar decision processes. The
219 classification algorithm, which consists of several thresholds of crop acreage proportions at the farm
220 scale, has been implemented in our bioeconomic model as a set of if-then rules to provide (i) a

221 classification of farm types at the initial state of the mosaic and (ii) a post-optimisation classification
222 that shows the evolution of farming systems from the initial cropping system mosaic to the simulated
223 one after scenario analysis.

224

225 **2.4. The model description**

226 **2.4.1. Objective function**

227 The objective function of our regional bioeconomic model is a Markowitz-Freund (Mosnier et al.,
228 2009). The optimal acreage at the regional scale is the one obtained from the maximisation of utility
229 U , which is the maximum of the sum over the full population of farmers of the total gross margin m_a
230 of activity a balanced with the sum of expected positive and negative variations in the gross margin,
231 respectively Z_a^+ and Z_a^- , multiplied by a risk-aversion coefficient ϕ at the farm scale (Equation 1). The
232 risk is then modelled using a linear approach (Mosnier et al., 2009).

233 The coefficients of variability are determined for each activity based on agro-economic expertise and
234 encompass both an agronomic risk (yield variability related to climate conditions, pest attacks or
235 diseases) and commercial outlet risk (from the variability in the selling price across the selling season)
236 aggregated together. We applied two variability coefficients Z_a^+ and Z_a^- (Equation 1 and 2) to each
237 activity based on an appraisal of this risk because this type of risk formulation is known for generating
238 good results in bioeconomic models (Arriaza et al., 2003). For instance, for sugarcane cropping
239 systems in the northern part of Basse-Terre, these positive and negative variations have been set to
240 respectively $-250 \text{ €} \cdot \text{ha} \cdot \text{yr}^{-1}$ and $+250 \text{ €} \cdot \text{ha} \cdot \text{yr}^{-1}$, because of its low commercial risk and low variability
241 in the crop yield.

$$242 \quad MAX U = \sum_f \sum_p \sum_a [X_{a,p} (\bar{m}_a - \phi_f (Z_a^+ + Z_a^-))] \quad (1)$$

$$243 \quad Z_a^+ - Z_a^- \geq 0 \quad (2)$$

$$244 \quad \bar{m}_a = (\bar{Y}_a P_a + S_a) - C_a \quad (3)$$

245 In Equation 3, m_a is the average gross margin of activity a based on a mean yield Y , a price P with
246 subsidies S and a given level of variable cost C (Equation 3). The area of activity a is symbolised by
247 X , and $X(a,p)$ represents the vector of decision variables, that is to say, the area covered by each
248 activity a (the cropping system in our case study) on plot p (Farms f can choose one or several
249 cropping systems on the same plot).

250

251 2.4.2. Constraint equations

252 Equations are primarily implemented in bioeconomic models as constraints to the adoption of
253 cropping systems by farmers. These equations impact the allocation process of cropping systems at
254 different scales.

255 In our case study, we mixed expertise and descriptive statistics to highlight the thresholds of variables
256 that described the locations of cropping systems (Leenhardt et al., 2010) and implemented them in
257 several equations at different scales. The complete list of equations is given in the Appendix.

258

259 At the field scale, we implemented a set of equations linking the cropping systems to the slope, field
260 area, rainfall amounts, altitude, soil type and land tenure, which were calculated for all individual
261 fields and affect the choice of cropping systems. For instance, mechanised cropping systems were
262 limited to a slope Slp_{max} of 15% because of the impossibility of ploughing or mechanically
263 harvesting on steeper slopes in field p with a slope of Slp (Equation 4).

264

$$265 \text{ If } Slp_p \geq Slp_{max_a}, \quad (4)$$

$$266 X_{a,p} = 0$$

267

268 At the farm scale, the farm size, agronomic rules for crop rotations, production quotas and workforce
 269 resources are the primary constraints for the adoption of cropping systems. For instance, the size of
 270 workforce, which was determined according to the observation of initial areas \mathbf{X}_{init} for cropping
 271 systems allocated to plots \mathbf{p} in 2010 and the work \mathbf{W} required for activity \mathbf{a} , was considered to be a
 272 limited resource for farmers since flexibility of work is mainly managed at farm scale (Equation 5).

273

$$274 \quad \sum_p \sum_a (X_{a,p} W_a) \leq \sum_p (X_{init_{a,p}} W_a) \quad (5)$$

275

276 At the sub-regional scale, environmentally and geographically protected indications constrain the
 277 adoption of cropping systems. At the regional scale, we defined the maximum thresholds for limiting
 278 the quantity of crops produced based on either production quotas for banana or sugar, respectively 77
 279 977 and 10 700 tons.yr⁻¹ (PDRG, 2011; CTCS, 2005) or current consumption for non-exported crops,
 280 such as plantain, based on the sum of production for local market and importation \mathbf{I} of the crop
 281 produced by activity \mathbf{a} (respectively 4500 and 150 tons (Equation 6).

$$282 \quad \sum_f \sum_p \sum_a (X_{a,p} \bar{y}_a) \leq \sum_f \sum_p \sum_a (X_{init_{a,p}} \bar{y}_a) + I_a \quad (6)$$

283 2.5. Calibration procedure

Farm types	Risk aversion coefficient Φ
Arboriculturists	1.3
Banana growers	1.2
Specialised cane growers	0.3
Diversified cane growers	1.4
Diversified	0.55
Breeders	2.4
Crop-gardeners	0
Mixed cane growers - breeders	2.3

284

285 Table 2: risk aversion coefficients used for the calibration of MOSAICA

286 The calibration procedure is based on the allocation of several sets of risk aversion coefficients θ to
287 farmers based on their farm type. These risk aversion coefficients at farm scale help reproduce
288 farmer's cropping plans based on a hypothesis about their level of risk aversion. Several iterations are
289 performed until 80% of farming systems are well-calibrated. After reaching this threshold, the model
290 can be considered satisfactory.

291

292 In our case study, we tested several sets of risk aversion coefficients θ per farm type as calibrating
293 coefficients of our model. The same risk aversion coefficient was allocated to each farm belonging to
294 the same farm type (Table 2). We established a range of hypotheses on the level of risk aversion per
295 farm type to start the calibration iteration. After running 100 iterations, we managed to obtain a set of
296 risk aversion coefficients that provided satisfying results at the farm scale in terms of cultivated crop
297 areas. The coefficient has a value that ranges from 0, a risk neutral farm type, to crop-gardeners,
298 approximately 3, a very risk-averse farm type, such as the breeders in this example (Acs et al., 2009).

299

300 **2.6. Evaluation of the model**

301 The base year outputs in a bioeconomic model should match those observed in reality. The percentage
302 of absolute deviation (PAD) between the observed acreage $X_{init}(a)$ for activity a and the simulated
303 acreage $X(a)$ for a field p , summed at a different spatial scale (i.e. at regional scale), is widely used to
304 check this match (Hazell and Norton, 1986; Leite et al., 2014). The best calibration is reached when
305 PAD is close to 0.

