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

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Abstract

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

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

Highlights

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

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

1. Introduction

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

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

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

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

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

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

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

2. Material and methods

2.1. Area of implementation

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

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

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

2.2. Overview of the bioeconomic model MOSAICA

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

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

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

2.3. Model inputs

2.3.1. Building the geographic databases

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

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

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

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

2.3.3. Farm typology

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

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

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

2.4. The model description

2.4.1. Objective function

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

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

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

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

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

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

2.4.2. Constraint equations

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

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

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

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

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

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

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

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

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

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

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

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

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

2.6. Evaluation of the model

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

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

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

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

2.7. Sustainability indicators at the regional scale

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

In our case study, one to three indicators were previously designed by Chopin et al. (submitted) for each sustainability issue (Table 3). None of the economic indicators and few of the social indicators are spatially explicit. They are determined based on the aggregated results of all individual fields at the regional scale (e.g. the agricultural added value is the aggregation of the gross margins at field scale). On the other hand, most environmental indicators account for the location of each cropping system. 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	%
		Ratio of potentially polluted water abstraction sources	%
Enhancing water quality	Ratio of potentially polluted water catchments	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)	%
	Amount of water needed for irrigation	Aggregation of cropping system needs for water based on the quantity of rainfalls and the average crop needs per month	m ³
	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

2.8. Policy scenarios

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

2.8.1. Current agricultural policy in Guadeloupe

Base year	POSEI	National subsidies	PDRG
	Transportation payments for sugarcane: 3.23€ per ton of sugarcane Payments for the adaptation of sugar companies to the common market organisation: 18.12€ per ton of sugarcane POSEI payments for banana under quotas of production: 400€ per ton of banana	Payments for a guaranteed price: 31.23€ per ton of sugarcane	Agri-environmental measures Fallow for banana: 658€ per ha Green harvest of sugarcane: 82€ per ha Replantation payments for sugarcane: 900€ per ha for the duration of the plantation
	48 330 100€ per year	21 200 000€ per year	2 657 028€ per year
« Area reallocation » scenario	Reallocation per ha 1767€ per ha	<i>Statu quo</i>	<i>Statu quo</i>
« Workforce reallocation » scenario	Reallocation per man work unit: 15564 € per person hired	<i>Statu quo</i>	<i>Statu quo</i>
« Decoupling » scenario	Initial amount at farm scale decoupled from crop production		<i>Statu quo</i>

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

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

2.8.2. Expected changes in Guadeloupe's agricultural policy

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

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

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

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

3. Results

3.1. Model calibration

3.1.1. At the regional scale

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

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

3.1.2. At the sub-regional scale

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

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

Number of farms in types at regional scale Initial \ simulated	Arboricul turists	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

3.1.3. At the farm scale

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

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%

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%

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

The evaluation of the model at the field scale showed that we correctly modelled the crops grown on 66% of plots, which represent 77% of the area of the territory (Table 5). This percentage can be considered satisfactory given the number of activities in the model the farmers can choose. This level of precision was homogeneous among 6 out of 7 for the sub regions but was lower for the southeastern Basse-Terre for which only 56% of areas were correctly modelled. This lower level of precision is related to the rotation of bananas and sugarcane that compose one cropping system but is allocated to several plots.

3.2. Analysis of the scenarios

3.2.1. Cropping patterns changes under scenarios

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

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

In the "area reallocation" scenario, the sugarcane and banana area greatly decreased from 14 000 hectares to less than 6000 and from close to 2000 hectares to 0, respectively. In parallel, the pasture area increased from close to 7000 to 12 000 hectares and fallow field areas increased from 2000 to close to 6000 hectares. Crop-gardening areas doubled from 900 hectares to 2000, and the orchard areas increased slightly from 1000 to 1200.

In the "workforce reallocation" sugarcane areas decreased from 14 000 to more than 8000 hectares, and the banana areas in Guadeloupe remained at 600 hectares. The increase in the pasture, fallow fields and crop-gardening areas were weaker. Pasture areas reached 10 000 hectares, fallow field areas

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

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

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

Figure 7: Cropping systems mosaics from the base year and the three scenarios

The new organisation of cropping systems into sub-regions is described in Figure 7.

