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A novel approach for assessing the contribution of agricultural systems to the sustainable development of regions with multi-scale indicators: Application to Guadeloupe

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Abstract

The assessment of agriculture at a regional scale is necessary to better guide regional agricultural planning. To improve the contribution of agriculture to sustainable regional development, assessments must take account of the locations and diversity of cropping systems. We have therefore developed a method based on a set of multi-scale indicators to assess the contribution of agriculture to the sustainable development of regions, and its evolution over time. This method can identify: i) sustainability issues, ii) relevant indicators that will provide information on impacts at the field scale, iii) a method to aggregate indicators, iv) data on cropping systems, and v) a database containing spatial units to analyse the whole region. Application of this method to Guadeloupe (2004-2010) enabled the definition of ten issues and 16 indicators, with three procedures to aggregate information from 36 cropping systems allocated to 11,908 fields between 2004 and 2010. Economic, social and environmental sustainability was poor in 2004, with high dependency on subsidies (47.3 M€.yr⁻¹), low agricultural added value (48.5 M€.yr⁻¹), low employment (only 1799

workers), significant risks of crop contamination and pressure on water quality. The total value of subsidies and the risks of river pollution tended to decrease between 2004 and 2010 because of a reduction in intensive banana cropping systems. In parallel, we were able to see that sugar cane, the most widespread crop in Guadeloupe, made only a small contribution to employment and food self-sufficiency during the studied period. The spatial representation revealed that improvements have been seen in southern Guadeloupe due to reductions in banana cultivation. This method was therefore helpful in identifying the most critical agricultural development issues and helping to highlight areas where relevant agricultural land use policies could be formulated.

1. Introduction

Agriculture has strongly affected ecosystems worldwide and been the cause of a broad range of environmental, economic and social issues at the local and global scales (MEA, 2005). Agriculture needs to face these new sustainability issues by increasing its services to society while reducing its negative externalities on the environment. The successful implementation of agricultural policies is often hampered by a lack of knowledge of the impacts of agricultural systems, such as farming systems and cropping systems, on the sustainable development of regions (Reidsma et al., 2011). A farming system refers to a resource management strategy designed to achieve economic and sustained production that will meet the diverse requirements of the farm household while maintaining a high level of environmental quality ([Cochet, 2012](#); Lal and Millar 1990). A cropping system refers to a set of management procedures applied to a given, uniformly treated agricultural area, which in this case is a field or group of fields ([Sebillotte, 1990](#)).

Study of the sustainability of cropping systems has produced a large body of scientific literature, together with several sets of economic, social and environmental indicators ([Schindler et al., 2015](#); [Carof et al., 2013](#); [Sadok et al., 2009](#)). However, most of these integrated assessments are performed at the scale of the cropping system ([Carof et al., 2013](#)) or farm ([Rosnoblet et al., 2006](#))

while policies which target sustainability issues (e.g. river pollution) go far beyond field or farm boundaries. Methods for the integrated assessment of agriculture at a regional scale are therefore urgently required.

At the regional scale, agriculture comprises several fields to which a farmer attributes and manages a cropping system or livestock production system. Regional agriculture is thus the result of farmers' cropping plans managed at the farm scale. Crop composition and crop arrangements play an important role in the environmental processes that take place within a region, such as the spread of pollution (Houdart et al., 2009), erosion (Joannon et al., 2006) or the conservation of biodiversity (Castelazzi et al., 2010), and they exceed the boundaries of fields and farms. In the present case, these large areas of environmental interest are called sub-regional areas and may be rivers, watersheds, or environmentally protected areas, for example. There is therefore a need to be able to assess the contribution of agriculture to the sustainable development of regions that will: i) link the field scale at which cropping systems are operated by farmers, and the regional scale at which regional externalities are generated, ii) be spatially explicit, meaning that they account for the spatial location of cropping systems, and iii) account for the diversity of cropping and livestock systems (Benoit et al., 2012; [Sattler et al., 2009](#); Dizdaroglu and Yigitcanlar, 2014; [Tirczka and Ferencsik, 1998](#)).

Category	Method or model	Regional level included (yes/no)	Cropping system diversity (yes/no)	Multi-issues (yes/no)	Spatial explicitness (yes/no)	References
Cropping system assessment methods	MASC	No	Yes	Yes	No	Sadok et al., (2009)
	ROTOR	sNo	Yes	Yes	No	Bachinger and Zander (2007)
	MODAM	No	Yes	Yes	No	Meyer-Aurich, 2005
Agricultural landscape assessment	SIPPOM-WOSR	Yes	Yes	disease dispersal	Yes	Lô-Pelzer et al., (2010)
	Landsfacts	Yes	Yes	GM pollen dispersal	Yes	Castellazzi et al., (2010)
	I-Pest	Yes	Yes	Water pollution	Yes	Houdart et al., (2009)
Land use studies	ASSESS	Yes	No	Yes	Yes	Hill et al., (2005)
	CLUE-S model	Yes	No	Yes	Yes	Verburg et al., (2002)

Table 1: Comparison of some examples of methods to address spatially explicit multi-issues assessments of agricultural landscapes

Indeed, most methods or models used to assess cropping systems focus on the field scale and have produce multi-criteria decision support tools (see Table 1 for some examples of the methods used for the integrated assessment of agricultural systems), but they did not incorporate the spatial location of the cropping system concerned ([Carof et al., 2013](#); [Sadok et al., 2008](#)). Furthermore, most agricultural landscape assessments are designed to determine the contribution of agriculture to sustainability issues at a broader level than farms, but focus on a particular issue such as disease spread ([Lô-Pelzer et al., 2010](#)) or water pollution by pesticides ([Houdart et al., 2009](#)) and no multi-criteria analyses of landscape sustainability have been performed to date. As for land-use studies, the contribution of urban, forest or agricultural land use to regional sustainability is mostly approached in terms of the provision of ecosystem services ([Wolff et al., 2015](#); [Lee et al., 2015](#)) but the data on agriculture are too aggregated to account for the diversity of cropping systems ([Dossa et al., 2011](#)). This is a drawback because each cropping system has different externalities. For this

reason, diversity should be included in a multi-scale assessment ([Deffontaines et al., 1995](#)). In France for example, regional planning, development schemes and other regional plans encompassing agriculture land use still adopt a simple view of agriculture. This could be modified by including an agricultural system approach so as to better inform the reorganization of activities and sectors within a region, and to identify both appropriate innovations that will improve the contribution of agriculture to sustainable development of regions and relevant incentives to foster the emergence of such innovations ([Boiffin et al., 2014](#)).

Here, we present a method to assess the contribution of agriculture to the sustainable development of regions using a set of multi-scale indicators that account for the location and type of farmers' cropping and livestock systems. This method includes several indicators that enable i) an overall assessment of the contribution of agriculture to sustainable regional development, and ii) a spatial view of the heterogeneity of this contribution within the region under study.

2. Methods

2.1. Overview of the integrated assessment of sustainability at a regional scale

The method we propose comprises five steps: i) the definition of several sustainability goals, ii) the selection of indicators, iii) a description of scale changes, iv) the collection of data describing the cropping and livestock systems, and (v) the creation of a geodatabase of fields which includes the spatial units to which they belong (Figure 1). The spatial explicitness of this method to assess farming systems is ensured by integrating spatial components from the geodatabase in the scale change procedure, in step 3.

