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Prototypage de mosaïques de systèmes de culture répondant à des enjeux de développement durable des territoires ; application à la Guadeloupe

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Résumé

L'agriculture actuelle est impliquée dans de multiples problématiques environnementales, sociales et économiques, aux échelles locales et globales. En agronomie, de nombreux travaux à l'échelle du champ et de l'exploitation visent aujourd'hui à concevoir des systèmes de culture et des systèmes de production en lien avec ces problématiques. En revanche, peu de travaux portent sur la conception et l'évaluation de systèmes agricoles à l'échelle du territoire, alors que cette échelle apparaît pourtant incontournable pour faire face à des enjeux de développement durable.

Pour combler ce manque, nous proposons un ensemble méthodologique permettant i) de simuler les conséquences de scénarios de politiques agricoles sur les choix d'assolement des agriculteurs, décrits individuellement, en modélisant l'évolution de leurs système de production et ii) d'évaluer l'impact de ces changements d'assolements à l'échelle du territoire, à l'aide d'indicateurs qui apportent de l'information spatiale sur la contribution de l'agriculture au développement durable.

L'ensemble méthodologique proposé débute par la construction d'une typologie des exploitations agricoles du territoire sur la base de la similarité de leur assolement. Parallèlement, l'adaptation d'indicateurs à l'échelle du territoire permet d'évaluer les impacts des externalités des systèmes de culture en mobilisant des procédures de changements d'échelles. Un modèle bioéconomique générique, multi-échelle, spatialement explicite, appelé MOSAICA, qui utilise la typologie et les indicateurs d'impact de l'agriculture à l'échelle régionale, est créé pour produire des mosaïques de systèmes de culture et évalue leur contribution au développement durable du territoire. Ce modèle, couplé à un itinéraire de définition de scénarios exploratoires et normatifs permet de tester l'impact de différents types de leviers agronomiques, socio-économiques, environnementaux, organisationnels et techniques sur les choix des exploitants et *in fine* sur la contribution de la mosaïque de systèmes de culture au développement durable du territoire.

Nous avons appliqué cet ensemble méthodologique à la conception de scénarios de développement agricoles durables en Guadeloupe. Nous avons dans un premier temps développé une typologie des systèmes de production comprenant huit types distincts et relevant de processus décisionnel différents. Puis nous avons adapté à l'échelle du territoire 19 indicateurs pour l'évaluation des mosaïques de systèmes de culture. L'évaluation de la mosaïque actuelle nous a permis de repérer de faibles niveaux de contribution aux enjeux d'autonomie alimentaire et énergétique. Différents scénarios normatifs et exploratoires intégrant des leviers de changement de la mosaïque ont été testés avec MOSAICA. Les évaluations réalisées nous ont permis d'identifier que des leviers agronomiques comme le développement du maraîchage sans intrants chimiques et des leviers sociaux comme la formation de main-d'œuvre supplémentaire permettraient d'améliorer la contribution de l'agriculture au développement durable du territoire Guadeloupéen.

La modélisation mécaniste de l'évolution du territoire agricole permet d'intégrer des connaissances sur la localisation, les performances, les impacts des systèmes de culture et sur les processus décisionnels des exploitants régissant l'orientation productive et le fonctionnement des exploitations. Cette démarche permet de visualiser les changements de système de culture et leurs impacts de manière spatialement explicite, ce qui permet de générer des connaissances sur les leviers susceptibles de faire évoluer positivement l'agriculture du territoire. La démarche et les outils mis en œuvre sont donc particulièrement utiles pour l'aide à la décision publique pour améliorer la durabilité de l'agriculture dans son ensemble.

Abstract

Current agricultural systems are responsible for many different environmental, social and economic issues at both local and global scales. Agricultural sciences have contributed to the design of several methods at the farm and field scale in order to prototype cropping systems and farming systems to address these issues. However, few methods have been designed at the regional scale, while this scale seems to be essential in order to address these issues.

In order to fill this gap, we here propose a new methodological framework for i) simulating the consequences of policy changes on farmer's cropping plan, described individually, by modeling the evolution of farming systems and to ii) assess the impacts of cropping system changes at the regional scale, with a set of indicators that generate spatially explicit information on the contribution of agriculture to sustainable development.

The methodological framework starts with the design of a farm typology over the territory based on the similarity of farmer's crop acreages. In parallel, a set of indicators is adapted to the landscape scale in order to assess the impacts of cropping system externalities by integrating a set of scale change procedures. A generic, multi-scale, spatially explicit bioeconomic model called MOSAICA, which uses the farm typology and the indicators, is created for generating cropping system mosaics and assessing their contribution to sustainable development. This model coupled to a scenario approach composed of exploratory and normative scenarios can simulate the impact of several types of agronomic, socio-economic, environmental, organizational and technical levers of change on the farmer's choices in terms of cropping systems and *in fine* the impacts of new cropping system mosaics on the contribution to sustainable development of territories.

We applied this methodological framework for building scenarios of sustainable agricultural development in Guadeloupe. We first developed a typology of farming systems encompassing eight types of farming systems that revealed several different farmer's decision processes. Then, we developed 19 indicators to assess cropping system mosaics. The assessment of the current cropping system mosaic showed low levels of response of the current mosaic to economic and social issues especially the food and energy self-sufficiency. Different normative and exploratory scenarios integrating levers of change have been simulated with MOSAICA. The assessment of cropping system mosaics from these scenarios highlighted the positive effect of agronomic levers of change such as organic crop-gardening and social levers such as the vocational training of supplementary workforce for improving the contribution of agriculture to sustainable development of the guadeloupean territory.

