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

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## Abstract

To improve agriculture faced with regional sustainability issues, agricultural landscapes providing a diversity and high level of ecosystem services are necessary. We have developed and tested the MOSAICA-f framework to build innovative multi-functional agricultural landscapes that can consider explicitly: 1) the performance of cropping systems at the field scale, 2) farmers' decision processes on the adoption of cropping systems, and 3) possible scenarios for innovations and policy changes at the regional scale. This framework is based on a scenario approach that encompasses normative, exploratory and optimized scenarios to assess the relevance of combinations of new agricultural policies, changes to the external context (market and regulations) and innovations in cropping systems. The impacts of these changes on sustainability issues are simulated using the regional bioeconomic model MOSAICA for farmers' decision processes regarding the adoption of cropping systems at the field scale throughout a region. Applied in Guadeloupe (French West Indies), the MOSAICA-f framework enabled the design of a scenario increasing agricultural added value, food and energy self-sufficiency, employment and the quality of water bodies and reducing greenhouse gas emissions. This sustainable scenario combines new cropping systems tuned to farm types with a reorientation of subsidies, an increased workforce and banning food crop production on polluted soils. It can be used to understand the potential contribution of agriculture to sustainability issues and to help local decision makers define policies that will account for the spatial diversities of farms and fields in a landscape. Beyond the design of such a win-win scenario, MOSAICA-f has revealed trade-offs in the provision of services by agriculture.

## Highlights:

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

## 1 Introduction

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

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

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

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

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

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

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

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

## 2 The MOSAICA-f framework

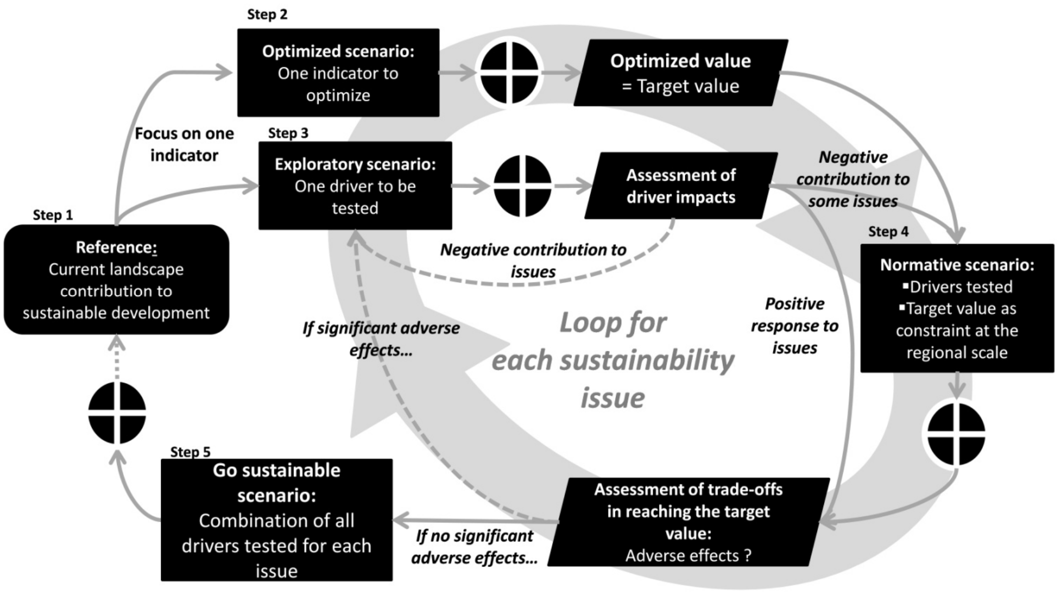

**Figure 1** The MOSAICA-f framework for designing multi-functional landscapes. Steps are represented by a pre modelling (square), a modelling (circle) and a post modelling phase (parallelogram).

The framework presented in the paper aims to use the MOSAICA bioeconomic model in an iterative manner in order to aid the building of multi-functional agricultural landscapes. The model is applied in several steps involving different types of scenarios in order to understand the potential for improvements to the landscape in terms of their contribution to regional issues and to identify relevant drivers for change that will optimise their contribution.

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

| **Variables to optimize** | **Tested drivers (changes in activity, equations and/or the geographical database)** | |
|---|---|---|
| | **No** | **Yes** |
| Optimization of the sum of the farmer's utilities (U*) | **Step 1: Reference mosaic**<br>The reference values of the indicator of interest, $Y_{ref}$, is obtained<br>=> Step 2 | **Step 3: Exploratory scenario**<br>Drivers tested to obtain the value of $Y_{expl}$<br>• If $Y_{expl} < Y_{ref}$ =>Change of driver<br>• if $Y_{expl} > Y_{ref}$ and $Y_{expl} < Y^{*}$ => Step 4<br>• If $Y_{expl} > Y^{*}$ => Use the Go sustainable scenario<br>**Step 5: "Go sustainable" scenario**<br>Drivers from step 4 are combined here |
| Indicator providing information of the response to the sustainability issue of interest (Y) | **Step 2: Optimized scenario**<br>Optimization of Y<br>Target value $Y^{*}$ obtained<br>=> Step 3 | - |
| Optimization of Z with the value of $Y^{*}$ to be reached | - | **Step 4: Normative scenario**<br>If $Y_{norm} = Y^{*}$ AND $W_{norm}, V_{norm} > 0.8 * W_{ref}, V_{ref}$<br>=> Step 5<br>Otherwise => step 3 |

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

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

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

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

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

mosaic (i.e., if Yexpl > Yref and Yexpl ≤ Y* in the case of maximization, the drivers are tested in step 4), while drivers that do not improve the contribution of the mosaic to the sustainability issue are removed from the analysis. If the Yexpl value obtained is higher than the optimized Y* value, the fourth step is skipped and the drivers are tested directly during the fifth step. Under these scenarios, the link between a specific driver and its contribution to the issues is examined, while the combination of several drivers to different sustainability issues is only addressed in the fifth step.