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

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

3.2.3. Farm type changes

Figure 8: Farm types evolution between the base year and the three scenarios at the Guadeloupean scale

The main trends in these scenarios were a decrease in "specialised cane-growers", "banana growers", "mixed cane-growers breeders" and "diversified cane-growers" and, in parallel, an increase in "breeders", "arboriculturists" and "crop-gardeners" (Figure 8).

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

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

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

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

4. Discussion

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

4.1. Model capabilities for multi-scale analysis

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

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

4.2. Spatial representation of the integrated assessment of agricultural systems

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

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

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

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

4.3 Limits of the model in the simulation of scenarios

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

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

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

4.4. Generic nature of the model

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

4.5 Possible model developments

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

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

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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

References

Acs, S., Berentsen, P., Huirne, R., van Asseldonk, M., 2009. Effect of yield and price risk on conversion from conventional to organic farming. *Australian Journal of Agricultural and Resource Economics* . 53, 393–411. doi: 10.1111/j.1467-8489.2009.00458.x.

Agreste, 2010. Recensement agricole 2010. Premières tendances. N°270. Novembre 2011.
http://agreste.agriculture.gouv.fr/IMG/pdf_D97111A02.pdf. Accessed 21 March 2014.

Andersen, E., Elbersen, B., Godeschalk, F., Verhoog, D., 2007. Farm management indicators and farm typologies as a basis for assessments in a changing policy environment. *Journal of Environmental Management* 82, 353-362. doi:10.1016/j.jenvman.2006.04.021.

Arriaza, M., Gomez-Limon, J.A., 2003. Comparative performance of selected mathematical programming models. *Agricultural Systems* 77, 155-171. doi:10.1016/S0308-521X(02)00107-5.

Aubry, C., Papy, F., Capillon, A., 1998. Modelling decision-making processes for annual crop management. *Agricultural systems*, 56(1), 45-65. doi:10.1016/s0308-521x(97)00034-6.

Bechini, L., Castoldi, N., 2009. On-farm monitoring of economic and environmental performances of cropping systems: Results of a 2-year study at the field scale in northern Italy. *Ecological Indicators* 9, 1096-1113.

702 Belhouchette, H., Louhichi, K., Therond, O., Mouratiadou, I., Wery, J., Ittersum, M.v., Flichman, G.,
703 2011. Assessing the impact of the Nitrate Directive on farming systems using a bio-economic
704 modelling chain. *Agricultural Systems* 104, 135-145. doi:10.1016/j.agry.2010.09.003.

705

706 Bergez, J.-E., Garcia, F., Leenhardt, D., Maton, L., Castelletti, A., Sessa, R.S., 2007. Chapter 7 -
707 Optimising irrigation management at the plot scale to participate at the regional scale water resource
708 management. *Topics on System Analysis and Integrated Water Resources Management*. Elsevier,
709 Oxford, 141-160. doi: 10.1016/B978-008044967-8/50007-5.

710

711 Blazy, J.-M., Ozier-Lafontaine, H., Dore, T., Thomas, A., Wery, J., 2009. A methodological
712 framework that accounts for farm diversity in the prototyping of crop management systems.
713 Application to banana-based systems in Guadeloupe. *Agricultural Systems* 101. 30-41. doi:
714 10.1016/j.agry.2009.02.004.

715

716 Börjeson, L., Höjer, M., Dreborg, K.-H., Ekvall, T., Finnveden, G., 2006. Scenario types and
717 techniques: Towards a user's guide. *Futures* 38, 723-739. doi:10.1016/j.futures.2005.12.002.

718

719 Bureau, J.C., Guyomard, H., Requillart, V., 2001. On inefficiencies in the European sugar regime.
720 *Journal of Policy Modeling* 23, 659-667. doi:10.1016/S0161-8938(01)00080-1.

721

722 Cabidoche, Y-M., Achard, R., Cattani, P., Clermont-Dauphin, C., Massat, F., Sansoulet, J., 2009.
723 Long-term pollution by chlordecone of tropical volcanic soils in the French West Indies: A simple
724 leaching model accounts for current residue. *Environmental Pollution* 157, 1697-1705. doi:
725 10.1016/j.envpol.2008.12.015.