The mechanistic modeling of the agricultural territory allows us to integrate a wide range of knowledge on the location of cropping systems, their levels of performance , their impacts and the decision process of farmer's that drive the farming system characteristics and the farm functioning. This methodological framework helps visualize the cropping system changes at the regional scale and their associated impacts at the landscape scale which is helpful in order to produce knowledge on the levers of change that can improve the response of local agriculture to local and global issues. The framework and tools designed are particularly useful for decision-aid on the future levels of contribution of agriculture to sustainable development.

Sommaire

Introduction générale

Défis pour l'agriculture

L'agriculture doit faire face à de grands défis au cours du XXIème siècle : répondre aux besoins croissants en nourriture de l'humanité et limiter simultanément ses impacts environnementaux, dans un contexte de changements globaux marqués.

Alors que selon le dernier rapport de la FAO (2013), 805 millions de personnes souffrent de sous-alimentation de manière chronique, la fonction première de l'agriculture reste de nourrir en qualité et en quantité suffisante une population totale dont on estime qu'elle va augmenter pour atteindre 9,6 milliards d'habitants en 2050 (United Nations, 2012). Cette augmentation, doublée de changements d'habitudes alimentaires des habitants des pays émergents, va entraîner une croissance des besoins en nourriture estimée à 70% d'ici 2050 (FAO, 2009).

Parallèlement, l'agriculture devra aussi limiter :

- sa contribution au changement climatique : l'agriculture est responsable depuis 1850 d'environ 10 à 15% des émissions anthropogéniques de gaz à effet de serre résultant directement de l'usage des terres (Smith *et al.,* 2007) ;
- la perte de biodiversité : l'agriculture est contributrice de la diminution de la biodiversité (Millenium Ecosystem Assessment, 2005 ; Nelson *et al.,* 2006);
- sa forte consommation en eau : l'agriculture réalise des prélèvements en eau de 3900 km^3 annuellement, et dans de nombreuses zones cet usage entre en conflit avec d'autres usages, comme la consommation d'eau potable par les populations ;
- son impact négatif sur la qualité des eaux superficielles et souterraines dû aux pollutions par les pesticides et engrais (Tilman *et al.,* 2011).

D'autres enjeux environnementaux doivent également être traités mais ces quatre enjeux résument les impacts négatifs que peut avoir l'agriculture sur l'environnement (Foley *et al.,* 2011).

Sur des territoires comme la Guadeloupe où elle s'étend sur 27% du territoire (Agreste, 2006), l'agriculture, de par sa nature d'activité économique est porteuse d'enjeux socio-économiques très forts. Elle emploie 1.7 % de la population active en Guadeloupe (Agreste, 2011) et représente 2,6 % du produit intérieur brut de la région, soit 268 millions d'euros de production agricole totale en valeur en 2009.

L'agriculture doit donc assurer sa fonction primaire de production de nourriture, tout en répondant aux problématiques environnementales et socio-économiques locales et globales, dont elle est directement ou indirectement responsable.

Conception de systèmes agricoles à différentes échelles spatiales

La conception de nouveaux systèmes agricoles est une piste de réponse importante de l'agronomie à ces problématiques de développement durable. Elle est déclinée à différentes échelles spatiales : l'échelle du champ, de l'exploitation et du territoire. Le territoire correspond à un espace géographique de coexistence des différents usages du sol, qui contribuent chacun à la production de services pour la société, et dont l'évolution est orientée par les politiques mises en œuvre par les décideurs. Ces services ecosystémiques sont les bénéfices que l'homme tire directement ou indirectement des fonctions de l'écosystème (Costanza *et al.,* 1997).

Au niveau du champ, échelle à laquelle l'agriculteur met en œuvre ses pratiques, ce travail de conception englobe le diagnostic agronomique, la modélisation biophysique du champ cultivé et l'expérimentation système permettant de modéliser et comprendre les interactions entre les pratiques agricoles au champ et leurs conséquences sur la plante et l'environnement, en fonction du climat et des sols notamment (Loyce et Wery, 2006).

Parallèlement, l'attention de l'agronome s'est portée sur la place de ce système de culture dans un système plus grand : le système de production mis en œuvre à l'échelle de l'exploitation agricole par l'agriculteur. Ce système recouvre la combinaison d'activités (systèmes de culture) et l'allocation de facteurs de production ou ressources de l'agriculteur aux différentes activités de l'exploitation agricole (Edwards-Jones, 2007). L'agronome s'intéresse alors aux composantes techniques du système de production, à l'organisation du travail, à l'assolement de l'agriculteur en lien avec la prise de décision de l'agriculteur qui traduit l'expression de ses contraintes et objectifs personnels.

Aujourd'hui, l'agriculteur est soumis à un ensemble de contraintes politiques, techniques, institutionnelles, climatiques, exogènes à son exploitation et doit répondre à des objectifs qui dépassent les frontières de son exploitation. De plus, on constate des difficultés à évaluer les impacts de l'agriculture à l'échelle du territoire, échelle à laquelle les décideurs souhaitent définir les politiques de développement. Ces difficultés viennent du décalage entre des informations disponibles sur les pratiques agricoles à l'échelle de la parcelle et le besoin d'information à l'échelle du territoire (Pelosi *et al.,* 2010). Jusqu'à présent, les agronomes se sont plutôt tournés vers le développement de méthodes d'évaluation de la durabilité des systèmes de culture à l'échelle du champ et des exploitations (Carof *et al.,* 2013). Cependant le développement récent de méthodes de changement d'échelles peut aider à transférer les informations parcellaires du champ au territoire afin d'évaluer la durabilité de l'agriculture à l'échelle du paysage.