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

## 2.2 Three components for the scenario analysis

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

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

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

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

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

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

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

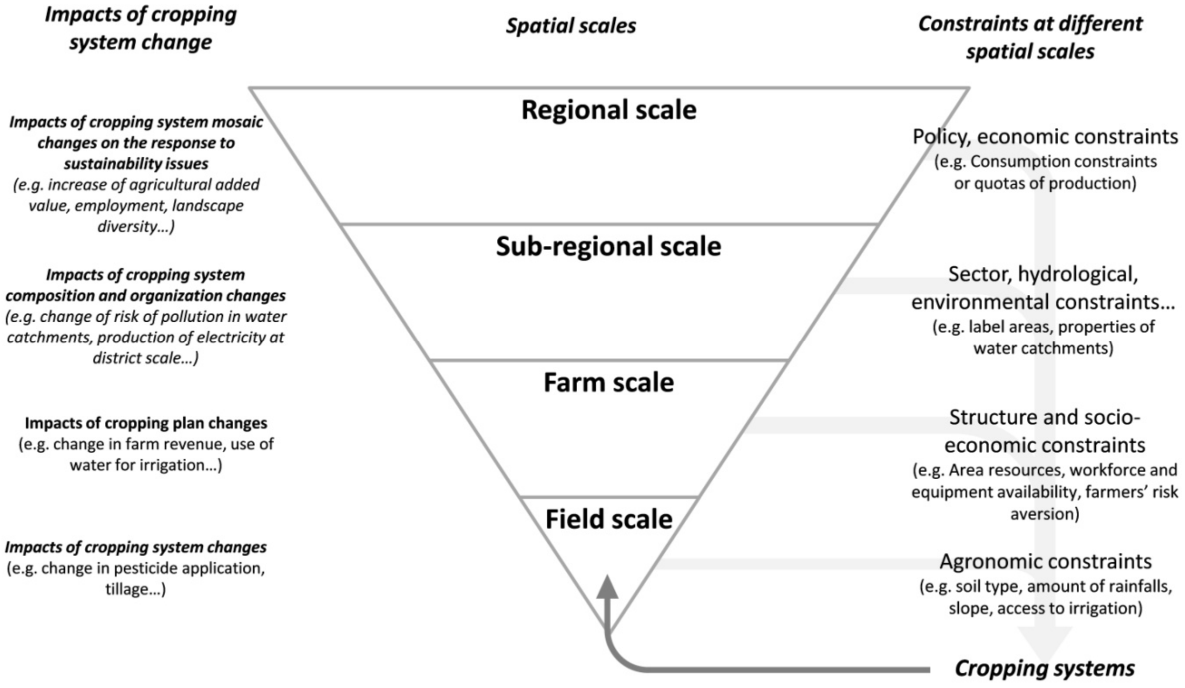

**Figure 2** Inter-relationships of spatial scales in the adoption of cropping systems at the field scale and the impacts of cropping system management at different spatial scales

The scenarios defined during the pre-modelling component were run using the MOSAICA regional bioeconomic model (Chopin *et al*., 2015b). This scenario simulates the decision processes of farmers in terms of adopting activities by linking them with a set of bio-economic parameters (frequently referred to as technical coefficients) that drive these decisions (Janssen and van Ittersum, 2007). MOSAICA can be used for the ex ante assessment of the impacts of policies and technological, agronomic or economic changes, amongst others (Janssen and van Ittersum, 2007; Belhouchette et al., 2011; van Ittersum et al., 2008; Louhichi et al., 2010). Farmers' choices concern the allocation of one or several activities a, that represent cropping systems, to field p. The simulation of farmers' choices is achieved by optimizing the sum of the farmers' utilities U (Equation 1) or by optimizing other variables in the agricultural system. The model variable to be optimized is calculated within the objective function.

$$MAX\ U = \sum_F \ ( \sum_P \sum_{\mathrm{a}} \big[ X_{a,p} \ ( \bar{m}_a - \ \phi_{\mathrm{F}} \ (\mathrm{Z}_{\mathrm{a}}^{+} + \mathrm{Z}_{\mathrm{a}}^{-}) \big] \qquad (1)$$

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

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

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

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

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

Under optimized scenarios, the objective function in Equation 1 is replaced by the target indicator, e.g. the production of energy for the sustainability issue “improving energy self-sufficiency”. The cropping system mosaics derived from an optimized scenario are obtained by maximization or minimization (depending on the desired direction of change) of the value of one indicator related to the sustainability issues (Table 1). The only modification of the model structure is replacement of the sum of the farmers' utilities in the objective function by the indicator to be optimized. The field characteristics, activities and constraint equations of the model are not modified in this type of scenario.

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

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

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

The contributions of cropping system mosaics to the sustainable development of a region were assessed using a set of indicators at the regional scale and calculated during the post-modelling component of the framework. Firstly, sustainability issues were selected from a review of the literature in the area of study. Secondly, interviews were carried out with decision-makers. In our case study, 13 regional decision-makers completed and validated the list of issues by means of a web-based survey. Thirdly, based on the sustainability issues identified at the regional scale, several indicators were used to assess the contribution of cropping system mosaics to these issues. These indicators could either be reused from previously published work, could be scale changed from one given scale to another, or could be newly designed when the issues highlighted are locally contextualized. For instance, some papers provide a calculation of indicators at the landscape scale (Gerdessen and Pascucci (2013); Walz (2015)) that can be reused to assess the consequences of agricultural landscape changes (Sepp and Bastian, 2007). Many indicators are available at the cropping system scale (Sadok et al., 2008; Carof et al., 2013) and may change with a given procedure, such as aggregation procedures (Ewert et al., 2011). Others are not available because some issues are specific to our study and need to be built using existing knowledge. This was the case in our study with respect to the "decrease food contamination due to chlordecone in soils" issue which has never been assessed using indicators. We therefore had to build an indicator based on existing knowledge relative to the contamination process of food crops by chlordecone pesticides.

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

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

### 3.1 Characteristics of the study area

The MOSAICA framework was tested in Guadeloupe, an island located in the Caribbean. This territory presents suitable conditions for implementing the framework for several reasons. First, due to its insularity, flows of agricultural products are recorded at both entrance to and exit from the territory (Agreste, 2011; INSEE, 2012). Second, Guadeloupe has to deal with many local issues that limit the economic, environmental and social sustainability of the territory and may be linked to agriculture. These issues include low food and energy self-sufficiency, a high level of unemployment and a risk of pollution of water resources by pesticides (rivers and drinking-water abstractions) used for local consumption (PDRG, 2011). Another challenge is to “decrease food contamination due to chlordecone in soils”. Chlordecone is a remnant pesticide that was used between 1965 and 1993 on 15% of cultivated land in Guadeloupe (Tillieut and Cabidoche, 2006). The regular consumption of food crops grown on these polluted soils can provoke severe health problems such as prostate cancer (Multigner et al., 2010). Third, Guadeloupe is a small territory that covers 1600 km² and includes a significant agricultural area of 31,300 hectares. Fourth, geographical data and statistical information on fields and farms in Guadeloupe, and knowledge regarding cropping system performances and farm functions, are available. This information describes the population of farmers and their activities. Finally, the region is heterogeneous, with rainy mountainous areas on volcanic soils and flat lands on dry calcic soils, which is of interest when testing the ability of the framework to account for biophysical and socio-economic variability.