306

$$307 \quad PAD (\%) = 100 * \frac{\sum_p |(X_{init}(a) - X_a)|}{\sum_p X_{init}(a)} \quad (7)$$

308 Because the purpose of our model is to ensure the correct prediction of the location of a cropping
309 system at various spatial scales, we checked the outputs of our model at multiple scales with this PAD

310 (Equation 7). We considered the results to be satisfactory when the percentage of absolute deviation
311 (PAD) was less than 15% for the primary crops at the regional scale, and 20% in the sub-regions and
312 farms, as recommended by authors who assess the reliability of bioeconomic farm models
313 (Kanellopoulos et al., 2010; Hazell and Norton, 1986; Janssen and van Ittersum, 2007).

314 **2.7. Sustainability indicators at the regional scale**

315 The impact of agriculture on society at a regional scale depends on the state of the cropping system
316 mosaic. To assess these impacts, MOSAICA includes a set of sustainability indicators at the regional
317 scale. The indicators consist of a quantitative externality assessment of a farmer's choice of cropping
318 plan at the regional scale, and they are related to (i) the technical coefficients of farmers' cropping
319 systems allocated at the field scale, (ii) the location of fields in the region, which drives the potential
320 impacts of cropping systems on the response of agriculture to sustainability issues and (iii) the
321 properties of the fields (e.g., rainfall amount, the size of the field, etc.). The indicator score then varies
322 depending on the cropping systems allocated within the whole cropping system mosaic.

323 In our case study, one to three indicators were previously designed by Chopin et al. (submitted) for
324 each sustainability issue (Table 3). None of the economic indicators and few of the social indicators
325 are spatially explicit. They are determined based on the aggregated results of all individual fields at the
326 regional scale (e.g. the agricultural added value is the aggregation of the gross margins at field scale).
327 On the other hand, most environmental indicators account for the location of each cropping system.
328 More information on the indicators can be found in supplementary material.

Sustainability objectives	Indicators	Description	Units
Improving agricultural revenue	Overall farm revenues	Aggregation of cropping system gross margins at regional scale	€.yr ⁻¹
	Repartition of revenue among the farm population	The Gini indicator measures the balance of farm revenue repartition (high value: inequity in repartition / low value: equity) (Ceriani and Verme, 2012)	-
Increasing autonomy from subsidies	Total amount of subsidies	Aggregation of cropping system subsidies at regional scale	€.yr ⁻¹
Reaching food self-sufficiency	Ratio of produced carbohydrates over needs	Aggregation of the entire production of carbohydrates, proteins and fats from crop production at regional scale divided by the needs of population calculated based on the local population size and average needs	%
	Ratio of produced proteins over needs		%
	Ratio of produced fats over needs		%
Producing local energy from agriculture	Energy potential produced by crops	Aggregation of cropping system potential production of energy at regional scale	MW.yr ⁻¹
Contributing to employment	Total number of workers	Aggregation of the number of workers needed for cropping systems at regional scale	pers.yr ⁻¹
Insuring safety of locally produced foodstuff	Area with a potential chlordecone contamination of food crops	Sum of the area for which contamination of crops is possible due to the contamination of soil, the type of crop grown and the soil type	ha
Improving the state of biodiversity	Risk for birds in high-value ecological zones	Average score of pesticide risk in these areas due to cropping system using pesticide with acute toxicity and the quantity of active ingredients	-
	Ratio of potentially polluted rivers	Qualitative score determined at the field scale with a decision tree with information on the quantity of active ingredients, the quantity of run-off based on expert knowledge for each type of soil, the half-life of the active ingredients in the environment, ... (see Tixier et al, 2006). The score obtained at water body scale is the average score from fields located around water bodies. The proportion of water bodies potentially polluted are the ones with a score above 7.	%
Ratio of potentially polluted water abstraction sources	%		
Enhancing water quality	Ratio of potentially polluted water catchments	Aggregation of cropping system needs for water based on the quantity of rainfalls and the average crop needs per month	%
	Amount of water needed for irrigation		m ³
Protecting soil quality	Area potentially eroded due to farming practices	Sum of field areas with a score above 6 obtained with a decision tree based on the type of soil, the crop cover of activities... (Tixier, 2005)	ha
Decreasing contribution to climate change	Overall CO ₂ emissions from farming activities	Aggregation of cropping system emissions from cradle to farm gate with the exportation of crops	tons CO ₂ .yr ⁻¹
Improving diversity of agricultural landscapes	Diversity of crops across the landscape	Simpson's diversity indicator: it assesses the diversity of crops through the calculation of the proportion of each crop in the entire agricultural area (Simpson, 1949)	-

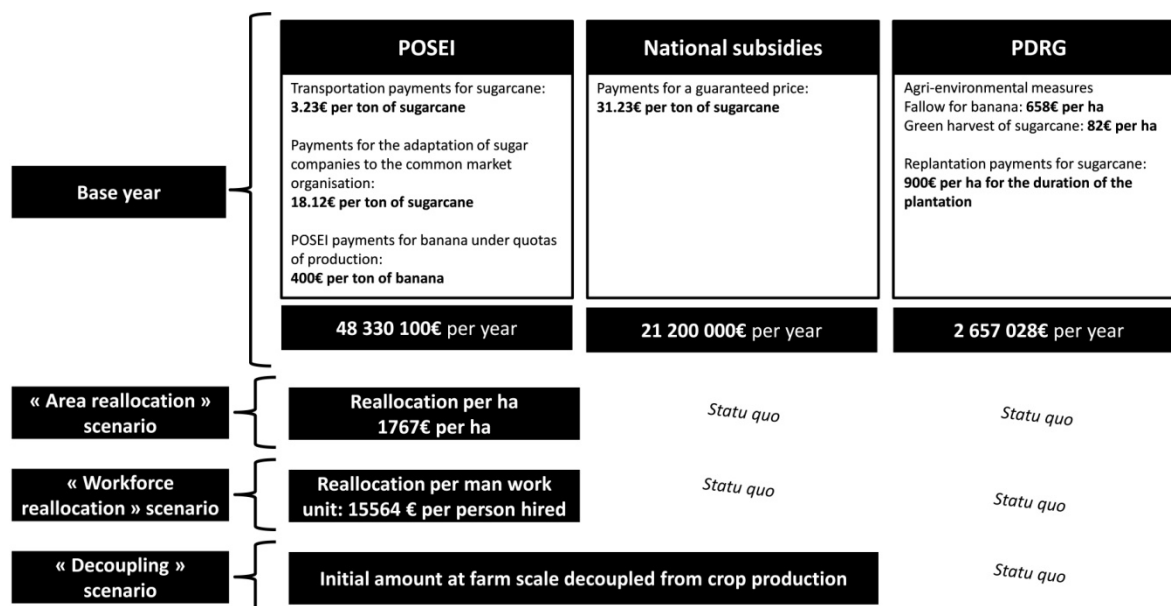
329 Table 3: Indicators for the assessment of cropping system mosaics with MOSAICA

330 **2.8. Policy scenarios**

331 The current policy and the scenarios developed to illustrate the use of MOSAICA are summarised in
 332 Figure 3. The cropping system mosaic, which was obtained with the calibration procedure, is used as
 333 the base year in the scenario analysis presented in the next sections.