La science agronomique est confrontée à la nécessaire prise en compte de ces interactions entre les activités agricoles à l'échelle du champ et de l'exploitation, les processus environnementaux et les dynamiques des territoires à l'échelle régionale. Cette préoccupation a participé à l'émergence de l'agronomie du paysage, ou "*landscape agronomy*" (Benoit *et al.,* 2012), qui consiste à comprendre les relations entre les systèmes de production conduits par les agriculteurs, les paysages agricoles créés par ces pratiques et leurs impacts sur les ressources naturelles à l'échelle du paysage. En tant que discipline scientifique, l'agronomie du paysage vise à alimenter la réflexion sur la production de nouvelles organisations et compositions du paysage agricole qui amélioreraient la fourniture de services à la société d'une manière plus durable. Elle permet d'envisager une meilleure prise en compte de l'hétérogénéité biophysique du territoire, de l'hétérogénéité des structures d'exploitation, de la localisation des différentes parcelles, des exploitations les unes par rapport aux autres ainsi que de leur possible complémentarité (prêt de matériel, partage d'une même ressource...). L'agronomie du paysage peut donc contribuer la conception de nouveaux systèmes agricoles à l'échelle du territoire, c'est-à-dire à la création de nouvelles mosaïques de systèmes de culture, en prenant en compte les différents paramètres agronomiques, biophysiques, structurels, socio-économiques des niveaux inférieurs. Ces mosaïques correspondent à des agencements spatialement explicites de systèmes de culture alloués aux parcelles à l'échelle du territoire (Vasseur *et al.,* 2013). Les changements dans la mosaïque des systèmes de culture représentent des moyens d'évolution du territoire agricole vers un plus grand niveau de durabilité du territoire. La place des agriculteurs y est centrale car ce sont les concepteurs de ces nouveaux paysages par leur choix à l'échelle parcellaire. Il est donc nécessaire dans cette réflexion sur le devenir du territoire agricole de comprendre la façon dont les agriculteurs pensent, conçoivent et construisent leurs systèmes de culture et comment ils contribuent ainsi à la production de nouveaux paysages (Deffontaines, 1996).

A l'instar de ce qui est pratiqué à l'échelle du champ, la modélisation peut être mobilisée pour la conception de systèmes à une échelle englobante. La modélisation de territoires agricoles performants en termes de fourniture de services ecosystémiques est un exercice compliqué, très peu éprouvé actuellement. Elle nécessite de nouvelles méthodes qui permettent de prendre en compte simultanément le fonctionnement du champ cultivé, la prise de décision de l'agriculteur et les logiques territoriales ainsi que les liens entre ces différents éléments pour représenter les conséquences de choix parcellaires à l'échelle de tout un territoire. Les méthodes actuelles se sont limités aux études de "*land use planning*" qui présentent des limites dans l'appréhension de la diversité des systèmes de culture et qui ne représentent pas suffisamment les processus décisionnels des agriculteurs. Face à ces constats, l'objectif principal de la thèse présentée dans ce document est de proposer un ensemble méthodologique visant à la compréhension et la modélisation du fonctionnement des systèmes agricoles à l'échelle du territoire pour apporter de l'information aux décideurs sur les moyens d'orienter les systèmes agricoles actuellement en place vers la satisfaction d'objectifs de développement durable et la résolution d'enjeux territoriaux.

Dans le premier chapitre, nous présentons un état de l'art sur les méthodes de conception et évaluation des systèmes agricoles. Nous identifions des manques dans les méthodes actuelles, dans la capacité à embrasser l'échelle du territoire. Ces manques sont traduits en deux objectifs de recherche qui sont traités par les quatre étapes de l'ensemble méthodologique présenté dans la thèse. Le territoire de la Guadeloupe, cas d'application de la méthode, est par la suite introduit ainsi que son agriculture. Puis l'application de notre méthode au territoire de la Guadeloupe est présentée sous forme d'articles scientifiques en anglais. Le dernier chapitre discute de manière critique l'ensemble méthodologique proposé et le travail réalisé en Guadeloupe, en pointant notamment les limites et les améliorations à conduire par la suite.

1. Problématique et démarche d'ensemble

Ce chapitre vise tout d'abord à dresser un bilan sur les méthodes de conception et d'évaluation de mosaïque de systèmes de culture à l'échelle du territoire. A travers cet état de l'art nous identifierons des pistes d'amélioration de ces méthodes, qui guideront la mise en place de notre ensemble méthodologique. Nous présenterons ensuite l'ensemble proposé en réponse à ces fronts de sciences et aux défis environnementaux et socio-économiques présentés dans l'introduction générale. Nous terminons ce chapitre par la présentation du territoire de la Guadeloupe et des enjeux de l'agriculture dans cet espace.

1.1.Besoin d'approches de conception à l'échelle du territoire

La conception de systèmes agricoles à l'échelle du champ et de l'exploitation a montré des limites en termes de réponse à des problématiques de développement durable locales et globales. Les démarches de conception à ces échelles ont vu la proposition de solutions inadaptées, à la diversité du milieu biophysique et du contexte socio-économique des exploitations agricoles du territoire, (Dale *et al.,* 2013; Antle and Stoorvogel, 2006). Ces méthodes de conception ne prennent pas suffisamment en compte l'organisation et la nature des systèmes de culture et des systèmes de production mis en œuvre par les agriculteurs à l'échelle du territoire, alors que ces éléments conditionnent la contribution de l'agriculture à répondre à ces problématiques locales et globales. L'échelle du territoire apparaît comme particulièrement adaptée pour observer les impacts agrégés de la mise en œuvre des système de culture sur les parcelles (Meynard *et al.,* 2008; Thieu *et al.,* 2011).

Afin de mieux orienter la réponse de l'agriculture aux problématiques de développement locales et globales, présentées dans l'introduction, il est nécessaire d'adopter une démarche de conception de systèmes agricoles à l'échelle du territoire (Dale *et al.,* 2013 ; Benoit *et al.,* 2012).