2.2. Description of the five steps

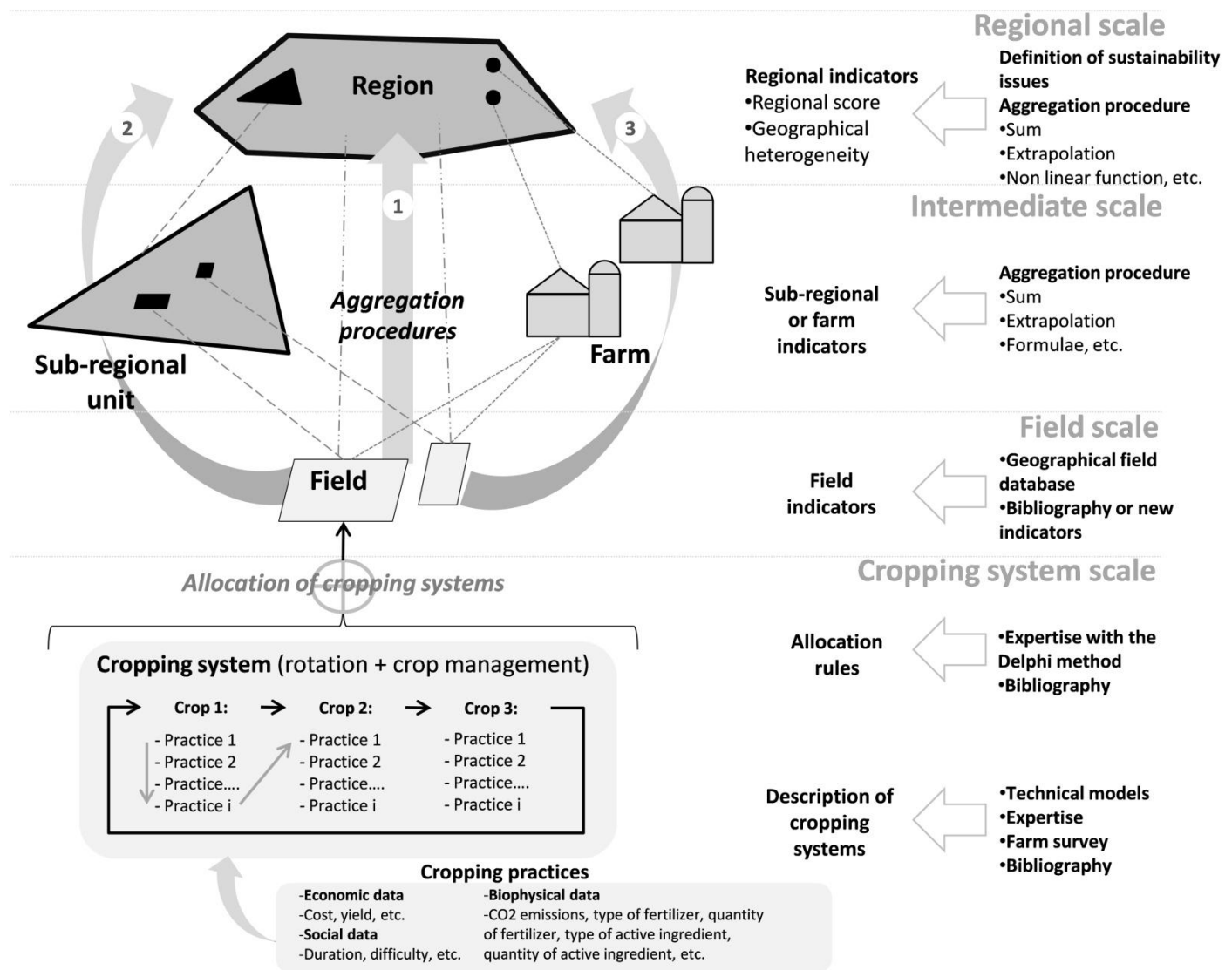


Figure 1: Method used to calculate multi-scale indicators for the sustainability assessment of agricultural landscapes. Arrows represent aggregation from field scale to regional scale: 1) directly, 2) with intermediate aggregation at a sub-regional level (e.g. watersheds, rivers...) or 3) with intermediate aggregation at the farm scale.

2.2.1. Sustainability issues

Most methods designed for the integrated assessment of agriculture are based on the three pillars of sustainability, which are then sub-divided into different categories. This categorization of sustainability issues matches the objective of assessing the multi-functionality of agriculture in an integrated manner (Bezlepkina *et al.*, 2014). Following the recommendations of Bezlepkina *et al.* (2014) and Alkan-Olsson *et al.* (2009), the issues are transformed into a goal oriented framework to

enable an assessment of the impact of changes to local agriculture on sustainability goals ([Alkan Olsson et al., 2009](#)). All issues are either economic, social or environmental, linked to the changes in cropping systems. Hence, issues linked, for instance, to the disappearance of agricultural land are not included since this problem is not directly correlated to the change in the characteristics of cropping systems. The issues include one or more indicators which provide information on the contribution to issues ([Bockstaller et al., 2015](#)). Some are local issues that are specific to the study area, while others are global in the sense that they are faced by policy-makers everywhere, such as climate change. The goals include both impacts on agriculture sustainability itself and the impact on a contribution to the sustainable development of society ([Alkan-Olsson et al., 2009](#)). The list of issues is first established from data in the literature contextualized to the studied area, based on agriculture orientation and planning documents and on local scientific knowledge ([Marraccini et al., 2013](#); [Gomes-Sal et al., 2003](#)). A more refined list based on policy-makers' perceptions of the importance of issues (as expressed during a series of meetings) is then finally validated using a web-based survey.

2.2.2. Selection of indicators

Several indicators need to be calculated at different spatial scales in order to assess the contribution of agriculture to the sustainability issues selected in the preceding step (Figure 1). The properties of these indicators should be addressed before the indicators are selected. The indicators need to be: (i) relevant to the previously defined sustainability issues and objectives ([Niemeijer et al., 2008](#)), (ii) measurable in space and quantifiable using simple techniques, (iii) understandable by policy makers, (iv) adaptable to the spatial and temporal scales of the assessment, (v) scientifically sound, and (vi) able to avoid repeating the same information with too many redundant indicators ([Bockstaller et al., 2008](#)). All these properties are used to select the indicators in our method. Many field scale indicators have been designed in recent decades ([Jørgensen et al., 2013](#)), and their multiplicity in existing methods was reviewed for their potential use in our study ([Sadok et al.,](#)

2009; Gaudino et al., 2014; [Bockstaller et al., 2008](#)). These indicators, which are calculated at the field scale, are then up-scaled to the regional scale in order to produce an overall regional score (Figure 1). Their representation of the territory at a lower scale provides a graphical representation of the heterogeneity of the contribution of agriculture to sustainability issues, in the same way as landscape function maps ([Willemen et al., 2010](#)). The choice of indicators is driven by the availability of data on cropping and livestock systems and of geographical information, and by the views of potential users collected during meetings with policy-makers.

2.2.3. Aggregation of information from the field to the regional scale for sustainability assessment

To calculate a score that reflects the contribution of agriculture to regional issues (considered as a mosaic of fields with managed cropping systems), the values of field scale indicators are aggregated at the regional scale using different procedures (Figure 1). Aggregation can be performed in one or two steps. The information can follow a path (see arrows in Figure 1) (i) directly up from the field to the regional scale, (ii) from the field to a given sub-regional scale and then to the regional scale, or (iii) from the field to the farm and then to the regional scale. The type of path depends on the entities to be targeted or on the organizational level (e.g. the farm) and the availability of information (e.g. farm income). Thus, for example, farm assessments that account for the diversity of their crop acreage would require a transformation from the field to the farm and another from the farm to the region. The environmental areas often considered in environmental sustainability are integrated in the flow of information from the field to the environmental area concerned, and from the environmental area to the regional scale. Indicators of sub-scales (field, farm or sub-region) are mapped to identify areas in one or more dimensions that require particular attention ([Bell and Morse, 1998](#)).