### 3.2 Adaptation of the MOSAICA model in Guadeloupe

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

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

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

- We described 36 activities covering the eight main crops in Guadeloupe: sugar cane, banana, pasture, orchards, pineapple, plantain, crop-gardening and tubers, with different management strategies.
- Constraint equations were implemented at different spatial scales to constrain the adoption of activities allocated at the field scale. For instance, we implemented a set of equations linking the cropping systems to slope, field area, soil type and land tenure at the field scale. At the farm scale, farm size, agronomic rules for crop rotations, production quotas and workforce resources were used as the primary constraints for the adoption of cropping systems. At the sub-regional scale, environmentally protected zones and geographically protected indications constrain the adoption of cropping systems. At the regional scale, we defined the maximum thresholds for limiting the quantities of crops produced (production quotas or overall local consumption from local production and importation).
- The farm typology used was described by Chopin et al. (2015a), in which eight types of farmers (orchard growers, banana growers, breeders, market gardeners, diversified cane-growers, diversified, mixed, specialized cane-growers) are defined using a classification algorithm that allocates each farm to one of the types after new cropping system mosaics are produced by simulation.
- The model was calibrated in Guadeloupe by allocating a risk aversion coefficient to each farm depending on its type under our farm typology. The model was considered to be valid because of the crop areas predicted by the reference mosaic, and because the areas calibrated at the regional, sub-regional, farm and field scales were similar (Chopin et al., 2015b).

|  |  | Sustainability goals to be reached |  |  |  |  |  |  | Drivers tested & their combinations |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Targeted objectives |  | Increasing food self-sufficiency | Increasing energy self-sufficiency | Decreasing the crop contamination by chlordecone | Decreasing the risk of pollution of water resources | Improving the agricultural added value | Increasing employment | Reducing $CO_2$ emissions | Quotas<br>↘of market-gardening variability<br>↗workforce availability | Energy cane activity for electricity production (45€.ton$^{-1}$)<br>Energy cane yield 25% higher than sugarcane<br>End of subsidies for sugarcane | Cultivation of pasture, market-gardening and tubers forbidden on potentially polluted soils | New market-gardening cropping systems<br>Taxes of 500€ per pesticide use<br>Trade payments for organic market-gardening (1000€.ton$^{-1}$) | Decoupling of subsidies from agricultural production |
| Indicators | Scenario type | Agricultural added value of local foodstuff (M€.yr$^{-1}$) | Potential production of electricity (MW) | Area of food products potentially contaminated (ha) | Mean pollution of water resources (score) | Total agricultural added value (M€.yr$^{-1}$) | Workforce needs (persons. yr$^{-1}$) | Quantity of $CO_2$ emissions (kT $CO_2$.yr$^{-1}$) |  |  |  |  |  |
|  | Initial | 45 | 33 | 592 | 4.5 | 96 | 2905 | 157 | 0 | 0 | 0 | 0 | 0 |
| Increasing food self-sufficiency | Optimized | 104* | 0 | 1115 | 2.7 | 106 | 3005 | 143 | 0 | 0 | 0 | 0 | 0 |
|  | Exploratory | 165 | 15 | 1601 | 3.3 | 173 | 3856 | 184 | **1** | 0 | 0 | 0 | 0 |
|  | Normative | - | - | - | - | - | - | - | **-** | - | - | - | - |
| Increasing energy self-sufficiency | Optimized | 6 | 56* | 246 | 4.3 | 57 | 372 | 44 | 0 | 0 | 0 | 0 | 0 |
|  | Exploratory | 47 | 52 | 511 | 4.5 | 85 | 2904 | 172 | 0 | **1** | 0 | 0 | 0 |
|  | Normative | 46 | 56° | 456 | 4.8 | 85 | 2884 | 165 | 0 | **1** | 0 | 0 | 0 |
| Decreasing the crop contamination by chlordecone | Optimized | 22 | 3 | 0* | 1.9 | 29 | 747 | 5 | 0 | 0 | 0 | 0 | 0 |
|  | Exploratory | 44 | 34 | 0 | 4.9 | 97 | 2901 | 152 | 0 | 0 | **1** | 0 | 0 |
|  | Normative | - | - | - | - | - | - | - | - | - | **-** | - | - |
| Decreasing the risk of pollution in water resources | Optimized | 19 | 2 | 552 | 1* | 25 | 652 | 11 | 0 | 0 | 0 | 0 | 0 |
|  | Exploratory | 45 | 26 | 1200 | 3.4 | 71 | 2783 | 183 | 0 | 0 | 0 | **1** | 0 |
|  | Normative | 90 | 26 | 1017 | 1° | 107 | 2902 | 141 | 0 | 0 | 0 | **1** | 0 |
| Improving the agricultural added value | Optimized | 94 | 45 | 310 | 4.7 | 143* | 2997 | 58 | 0 | 0 | 0 | 0 | 0 |
|  | Exploratory | 90 | 0 | 965 | 2.9 | 162 | 2772 | 135 | 0 | 0 | 0 | 0 | **1** |
|  | Normative | - | - | - | - | - | - | - | - | - | - | - | **-** |
| Go sustainable scenario | Exploratory | **120** | **35** | **0** | **4** | **206** | **3866** | **150** | **1** | **1** | **1** | **1** | **1** |

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

### 3.3 Step 1: Diagnosis of the reference contributions of agriculture to sustainable development

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

### 3.4 Step 2: Optimized scenarios

Optimizing the current situation regarding the added value of local foodstuffs produced by agriculture (food self-sufficiency) resulted in a target value of 104 millions € per year. This value was used as a target value. Under the second optimized scenario for energy self-sufficiency, we optimized electricity production and obtained a target value of 56 MW.yr-1. This scenario also reduced the number of employees required for crop management from 2905 to 372 persons. The risk of crop contamination by chlordecone reached a negligible value when local foodstuffs decreased from 45 to 6 million per year and employment decreased from 2902 to 747 persons. The risk of pollution of water resources was high in the diagnosis of the reference situation but decreased from 4.5 to 1 unit of the I-PHY indicator. However, major reductions in the achievements of other sustainability goals, such as employment, the agricultural added value of local foodstuffs and the potential production of electricity, were observed, with decreases from 2905 to 652 persons, 45 to 19 millions € per year and 33 MW.yr-1 to 2 MW.yr-1, respectively. The overall agricultural added value increased from its reference level of 96 to 143 millions € per year, and most sustainability issues improved, except for the risk of pollution of water resources, which increased from 4.5 to 4.7 units of the I-PHY indicator. These new optimized values were used as target values under the normative approach (step 4).