726

727 Cabidoche, Y.M., Lesueur-Jannoyer, M., 2012. Contamination of Harvested Organs in Root Crops
728 Grown on Chlordecone-Polluted Soils. *Pedosphere* 22, 562-571. doi:10.1016/S1002-0160(12)60041-1.

729

730 Ceriani, L., Verme, P., 2012. The origins of the Gini index: extracts from *Variabilità e Mutabilità*
731 (1912) by Corrado Gini. *The Journal of Economic Inequality* 10, 421-443. doi: 10.1007/s10888-011-
732 9188-x.

733

734 Chavez, M.D., Berentsen, P.B.M., Oude Lansink, A.G.J.M., 2014. Analyzing diversification
735 possibilities on specialized tobacco farms in Argentina using a bio-economic farm model. pp. 35-43.
736 doi:10.1016/j.agsy.2014.03.009.

737

738 Chopin, P., Blazy, J.-M., 2013. Assessment of regional variability in crop yields with spatial
739 autocorrelation: Banana farms and policy implications in Martinique. *Agriculture, Ecosystems &*
740 *Environment* 181, 12-21. doi:10.1016/j.agee.2013.09.001.

741

742 Chopin, P., Blazy, J.-M., Doré, T., 2015. A new method to assess farming system evolution at the
743 landscape scale. *Agronomy for Sustainable Development* 35, 325-337. doi: 10.1007/s13593-014-
744 0250-5.

745

746 Chopin, P., Blazy, J.-M., Doré, T., Guindé, L.,. Contribution of agricultural landscapes to the
747 sustainable development of territories: Application to Guadeloupe. Submitted to *European Journal of*
748 *Agronomy*.

749

750 Clostre, F., Letourmy, P., Lesueur-Jannoyer, M., 2015. Organochlorine (chlordecone) uptake by root
751 vegetables. *Chemosphere* 118, 96-102.

752 CTCS (Centre technique Interprofessionnel de la canne à sucre de la Guadeloupe), 2005. Manuel
753 technique de la canne à sucre. <http://www.ctcs-gp.com/>. Accessed 04 October 2013.

754

755 Cunningham, S.A., Attwood, S.J., Bawa, K.S., Benton, T.G., Broadhurst, L.M., Didham, R.K.,
756 McIntyre, S., Perfecto, I., Samways, M.J., Tschardtke, T., Vandermeer, J., Villard, M.-A., Young,
757 A.G., Lindenmayer, D.B., 2013. To close the yield-gap while saving biodiversity will require multiple
758 locally relevant strategies. *Agriculture, Ecosystems & Environment* 173, 20-27.
759 doi:10.1016/j.agee.2013.04.007.

760

761 Colmet-Daage ,F., Bernard, Z., Gautheyrou, J., Gautheyrou, M., Lagache, F., de Crecy, J., Poumaroux,
762 A., Pallud, A., 1969. Carte des sols de la Martinique. BSA, ORSTOM, Pointe-à-Pitre.

763

764 Delmotte, S., Lopez-Ridaaura, S., Barbier, J.-M., Wery, J., 2013. Prospective and participatory
765 integrated assessment of agricultural systems from farm to regional scales: Comparison of three
766 modeling approaches. *Journal of Environmental Management* 129, 493-502.
767 doi:10.1016/j.jenvman.2013.08.001.

768

769 Djanibekov, N., Sommer, R., Djanibekov, U., 2013. Evaluation of effects of cotton policy changes on
770 land and water use in Uzbekistan: Application of a bio-economic farm model at the level of a water
771 users association. *Agricultural Systems* 118, 1-13. doi:10.1016/j.agry.2013.02.004.

772

773 Dogliotti, S., van Ittersum, M.K., Rossing, W.A.H., 2005. A method for exploring sustainable
774 development options at farm scale: a case study for vegetable farms in South Uruguay. *Agricultural*
775 *Systems* 86, 29-51. doi:10.1016/j.agsy.2004.08.002

776

777 Dogliotti, S., Rodriguez, D., Lopez-Ridaaura, S., Tiftonell, P., Rossing, W.A.H., 2014. Designing
778 sustainable agricultural production systems for a changing world: Methods and applications.
779 *Agricultural Systems* 126, 1-2. doi:10.1016/j.agsy.2014.02.003.