The information is also aggregated using different methods. To obtain a score at a regional scale, indicators that are calculated at the field scale need to be transformed to higher scales (dotted lines

in Figure 1). Field information can be summed, averaged or weighted by the area of the entities considered or by a coefficient under non-linear processes, extrapolated or interpolated ([Dalgaard et al., 2003](#); [Scholes et al., 2013](#); [Sepp and Bastian, 2007](#)). The selection of the aggregation procedure depends on the characteristics of the regional indicators and on the spatial explicitness of the issues. Indicators for the regional balance of the distribution of agricultural income require farm income to be calculated based on summing the income from each field and then using a non-linear equation to obtain the information at regional level using Gini's equation (1921). Indicators that do not account for field location variables only require a sum, mean, or non-linear function to address non-linear processes ([Dalgaard et al., 2003](#); [Scholes et al., 2013](#)). These indicators may encompass the agricultural value added or total subsidies, or the sum of CO₂ emissions at a regional scale, for instance. Indicators of the location of a field require data such as the presence of fields in a specific area or the distance from the field to another spatial entity, which may be another field, or a given sub-region (for instance, pressure on rivers is calculated using the mean of field scale indicators located less than 200 meters from the river). If indicators are related to spatially located issues, they need to be able to handle spatially explicit information that encompasses distances and the presence/absence of area, that will enable spatial weighting of the importance of fields to the assessment of given indicators. Hence, *ceteris paribus* fields close to water bodies will have a greater impact on levels of potential pollution than those located further away. The indicators are then enriched with additional information at the cropping system scale so as to turn them into spatially explicit indicators based on scientifically sound information regarding the impact of location on the different issues. This addition of spatial information via a major database, and their handling with powerful software (here the GAMS platform), improve the ability of the bioeconomic model to perform spatially explicit assessments despite the limitations of such models in the literature ([Delmotte et al., 2013](#)).

2.2.4. Cropping system information at the field scale

The cropping system scale is the baseline at which information on farmers' practices is provided. Data on crop management systems, livestock management systems and crop rotations should be recorded. Depending on the type of indicator, this information may include economic data on costs, social data on the duration of practices, or environmental data concerning the types of pesticides, organic matter, organic amendment and fertilizers used, and their effects on CO₂ emissions, for instance. Different sources of information can be used to supplement the description of cropping and livestock systems, such as economic data (e.g., prices and production costs) available from the documentation supplied by local agricultural institutes. This type of information can be used for an economic analysis of the cropping or livestock systems, which may include the calculation of gross margins based on an average crop price, or crop yields minus the costs of production. Expertise from local advisers can be used by applying the Delphi method ([Linstone and Turoff, 1975](#)). Each expert on a given crop is interviewed individually, and then a meeting is held with all the experts to discuss any differences that emerged during the individual interviews and to reach an agreement on them. If there is a deficit of expert knowledge, or when experts cannot agree on a given characteristic of the cropping system, several on-farm interviews may be conducted to describe the cropping system concerned.

2.2.5. Geographical database on fields and definition of the cropping system

A geodatabase of fields is required to calculate field indicators. This type of geodatabase can generally be built using information provided by the farmers or from aerial or satellite photos. Information on the biophysical context, and the field characteristics necessary to calculate field indicators (e.g. altitude, rainfall, distances to nearby cities, involvement in an irrigation scheme) can either be obtained from the stakeholders (e.g. advisors, NGOs, etc.) or using geographical information systems (GIS), census data, on-farm surveys or field measurements. Data on spatial location to enable a spatially explicit assessment can be generated using spatial analysis tools that will provide information on the distance of fields from different locations (other fields, farms,

environmental devices). Such tools may include Euclidian distance, Manhattan distance, extraction, or overlap available in different types of spatial analysis software. The resulting spatial information can easily be stored in databases and then used for the scale change procedure. Farm spatial data are also required and their locations may be the centroids of fields or farm addresses obtained from census data. Information on the location of a field relative to the spatial unit of interest can be obtained from spatial statistical tools using GIS software.

3. Results

We used the method to assess the sustainability of agriculture in Guadeloupe, which is an archipelago in the Caribbean with a tropical climate and rainfall ranging from 1,000 to 5,000 mm yr⁻¹. The total farmed area covers 31,300 hectares and it is cultivated by 8,000 farmers (Agreste, 2011). Farm sizes range from less than one hectare to more than a thousand hectares, and most farms are specialized in sugar cane, banana, market-gardening, orchards or cattle breeding ([Chopin et al., 2015](#)). The biophysical context of the farms varies from dry plains on calcic soils to Andisols and Nitosols at high altitudes with high rainfall, where crops are grown on sloping fields with fertile clay soils. The variability of the socioeconomic and biophysical context is at the origin of the considerable heterogeneity of cropping and livestock system's externalities at the field scale, as shown by [Blazy et al. \(2009\)](#) in the case of banana production in Guadeloupe, where agronomic performance ranged from 10 to more than 40 Mg.ha⁻¹. A detailed description of all farming systems and their locations was presented in a typology by [Chopin et al. \(2015\)](#).

3.1. The ten sustainability issues in Guadeloupe

The sustainability goals were first defined by a team of researchers through a review of eight agricultural development studies issued by different policy-makers such as the Guadeloupean Rural Development Programme (PDRG, 2012). These issues were then discussed with policy-makers

individually during nine face-to-face interviews. After these individual discussions, 13 regional decision-makers completed and validated the list of issues by means of a web-based survey.

In Guadeloupe, economic sustainability requires an increase in agricultural income and a reduction in subsidies, which mainly apply to banana and sugarcane production (PDRG, 2011), because the global banana and sugar markets are tending to reduce the subsidies permitted for planters. From a social point of view, first of all, the Regional Council for Guadeloupe is interested in increasing local production in order to improve the current level of food self-sufficiency (PDRG, 2011). Secondly, foodstuffs need to be safe and free from contaminants, and especially chlordecone, used for the treatment of banana and which has caused long-lasting soil contamination of 20% of the cultivated area in Guadeloupe (Cabidoche *et al.*, 2009), and has serious impacts on human health ([Multigner et al., 2008](#)) through the consumption of food grown on contaminated soil ([Clostre et al., 2015](#)). Thirdly, the development of local agriculture through the creation of more jobs, particularly for young adults (whose unemployment rate reaches 46%) is a major challenge (PDRG, 2011). According to local policy-makers, six issues need to be taken into account for the environmental dimension of sustainable development. Improving biodiversity is important given that Guadeloupe is a biodiversity hotspot, with endemic birds, fish species and bats ([Myers et al., 2000](#)). Pesticide pollution and the use of water for irrigation need to be reduced in order to improve the overall quality of water catchments, sources of water abstraction and rivers. Reducing CO₂ emissions is also an important challenge for agriculture worldwide, and Guadeloupe can contribute to this through changes to crop management ([Bockstaller et al., 2015](#); [Colomb et al., 2014](#)). Agriculture must reduce its consumption of resources by developing renewable energies to replace fossil fuels, which currently represent 85% of the energy mix, and in particular by developing biomass energy (Prerure, 2008). Finally, the current homogenized agriculture should be diversified to enhance the aesthetic quality of the landscape.

Dimension	Sustainability issues	Regional indicators	Units
Economic	Improving agricultural income	Total farm income	€·yr ⁻¹
		Distribution of income in the farming population	-
	Decreasing dependence on subsidies	Total amount of subsidies	€·yr ⁻¹
Social	Achieving food self-sufficiency	Ratio of carbohydrates produced to needs	%
		Ratio of proteins produced to needs	%
		Ratio of fats produced to needs	%
	Contributing to employment	Total workforce needs	pers
	Ensuring the safety of locally produced foodstuffs	Area of risk of chlordecone contamination of food crops	ha
Environmental	Improving biodiversity	Percentage area with a risk for birds in high-value ecological zones	%
	Enhancing water quality	Proportion of potentially polluted rivers (%)	-
		Proportion of potentially polluted water catchments (%)	-
		Proportion of potentially polluted sources of water abstraction (%)	-
		Amount of water used for irrigation	m ³
	Reducing the contribution to climate change	Total emissions from farming activities in CO ₂ equivalent	tons equivalent CO ₂ ·yr ⁻¹
	Preserving non-renewable resources	Energy produced from crops	MW·yr ⁻¹
	Improving the diversity of agricultural landscapes	Diversity of crops across the landscape	-

Table 2: List of regional indicators to be determined

3.2. Field indicators and scale change procedure

The indicators used are listed in Table 2 and the algorithms applied for their calculation are in the Supplementary Material.