### 3.5 Step 3: Exploratory scenarios

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

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

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

2. The second exploratory scenario was a combination of the introduction of energy cane for electricity production with a price of 45 €.ton-1, a 25% increase in sugar cane yield potential, and the cessation of subsidies supporting sugar cane cultivation to increase the production of biomass for electricity production. These changes increased electricity production from 33 MW.yr-1 in the reference mosaic to 52 MW.yr-1 under the exploratory scenario, which is below the target value of 56 MW.yr-1. A normative scenario was therefore necessary in step 4 to understand the possible effects of reaching the target value on the other sustainability goals.
3. The third exploratory scenario consisted of banning vegetable, pasture and tuber cultivation on soils potentially contaminated by chlordecone in order to decrease the risk of crop contamination. This ban was spatially targeted on the 3708 of the 25,057 fields in the region where the risk of soil contamination by chlordecone is significant. This ban was effective because the areas with potential risks of contamination of foodstuffs dropped from 592 ha in the reference cropping system mosaic to zero under the exploratory scenario. Banning market gardening and tuber production in highly chlordecone-contaminated zones was an efficient strategy for completely reducing the risks of crop contamination by chlordecone while maintaining the values of the others objectives near the values achieved in the reference state.
4. The fourth exploratory scenario consisted in introducing new organic cropping systems to decrease the risk of pollution of water resources by pesticides. The technical coefficients of these activities were defined using expert knowledge. The

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

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

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

### 3.6 Step 4: Normative scenarios

Normative scenarios were tested in step 4 to assess the potential of the mosaic to attain the target values for "increasing energy self-sufficiency" and "decreasing the risk of pesticide pollution of water resources" without significantly reducing the contributions of the cropping system mosaic to other sustainability domains.

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

Regarding the risk of pollution of water resources, the normative scenario successfully allowed the crop mosaic to reach the target value of 1, which corresponds to a very low risk of this pollution. The agricultural added value of local food crops increased from 45 to 90 millions € per year, while the overall agricultural added value increased from 96 to 107 millions € per year. CO2 emissions decreased from 157 to 141 kt equivalent CO2.yr-1. In parallel, the area of food products that was potentially contaminated due to chlordecone in soils increased from 552 ha to 1017 ha, and potential electricity production fell from 33 to 26 MW.yr-1.

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

All of the drivers tested under the exploratory scenarios helped to reach or exceed the target values fixed by the optimized scenarios. When the drivers did not reach these values, we noticed that reaching them under the normative scenarios had no significant negative side effects. Next, these drivers were combined in step 5 under a "Go sustainable” scenario, which reflects optimization of the overall farmers' utilities for the selected political, agronomic or external drivers of change.

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

3.8.1 Improvements in the contributions of agriculture to sustainable development

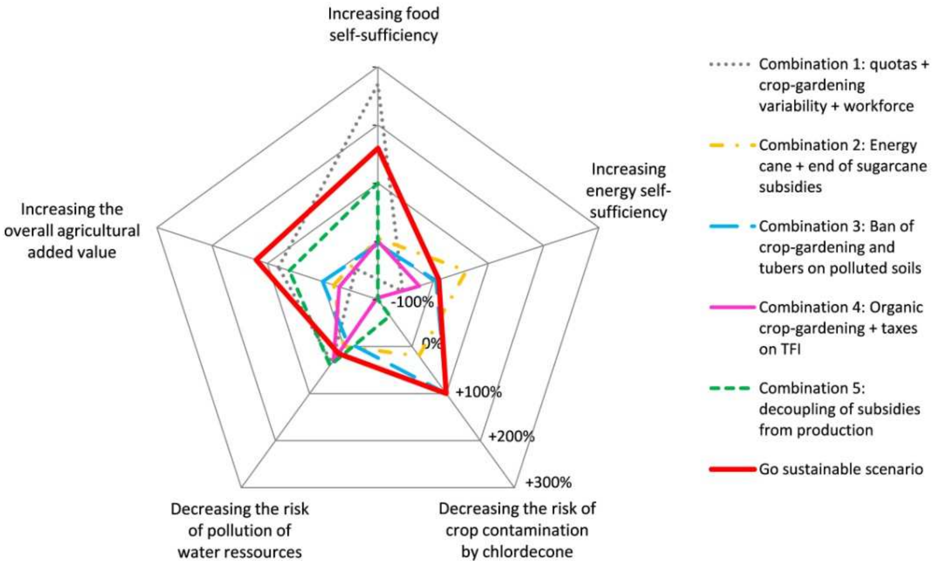

**Figure 3** Evolution of the contributions of each mosaic from exploratory scenarios compared to the initial values from the current cropping systems mosaic assessed as deviations from the initial values. Positive deviational values are an improvement of the generated mosaic to respond to sustainability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

This exploratory scenario revealed major improvements due to the contributions of cropping system mosaics to all sustainability issues in the analysis when compared to the reference situation (Table 2 and Figure 3). The agricultural added value of local production increased from 45 to 120 millions € per year, electricity production increased from 33 to 35 MW.yr-1, the area at risk of crop contamination decreased from 592 to 0 ha, the risk of pollution of water resources decreased from 4.5 to 4, the total agricultural added value increased from 96 to 206 millions € per year, the provision of employment increased from 2905 to 3866 persons and the CO2 emissions from agriculture decreased from 157 to 150 Kton-1 of CO2 equivalent.yr-1. The impacts were therefore very positive with respect to all sustainability issues, even if the risk of pollution of water resources remained significant under the “Go sustainable” scenario.