1.2.Le territoire agricole : un concept complexe à bien définir

Le territoire est un objet d'étude polysémique complexe. Parmi les nombreuses définitions qui lui sont attribuées par un ensemble d'auteurs issus de différentes disciplines (géographie, économie, sociologie...), nous avons retenu dans la thèse les définitions suivantes :

- la portion de surface terrestre appropriée par un groupe social pour assurer sa production et la satisfaction de ses besoins vitaux (Le Berre, 1992) ;
- un support biophysique qui conduit à la production de denrées agricoles consommables et de différents services rendus par l'agriculture (Deffontaines and Thinon, 2001);
- un espace politique au sein duquel des acteurs interagissent et contribuent à son évolution (Laganier *et al.,* 2002).

L'agriculture, une des utilisations possibles des territoires, contribue fortement à son aménagement et à sa structuration économique, sociale et écologique. Les agriculteurs, acteurs premiers de la production agricole, construisent, orientent l'utilisation de leur territoire par leur choix de pratiques dans le temps et modifient ainsi la contribution de l'agriculture au développement durable du territoire (Deffontaines *et al.,* 1993).

Le scénario est un outil particulièrement prisé pour étudier le devenir du territoire à travers des travaux de prospective par exemple. Nous en présentons ici les caractérsitiques.

1.3.Scénarisation

1.3.1. Définition

Les scénarios sont décrits comme des séquences hypothétiques d'évènements futurs qui conduisent un système donné d'un état initial à un état final dans le futur (Kahn and Wiemer, 1967). Leur utilisation s'est fortement développée pour les études environnementales où il s'agissait d'évaluer des impacts environnementaux sur un système donné et d'identifier la pertinence de politiques en matière d'environnement. L'IPCC (GIEC en français) décrit les scénarios comme des images du futur, c'est-à-dire des futurs alternatifs qui ne sont ni des prédictions ni des prévisions mais qui sont des images alternatives de comment le futur pourrait voir le jour (Nakicenovic *et al.,* 2000 ; Patel *et al.,* 2007). Les scénarios attirent l'attention, aident à « penser en grand », à penser globalement, ils forment un pont entre les experts (par exemple les chercheurs) et les politiques (Börjeson *et al.,* 2006 ; Meyer, 2007).

1.3.2. Eléments des scénarios

Selon Leenhardt *et al.(*2012), les éléments suivants peuvent être inclus dans les scénarios :

- Une situation initiale du système qui correspond à la description du système pour une année de référence appelée année de base
- Les forces de changement qui sont les changements internes ou externes au système
- L'évolution du système, qui est le changement de trajectoire du système sous l'impact des forces de changements
- L'image du système dans le futur, aussi appelée situation finale
- L'impact qui permet de comparer les images dans le futur

L'impact s'apparente à l'évaluation des conséquences du scénario avec des indicateurs, et qui permettent finalement de juger des améliorations apportées au système par le scénario. Cette évaluation se fait généralement à partir de scénarios quantitatifs car ils permettent de chiffrer une situation future en utilisant des modèles et des indicateurs pour la génération d'informations et/ou de données numériques.

1.3.3. Types de scénarios

Trois types de scénarios sont principalement développés dans les démarche de scénarisation : les scénarios tendanciels, normatifs et exploratoires (Van Notten *et al.,* 2003 ; Godet *et al.,* 1994 ; Ducot *et al.,* 1980 ; Shearer *et al.,* 2005 ; Westhoek *et al.,* 2006) :

Le scénario tendanciel également appelé scénario «baseline » ou « business as usual » traduit le devenir du système étudié dans le cas où aucune nouvelle politique n'intervient. Les scénarios exploratoires également appelés scénarios descriptifs sont des scénarios qui débutent dans le présent et explorent des tendances possibles d'évolution dans le futur. Ce sont des scénarios qui incluent des forces de changement ("drivers") qui peuvent être spatialement différenciées. Les scénarios normatifs débutent avec une vision du futur, qui peut être optimiste, pessimiste, ou neutre et visent à conduire une analyse « à reculons » pour visualiser comment ce futur pourrait émerger.

La combinaison des différents types de scénarios est particulièrement utile pour étudier le potentiel d'un système agricole donné en termes de réponse à des problématiques de développement durable à l'échelle du territoire (Nassauer *et al.,* 2004).

La réflexion sur le devenir du territoire fait face à la difficulté de mise en place d'expérimentations à cette échelle. L'étude du devenir du territoire et l'évaluation de la contribution des usages des sols au développement durable doit donc se faire à travers la modélisation des externalités des différents usages des sols.

1.4. Modéliser le territoire agricole pour représenter ses évolutions possibles

La gestion du territoire concerne les actions et décisions qui impactent l'espace géographique : sa structure, sa composition, ses propriétés, de manière plus ou moins permanente. Les principales études qui traitent de cet aspect sont les études de land use planning, qui visent à planifier l'usage des sols.

1.4.1. Planification des usage des sols à l'échelle du territoire

Ces études portent sur l'évolution des différents usages du sol au sein des territoires : les usages agricoles, urbains et forestiers. Elles ont plusieurs buts parmi lesquels i) l'analyse de l'évolution de ces usages dans le passé, ii) la compréhension des déterminants de ces évolutions, iii) la visualisation des états du territoire à travers des scénarios socio-économiques et environnementaux, iv) la détermination des effets de ces scénarios d'un point de vue environnemental, économique et social (Veldkamp and Fresco, 1996 ; Irwin and Geoghegan, 2001).