From an economic point of view, increasing both total agricultural income and the fair distribution of this income among the farming population will improve economic sustainability. Total farm

income is the sum of crop gross margins at the field scale. The gross margin of each field is calculated from the mean crop income of each cropping system and livestock systems, which is aggregated from the field to the region, as shown in Figure 1 (path 1) with a sum. Gross margin is calculated using average yield data, crop prices and variable costs taken from the description of the cropping system. The distribution of agricultural income among the farming population is assessed using the Gini coefficient, which measures the overall inequality of a variable across a population (Gini, 1921). Income is first aggregated with a sum at the farm scale. The Gini indicator then aggregates the information on income at the farm scale to the regional scale accounting for the ranking of a farmer's income in the entire farming population. Its value can range from 0, for perfect equity, to close to 1, for an unbalanced distribution of income (Gini, 1921). Independence from subsidies is assessed from the total amount of subsidies from the field to the region by summing coupled subsidies (banana production) and decoupled subsidies (e.g. agri-environmental measures) from crop production ([Zahm *et al.*, 2008](#)).

Level of soil contamination		High		Average		Low	
Type of soil		Others	Andic	Others	Andic	Others	Andic
Crop category	Tubers	Risk of contamination of crops by chlordecone					
	Pastures						
	Crop-gardening						
	Others						

Table 3: Decision-support system used to assess the risk of crop contamination by chlordecone in the field. The shaded area indicates "presence of a risk" combinations. The types of soil labelled as "other" include Ferrasols and Nitosols.

Concerning the social dimension, the food self-sufficiency objective is calculated based on three indicators for the supply of the main nutrients, carbohydrates, fats and proteins, by crop. The indicator is the ratio between the total production of each of the three nutrients and the total needs of the population, calculated using the amount of nutrients required by an average person and the total population of the island, which is 400,000 inhabitants (PDRG, 2011). The contribution to employment is assessed from the total workforce required for the cropping system, summed from the field to the region calculated at field scale (Zahm et al., 2008) with no intermediate scale. The local production of safe food crops is assessed by calculating the risk of consumer exposure to crops that are contaminated by chlordecone. This indicator includes the range of characteristics of absorption of this compound by the crop (Clostre et al., 2015), soil adsorption of the pollutant (Cabidoche et al., 2009) and the risk of chlordecone content in the field (Tillieut and Cabidoche, 2006) (Table 3). We designed a decision tree to incorporate these processes qualitatively, with the four qualitative risks of the presence of chlordecone, four crop categories (tubers: yam, sweet potatoes, cassava and taro; pasture; market-gardening and other: banana, sugar cane, pineapple, orchards, and plantain), and the soil types into two categories: high adsorption (Ferralitic and Nitosols) and low adsorption (Andisols), based on the findings of Clostre et al. (2015), in order to assess whether, based on expert knowledge, a given field represented "a risk of contamination" or not. At the regional scale, the surface area of the fields rated as having the "presence of a risk of

contamination" was summed to provide the agricultural area with a probable risk of crop contamination. It should be noted that the contamination of water reservoirs by chlordecone is mainly caused by leaching during rainfall events, and these reservoirs are well protected using activated carbon, not by the type of the crop grown or management practices, which is why no indicator was designed to assess this issue (Cabidoche et al., 2009).

Concerning the environmental dimension, the impacts of the cropping systems on biodiversity was assessed through the risk of bird contamination due to the ingestion of pesticides. Birds were used to calculate this indicator because in Guadeloupe they are valued due to the presence of "Near Threatened" endemic species ([Villard et al., 2010](#)). The risk of a loss of biodiversity is assessed using a load index of birds (Gaudino *et al.*, 2014) calculated at the field scale in high-value ecological zones, with a quotient for the quantity of active ingredient spread by the level of toxicity (LD50). We summed the load index of all of the fields and divided it by the total cultivated area in these zones. A load index higher than 1 indicates significant pesticide pressure on bird biodiversity. The enhancement of water quality was assessed using three indicators at the regional scale, based on the same field indicator but with a different aggregation procedure. This field scale indicator consists of an adapted version of the Rpest indicator provided by [Tixier et al. \(2006\)](#). The Rpest indicator was determined by following a decision tree with parameters that described the situation in the field (runoff and drainage) and the cropping systems (quantity of active ingredients, DT50 for mammals, acceptable daily intake (ADI), and toxicity to fish). These calculations resulted in a score ranging from 0 to 10 per field for the calculation of the three regional indicators. Concerning the pollution of water abstraction sources, a weighted mean of the Rpest score for the surface area of fields in the total cultivated area within these perimeters was determined for each abstraction source, based on the score obtained for fields located within 200 metres of the source. This distance was considered to be a perimeter for the immediate protection of water quality. Next, the ratio of water abstraction sources with a score greater than 7 was calculated based on the value recommended by [Tixier et al. \(2006\)](#). Calculation of the ratio of polluted rivers was the same,

except that the buffer zone around rivers was 50 metres, as recommended in Houdart *et al.* (2009) for the risk of river pollution in Martinique, being a distance at which substances generally enter rivers without being degraded. The calculation of the risk of water catchment pollution was determined by the average Rpest score for each field and each water catchment, according to the method described by [Macary *et al.* \(2014\)](#). The amount of water used for irrigation was also calculated to estimate the enhancement of water quality, as being the difference between potential evapotranspiration multiplied by the mean crop coefficient minus the rainfall amount for each month, summed for the entire year. Crop needs were determined based on crop coefficients, which vary with the developmental stage of the crop. Next, at the field scale, the level of irrigation was calculated, but only for fields included in water schemes. The amount of irrigation in each field was then summed to obtain a regional amount of irrigation water. CO₂ emissions were assessed from the sum of the total emissions by all cropping and livestock systems, from the field to the region. We considered emissions caused by cropping practices (e.g. tillage), produced during the manufacture of inputs, exports of agricultural products and from enteric fermentation by livestock. Soil carbon storage was not included in the calculation because of the short duration of the study period. The local production of electricity was assessed by summing the production of electricity from field to regional scale with no intermediate scale. Landscape diversity was assessed using an average of reciprocal Simpson's diversity index ([Simpson, 1949](#)) calculated in six homogeneous sub-regions based on the socio-economic and biophysical context of the farms. The values of indicators for each sub-region ranged from a score of 1, which is a homogenized landscape composed of one crop category, to a score of 7, which is a heterogeneous landscape composed of the seven types of crops equally represented in the landscape.