334

335 **2.8.1. Current agricultural policy in Guadeloupe**



336

337 Figure 3: Description of the current agricultural policy in Guadeloupe and the changes tested in
 338 scenarios

339

340 Currently, agriculture in Guadeloupe is highly subsidised by several agricultural policies. The primary
 341 policies in favour of the Outermost Regions are i) the POSEI ("Program of specific options for
 342 isolation and insularity") arrangements, ii) the rural development program of Guadeloupe 2007-2013
 343 that encompass the less favoured area measures, the agri-environmental measures and the structural
 344 measures to sectors and iii) national subsidies (Figure 3 - see Supplementary materials for more
 345 details).

346

347 **2.8.2. Expected changes in Guadeloupe's agricultural policy**

348 The current policy towards Outermost Regions is going to change because of the pressure from the
349 World Trade Organization to liberalise the sugarcane and banana markets (European Union, 2012)..
350 For sugar, national subsidies are going to disappear by 2017, and the banana contingent from the RUP
351 may disappear by 2020. We will then test the impact of three scenarios in terms of changes in the
352 subsidy levels and characteristics of the cropping system mosaics at the regional scale and the effects
353 of these mosaics on the contribution of agriculture to the sustainable development of society.

354 In the "Area reallocation" scenario, the entire quantity of subsidies from the first pillar, or 48.34
355 M€.yr⁻¹, is reallocated to each crop equally for 1768 € per hectare of production, including sugarcane
356 and bananas (Figure 3).

357 In the "Workforce reallocation" scenario, the amount of subsidies from the first pillar is reallocated,
358 for each unit of hired workforce with 15 569 € per unit of workforce. The rationale behind distributing
359 subsidies according to the number of hired labourers is the fact that the unemployment rate is high in
360 Guadeloupe (27%) and such subsidies could offer new opportunities for stimulating the labour market
361 (Figure 3).

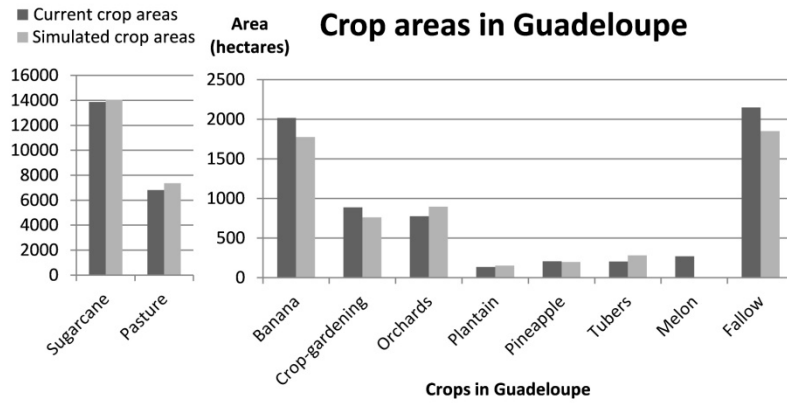
362 In the "Decoupling" scenario, the current level of payments from national subsidies and POSEI
363 payments are defined at farm level, and represent 69.8 M€.yr⁻¹, and they are maintained at farm level
364 but completely decoupled from agricultural production (Figure 3). Subsidies to agriculture are no
365 longer linked to crop production like in the CAP decoupling scheme in Europe (Viaggi et al., 2011).

366

367 **3. Results**

368 **3.1. Model calibration**

369 **3.1.1. At the regional scale**



370

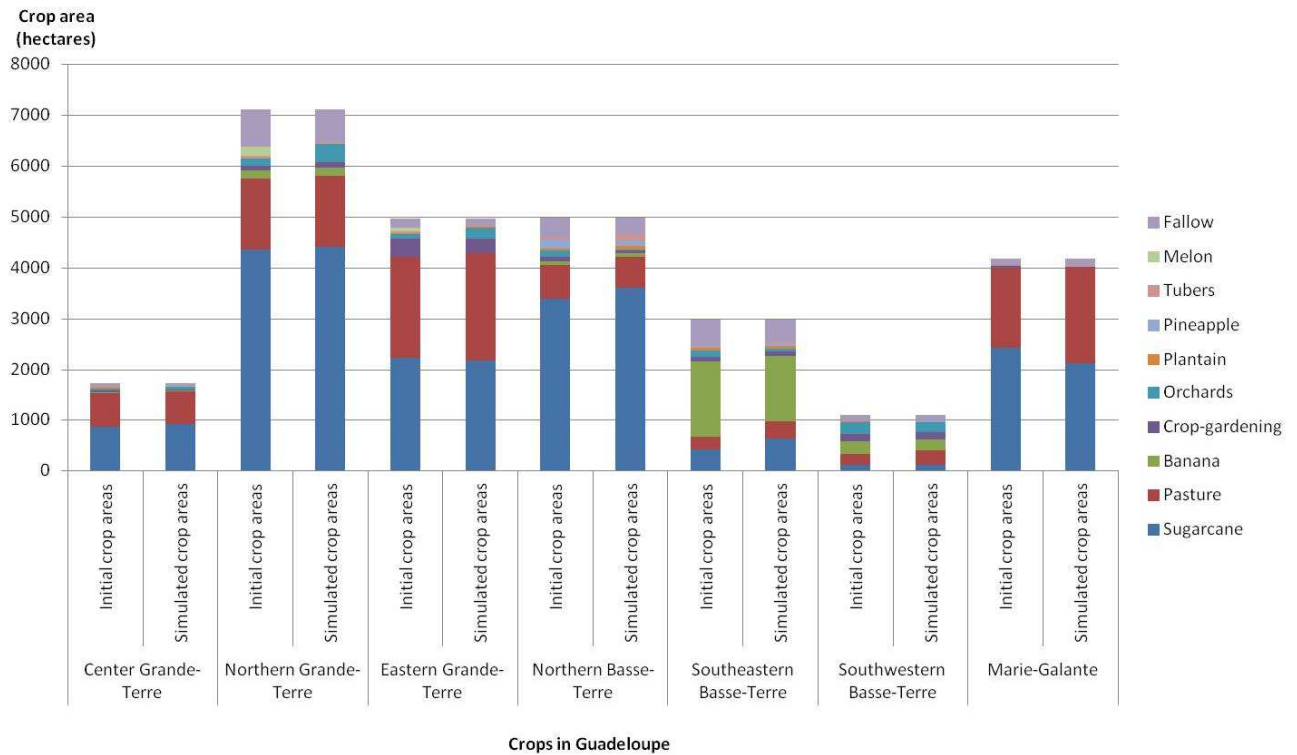
371 Figure 4: Comparison of the regional crop areas between the observed situation and the simulated one
 372 after the calibration step

373

374 We first compared the simulated acreage allocated to different crops under the current policy with
 375 those observed in Guadeloupe in the geographic database. The calibration procedure used in the
 376 modelling framework resulted in a good match for 8 out of 10 agricultural uses over the territory
 377 (Figure 4). Results for melons were not satisfactory with a PAD of 100% because the melon cropping
 378 system was not adopted by farmers because they rent out their land to a company which produces
 379 melon for export and renting out land is not taken into account in the model. However, we show that,
 380 at this scale, the model provides reliable information despite some deviations compared with the initial
 381 state of the system for two minor crops.