Toutefois, dans ces études, les logiques agronomiques de localisation des cultures ou de performances agronomiques ne sont pas prise en compte car les différentes espèces cultivées sont rassemblées sous la forme d'un usage unique appelé "agricultural use". Certaines études présentent une diversité d'usages agricoles plus large en cartographiant une différenciation par type de culture. Mais ces exemples, plutôt rares, ne prennent pas en compte la diversité de conduite des différentes espèces cultivées sur le territoire. Cette limite est due notamment aux étendues très larges sur lesquelles ces études sont réalisées qui contraignent le grain auquel la diversité des pratiques est approchée. C'est un problème car les changements dans la gestion des cultures peuvent avoir de plus grandes conséquences sur l'environnement, la société et l'économie que les changements de culture seuls (Ellis and Ramankutty, 2008). Dans ces études, la parcelle et l'exploitation agricole disparaissent au profit d'un pixel large qui simplifie la diversité des pratiques agricoles et des processus biologiques et décisionnels qui interviennent au sein du territoire.

Pour mieux évaluer l'impact des changements de gestions des cultures, il est nécessaire d'intégrer le concept de système de culture dans ces travaux de planification des usages à l'échelle du territoire.

Le système de culture correspond à l'ensemble des modalités techniques mises en œuvre sur des parcelles cultivées de manière identique. Chaque système se définit par la nature des cultures et leur ordre de succession et les itinéraires techniques appliqués à ces différentes cultures (Sebillotte, 1974). Le système de culture s'intègre dans un système plus grand, le système de production. Un système de production agricole se définit comme étant une combinaison d'activités (comprenant les systèmes de culture) utilisant de la main d'œuvre, de la terre, de l'équipement, de la connaissance et les ressources en capital sur une période et un espace donnés pour la productions de biens, consommés sur la ferme ou vendus, et de services ecosystémiques (Boiffin *et al.,* 2004).

La recherche agronomique initialement très active sur les fronts de recherche de modélisation à l'échelle du champ et de l'exploitation agricole, se porte désormais sur la modélisation de changements de systèmes de culture à l'échelle du territoire. Ce territoire est perçu comme une entité spatiale d'organisation des systèmes de culture des agriculteurs qui comprend ou non des éléments non agricoles. Le scénario décrit alors des modifications des facteurs d'organisation des systèmes de culture, comme les déterminants de la localisation des systèmes de culture ou de leur adoption par les agriculteurs. Leurs conséquences sont modélisées en termes de réorganisation de la mosaïque de systèmes de culture et d'impacts sur la contribution de l'agriculture au développement durable du territoire.

1.4.2. Modélisations agronomiques à l'échelle du territoire

Des recherches sur l'impact de l'agencement spatial, temporel et spatio-temporel des systèmes de culture sur des processus biologiques ont été réalisées ces dernières années et ont mobilisé des modèles mathématiques. Ces modèles s'appuient sur la formalisation d'un ensemble de règles temporelles et spatiales pour l'allocation des systèmes de culture afin de créer des mosaïques de systèmes de culture en vue de répondre à un objectif donné. Ainsi ces travaux ont donné lieu à la modélisation de l'impact de mosaïques de systèmes de culture sur les transferts de pollen entre culture OGM et non OGM (Castellazzi *et al.,* 2010), sur des processus érosifs (Ronfort *et al.,* 2011), sur la diffusion de maladies (Hossard *et al.,* 2013), ou encore l'évolution de populations de ravageurs (Rusch *et al.,* 2011).

Ces modèles intègrent généralement des règles de localisation des cultures qui émanent de descriptions des systèmes de culture. Cette description peut se faire par télédétection, utilisation de bases de données ou expertise (Leenhardt *et al.,* 2010). Toutefois, la télédétection ne permet pas de différencier les systèmes de culture pour une même espèce sauf au niveau des rotations tout comme l'utilisation de base de données pour lesquelles seules les successions culturales sont décrites (Leenhardt *et al.,* 2010 ; Plourde *et al.,* 2013). L'expertise permet de contourner ce problème en associant par exemple à une succession de culture des itinéraires techniques particuliers déterminés à dires d'expert (Mignolet *et al.,* 2007 ; Clavel *et al.,* 2011).

Certaines limites découlent du développement actuel de ces modèles agronomiques à l'échelle du territoire:

Ces modèles sont statistiques ou empiriques et ne rendent pas compte du processus décisionnel de l'agriculteur face à des changements socio-économiques ou environnementaux, ou à l'introduction de nouveaux systèmes de culture à différentes échelles spatiales. Ces leviers spatialement différenciés sont pourtant indispensables en vue d'améliorer la contribution de l'agriculture au développement durable du territoire (Cunningham *et al.,* 2013 ; Spiertz *et al.,* 2012).

Ces modèles évaluent l'impact de changements de la mosaïque des systèmes de culture sur un processus biologique donné mais ne fournissent pas d'évaluation multicritère de la contribution des mosaïques de système de culture au développement durable du territoire. Les solutions proposées par ces modèles sont donc susceptibles d'être positives pour le processus biologique étudié mais inacceptables, par exemple, d'un point de vue économique.

D'une part, il semble nécessaire d'assurer une évaluation de la mosaïque de systèmes avec un ensemble d'indicateurs pour rendre compte de la contribution de la mosaïque de systèmes de culture à des enjeux économiques, sociaux et environnementaux du territoire. Ces ensembles d'indicateurs devraient être spatialement explicites, pour cibler les zones où les changements ne sont pas satisfaisants et repérer les dynamiques territoriales qui devraient être soutenues ou au contraire évitées. D'autre part, il apparaît indispensable de dépasser ces limites en concevant des démarches de modélisation mécanistes qui simulent les comportements des agriculteurs en termes de choix de systèmes de culture face à de multiples changements à différentes échelles spatiales. En amont, afin de générer ces dynamiques territoriales induites par les forces motrices des scénarios, des modèles bioéconomiques peuvent être utilisés.