780

781 Dury, J., Schaller, N., Garcia, F., Reynaud, A., Bergez, J.E., 2011. Models to support cropping plan
782 and crop rotation decisions. A review. *Agronomy for Sustainable Development* 32, 567-580.
783 doi:10.1007/s13593-011-0037-x.

784

785 ESRI (Environmental Systems Research Institute), 2009. ArcGIS 9.3.1. Environmental Systems
786 Research Institute, Redlands, California, USA.

787

788 European Union, 2012. Règlement (UE) No 1308/2013. Du parlement européen et du conseil du 17
789 décembre 2013 portant organisation commune des marchés des produits agricoles et abrogeant les
790 règlements (CEE) no 922/72, (CEE) no 234/79, (CE) no 1037/2001 et (CE) no 1234/2007 du Conseil.
791 <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2013:347:0671:0854:fr:PDF>. Accessed
792 24 September 2014.

793

794 Flichman, 2002. Economic models for Assessing Sustainability of Agricultural Trade
 795 liberalisation, 2002, SIAP Workshop: Methodological Tools for Assessing the Sustainability Impact of
 796 The EU's Economic Policies, with Applications to Trade Liberalisation Policies, Cepii.

797

798 Flichman, G., 2011. Bio-Economic Models applied to Agricultural Systems. Springer. doi:
 799 10.1007/978-94-007-1902-6.

800 Groot, J.C.J., Rossing, W.A.H., Jellema, A., Stobbelaar, D.J., Renting, H., Van Ittersum, M.K., 2007.
 801 Exploring multi-scale trade-offs between nature conservation, agricultural profits and landscape
 802 quality - A methodology to support discussions on land-use perspectives. Agriculture Ecosystems &
 803 Environment 120, 58-69.

804

805 Harold, A.L., Murray, T., 2002. The Delphi Method, Techniques and Applications, New Jersey
 806 Institute of Technology. <http://is.njit.edu/pubs/delphibook/>. Accessed 24 September 2014.

807

808 Hazell, P.B.R., Norton, R.D., 1986. Mathematical Programming for Economic Analysis in
 809 Agriculture. Macmillan Publishing Company, New York.

810

811 Hou, Y., Burkhard, B., Müller, F., 2013. Uncertainties in landscape analysis and ecosystem service
 812 assessment. Journal of Environmental Management 127, Supplement, S117-S131.
 813 doi:10.1016/j.jenvman.2012.12.002.

814

815 Howitt, R.E., 1995. Positive mathematical programming. American Journal of Agricultural Economics
 816 77, 329–342. doi: 10.2307/1243543.

817

818 Janssen, S., van Ittersum, M.K., 2007. Assessing farm innovations and responses to policies: A review
819 of bio-economic farm models. *Agricultural Systems* 94, 622-636. doi:10.1016/j.agsy.2007.03.001.

820

821 Kanellopoulos, A., Berentsen, P., Heckeleei, T., Van Ittersum, M., Lansink, A.O., 2010. Assessing the
822 Forecasting Performance of a Generic Bio-Economic Farm Model Calibrated With Two Different
823 PMP Variants. *Journal of Agricultural Economics* 61, 274-294.

824

825 Laborte, A.G., Van Ittersum, M.K., Van den Berg, M.M., 2007. Multi-scale analysis of agricultural
826 development: A modelling approach for Ilocos Norte, Philippines. *Agricultural Systems* 94, 862-873.
827 doi:10.1016/j.agsy.2006.11.011.

828

829 Leenhardt, D., Angevin, F., Biarnes, A., Colbach, N., Mignolet, C., 2010. Describing and locating
830 cropping systems on a regional scale. A review. *Agronomy for Sustainable Development* 30, 131-138.
831 doi:10.1051/agro/2009002.

832 Leite, J.G.D.B., Silva, J.V., van Ittersum, M.K., 2014. Integrated assessment of biodiesel policies
833 aimed at family farms in Brazil. *Agricultural Systems*, 64-76. doi:10.1016/j.agsy.2014.08.004.

834

835 Lin, W., Dean, G.W., Moore, C.V., 1974. An empirical test of utility vs. profit maximization in
836 agricultural production. *American Journal of Agricultural Economics* 56, 497-508.