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

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

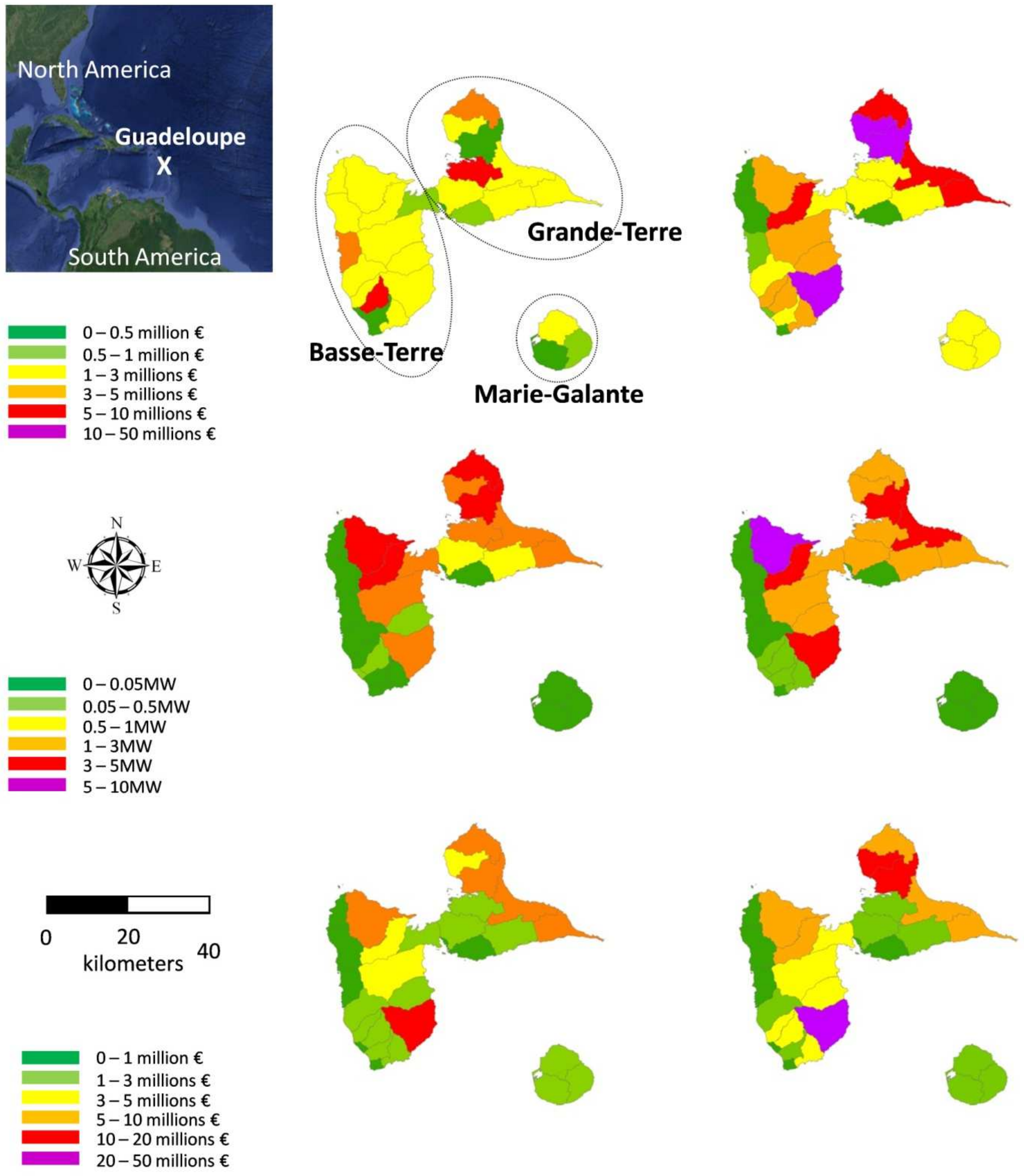

**Figure 4** Comparison of the evolution of the contributions of cropping system mosaics to the increasing added value of agricultural from local food stuff (top) to the contributions to electricity production (middle) and the production of added agricultural value (bottom) between the current mosaic (on the left) and the "Go sustainable" scenario (on the right).

The contributions of the different cropping systems to sustainability issues can also be analysed spatially. We illustrate this spatial analysis in Figure 4, which shows the changes in the spatial variations of the contributions of sub-regions to food and energy self-sufficiency and the increases in overall agricultural added value and agricultural added value from local foodstuffs. Using the same method, the spatial variability of the contributions of cropping system mosaics to local issues is displayed at the sub-regional and field scales in order to analyse reductions in risk of pollution of water resources and in the risk of food contamination (see Supplementary Materials – Figure A).

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

As for decreasing the risk of pollution of water resources, we observed an evolution of the effects of pesticide application in rivers and drinking-water abstractions (Supplementary materials). In the reference cropping system mosaic, most rivers in south-western Basse-Terre are potentially polluted by the pesticides used for banana cultivation and intensive market crop-gardening/orchard production. The reduction in the risk of pollution of water resources in the scenario in southern Basse-Terre was important when banana and market crop-gardening were replaced by less intensive cropping systems. The targeted reduction in the risk of crop contamination by chlordecone was attained, with all the area potentially contaminating crops in southern Basse-Terre being transformed into an area free of risk of contamination. This was due to the change from pasture in this zone to non-contaminating crop-gardening, including for instance tomatoes and cauliflowers (and not cucurbitaceae that are highly contaminated by chlordecone) or plantain (Cabidoche and Lesueur-Jannoyer, 2012).

### 3.9 Analysis of modifications to the agricultural system under the "Go sustainable" scenario

3.9.1 Cropping system changes

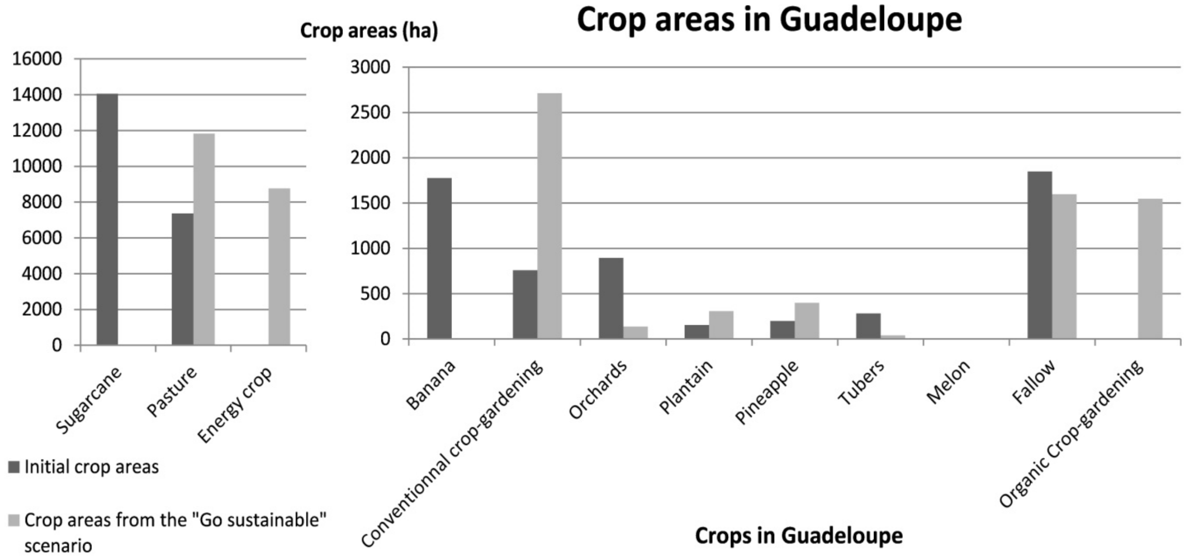

**Figure 5** Evolution of the crop areas at the regional scale between the initial situation and the cropping system mosaics obtained in the "Go sustainable" scenario