382

383 **3.1.2. At the sub-regional scale**



384

385 Figure 5: Comparison of the sub-regional crop areas between the observed situation and the simulated
 386 one after the calibration step

387

388 At the sub-regional scale, a comparison of the initial and simulated acreages reveals the predictive
 389 quality of the model (Figure 5). In Grande-Terre and Marie Galante, sugarcane and pastures were well
 390 simulated with, for instance, PAD values of 5% and 1%, respectively, for the centre of Grande-Terre.
 391 Bananas are well represented in the north with a PAD of 1%. For the east of Grande-Terre, the crop-
 392 gardening level is quite underestimated but acceptable, with a PAD of 20%. In Basse-Terre, the north
 393 is well-simulated for sugarcane, pasture and bananas. In the south-east, only the sugarcane level is
 394 underestimated because of a conflict in the simulation between sugarcane and fallow fields as adopted
 395 within a banana-based system for rotations. In the south-west, the simulation results are good for
 396 orchards, bananas, crop-gardening, sugarcane and fallow fields but less favourable for pasture with
 397 28%. We conclude from these results that the MOSAICA model accurately reproduces the agricultural
 398 landscape characteristics of the sub-regions in Guadeloupe.

Number of farms in types at regional scale Initial \ simulated	Arboriculturists	Banana growers	Specialised cane growers	Diversified cane growers	Diversified	Breeders	Crop gardeners	Mixed cane-growers breeders	Total (initial)	Matches
Arboriculturists	60	0	0	14	37	3	0	7	121	50%
Banana growers	2	159	0	7	15	3	0	19	205	78%
Specialised cane growers	0	0	1473	50	0	53	0	1	1577	93%
Diversified cane growers	14	0	257	665	24	71	0	19	1050	63%
Diversified	17	0	0	73	150	17	11	18	286	52%
Breeders	0	0	0	1	0	1072	0	16	1089	98%
Crop gardeners	0	0	0	0	13	0	141	0	154	92%
Mixed cane-growers breeders	0	1	0	35	1	235	0	582	854	68%
Total (simulated)	93	160	1730	845	240	1454	152	662	5336	81%

399

Table 4: Comparison of the number of types correctly modeled with the calibration procedure

400 3.1.3. At the farm scale

401 Based on the farm type algorithm implemented in MOSAICA at the farm scale, we compared changes
402 in the number of farms in the types in the original geographic database to the simulated one from the
403 calibrated procedure (Table 4). We observed an overall good simulation level at the farm scale with
404 approximately 81% of the farms classified in the right type. Results were good for “breeders”,
405 "specialised cane-growers" and "crop-gardeners", "banana growers" and "mixed cane-growers
406 breeders" showing that these types of farms were correctly classified, while results were average for
407 "diversified cane-growers", "arboriculturists", and "diversified". However, most of the misclassified
408 farms were classified in groups that are really close to their initial type in terms of crop area. For
409 instance, 35% of "arboriculturists" were initially classified in the "diversified" group in this
410 simulation, and the "diversified" group is close to "arboriculturists" in term of acreage. The
411 hypothesised level of risk aversion of farmers initially stated by the research team proved to be
412 appropriate to reproduce the behaviour of farmers in terms of their choice of cropping system after a
413 few iterations. At the farm level, the model provides a good-quality reproduction of current farming
414 systems.

415

416 3.1.4. At the field scale

Areas with homogeneous soil and climate conditions	Areas with a match between the initial and simulated crop (hectares)	Total area (hectares)	Proportion of matched areas
Center Grande-Terre	1296	1740	73%
Eastern Grande-Terre	4034	5007	76%
Marie-Galante	3114	4218	70%
Northern Basse-Terre	3924	5035	76%
Northern Grande-Terre	5636	7201	74%
Southeastern Basse-Terre	1984	2999	56%
Southwestern Basse-Terre	991	1150	74%
Sum	20978	27350	77%

417

418

419

420

421

Areas with homogeneous soil and climate conditions	Number of fields with a match between the initial and simulated crop	Total number of fields	Proportion of matched fields
Center Grande-Terre	924	1540	60%
Eastern Grande-Terre	2574	3911	66%
Marie-Galante	3948	6054	65%
Northern Basse-Terre	2645	4251	62%
Northern Grande-Terre	3729	5269	71%
Southeastern Basse-Terre	1875	3056	61%
Southwestern Basse-Terre	724	976	74%
Sum	16419	25057	66%

422

423 Table 5: Results of calibration compared with the current crop areas and the number of fields

424 The evaluation of the model at the field scale showed that we correctly modelled the crops grown on

425 66% of plots, which represent 77% of the area of the territory (Table 5). This percentage can be

426 considered satisfactory given the number of activities in the model the farmers can choose. This level

427 of precision was homogeneous among 6 out of 7 for the sub regions but was lower for the south-

428 eastern Basse-Terre for which only 56% of areas were correctly modelled. This lower level of

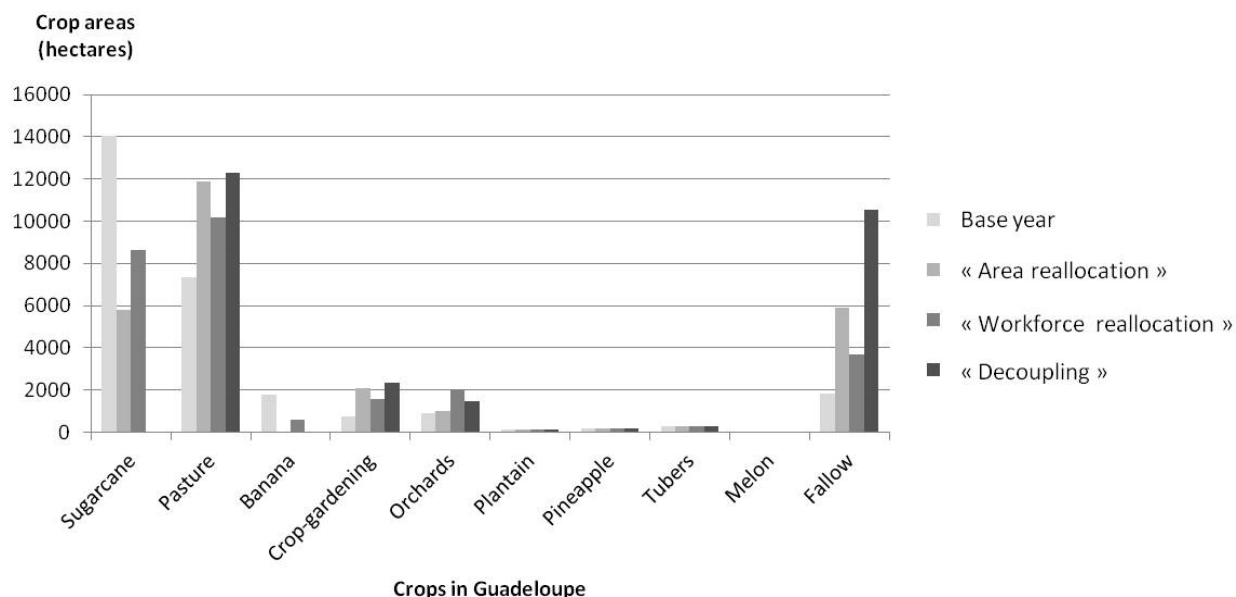
429 precision is related to the rotation of bananas and sugarcane that compose one cropping system but is

430 allocated to several plots.