837

838 Louhichi, K., Kanellopoulos, A., Janssen, S., Flichman, G., Blanco, M., Hengsdijk, H., Heckeleei, T.,
839 Berentsen, P., Lansink, A.O., Ittersum, M.V., 2010. FSSIM, a bio-economic farm model for

840 simulating the response of EU farming systems to agricultural and environmental policies. *Agricultural*
841 *Systems* 103, 585-597. doi:10.1016/j.agsy.2010.06.006.

842

843 Mosnier, C., Ridier, A., Képhaliacos, C., Carpy-Goulard, F., 2009. Economic and environmental
844 impact of the CAP mid-term review on arable crop farming in South-western France. *Ecological*
845 *Economics* 68, 1408-1416.

846

847 Multigner, L., Kadhel, P., Rouget, F., Blanchet, P., Cordier, S., 2015. Chlordecone exposure and
848 adverse effects in French West Indies populations. *Environmental Science and Pollution Research*, 1-
849 6.

850

851 PDRG, 2011. Programme de Développement Rural de la Guadeloupe. TOME 1. Données générales.
852 V4-Tome 1-etat des lieux et stratégie-sept2011. 1/76. [http://agriculture.gouv.fr/IMG/](http://agriculture.gouv.fr/IMG/pdf/PDRG_V4_Tome1.pdf)
853 [pdf/PDRG_V4_Tome1.pdf](http://agriculture.gouv.fr/IMG/pdf/PDRG_V4_Tome1.pdf) the 24/06/2014. Accessed 24 December 2014.

854

855 POSEI France, 2012. Programme portant sur les mesures spécifiques dans le domaine de l'agriculture
856 en faveur des régions ultrapériphériques. Tome 1. Chapitre 1 à 3. Version 2012 applicable à partir du
857 01 janvier 2012. Décision d'exécution C(2012) 115 du 20 janvier 2012. [http://www.odeadom.fr/wp-](http://www.odeadom.fr/wp-content/uploads/2012/03/posei-france-2012_vf_toustomes.pdf)
858 [content/uploads/2012/03/posei-france-2012_vf_toustomes.pdf](http://www.odeadom.fr/wp-content/uploads/2012/03/posei-france-2012_vf_toustomes.pdf). Accessed 17 September 2014.

859

860 Ronfort, C., Souchere, V., Martin, P., Sebillotte, C., Castellazzi, M.S., Barbottin, A., Meynard, J.M.,
861 Laignel, B., 2011. Methodology for land use change scenario assessment for runoff impacts: A case
862 study in a north-western European Loess belt region (Pays de Caux, France). *Catena* 86, 36-48. doi:
863 10.1016/j.catena.2011.02.004.

864

865 Rusch, A., Valantin-Morison, M., Roger-Estrade, J., Sarthou, J-P., 2012. Using landscape indicators to
866 predict high pest infestations and successful natural pest control at the regional scale. *Landscape and*
867 *Urban Planning* 105, 62-73. doi: 10.1016/j.landurbplan.2011.11.021.

868

869 Simpson, E.H., 1949. Measurement of diversity. *Nature* 163, 688. doi:10.1038/163688a0.

870

871 Schaldach, R., Alcamo, J., 2006. Coupled simulation of regional land use change and soil carbon
872 sequestration: A case study for the state of Hesse in Germany. *Environmental Modelling & Software*
873 21, 1430-1446. doi:10.1016/j.envsoft.2005.07.005.

874

875 Schipper, R.A., Bouman, B.A.M., Jansen H.G.P, Hengsdijk, H., Nieuwenhuyse, A., 2000. Integrated
876 biophysical and socio-economic analysis of regional land use. In Bouman et al. 2000, 115-44.

877

878 Schipper, R.A., Jansen, H.G.P., Bouman, B.A.M., Hengsdijk, H., Nieuwenhuyse, A., Saenz, F., 2001.
879 Integrated bioeconomic land-use models: an analysis of policy issues in the Atlantic Zone of Costa
880 Rica. In: Lee, D.R., Barrett, C.B. (Eds.), *Tradeoffs or Synergies? Agricultural Intensification,*
881 *Economic Development and the Environment.* CAB International, pp. 267–284.