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

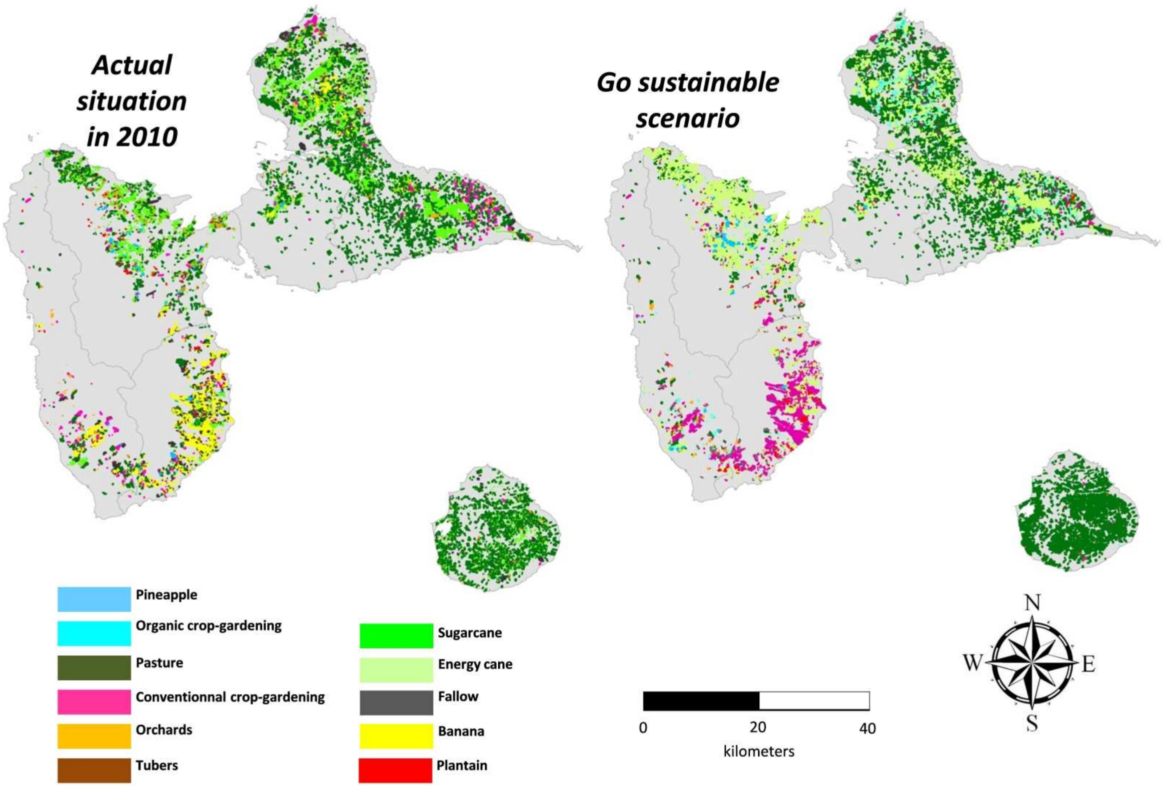

**Figure 6** Evolution of the crop arrangement in Guadeloupe at the regional scale between the initial situation and the cropping system mosaics from the "Go sustainable" scenario

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

### 3.9.2 Farming systems changes

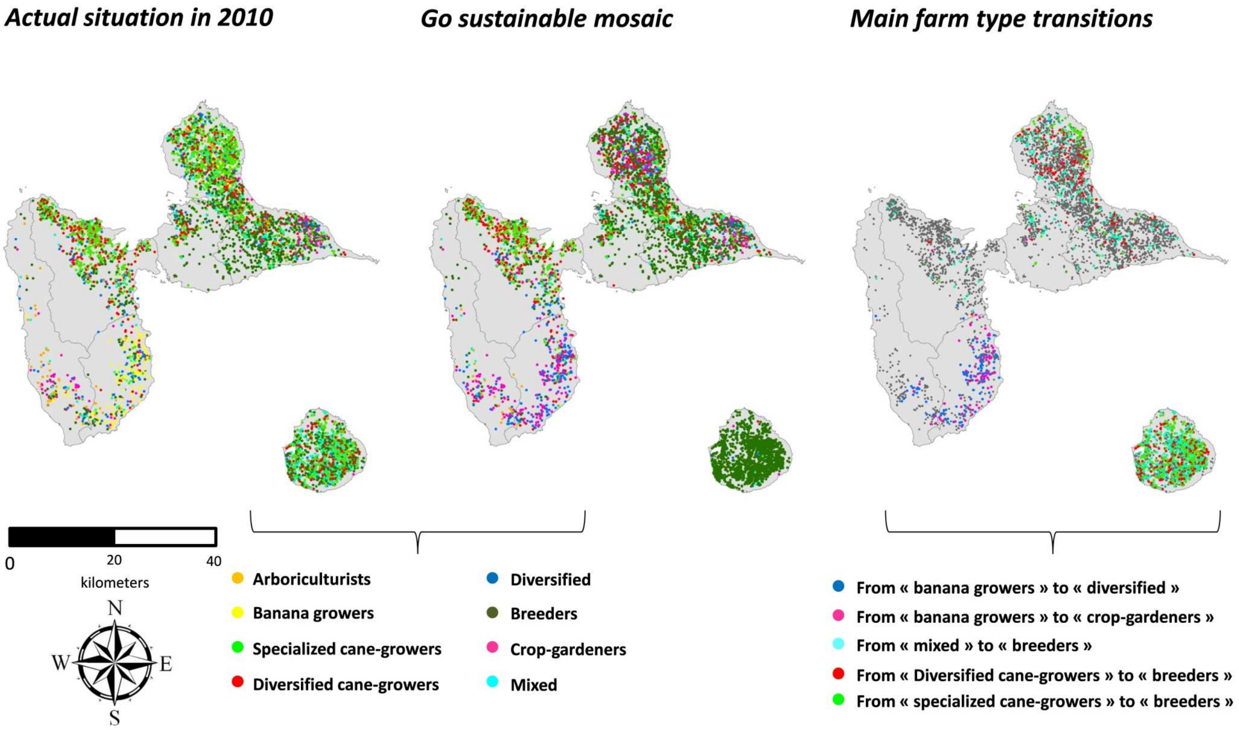

**Figure 7** Evolution of the farm types in Guadeloupe at the regional scale between the initial situation and the cropping system mosaics from the "Go sustainable" scenario

The changes in farm types are shown in Figure 7, and the trajectories of change are shown in Table 3 (see Supplementary materials – Figure B). The main trend was a change from mixed and specialized cane-growers towards livestock breeders. This was especially true in the Marie-Galante island, where under this scenario there is no industry for the production of electricity with energy cane (See Figure 7). However, a small proportion of cane-growers changed to crop-gardeners and to diversified cane-growers type, especially in northern and eastern Grande-Terre.