431

432 3.2. Analysis of the scenarios

433 3.2.1. Cropping patterns changes under scenarios



434

435 Figure 6: Acreages evolution between the base year and the three scenarios at the Guadeloupean scale

436

437 The general trends observed throughout the three scenarios demonstrate a sharp decrease in sugarcane
438 and banana production over the island (Figure 6). By contrast, the areas devoted to pasture and fallow
439 fields increase and the area devoted to crop gardening and orchards increase more progressively, as
440 well.

441 In the "area reallocation" scenario, the sugarcane and banana area greatly decreased from 14 000

442 hectares to less than 6000 and from close to 2000 hectares to 0, respectively. In parallel, the pasture

443 area increased from close to 7000 to 12 000 hectares and fallow field areas increased from 2000 to

444 close to 6000 hectares. Crop-gardening areas doubled from 900 hectares to 2000, and the orchard areas

445 increased slightly from 1000 to 1200.

446 In the "workforce reallocation" sugarcane areas decreased from 14 000 to more than 8000 hectares,

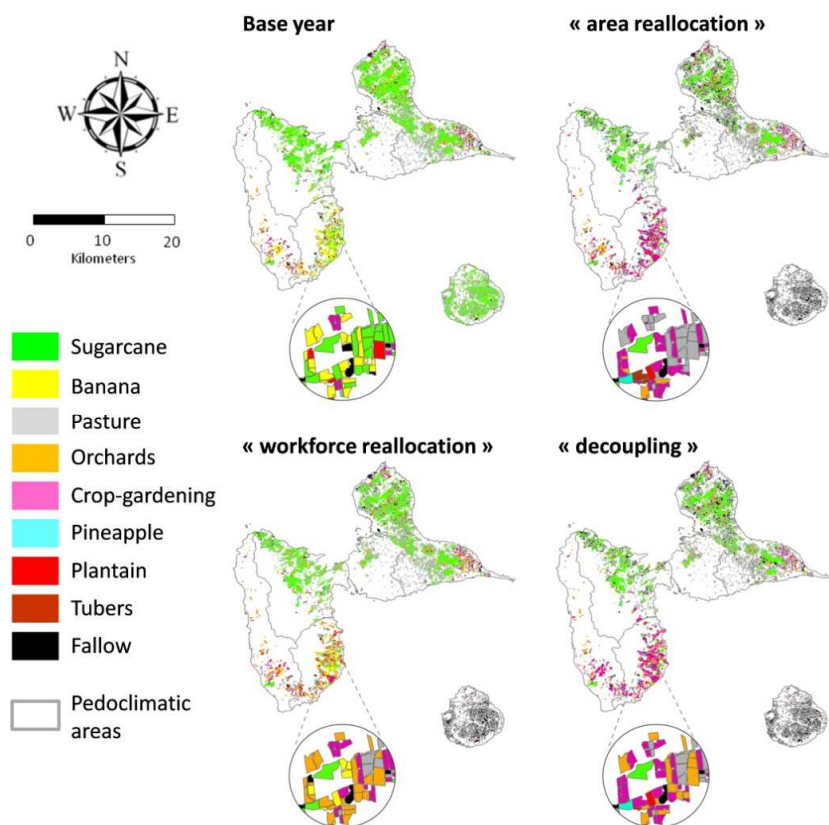
447 and the banana areas in Guadeloupe remained at 600 hectares. The increase in the pasture, fallow

448 fields and crop-gardening areas were weaker. Pasture areas reached 10 000 hectares, fallow field areas

449 increased to 4000 hectares, and crop-gardening areas accounted for 1500 hectares. The orchard area
450 increased from 1000 to 2000 hectares.

451 In the "decoupling" scenario, sugarcane and banana disappeared, and the pasture area remained at the
452 same level as that for the "area reallocation" scenario, at 12 000 hectares. The fallow area greatly
453 increased from an initial 2000 to more than 10 000 hectares. The level reached by crop-gardening in
454 this scenario was the highest, at 2500 hectares, and the orchard areas were close to their level in the
455 "area reallocation" scenario, at 1500 hectares.

456 3.2.2. Change in cropping system organisation at the sub-regional scale

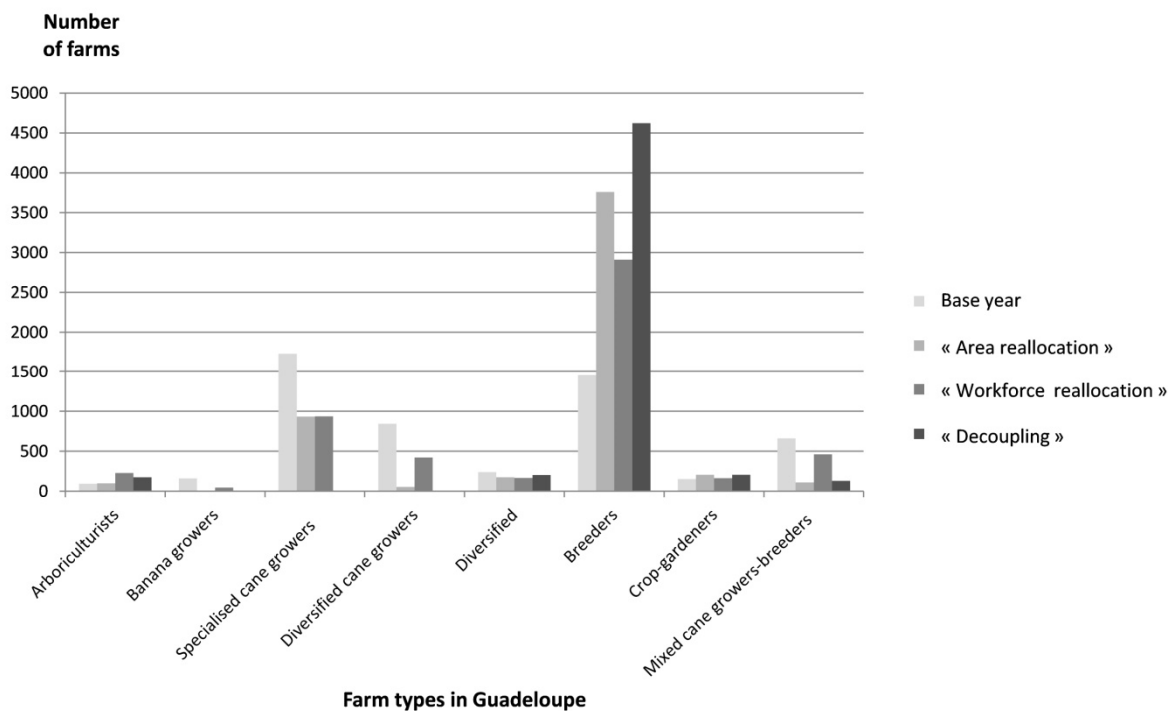


457
458 Figure 7: Cropping systems mosaics from the base year and the three scenarios
459 The new organisation of cropping systems into sub-regions is described in Figure 7.

460 In the three scenarios, the sugarcane in the northern and eastern Grande-Terre and Marie-Galante is
461 largely replaced by pasture areas, especially in the "area reallocation" and "decoupling" scenarios. The
462 northern Basse-Terre follows the same trend. Furthermore, bananas are largely replaced by crop-
463 gardening in the "area reallocation" and "decoupling" scenarios, and less in the "workforce

464 reallocation" scenario. The "area reallocation" and "decoupling" scenarios helped develop orchards
 465 and pasture instead of bananas and sugarcane, and the "workforce reallocation" scenario helped to
 466 maintain the banana area.