3.3. Definition of cropping systems and the geographical database on fields

We identified the practices used in 21 cropping systems and in the most common cattle rearing system (well distributed throughout the area) based on previously published data (e.g., Blazy *et al.*

(2009) for banana production); technical models for tuber production (Causeret *et al.*, 2012); expertise based on the Delphi method and on-farm surveys for market gardening. The livestock activities considered were mainly extensive, with cattle raised on pasture with no other sources of fodder. Pig and poultry systems have very low spatial weights in Guadeloupe and were consequently not included in this study. Economic data came from the economic guide published by the local Chamber of Agriculture, which combines all the crop yields, gross margins and costs of different practices. Social information, including information on food nutrient content for food self-sufficiency was obtained from the FAO fruit and vegetable database (FAO, 2012). Employment was based on the time required for crop management using technical models such as IGNAMARGE® (Causeret *et al.*, 2012), which provides a duration of practices. Environmental information, including data on pesticides (DT50, LD50, etc.) was obtained from the European Union Pesticides Database (European Commission, 2011). The different cropping system parameters (DT50, ADI, etc.) were averaged according to the proportion of each dose of pesticide in the total amount applied. The active ingredients were identified from the commercial products used by farmers. The pesticide rates used in the calculations were the registered recommended rates, approved by the European Commission. The Kc crop coefficients for irrigation were obtained from the FAO irrigation manual (FAO, 1986). CO₂ emissions in Guadeloupe were taken from CLIMAGRI (Colomb *et al.*, 2014). The production of electricity from sugar cane bagasse was based on the calorific power estimated by local engineering consultants (Explicit, 2010).

In parallel, we constructed the geographical database using the information required to calculate the indicators. The initial geographic database contained 11,908 fields (covering 13,889 ha) owned by 3,591 farmers, and the crops grown in the fields between 2004 and 2010. The area covered by the field database thus represented almost half of the agricultural area. The fields were spatially intersected to different spatial units to reveal their presence or not in these units: rivers with a 50-metre buffer zone, water catchments, water abstraction sources with a 200-metre buffer zone, high-value ecological zones, irrigation schemes, sub-regions for water quality and landscape diversity

indicators. The amount of rainfall was based on the values determined using a shapefile from Meteo France, which provides results from meteorological stations, and was interpolated using the kriging tool from ArcGIS 9.3 (ESRI, 2009). Total run-off and drainage were calculated for each field for an entire year using a shapefile of the mean historical level of annual rainfall. Mean evapotranspiration was calculated for both of the islands of Guadeloupe, at 3.5 mm.day^{-1} in Basse-Terre and 4 mm.day^{-1} in Grande-Terre (Cornet, pers. comm.). The types of soil were added, based on an intersection with the soil shapefiles from the soil map (Colmet-Daage, 1969). The map for the risk of chlordecone contamination was used to generate this in the fields (Tillieut and Cabidoche, 2006). The cropping systems and cattle rearing system were allocated to fields based on "if-then rules" defined by expertise (Clavel *et al.*, 2011). For instance, the intensive banana cropping system that is described in the Supplementary Materials was allocated to fields if the crop that was grown in 2010 on the given field was "banana", if the size of the farm owning the field was more than 15 hectares and if the slope of the field was less than 15%.

3.4. Assessment of the sustainability of agriculture in Guadeloupe over several years

The range of indicators was calculated for the period from 2004 to 2010 (Table 4) and three indicators with different aggregation procedures were spatialised for the two most contrasting years (Figure 2).

Regional indicators	Results							
	2004	2005	2006	2007	2008	2009	2010	CF*
Total farm income (€.yr-1)	48.5	47.7	46.3	47.5	47.5	47.8	47.8	2%
Distribution of agricultural income in the farming population (-)	0.72	0.71	0.7	0.71	0.71	0.71	0.71	1%
Total amount of subsidies (€.yr-1)	47.3	45.5	43.0	42.3	41.7	41.2	42.6	5%
Ratio of carbohydrates produced to needs (%)	5.5	5.4	5.4	5.7	5.8	5.8	5.7	3%
Ratio of fat produced to needs (%)	4.4	4.5	4.5	4.6	4.6	4.6	4.6	2%
Ratio of proteins produced to needs (%)	17.0	17.1	17.1	17.3	17.3	17.4	17.3	1%
Total workforce requirements (persons)	1799	1717	1568	1573	1559	1554	1612	6%
Area of the risk of contamination of food crops (ha)	165	181	204	209	215	253	251	16%
Mean toxicity in fields in high-value ecological zones	0.71	0.47	0.50	0.51	0.49	0.48	0.48	16%
Proportion of potentially polluted rivers (%)	38.7	25.8	22.0	22.6	29.0	32.3	35.5	48%
Proportion of potentially polluted water catchments (%)	36.1	32.5	31.9	30.7	32.5	33.7	36.1	6%
Proportion of potentially polluted sources of water abstraction (%)	52.2	43.5	47.8	47.8	47.8	47.8	47.8	5%
Amount of water used for irrigation (m3)	9.16	9.12	8.64	9.11	8.91	8.83	8.89	2%
Total emissions of CO2 from farming activities (tons of CO2 equiv.yr-1)	94.3	91.7	87.2	86.6	86.4	86.2	88.9	4%
Energy produced by crops (Mw)	13.6	13.6	14.0	14.1	14.1	14.1	14.0	2%
Diversity of crops across landscapes (-)	2.45	2.53	2.65	2.69	2.70	2.72	2.66	4%

* CF: Coefficient of variation

Table 4: Results of the assessment of agricultural landscapes between 2004 and 2010