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

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

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

## 4 Discussion

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

The MOSAICA-f framework can help to parameterize a multi-functional scenario to improve the contributions of agricultural systems at a regional level to several sustainability issues. To achieve this and attain one or several goals, the framework can design scenarios made up of changes to drivers that can optimally modify the agricultural landscapes. Most current scenario analyses only compare business-as-usual scenarios with highly contrasted exploratory scenarios (Kok et al., 2011; Milestad et al., 2014; Vervoort et al., 2014; Gutzler et al., 2015). The set of scenarios produced by these approaches are useful in that they can provide decision-makers with contrasting views regarding the development potentials of the system being modelled (Herrero et al., 2014). However, in the past, we lacked a modelling framework for the iterative design of a multi-functional scenario, achieved through the simultaneous modification of several drivers of change. We propose such a framework based on the development of multi-functional scenarios and achieved by combining exploratory, normative and optimized scenarios across our 5-step method. The exploratory approach used (step 3) after the optimized approach (step 2) mimics the backward approach used in scenario analysis (van Vliet et al., 2012; Borjeson et al., 2006, Quist et al., 2011; Kok et al., 2011) to show how visions of the future and goals that are generated under an optimized scenario could be met (Ramos, 2010). Normative scenarios (step 4) indicate whether the agricultural systems can or cannot achieve these regional goals, and exploratory scenarios are helpful when selecting a set of drivers to meet these goals. For each goal, the targets defined with the optimized scenarios can provide information on the structural gap between the reference cropping system mosaic and the optimal cropping system mosaic for a given sustainability issue (Acosta-Alba et al., 2012; Bryan et al., 2011). Targets are often thresholds that must be attained and their definition is based on expert knowledge when this is available. In our test case, targets were not available for each domain; thus, the optimized scenario was used to provide information regarding potential development of the reference landscape mosaic. This combination of scenarios is possible at the regional scale because the MOSAICA model allows for the optimisation of indicators and the change of constraints at the regional scale. This is not possible using regional approaches where models are run at the farm scale and the results are then up-scaled to the regional level.

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

### 4.2 Spatially explicit multi-scale analysis

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

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

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

### 4.3 Framework implementation with decision-makers

The MOSAICA-f framework could help decision makers by providing knowledge on drivers towards a better contribution to the sustainable development of a region. However, the MOSAICA framework requires a well-adapted interaction between modellers and stakeholders, including decision-makers, to fulfil these sustainability objectives. Participatory modelling with optimization tools requires particular attention because parameterization of the different scenarios within the model, and simulation, require large amounts of time (Delmotte et al., 2016). Because of this time requirement, decision-makers and modellers need to manage the framework together. Nevertheless the scientific and modelling skills required to ensure appropriate use of the MOSAICA model for scenario simulation implies that both the modelling component and the overall 5-step approach are managed by a multidisciplinary group of scientists. This group should i) have wide-ranging knowledge of cropping system performance, farm function and impact assessment and ii) have the programming skills required to modify the MOSAICA model for each type of scenario. Decision-makers need to participate actively in scenario design and the diagnosis and definition of the issues they want to address (Walz et al., 2007). Co-designing or co-selecting sustainability issues and/or indicators for the contribution of agriculture to sustainable development (Mascarenhas et al., 2015), while considering the variables used and produced by the model; are also important to successful participatory approaches (Therond et al., 2009). Meetings with decision-makers should be organized by the modelling team and local experts in order to exchange possible drivers of local agriculture changes so as to target relevant drivers of changes to farming systems. A range of values to be tested for each driver needs to be defined. The modellers should then run the simulation of the different scenarios and present their results to decision-makers. Feedback from decision-makers should integrate the new drivers that emerged from group thinking (e.g. brainstorming) with the range of values to be tested. This loop between decision-makers and modellers could operate continuously as the model integrates new sustainability issues (e.g., crop diseases) and indicators with a broader diversity of cropping systems or the addition of new fields within the field characteristics database.

An analysis of the sensitivity of model outputs to model inputs or the drivers tested under the exploratory scenarios would also be important prerequisites for stakeholder discussions on the scenarios presented in this paper. Sensitivity analysis could be used in two ways: i) to assess the impacts of input variable uncertainty on the framework outputs, and ii) to refine the analysis of a given scenario by assessing the impacts of driver values on scenario outcomes. The former specifically targets the uncertainty in the model inputs from calibration of the model, such as the technical coefficients that define cropping systems. The outcomes of this use regarding the uncertainty of indicator values must be discussed with decision makers in order to determine whether it can fit into their decision process or to convince them to invest in data acquisition and/or model development so as to reduce uncertainty. The latter use would focus on how, and to what extent, a particular driver can help to attain a target value and improve the contribution of agriculture to sustainable development. Different driver values should be tested step by step to identify which has the best potential effect in terms of multi-functionality in the post-modelling components. The Morris method could be used for this sensitivity analysis because it i) is a reliable technique to identify and rank important variables in terms of their impacts on the output variability of a modelled system (DeJonge et al., 2012; Drouet et al., 2011), and ii) is well-adapted to analyze a combination of variables, such as the combination of drivers tested within our framework.