467 3.2.3. Farm type changes



468
 469 Figure 8: Farm types evolution between the base year and the three scenarios at the Guadeloupean
 470 scale
 471 The main trends in these scenarios were a decrease in "specialised cane-growers", "banana growers",
 472 "mixed cane-growers breeders" and "diversified cane-growers" and, in parallel, an increase in
 473 "breeders", "arboriculturists" and "crop-gardeners" (Figure 8).

474

475 **3.2.4. Changes in sustainability levels**

Sustainability objectives	Indicators	Base year	"Area reallocation"	"Workforce reallocation"	"Decoupling"
Improving the agricultural added value	Overall farm revenues (M€.yr ⁻¹)	96	138	125	162
	Repartition of the revenue among the farm population	0.65	0.65	0.74	0.71
Increasing the independence from subsidies	Total amount of subsidies (M€.yr ⁻¹)	75	60	62	72
Reaching food-self sufficiency	Ratio of produced carbohydrates over needs	15%	20%	22%	22%
	Ratio of produced proteins over needs	22%	28%	27%	29%
	Ratio of produced fats over needs	9%	13%	19%	16%
Producing local energy from agriculture	Energy potential produced by crops (MW.yr ⁻¹)	33	16	24	0
Contributing to employment	Total number of workers (persons)	3105	2566	2928	2772
Insuring safety of locally produced foodstuff	Area with a potential chlordecone contamination of food crops	1170	2013	1529	1843
Improving the state of biodiversity	Risk for birds in high-value ecological zones	1.0	0.5	0.7	0.1
Enhancing water quality	Ratio of potentially polluted rivers	39%	8%	30%	22%
	Ratio of potentially polluted water abstraction sources	36%	22%	30%	22%
	Ratio of potentially polluted water catchments	30%	12%	20%	11%
	Amount of water needed for irrigation	17.7	14.7	19.6	15.1
Protecting soil quality	Area potentially eroded due to farming practices	33.0	33	32.7	31
Decreasing the contribution to climate change	Overall CO ₂ emissions from farming activities (CO ₂ equivalent)	158	142	149	135
Improving the diversity of agricultural landscapes	Diversity of crops across landscape	3.0	3.1	3.4	2.7

476

477 Table 6: Evolution of the provision of ecosystem services between the base year and the three

478 scenarios developed

479 We examined the values of the indicators that contributed to the sustainable development of cropping

480 system mosaics in the three scenarios (Table 6).

481 In terms of economic sustainability, these three developed scenarios were relevant because they

482 performed better than the base year in terms of economic sustainability, except for the repartition of

483 the revenue among the farm population that was better for the base year. For the economic
484 sustainability, the "area reallocation" scenario performed well with a good level of added agricultural
485 value, at 138M€.yr⁻¹, with the lowest subsidy level of 60M€.yr⁻¹. This increase in added agricultural
486 value is related to the increase in the cultivation of crop-gardening and orchards, and the decrease in
487 the subsidy level is related to the decrease in bananas and sugarcane.

488 For social sustainability, the scenarios performed better in terms of food self-sufficiency, especially
489 scenario 3, with an increase of nearly 50% in food-self-sufficiency for each nutrient. The production of
490 electricity among the scenarios strongly decreased from 33 MW to 0 MW in the "decoupling" scenario
491 because of the reduction in bagasse production from sugarcane in all scenarios. The total need for
492 workers was 3105 people during the base year, and this need decreased in the scenarios to 2566 for
493 "area reallocation". The risk of food crop contamination by chlordecone strongly increased in the "area
494 reallocation" scenario to 2,566 ha and less in the "workforce reallocation" scenario and engaged in
495 "decoupling" to reach 1,529 and 1,843 hectares respectively. This is due to the cultivation of crop-
496 gardening and tubers on chlordecone contaminated soils in the south of Basse-Terre.

497 In focusing on environmental sustainability, the pressure on biodiversity and water resources
498 decreased over the three scenarios. This was especially true for the "area reallocation" scenario for
499 which the pesticide pressure in water abstraction sources, water catchments and rivers was two times
500 less important than the base year with 8% of rivers, 22% of water abstractions sources and 12% of
501 water catchments. The amount of water for irrigation decreased from that in the base year in the "area
502 reallocation" and "decoupling" scenarios by 3 Mm³ and 2 Mm³, respectively. In the "workforce
503 reallocation" scenario, the water irrigation increased by 2 Mm³. The CO₂ emissions decreased in all
504 scenarios from 158 to a minimum of 135 millions of kg of CO₂ equivalents in the "decoupling"
505 scenario. The diversity of crops increased from the base year to the "workforce reallocation" scenario
506 from 3 to 3.4, remaining the same in the "area reallocation" scenario and decreasing in the
507 "decoupling" scenario to 2.7.

508

509 **4. Discussion**

510 The primary strengths of MOSAICA are its abilities (i) to model the impacts of scenarios on the
511 composition and organisation of the cropping system mosaics and (ii) to assess the consequences of
512 these changes for regional sustainability issues with spatially explicit indicators.

513

514 **4.1. Model capabilities for multi-scale analysis**

515 The regional bioeconomic model MOSAICA has the ability to design cropping system mosaics that
516 result from the integration of different information at multiple scales. The model integrates field, farm,
517 sub-regional and regional information, linking it all together. The combination of changes at these
518 different scales modifies the farmer's choice and subsequently the entire cropping systems mosaic. The
519 modelling of farmer cropping system choices and the *in fine* creation of cropping system mosaics
520 resulting from the modification of a set of rules at different spatial scales is innovative for the creation
521 of landscape mosaics. The design of such modelling approaches at regional scale requires a large
522 amount of data and simplification of the diversity of farming contexts, farming and cropping systems
523 in the entire region. In bioeconomic models, this spatial scale chain has rarely been implemented
524 because of the lack of field and farm data. Most studies either link the field scale with the farm scale
525 (Chavez et al., 2014) or the farm scale with the regional scale (Louhichi et al., 2010; van Ittersum et
526 al., 2008), but the field-farm-region chain with individual data has, to our knowledge, never previously
527 been represented in an entire region in a spatially explicit way. This inter-relation of scales can help in
528 design and assessment innovations at multiple scales and measure their impact at the regional scale to
529 improve sustainable development of regions (Dogliotti et al., 2014). This multi-scale modelling is
530 especially important for addressing sustainability issues, such as food security or biodiversity
531 preservation, that require multi-scale, relevant strategies for resolution (Spiertz et al., 2012;
532 Cunningham et al., 2013).

533

534 The gaps revealed in the database should be taken into account while performing the scenario analysis.
535 They are the origins of inconsistencies in the analysis of the scenario impacting cropping system
536 changes (Schaldach and Alcamo, 2006), especially when addressing ecosystem service assessments
537 (Hou et al., 2013).