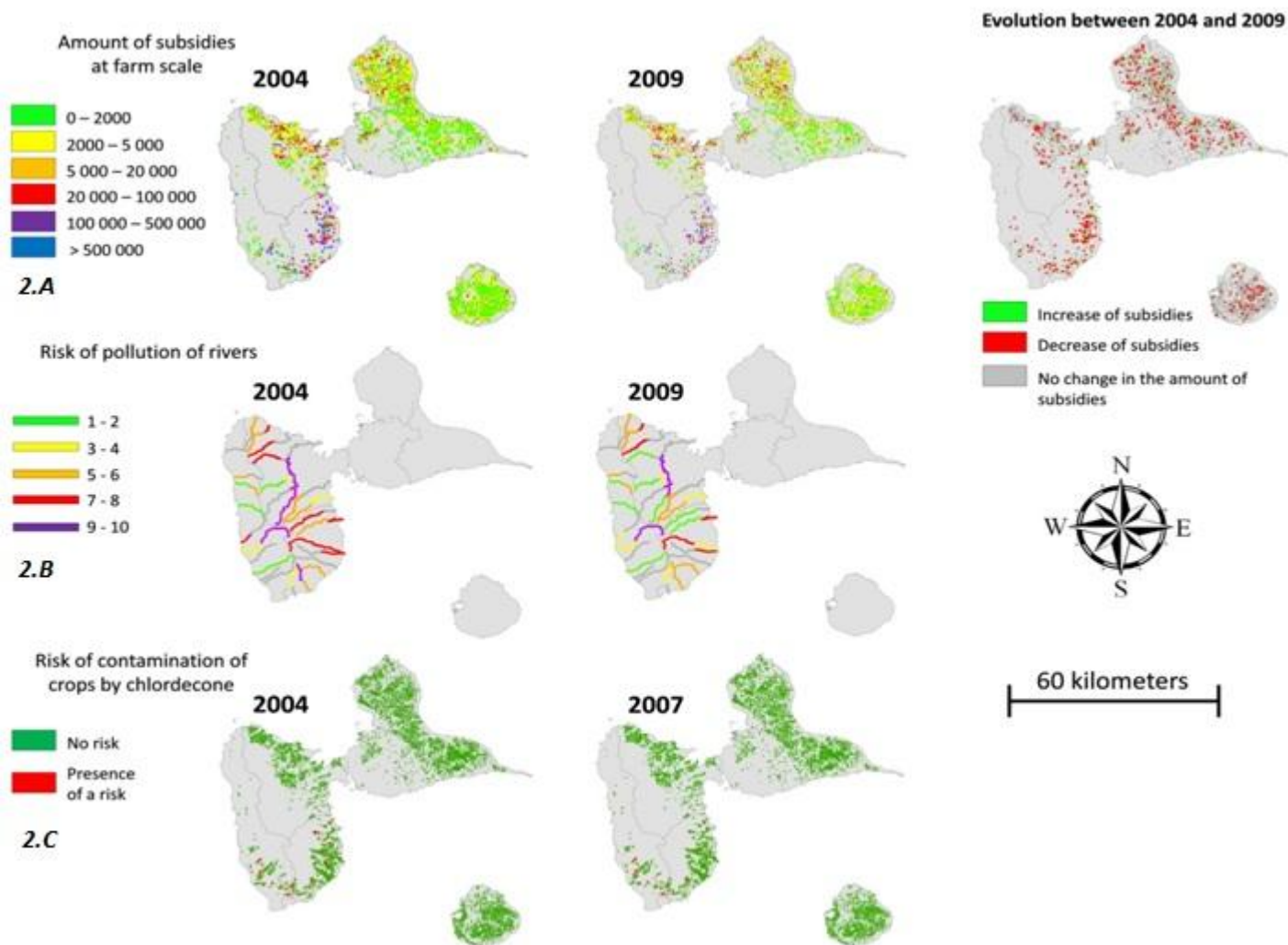


Figure 2: Figure 2: Maps of three calculated indicators: farm subsidies mapped at the farm scale (figure 2.A), the risk of river pollution (figure 2.B) and the risk of crop contamination by chlordecone (Figure 2.C). These maps help to visualize the contribution of different spatial entities to a given issue at different spatial scales. Mapping an indicator for the most contrasted years helps to reveal changes in the contribution of agricultural landscapes to these three issues over time.

Economic sustainability was low considering the high level of subsidies ($47.3 \text{ M€}.\text{yr}^{-1}$) compared to total agricultural income ($48.5 \text{ M€}.\text{yr}^{-1}$) and the high level of inequity in the distribution of agricultural income between farmers, as demonstrated by the high Gini coefficient (0.72). Economic sustainability varied considerably across the territory. Banana growers in southern Basse-Terre tended to obtain more subsidies for banana production other producers and had the highest income in the farming population. These subsidies fell from $47.3 \text{ M€}.\text{yr}^{-1}$ in 2004 to $41.2 \text{ M€}.\text{yr}^{-1}$ in 2009. This decrease was greater in south-western Basse-Terre considering the number of farms, because of the reduction in area under banana after hurricane Dean in 2007 (Figure 2.A).

Social sustainability was also low considering that only 4.4% of the fat, 5.5% of the carbohydrates and 17.0% of the protein needs were covered by local production. Carbohydrate production was low because bananas and sugar are mainly exported to metropolitan France. Agriculture employed a relatively high level of on-field workforce (1799 workers in 2004), but its spatial heterogeneity indicated that most of the workforce was concentrated in southern Basse-Terre for the cultivation of banana. While this area decreased over time, the total workforce followed the same trend. The contribution of other areas to employment was low because sugar cane occupies half the area and does not require a large workforce (approximately 60 hrs.ha-1.yr-1). Other districts could contribute more to employment throughout the territory with labour-intensive cropping systems such as market-gardening. The assessment of the risk of contamination of food crops was important as this risk increased across years from 165 to 251 ha because of the replacement of banana plantations by pasture (Figure 2.C).

The level of pressure on bird biodiversity was low because the indicator value was less than 1, due to low intensity cropping systems in high ecological areas, which were mainly under pasture. The inter-year variation of the level of contamination, with a peak in 2005, was due to the rotation with market-gardening that increased the overall use of pesticides in these zones in 2005. The amount of water used for irrigation was high (9.2 Mm³), close to the 9 Mm³ water consumption of inhabitants of the island due to its intensive use for market-gardening in dry areas and banana production in the south-western part of the island. The Rpest indicator was aggregated at three levels. At the regional level, a high proportion of rivers (38.7%) were potentially polluted (Figure 2.B). The amount of potentially polluted water catchments (36.1%) was significant, especially considering the size of some of the polluted catchments. The number of potentially polluted water sources was also very important (52.2%). Southern Basse-Terre was exposed to pesticide pollution in the rivers and water sources close to the sea. The centre of Grande-Terre was also potentially polluted by three sources, with an Rpest score higher than 7. At the river scale, there was a decrease between 2004 and 2007 in the risk of pollution, especially in the south-eastern part of Basse-Terre (Figure 2.B). In southern

Basse-Terre, water resources were polluted due to highly intensive banana cultivation in the plain and the development of market-gardening. Central Grande-Terre was also potentially polluted due to the intensity of market-gardening in this area. Total GHG emissions from agriculture in Guadeloupe were low compared with other sectors (2% for agriculture and 30% for residents) due to the low level of mechanization of cropping systems which was higher in southern Basse-Terre due to the significant quantity of fertilizers used in banana cropping systems (400 kg of nitrogen.ha⁻¹.yr⁻¹). The amount of electricity produced from biomass (13.6 MW) was far below the amount of potential renewable energy that could be produced using energy crops (Prerure, 2008). The diversity of crops in the landscape was low in Guadeloupe, with an average of 2.45 crops but with high heterogeneity when the sub-regions are taken into account: from 2.1 in Marie-Galante and northern Basse-Terre to more than 5 in south-western Basse-Terre. In Grande-Terre, this score was low because agriculture was dominated by pasture and sugar cane; although the eastern part of southern Basse-Terre comprised only banana, sugar cane and pasture, the western part was much more diversified, with pasture, orchards, banana, market-gardening and sugar cane.

In our assessment, seven out of 16 indicators had a coefficient of variation of 5% or higher between the values calculated in 2004 and 2010. The coefficient of variation is the ratio of the standard deviation to the mean based on the 7 values of each indicator obtained from 2004 to 2010. The evolution observed for these values was mainly due to the decrease in the area cultivated with banana. Hence the total amount of subsidies, the total workforce requirements, the area affected by a risk of contamination of food crops, the proportion of potentially polluted rivers, the proportion of potentially polluted sources of water abstraction, the mean toxicity in fields in high-value ecological zones, and the diversity of crops across the region were related to the decline of banana cropping systems. These highly intensive cropping systems are highly subsidized so their replacement by pasture between 2004 and 2010 reduced the overall amount of subsidies. The decrease of banana came with a drop in the workforce because banana is highly labour-intensive while pasture uses less workforce. The appearance of pasture improved the risk of contamination of food products due to

the contamination pattern of cattle on contaminated soils. The reduction in the pollution of water bodies (rivers and abstraction sources) was also due to this replacement which decreases the pesticide pressure in water bodies. The visual diversity of the landscape was improved by replacing some banana fields with cattle breeding.

4. Discussion

4.1. Added value of the method designed

The method we have developed is similar to some existing methods regarding the steps of the sustainability assessment ([Binder *et al.*, 2012](#); Gómez-Limón and Riesgo, 2009) but its originality lies in the fact that it uses information on cropping and livestock systems and aggregates this information in order to describe agriculture externalities at the regional scale using multi-scale indicators. This type of assessment is rare in the scientific literature despite the large number of studies on agricultural sustainability which mainly focus on a particular sustainability objective at a regional level ([Rusch *et al.*, 2012](#); [Hossard *et al.*, 2015](#); [Bechini *et al.*, 2011](#)) or at the scale of a cropping system ([Sadok *et al.*, 2008](#); [Carof *et al.*, 2013](#)). An integrated assessment at the regional scale using cropping system information enables a synthesis of the main externalities of agriculture at the regional scale and provides a quantitative assessment of changes based on pressure indicators ([Liu *et al.*, 2013](#)). Indicators can show how a change to the system can affect its performance in terms of its contribution to sustainability issues. During our work, we spatially aggregated data from various cropping systems to calculate indicators, so an aggregation of indicator values could be achieved. This was done by aggregating regional values of indicators to provide a global assessment of the sustainability of agriculture at the regional scale, but it could also result from the aggregation of values at a smaller scale (such as a farm) in order to visualize the contribution of farms in all regions to the sustainability of agriculture.