## 5 Conclusions

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

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## Supplementary material

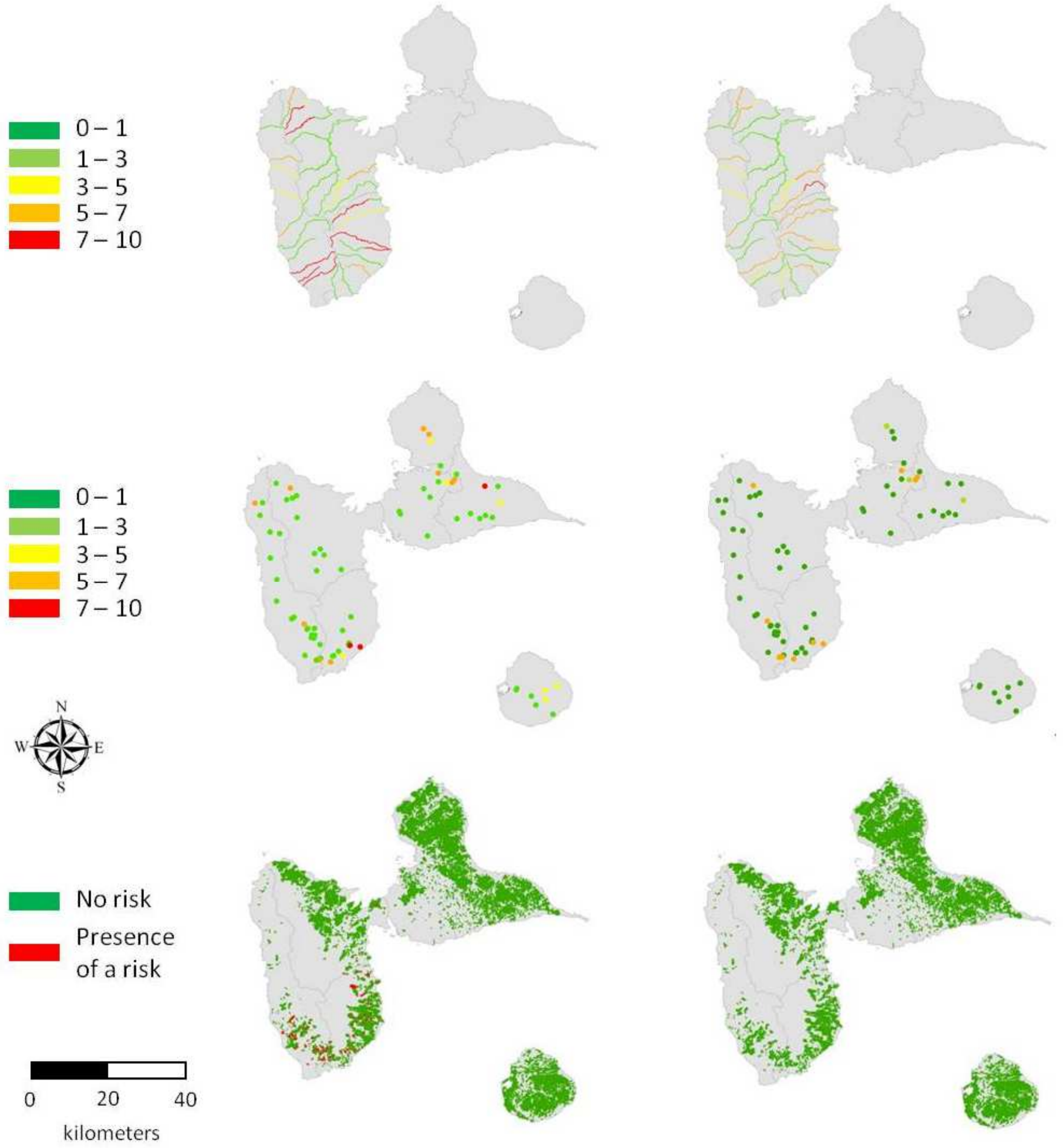

**Figure A:** Comparison of the evolution of the contribution of cropping system mosaics to the decrease of pollution in rivers (top), drinking-water abstraction (middle) and to the decrease of the area of risk of contamination of crops by chlordecone (bottom) between the current mosaic (left) and the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

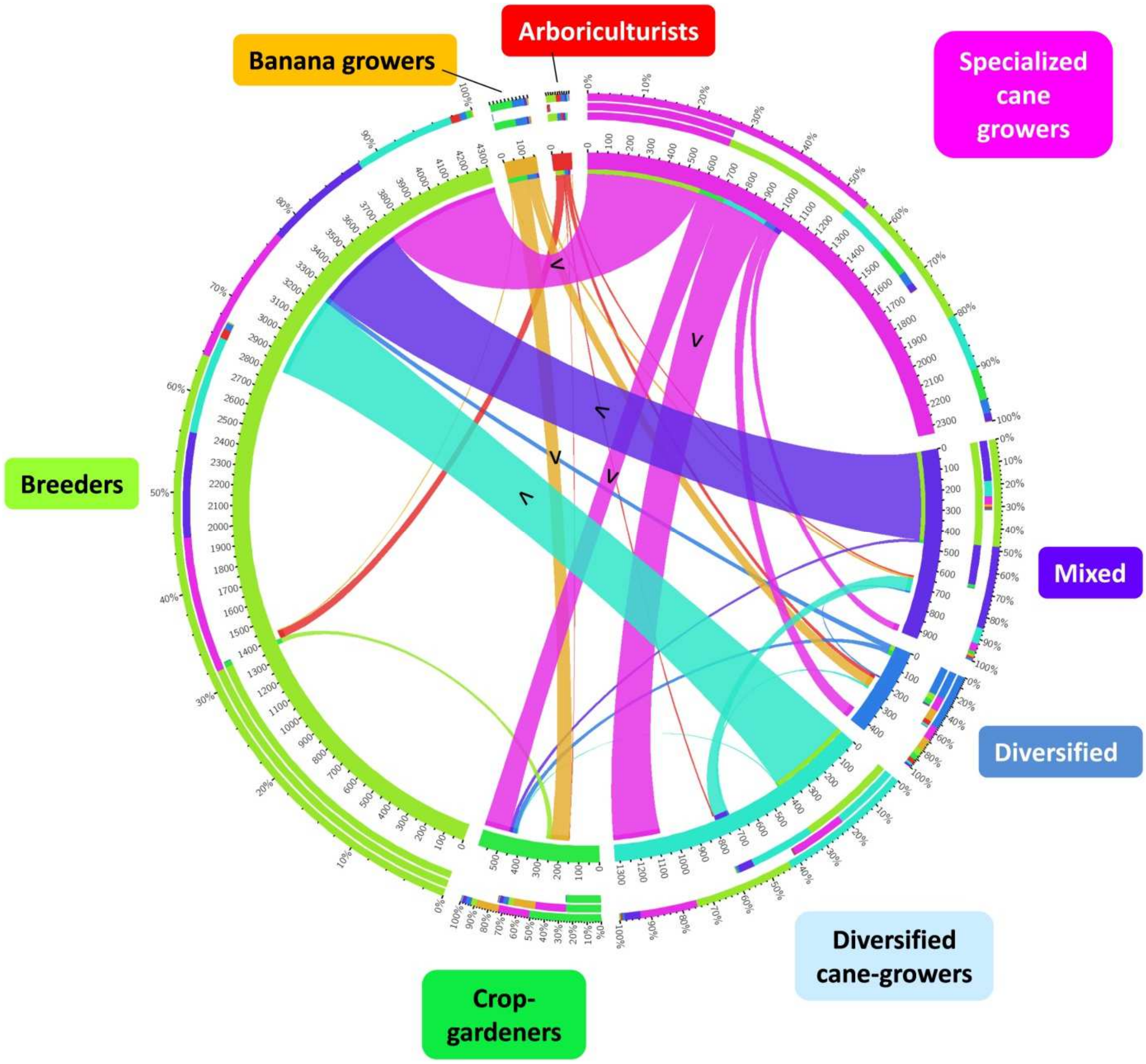

**Figure B: Trajectories of farming system changes within the territory.** Arrows represent the directions of farming system changes from the initial to the "Go sustainable" mosaic. Ribbons between types represent the transition of farms from a given type in the initial cropping system mosaic to another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