538

539 **4.2. Spatial representation of the integrated assessment of agricultural systems**

540 This model allows for the *ex ante* assessment of new cropping system mosaics with a set of indicators
541 that provide information on the impacts of the new cropping systems in a spatially explicit way and
542 the trade-offs in the provision of services. For instance, in our case study, the "decoupling" scenario is
543 very good in terms of providing added agricultural value, but the risk of crop contamination from
544 chlordecone is higher because of the development of crop-gardening cropping system in the south-
545 eastern part of Basse-Terre, which is very polluted (Cabidoche et al., 2009). Bioeconomic models have
546 historically been designed and applied to assess the impact of policy changes on economic,
547 environmental and social indicators of agricultural systems, but most of these models were not
548 spatially explicit, and the indicators were mostly calculated at the farm scale in bioeconomic farm
549 models (Janssen and van Ittersum, 2007).

550 The spatially explicit assessment with the model will help decision-making in the implementation of
551 spatial policies. Thus, in the "workforce reallocation" scenario, the amounts of intensive cropping
552 system, crop-gardening and orchard areas are lower than they are in the "decoupling" scenario, but
553 their environmental impacts are generally higher than in the "decoupling" scenario. This finding is the
554 result of intensive cropping systems that are close to environmental areas in the "workforce
555 reallocation" scenario, despite being less prevalent in the territory. The field scale allocation of
556 cropping systems that are linked to a specific spatial location in the territory is appropriate for the
557 ecosystem services provision issue.

558 The model is also able to focus on the farm scale and thus help make decision-makers become aware
559 of the possible impact of policies on farming systems. In Guadeloupe, the test of three exploratory

560 scenarios with changes in the current agricultural policy raises awareness of the great impacts that this
561 type of change could have on the agricultural areas and the farm cropping plan. The use of farm
562 typology is particularly useful for visualising the evolution of farms within the territory from the base
563 year to different situations. This evolution is an indicator of the farmer cropping plan changes within
564 the territory and provides information on the trajectories of change and the inner reorganisation of
565 farms.

566

567 **4.3 Limits of the model in the simulation of scenarios**

568 Farmer's decision processes are simplified in MOSAICA and its representation could be improved
569 with more information on farms and farmers. Farmers' attitudes towards innovation and the roles of
570 skills, training, and investment capacity are not taken into account in the present model but could lead
571 to differentiated responses to scenarios. Moreover, the fixed costs and the transaction costs that can
572 decrease the gross margin of new activities at the farm scale could be included in the study if
573 information on the farm investment is available. The possible market for land and off-farm labour
574 could be added to the analysis to account for the changes in the size of farm and labour over time.
575 Technical coefficients were implemented in an empirical way and do not differ between farm types or
576 between the different biophysical conditions. In our case study, the model incorporates the average
577 technologies and average economic performance that may strongly differ among farms. Moreover, the
578 labour constraint was defined at farm scale, in a second version of the model this constraint could be
579 implemented at regional scale to allow for the exchange of workers between farms.

580 The positive mathematical programming (PMP) approach (Howitt, 1995) or the extended variant of
581 PMP (Kanellopoulos et al., 2010), which are used in bioeconomic models (e.g. the Farming system
582 simulator, see Louhichi et al., 2010), could have been implemented in our model to ensure perfect
583 calibration depending on the ex-post experiments and validation of the model predictions with these
584 two calibrating procedures. The implementation of non-linear cost function could have produced a
585 smoother response to our scenarios. This response would have been more representative of the

586 diversity of farmer's responses to policy change. However, given the satisfactory results achieved with
587 our calibration with risk, we consider it is sufficiently satisfactory to be used. Furthermore, this type
588 of model provides accurate predictions of farmer behaviour (Arriaza et al., 2003; Lin et al., 1974).

589 **4.4. Generic nature of the model**

590 The MOSAICA model we presented in this paper is generic and can be transferred to other regions.
591 The databases of activities in addition to the geographic database are independent from the model as in
592 the Farming System SIMulator (FSSIM) model (Louhichi et al., 2010). Moreover, the calibration
593 procedure can be reused because the typology of farms can be built directly from the geographic
594 database of fields and their use in a given year by following the method of Chopin et al. (2015).
595 Nevertheless, the model requires some modifications before being implemented elsewhere. If new
596 drivers of crop location are known, they can be incorporated in the model equations. A database of
597 fields and farms, as complete as possible, should be available and representative of a clearly-delimited
598 agricultural area to allocate the cropping systems to plots and to perform a spatially explicit
599 assessment of the contribution of the cropping system mosaics to sustainable development. Cropping
600 systems should be well defined in the area based -for instance- on available data or expertise. For the
601 calibration of the model, a hypothesis concerning the risk aversion of farmers should be based on good
602 knowledge of -or expertise on- the farming system in the area concerned to provide a satisfactory
603 outcome for decision aid in regional planning. The indicator database is flexible and allows the
604 switching on and off of indicators based on their relevance for the area under study.

605 **4.5 Possible model developments**

606 Despite being able to provide a possible image of the future from these exploratory predictive
607 scenarios (Borjesön et al., 2006), decision-aid could benefit from further development of the model.
608 For instance, MOSAICA does not reveal the transition from the base year to these possible futures.
609 MOSAICA is static, but could be transformed into a dynamic model by characterising the inter-annual
610 variations in cropping system externalities; for instance, the annual gross margin of perennial cropping
611 systems is generally low in the first years after implementation and increased when full production is

612 reached. This multi-annual characterization of cropping system would make it possible to take into
613 account temporal aspects of the transition of agricultural systems from the present to future states. The
614 bioeconomic model could be linked to other modelling tools that account for market and sector-level
615 changes. These models could simulate increases in farm area or the disappearance of farms due, for
616 instance, to insufficient revenues. Moreover, to allow higher variability in the performance of cropping
617 system at the different locations in a given region, MOSAICA could be coupled to crop models
618 adapted to the different soil and climate conditions, or fed with the results of crop models in order to
619 obtain differentiated performances of the cropping system depending on the local biophysical
620 conditions of the fields in question (Djanibekov et al., 2013). Furthermore, marginally developed
621 livestock production could have been introduced since it could benefit from agricultural policies and
622 then become a more important activity at the farm and regional scale. Adding new activities to the
623 database could be useful to test whether or not these systems would have positive impacts at the
624 regional scale and under which conditions they could be implemented by farmers. These additions
625 could better reproduce possible changes in the cropping system mosaic and hence provide more
626 precise information for decision-makers and stakeholders.

627

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641

642 **Appendix**

643 *If $A_p \leq Amin_a$,* (8)

644 *$X_{a,p} = 0$ for activities "mechanized sugarcane" (A is the field area). No harvest possible under 0.3ha
645 by harvest operator*

646

647 *If $Alt_p \geq Alt max_a$,* (9)

648 *$X_{a,p} = 0$ for activities "mechanized sugarcane" no access above 250 meters*

649

650 *If $Rain_p \leq Rain min_a$ AND If $Irri_p = 0$,* (10)

651 *$X_{a,p} = 0$; Rain min is determined based on crop water needs; Irri_p is the access to irrigation (0: no
652 access/1: access to irrigation due to presence in irrigation schemes);*

653

654 *If $Soil_p = 2$,* (11)

655 *$X_{pineapple,p} = 0$, Soil_p is soil type of field p and 2 is the value attributed to calcic soils for pineapple
656 based activities.*

657

658 *If $Lt_p = 1$,* (12)

659 $X_{pluriannual\ a,p} = 0, 1$ is a value of a land tenure different from properties or land rent. Pluri-annual
660 crop such as banana or orchards cannot be grown on this field.