Cette évaluation à l'échelle du territoire fait actuellement défaut malgré un front de recherche important sur l'évaluation de la durabilité des systèmes de culture pour pouvoir rendre compte de la contribution de la mosaïque des systèmes de culture aux différentes problématiques de développement durable.

1.4.2.1. L'évaluation des systèmes de culture : du champ jusqu'au territoire

De nombreux travaux sur l'évaluation de la durabilité des systèmes de culture ont vu le jour ces dix dernières années et s'appuient, pour la majeure partie, sur un ensemble d'indicateurs qui permettent d'évaluer les différentes caractéristiques des systèmes de culture en lien avec les problèmes de durabilité (Carof *et al.,*2013).

Les indicateurs sont des variables qui fournissent des informations sur des processus difficiles à quantifier ou évaluer de manière précise (Gras *et al.,* 1989). Il peut s'agir concrètement de variables, de combinaisons de variables, de valeurs en sortie de modèles de simulation et de mesures (Ness *et al.,* 2007). Les indicateurs doivent être mesurables, dans des termes qualitatifs ou quantitatifs, être déterminés par les ressources disponibles et être pertinents au regard des problématiques traitées

(Niemeijer and Groot, 2008). De plus, ils doivent être sensibles à l'action publique locale, être lisibles et pouvoir faire l'objet d'une comparabilité : « une variable positionnée par rapport à une référence » (Girardin *et al.,* 2000). Ces indicateurs peuvent correspondre à des émissions, des impacts potentiels ou des états donnés du système étudiés.

Pour pouvoir évaluer de manière ex ante les impacts des systèmes de culture à l'échelle du territoire, les agronomes ont développé des procédures de changement d'échelles. Le changement d'échelle se définit comme étant un élément transféré d'un objet à une échelle donnée à un autre objet à une autre échelle (Volk and Ewert, 2011). Les données spatiales peuvent être extrapolées à des zones similaires ne présentant pas un nombre de données suffisant, agrégées à des échelles supérieures par des sommes ou des moyennes par exemple, ré-échantillonnées en sortie d'un modèle, ou provenir directement d'un modèle (Ewert *et al.,* 2011). Cette problématique de changement d'échelle est particulièrement importante lorsque les données sur une zone d'étude sont limitées, par exemple par l'étude d'un faible échantillon d'exploitations à l'échelle du territoire (Bechini *et al.,* 2011). Le choix des méthodes de changement d'échelle influe donc sur la qualité des résultats en sortie d'une évaluation (Vogeler *et al.,* 2014).

L'intégration de méthodes de changements d'échelle pour évaluer les réponses des mosaïques de systèmes de culture à des problématiques de développement durable est un challenge important. Cette évaluation permettrait de comparer des mosaïques de systèmes de culture, résultant de différents types de scénarios, et ainsi de construire une méthode de conception et d'évaluation multicritère de mosaïques de systèmes de culture en réponse à des problématiques de développement durable. Ces méthodes de changements d'échelle peuvent être intégrées aux modèles bioéconomiques.

1.4.2.2. Les modèles bioéconomiques

Les modèles bioéconomiques sont des modèles économiques qui lient les décisions des agriculteurs avec des objectifs et des contraintes, en particuliers en ce qui concerne la gestion de leurs ressources en fonction des paramètres décrivant les activités culturales possibles (Janssen et van Ittersum, 2007). Ils incluent des composantes biophysiques qui permettent de prendre en compte la variabilité spatiale des performances des activités culturales (Flichman, 2002). Ces activités culturales sont des processus qui décrivent la transformation d'inputs, tels que des engrais ou de la main d'œuvre, en outputs désirables (production d'une denrée donnée) ou non (émissions de gaz à effet de serre) (Flichmann *et al.,* 2011). Les activités sont décrites à travers la définition de coefficients techniques ou coefficients input-output. Ce sont ces coefficients techniques qui permettent d'évaluer les conséquences de l'adoption de ces activités à l'échelle des fermes. Les modèles bioéconomiques sont donc particulièrement bien adaptés pour l'évaluation intégrée des systèmes de culture ou des systèmes de production.

Ces modèles sont basés sur un processus d'optimisation et tendent à reproduire le comportement des agriculteurs limités par leur accès aux ressources productives (Anderson *et al.,* 1986). Ces modèles permettent de tester l'impact de l'arrivée de nouvelles activités sur les choix des exploitants (Lopez-Ridaura, 2005 ; Dogliotti *et al.,* 2006) et de changements de paramètres de production comme par exemple le prix des cultures (Mosnier *et al.,* 2009) pour de la prédiction à court ou moyen terme (van Ittersum *et al.,* 1998).

Parmi les modèles d'optimisation, les modèles de programmation linéaire sont les plus utilisés (Janssen and van Ittersum, 2007). Dans ces modèles, la fonction d'utilité représente la rationalité économique du processus décisionnel des agriculteurs en termes de choix d'activités culturales (Edwards-Jones and McGregor, 1994). Le modèle optimise le processus d'allocation de facteurs de production à l'échelle de l'exploitation pour identifier la combinaison d'activités qui maximise cette fonction d'utilité (Barbier *et al.,* 1998 ; Siebert *et al.,* 2006).