As well as the values provided at the regional scale, the multi-scale indicators are also spatialized on the geographical units of interest so that they can provide information on the heterogeneity of the contribution of fields, farms or sub-regions to a given issue. The spatial explicitness of the approach reveals the different locations within a territory where improvements in sustainable development are necessary. Using this type of analysis, agronomists could design more appropriate cropping and livestock systems for areas with the most important sustainability issues. The range of indicators we recommend is useful not only for the diagnosis of sustainability but also for the ex ante analysis of innovative cropping and livestock systems at the regional scale.

4.2. Relevance of the method to understanding contributions to sustainable development in Guadeloupe

This multi-criteria assessment in Guadeloupe highlighted the decline of the banana cropping system and its replacement by pasture as the main driver of change in the values of indicators between 2004 and 2010. This replacement was positive regarding most of the criteria considering the negative contribution of banana farming systems to economic and environmental sustainability. The results produced on a given year helped to visualize the heterogeneity of the contributions of cropping systems to local issues. For water pollution, decision makers need to focus on pursuing efforts to reduce pollution in south-western Basse-Terre and start to reduce the pressure of cropping systems on water bodies in the northern part of Basse-Terre, such as intensive pineapple production. The observation of mapped indicators, and the characteristics of cropping systems described by farmers will help to understand the contributions of different parts of the region to regional issues and visualize what changes to agricultural practices could be achieved in order to improve these levels. The indicators could then be used as a basis to orient the design of cropping systems and to develop targeted policies that would favour the emergence of new cropping systems.

4.3. Usefulness of the method to decision-makers

The identification of drivers for change helps to prioritize the actions that need to be implemented in the region to improve the contribution of agriculture to its sustainable development ([Wolff et al., 2015](#)). Mapping can help to group homogeneous portions of space and then provide foundations for the design of actions such as environmental protection zones or water catchment protection areas. The cropping system characteristics required to improve the contribution of agriculture to sustainable development may help to identify relevant economic incentives, such as agri-environmental schemes that would encourage farmers to adopt environmentally-friendly farming practices such as reducing the impact of pesticides on water bodies. Examples of such incentives already exist in the French West Indies, such as that which has been prototyped to favour the adoption of composts to enhance carbon sequestration in yam-based cropping systems ([Blazy et al., 2015](#)). Direct or indirect subsidies are important drivers of changes to practices because fixed and transaction costs are key drivers for the adoption of new cropping systems ([Barreiro-Hurlé et al., 2010](#)). More generally, decision-makers also need to facilitate the emergence of new systems by accounting for the entire agricultural innovation system (AIS) that involves not only technical changes but also institutional changes where innovation is the result of networking and interactive learning processes among heterogeneous stakeholders ([Klerkx et al., 2010](#)).

Implementing these indicators in a regional model that simulates farmers' decision-making processes with respect to the allocation of cropping systems that produce agricultural land systems, could be achieved in order to assess the sustainability of new agricultural land systems at the regional scale. Scenario analysis conducted during a participatory process with decision-makers using these indicators would help the design of policies ([Walz et al., 2007](#)). Using this assessment, policy-makers can visualize the contribution of current cropping systems to sustainable development and explore the changes to sustainability that would be possible with new cropping systems.

4.4. Uncertainties affecting the method

Uncertainties may arise from: (i) imprecise indicators, (ii) the choice of indicators with policy-makers in the second step, (iii) the definition of cropping and livestock systems in the fourth step and iv) the absence of an aggregation of indicators so as to better compare agricultural landscapes. First, the indicators could have been more precise if a more detailed knowledge of the processes assessed (such as pollution) had been available. Likewise, the information and knowledge required to calculate the indicators needed to be available for the entire study area. For instance, pollution is difficult to assess because the sorption/desorption process and the mobility of different types of molecules in the ranges of tropical soils are still not fully understood. The variability of soil types in Guadeloupe makes it difficult to predict a level of pollution, which is why we constructed an indicator that could assess the potential for pollution thus simplifying the parameter values, such as the type of soil in the Rpest indicator. For this type of indicator, a comparison of values at the regional scale over different years should take priority over the value itself, considering the significant simplification of the process of water fluxes in soils. In the same way, food self-sufficiency does not account for the diversity of the foods produced. This is due to the fact that information is lacking on some cropping systems (such as horticulture or orchard cropping systems) regarding the exact nature of certain crops. We considered different crop management pathways that were the same; for instance, considering pepper or squash for horticulture, or avocados and guava for orchard, despite the different nature of the fruits or vegetables produced. Secondly, the choice of indicators could have been different and better targeted for decision-making with policy-makers involvement in this step, so as to ensure a better match between the indicators and the expectations of policy-makers. However, due to the lack of knowledge among policy-makers of the parameters involved in certain complex biophysical processes such as water pollution, the indicators were not co-constructed with policy-makers. For this reason, stakeholders were only involved in the selection of local and global issues and not in the choice of indicators that could be appropriate for our case study. Third, a lack of precision could also be due to the description of cropping systems, because

diversity is masked by the type of cropping system described. This was due to the lack of a database with individual descriptions of crop management systems. However, the use of simplified data can nevertheless provide information and highlight areas to which policy-makers should pay attention. Fourthly, the indicators and issues were not aggregated, so it remained difficult for decision makers to obtain an overview of agricultural sustainability and its contribution to society. Nonetheless, our multi-scale assessment could help decision makers to understand their territory and the geographical variations in the contribution of different units to the sustainability of local agriculture. It can also identify the weakest components that require special economic, social or environmental policies or improvements ([Bockstaller et al., 2008](#); [Bockstaller et al., 2015](#)).

5. Conclusions

This paper describes a new method for the assessment of agriculture at the regional scale based on a set of indicators enabling both ex post and ex ante assessment. The method allocates a global score to each indicator at the regional scale and reveals the heterogeneity of the contributions of agriculture to sustainability issues at different times. The regional values and spatialisation of these indicators could help decision-makers to understand the origins of the level of sustainability by studying the heterogeneity of the contributions of fields to different sustainability issues. This assessment can provide a basis to explore changes to cropping and livestock systems at the field scale alongside relevant technical, agronomic, environmental, and economic or policy changes. The indicators developed here will be particularly useful in scenario analysis when exploring the possible impacts of a range of the aforementioned changes on the contribution of agriculture to the sustainable development of regions. A major challenge for future regional sustainability assessments will be the comprehensive aggregation of indicators and goals in order to assess the impact of a very broad range of policies on the sustainability of agriculture and its contribution to the sustainable development of societies.

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Supplementary material

Regional Indicator	Calculation	Variables used
Total farm income	$AAV = \sum_{p=1}^P \sum_{c=1}^C (Pb(c) - VC(c) * X(p, c))$	<p>p : fields</p> <p>c : cropping system</p> <p>Pb(c) : product of the crop sales c (€.yr⁻¹)</p> <p>VC(c) : variable costs of the crop c (€.yr⁻¹)</p> <p>P: total number of plots (in our case study 11,908)</p> <p>C: total number of cropping and livestock systems (in our case study 21)</p>
Distribution of the AAV among the farmer population	$Gini = \frac{2 * \sum_{f=1}^F Rev(f) * Rank(f)}{Nb_f * \sum_{E=1}^E Rev(f)} - \frac{Nb_f + 1}{Nb_f}$	<p>Rev(f): revenue of farm f (€.yr⁻¹)</p> <p>Rank(f): rank of farm income in the farm population (ascending order)</p> <p>Nbf: number of farms in the population (in our case study 3,591 farms)</p>
Total amount of subsidies	$Sub = \sum_{p=1}^P \sum_{c=1}^C (Yie(c) * Sbc(c) + Sbd(c) * X(p, c))$	<p>Yie(c): yield of crop c (ton.ha⁻¹.yr⁻¹)</p> <p>Sbc (c): Subsidies coupled to production (€.ton⁻¹)</p> <p>Sbd(c): Subsidies decoupled to production (€.ha⁻¹.yr⁻¹)</p>
Ratio of produced carbohydrates to needs	$GLU = \frac{\sum_{p=1}^P \sum_{c=1}^C Glu(c) * Yie(c) * X(p, c)}{GluN * popsize}$	<p>Glu(c): carbohydrate content of 1 ton of crop c (kg.ton⁻¹)</p> <p>Yie(c): yield of crop c (ton.ha⁻¹.yr⁻¹)</p> <p>GluN: carbohydrate needs of an</p>