661

662 If $(\sum_p X_{init_{a,p}}) \leq 10$, (13)

663 $X_{a,p} = 0, 10$ is a subjective size threshold for the mechanization of pineapple cropping system. Material
664 can be amortised only with an important farm size. No lending as been considered her.

665

666 $\sum_p \sum_a (X_{a,p}) \leq \sum_p (X_{init_{a,p}})$ (14)

667 Land ressource constraint at farm scale

668

669 $(\sum_p X_{a,p}) \leq Rot_a * (\sum_p X_{init_{a,p}})$, (15)

670 where X_a is here either pineapple or tubers and Rot value is the return frequency which is 0.33 for
671 pineapple and 0.5 for tubers.

672

673 $(\sum_p X_{ban,p} * Y_{ban}) \leq (\sum_p X_{init_{ban,p}} * Y_{ban})$, (16)

674 where X_{ban} is the area of banana.

675

676 If $IGP_p = 0$, (17)

677 $X_{melon,p} = 0$, IGP_p is the location or no of field p in protected geographic indication area for melon
678 production.

679

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Supplementary materials

908 1°) Details on the indicators:

909 Economic indicators:

- 910 • **The overall farm revenue** is calculated through an aggregation of gross margins for cropping
911 systems.
- 912 • **The repartition of revenue among the farm population** is the Gini indicator, and it
913 measures equity in the repartition of farm revenue (Ceriani and Verme, 2012).
- 914 • **The total amount of subsidies** is the aggregation of every subsidy provided to farmers for
915 agricultural production.

916 Social indicators:

- 917 • **Three ratios of food nutrients produced over needs (proteins, carbohydrates and lipids)**
918 are calculated based on the nutrient contents of each crop, and the needs are calculated for the
919 total population in Guadeloupe and the average person's needs.
- 920 • **The energy potential produced by crops** measures the energy that can be produced from
921 crop or crop residues, primarily bagasse from sugarcane cultivation.
- 922 • **The total number of workers** is the aggregate workforce need from each cropping system.
- 923 • **The area with a potential chlordecone contamination of food crops** measures the area with
924 crop contamination risk from chlordecone, a soil pollutant from former pesticide applications
925 in banana fields; this risk considers the soil type, the crop and the level of pollution (see
926 Clostre et al., 2015).

927 Environmental indicators:

928 Most environmental indicators are spatially explicit.

- 929 • **The risk for birds in high-value ecological zones** is the mean quantity of toxicity in the
930 fields located in ZNIEFF areas (bird protection areas in Guadeloupe) depends on the level of
931 toxicity of pesticides in cropping systems within ZNIEFF areas with the load index (Bechini
932 and Castoldi, 2009).
- 933 • **The ratios of potentially polluted rivers, water abstraction sources and water catchments**
934 are based on the intensity of cropping systems within a buffer area for rivers and within
935 perimeters for water catchments and abstraction sources. It is calculated through an
936 aggregation of the R-pest indicator at the cropping system scale (Tixier et al., 2007).
- 937 • **The amount of water needed for irrigation** is based on crop needs and mean rainfalls in the
938 area on a monthly basis. For each month, the water need is calculated, and all the needs from
939 each field and each period are aggregated for fields located in the irrigation perimeters.
- 940 • **The area potentially eroded due to farming practices** depends on the soil type, the slope
941 and the soil cover by crops.

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- **The overall CO₂ emissions from farming practices** is not spatially explicit and only represents the aggregation of CO₂ emissions from the farm to the region based on the emissions of cropping system and grazing livestock inputs from the cradle to the farm gate.
 - **The diversity of crops across the landscape** is based on the Inverse Simpson's Diversity index, which calculates the diversity of crops in each sub-region and the mean level of diversity at the Guadeloupe scale (Simpson, 1949).

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949 **2°) Details on the current policies:**

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- **POSEI** arrangements are subsidies that account for the geographic and economic handicaps of the Outermost Regions, their remoteness, insularity, small size, topography and climate and their economic dependence on a few products (POSEI France, 2012). POSEI measures are funded under the first pillar of the Common Agricultural Policy, and they fall into two categories, that is, the specific supply arrangement and measures to support local agricultural production.

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- For sugarcane, the POSEI provides a subsidy to the sugar companies and a transportation subsidy to the farmers. The subsidy provided to the industry is 14 M€.yr⁻¹, and this amount is used to increase the sugarcane payment to farmers from 14.22 €·ton⁻¹ to 32.34 €·ton⁻¹ on average with a subsidy of 18.12 €·ton⁻¹ depending on the saccharine richness of the sugarcane in the sub-regions. The other subsidy is used for helping farmers to pay for the sugarcane transport from the farmer's fields to the nearest collective point. This amount depends on the area in which the field is located and varies from 2.75 €·ton⁻¹ in the eastern Grande-Terre, the northern Basse-Terre and Marie-Galante, to 3.23 €·ton⁻¹ in the centre of Grande-Terre, and 4.76 €·ton⁻¹ in other areas.
 - For banana production, the POSEI provides a protection subsidy of 400 €·ton⁻¹ that is based on an historic production quota that was allocated to banana farms. This subsidy is provided at the farm scale, but its amount depends on the banana production of farms compared with the farm historical reference of banana production. An 80% production of the farm's historical reference ensures 100% subsidies, and below 80%, the decrease in production decreases the amount of subsidies proportionally. This subsidy can then be compared with a payment coupled to production.

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- **The rural development program of Guadeloupe (PDRG)** is financed by the European Union and national subsidies that are provided for agri-environmental measures, the replanting of sugarcane, fallowing and production in less favoured areas. These agri-environmental measures are also compensatory measures of the yield reductions that result from applying a set of management practices aimed at protecting the environment. Payments for bananas were approximately 658 €·ha⁻¹ for banana farms when using fallow fields in their rotation to manage the population of nematodes, and 82 €·ha⁻¹ was provided for harvesting the sugarcane without burning it because of the loss of leaves for soil protection. Payments for orchards, crop-gardening, plantains, and pineapples are not provided (PDRG, 2011). The rural development program also provides a subsidy for the replanting of sugarcane fields for the

984 duration of the sugarcane plantation. This amount is 900 €.ha⁻¹ for seven years on average.
985 Compensatory payments for Guadeloupean farms located in mountainous areas are not
986 integrated into the amount of subsidies when currently considering the small number of
987 farmers that received this subsidy, or approximately 50, in 2010.
988

989 • **National subsidies** are provided for sugarcane cultivation as a transition payment coupled to
990 production after the reform of the sugar Common Market Organization in 2007. Its value
991 varies depending on the level of saccharine richness but is on average 23.81 €.ton⁻¹ of
992 sugarcane (CTCS, 2005).
993

994 • Sugarcane farmers are also remunerated for providing **bagasse**, a residue from sugarcane
995 pressing, for electricity production. The amount of this payment is 10 €.ton⁻¹ of sugarcane and
996 is not provided for the farmers in Marie-Galante who use the bagasse is directly in the sugar
997 factory instead of selling it to a power plant, as in Grande-Terre and Basse-Terre.

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