Bien que principalement utilisés à l'échelle de l'exploitation agricole, les modèles bioéconomiques ont vu leur usage adapté à l'échelle du territoire (van Ittersum *et al.,* 2004 ; Roetter *et al.,* 2005 ; Delmotte, 2011 ; Mérel *et al.,* 2014). Contrairement aux modèles de land use, à l'échelle du territoire, Les modèles bioéconomiques sont plutôt utilisés à l'échelle de l'exploitation agricole. Ils ne sont généralement pas multi-échelle bien qu'ils aient la capacité de participer à l'évaluation territoriale par des agrégations successives des coefficients techniques des activités culturales (Ewert *et al.,* 2011). Ils possèdent toutefois la capacité de représenter les interrelations entre les différentes échelles : du champ à l'exploitation et de l'exploitation à la région (Delmotte *et al.,* 2013).

Actuellement, les modèles bioéconomiques utilisés pour la planification environnementale modélisent l'impact du choix des exploitants en termes d'activités culturales sur un processus environnemental donné : l'érosion (Schuler et al. 2013 ; Schönhart *et al.,* 2011), la perte de matière organique des sols (Schönhart *et al.,* 2011), les impacts des engrais sur l'eau (Belhouchette *et al.,* 2011), sur la biodiversité infra-parcellaire (Bamière *et al.,* 2011), sur le paysage (Mouysset *et al.,* 2011 ; Schönhart *et al.,* 2011), les émissions de gaz à effets de serre (Acosta-alba *et al.,* 2012). Ces modèles sont également utilisés pour traiter des problématiques socio-économiques telles que l'autosuffisance alimentaire (Van Wijk *et al.,* 2014) ou encore la production de biomasse (Egbendewe-Mondzozo *et al.,* 2011). On trouve peu d'études (voir Acosta-Alba *et al.,* 2012 ; Mosnier *et al.,* 2009) qui étudient l'impact de changements de système de culture sur plusieurs problématiques de développement durable à l'échelle du territoire.

De plus, malgré leur usage possible pour l'évaluation spatialement explicite de l'externalité des systèmes de culture, les modèles bioéconomiques développés à l'échelle de l'exploitation ou à l'échelle du territoire sur plusieurs fermes types, ne sont généralement pas spatialement explicites. L'adoption des activités culturales est contrainte par des variables biophysiques mais leur localisation par rapport aux écosystèmes est peu prise en compte : ils apportent de l'information sur les pressions agricoles dans le cadre de différentes politiques mais ne rendent pas compte de la variabilité de l'externalité de ces pratiques à l'échelle du territoire. Or c'est la localisation des agriculteurs sur le territoire doublée de leurs choix à l'échelle de la parcelle qui vont conditionner l'importance des impacts économiques, sociaux et environnementaux de la mosaïque des systèmes de culture. A titre d'exemple les décideurs tentent de préserver les zones à risque environnemental élevé des pratiques à fort impact environnemental, alors que cette priorité aux systèmes de culture peu intensifs est moins primordiale dans des zones peu sensibles d'un point de vue strictement environnemental (Phalan *et al.,* 2011 : voir les débats autour du land sparing).

Il est donc nécessaire d'intégrer à ces modèles bioéconomiques les différentes échelles spatiales pour lesquelles des facteurs biophysiques, économiques, sociaux, environnementaux et agronomiques peuvent orienter les choix des exploitants à l'échelle du champ.

Dans la suite, nous résumons rapidement les différents objectifs identifiées au cours des précédents paragraphes puis nous présentons la démarche de la thèse pour concevoir et évaluer des mosaïques de systèmes de culture.