		average person (kg.yr ⁻¹ .pers ⁻¹) popsi ze: size of the population considered (pers)
Ratio of produced proteins to needs	$PROT = \frac{\sum_{p=1}^P \sum_{c=1}^C Prot(c) * Yie(c) * X(p,c)}{ProtN * popsi$	Prot(c) : protein content of 1 ton of crop c (kg.ton ⁻¹) ProtN : protein needs of an average person (kg.yr ⁻¹ .pers ⁻¹)
Ratio of produced fats to needs	$LIP = \frac{\sum_{p=1}^P \sum_{c=1}^C Lip(c) * Yie(c) * X(p,c)}{LipN * popsi$	Lip(c) : fat content of 1 ton of crop c(kg.ton ⁻¹) LipN : fat needs of an average person (kg.yr ⁻¹ .pers ⁻¹)
Total workforce needs	$JOB = \sum_{p=1}^P \sum_{c=1}^C Work(c) * X(p, c)$	Work(c) : workforce required for crop c (pers.ha ⁻¹)
Area of risk of contamination of food crops	$CLD = \frac{\sum_{p=1}^P \sum_{c=1}^C Cld(c) * X(p,c)}{Atot}$ on field with a pollution risk	Cld(c) : crop potentially contaminated by chlordecone (qualitative score) Atot : total agricultural area (ha)(in our case study 13,889 ha)
Percentage area with a risk for birds in high-value ecological zones	$BIRD = mean(\sum_{p=1}^P \sum_{c=1}^C \frac{D(pes) * QAI(pes)}{LD50(pes)} * X(p, c)$ For all fields located in high-value ecological zones	D(pes) : dose of the pesticide (pes) (L.ha ⁻¹) QAI(pes) : quantity of active ingredient (pes) (g.L ⁻¹) LD50(pes) : acute toxicity of pesticide (pes) for the bird population (g)
Number of potentially polluted rivers	RPEST(p,c) => Decision Tree $RPEST = \frac{\sum_{c=1}^C RPEST(p,c) * X(p,c)}{X(p)}$	RPEST(p,c) : Decision tree from Tixier <i>et al.</i> (2006) encompassing the ➤ Quantity of active ingredients (L.ha ⁻¹) ➤ Quantity of runoff based
Number of potentially		

polluted sources of water abstraction	for $RPEST(p,c) > 7$	<p>on expert knowledge for each type of soil ($m^3 \cdot ha^{-1} \cdot yr^{-1}$)</p> <ul style="list-style-type: none"> ➤ Half-life of the active ingredient in the environment (days) ➤ Acute reference dose obtained from the EU pesticide database ($g \cdot kg^{-1}$) ➤ LD50: toxicity for fish ($g \cdot kg^{-1}$) ➤ Groundwater ubiquity score ➤ Drainage obtained based on expert knowledge ($m^3 \cdot ha^{-1} \cdot yr^{-1}$)
Number of potentially polluted water catchments		
Amount of water used for irrigation	<p>IRR (p) $= \sum_{m=1}^{12} (H2O_{need}(c) - Rain(p)) * X(p,c)$</p> <p>IRRI $= \sum_{p=1}^P IRRI(p)$</p>	<p>H2O need(c): crop water needs are determined based on the crop coefficient K_c and yearly mean evapotranspiration ($m^3 \cdot month^{-1}$)</p> <p>m : month</p> <p>Rain(p): rainfall is determined based on the mean levels of rainfall per month based on 30 years of data ($mm \cdot month^{-1}$)</p>
Percentage of the area potentially eroded due to farming practices	<p>RERO(p,c) => Decision tree</p> <p>RERO $= \frac{\sum_{c=1}^C X(c,f) * RERO(p,c)}{X(f)}$</p> <p>for $RERO(f) > 7$</p>	<p>RERO(p,c): decision tree based on:</p> <ul style="list-style-type: none"> ➤ the type of soil ➤ the crop cover (%) ➤ the number of mechanized interventions ($nb \cdot yr^{-1}$) ➤ furrow depth (cm) ➤ rainfall ($mm \cdot yr^{-1}$)
Total emissions of CO ₂ from farming	$CO_2 = \sum_{p=1}^P \sum_{c=1}^C \sum_{otk=1}^{OTK} GES(p, c, otk)$	GES (p,c,otk) : CO ₂ equivalent produced by agricultural practices (otk) for crop c on plot p ($kg \text{ eq CO}_2$)

activities		
Energy produced by crops	$ELEC = \sum_{p=1}^P \sum_{c=1}^C Elec(c) * Yie(c) * X(p, c)$	Elec(c) : potential production of electricity from one ton of biomass (MW.yr ⁻¹)
Diversity of crops across the landscape	$ISDI(subR) = \frac{1}{\sum_{c=1}^C P(subR, c)^2}$ $ISDR = \frac{\sum_{SubR=1}^{SUBR} ISDI(subR)}{nbSubR}$	ISDI(subR) Reciprocal Simpson's Diversity Index in sub-regions P(subR,c) : proportion of crop c in sub-regions (%) nbSubR : number of sub-regions considered

Table: Details of the calculation of the regional indicators for a sustainability assessment

Indicators	Information required on cropping system	Intensive banana cropping systems
Total farm income	Yield Price of crops Costs of practices Subsidies Gross margin	44 ton.ha ⁻¹ 540€.ton ⁻¹ 32540 €.ha ⁻¹ 19197 €.ha ⁻¹ 10417 €.ha ⁻¹
Distribution of agricultural income among the farm population	Gross margin	10417 €.ha ⁻¹
Total amount of subsidies	Subsidies	19197 €.ha ⁻¹
Ratio of produced carbohydrates to needs	Carbohydrate content	228 kg.ton ⁻¹
Ratio of produced proteins to needs	Protein content	10.9 kg.ton ⁻¹
Ratio of produced fat to needs	Fat content	3.3 kg.ton ⁻¹
Potential energy that could be produced by the crop	MW	0 kW.ton ⁻¹
Total workforce required	Number of people	0.9 pers.ha ⁻¹
Area of risk of contamination of food crops	Uptake of Chlordecone	No
Percentage of area with a risk for birds in high-value ecological zones	Quantity of active ingredient Mean LD50	7.8 kg.ha ⁻¹ 20 mg.kg ⁻¹
Number of potentially polluted rivers	Mean DT50	20 days
Number of potentially polluted sources of water abstraction	Mean Dose of QMA Mean ADI	7.8 kg.ha ⁻¹ 0.025 mg.day ⁻¹
Number of potentially polluted water catchments	Mean Aquatox Mean Groundwater Ubiquity Score (GUS)	824 mg.L ⁻¹ 3.54
Criticality ratio of water use for the irrigation of crops	Crop coefficient	1.2
Percentage of the area that is potentially eroded due to farming practices	Crop cover Furrow depth Number of uses of heavy machinery	80% 35 cm 0.2 times.yr ⁻¹
Overall emissions of CO ₂ from farming activities	Eq CO ₂	0.7 kg eq CO ₂ .kg ⁻¹ of fruit
Diversity of crops across the landscape	Crop category	"Banana"

Table: Description of cropping systems: example of the intensive banana cropping system.