882

883 Spiertz, H., 2012. Avenues to meet food security. The role of agronomy on solving complexity in food
884 production and resource use. *European Journal of Agronomy* 43, 1-8. doi:10.1016/j.eja.2012.04.004.

885

886 Thenail, C., Joannon, A., Capitaine, M., Souchère, V., Mignolet, C., Schermann, N., Di Pietro, F.,
887 Pons, Y., Gauchere, C., Viaud, V., Baudry, J., 2009. The contribution of crop-rotation organization in
888 farms to crop-mosaic patterning at local landscape scales. *Agriculture, Ecosystems & Environment*
889 131, 207-219. doi:10.1016/j.agee.2009.01.015.

890

891 Tillieut O., Cabidoche Y.-M., 2006. Cartographie de la pollution des sols de Guadeloupe par la
892 chlordécone : Rapport technique. DAAF-SA & INRA-ASTRO, Abymes, 23p.

893

894 Tixier, P., Malézieux, E., Dorel, M., Bockstaller, C., Girardin, P., 2007. Rpest: An indicator linked to a
895 crop model to assess the dynamics of the risk of pesticide water pollution: Application to banana-
896 based cropping systems. *European Journal of Agronomy* 26, 71-81.

897

898 van Ittersum, M.K., Ewert, F., Hecke, T., Wery, J., Alkan Olsson, J., Andersen, E., Bezlepina, I.,
899 Brouwer, F., Donatelli, M., Flichman, G., Olsson, L., Rizzoli, A.E., van der Wal, T., Wien, J.E., Wolf,
900 J., 2008. Integrated assessment of agricultural systems – a component-based framework for the
901 European Union (SEAMLESS). *Agricultural Systems* 96, 150–165. doi:10.1016/j.agsy.2007.07.009.

902

903 Viaggi, D., Raggi, M., Gomez y Paloma, S., Farm-household investment behaviour and the CAP
904 decoupling: Methodological issues in assessing policy impacts. *Journal of Policy Modeling* 33, 127-
905 145.

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Supplementary materials

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1°) Details on the indicators:

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Economic indicators:

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- **The overall farm revenue** is calculated through an aggregation of gross margins for cropping systems.

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- **The repartition of revenue among the farm population** is the Gini indicator, and it measures equity in the repartition of farm revenue (Ceriani and Verme, 2012).

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- **The total amount of subsidies** is the aggregation of every subsidy provided to farmers for agricultural production.

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Social indicators:

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- **Three ratios of food nutrients produced over needs (proteins, carbohydrates and lipids)** are calculated based on the nutrient contents of each crop, and the needs are calculated for the total population in Guadeloupe and the average person's needs.

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- **The energy potential produced by crops** measures the energy that can be produced from crop or crop residues, primarily bagasse from sugarcane cultivation.

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- **The total number of workers** is the aggregate workforce need from each cropping system.

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- **The area with a potential chlordecone contamination of food crops** measures the area with crop contamination risk from chlordecone, a soil pollutant from former pesticide applications in banana fields; this risk considers the soil type, the crop and the level of pollution (see Clostre et al., 2015).

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Environmental indicators:

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Most environmental indicators are spatially explicit.

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- **The risk for birds in high-value ecological zones** is the mean quantity of toxicity in the fields located in ZNIEFF areas (bird protection areas in Guadeloupe) depends on the level of toxicity of pesticides in cropping systems within ZNIEFF areas with the load index (Bechini and Castoldi, 2009).

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- **The ratios of potentially polluted rivers, water abstraction sources and water catchments** are based on the intensity of cropping systems within a buffer area for rivers and within perimeters for water catchments and abstraction sources. It is calculated through an aggregation of the R-pest indicator at the cropping system scale (Tixier et al., 2007).

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- **The amount of water needed for irrigation** is based on crop needs and mean rainfalls in the area on a monthly basis. For each month, the water need is calculated, and all the needs from each field and each period are aggregated for fields located in the irrigation perimeters.

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- **The area potentially eroded due to farming practices** depends on the soil type, the slope 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).

2°) Details on the current policies:

- **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.
 - 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.
- **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

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

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

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