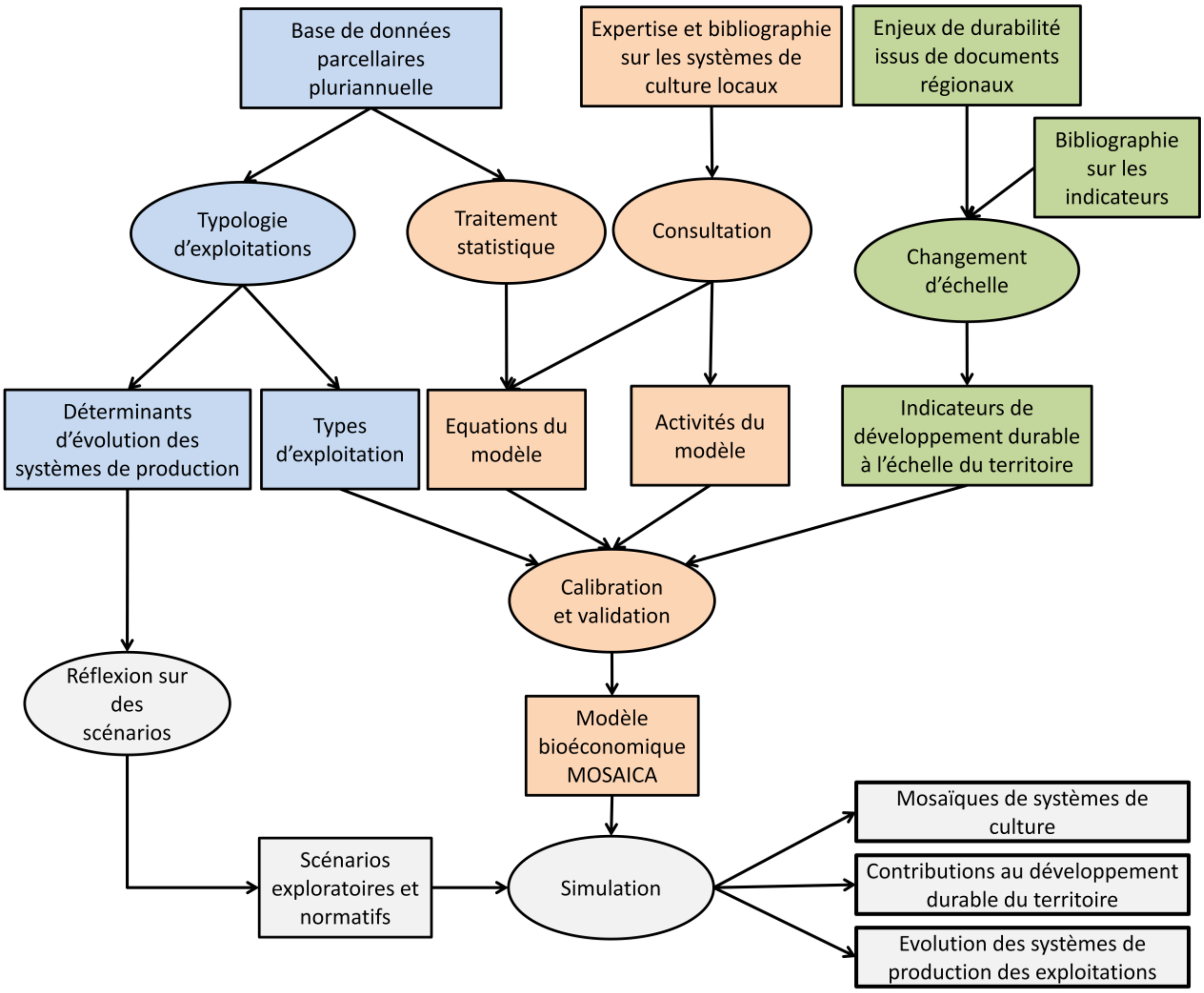

Figure 1 : Ensemble méthodologique pour la conception et l'évaluation multicritère de mosaïques de systèmes de culture. Le diagnostic des systèmes de production actuels et l'établissement de connaissances sur les changements d'exploitations est représenté en bleu, la construction du modèle bioéconomique régional en rouge, la mise en place d'un ensemble d'indicateurs pour l'évaluation de mosaïques de systèmes de culture en vert et l'évaluation multicritère de nouvelles mosaïques de systèmes de culture en réponse à des scénarios en gris. Les ellipses sont des processus et les rectangles représentent des entrées et sorties des processus.

1.5.Présentation des objectifs et de la démarche proposée dans la thèse

Les deux objectifs identifiés sont les suivants:

i) simuler des scénarios de changements économiques, sociaux, techniques, agronomiques et environnementaux modifiant les choix d'assolement des agriculteurs, décrits individuellement, en modélisant l'évolution de leurs systèmes de production de manière spatialement explicite ;

ii) évaluer l'impact de ces changements d'assolements par des indicateurs spatialisés qui apportent de l'information sur la contribution de l'agriculture au développement durable du territoire.

Pour répondre à ces objectifs, nous avons conçu une démarche en quatre étapes (Cf. Figure 1) :

- La première étape de notre démarche est un diagnostic des systèmes de production en place dans les exploitations avec une typologie d'exploitation réalisée sur les données enregistrées dans le référentiel parcellaire graphique qui comprend l'ensemble des agriculteurs sur lesquels nous allons simuler les choix de systèmes de culture dans différents contextes. Cette typologie a pour but de modéliser la diversité des assolements sur le territoire et de modéliser les changements de types de système de production dans le temps et l'espace.

- Dans la deuxième étape, nous allons construire un ensemble d'indicateurs appropriés à l'échelle du territoire pour évaluer la mosaïque actuelle des systèmes de culture. Ces indicateurs utilisent l'information à l'échelle du système de culture qui est portée à l'échelle du territoire par des méthodes de changement d'échelle. La mise en place de ces indicateurs permet de réaliser 1) un diagnostic de la contribution actuelle de la mosaïque de systèmes de culture au développement durable de manière spatialement explicite, 2) d'effectuer un tel diagnostic pour toute nouvelle mosaïque et 3) de définir des enjeux utiles pour la définition de scénarios visant à concevoir des mosaïques de systèmes de culture plus durables.

- Dans la troisième étape, nous allons construire un modèle bioéconomique régional avec en entrée i) la description des agriculteurs du territoire, sur la base des informations disponibles dans le référentiel, avec des informations sur le contexte biophysique et socioéconomique provenant de traitements de systèmes d'information géographique (SIG), ii) les systèmes de culture actuellement pratiqués par les agriculteurs, iii) la typologie des systèmes de production. Les systèmes de culture seront décrits sur la base des connaissances existantes et publiées et de l'expertise sur les facteurs qui permettent de localiser les systèmes de culture sur le territoire. Le modèle sera spatialement explicite avec une modélisation des interrelations entre les échelles du champ, de l'exploitation et de la région. Le modèle permettra de générer des mosaïques de systèmes de culture, en optimisant la somme des utilités des exploitants du territoire, et d'évaluer leur impact sur la contribution de l'agriculture au développement du territoire en intégrant les indicateurs développés dans la seconde étape.

- Dans la dernière étape, l'utilisation du modèle nous permettra de i) tester l'impact de scénarios exploratoires et normatifs sur l'organisation des systèmes de culture à l'échelle du territoire et ii) d'évaluer l'impact de ces changements de composition et d'organisation de la mosaïque de systèmes de culture sur la contribution au développement durable du territoire. Ces scénarios exploratoires comprennent des changements agronomiques, socio-économiques, environnementaux aux différentes échelles spatiales intégrées au modèle.

Ces mosaïques de système de culture évaluées conduisent à la production d'informations sur les leviers de changements susceptibles de conduire à une agriculture qui augmente sa contribution au développement durable du territoire.

Cette démarche est appliquée au territoire de la Guadeloupe. Les territoires insulaires sont particulièrement bien adaptés à ces travaux du fait de flux et de limites claires (Spinalis *et al.,* 2009). L'agriculture est la source de nombreux problèmes environnementaux et sociaux sur ce territoire mais peut également répondre à un certain nombre de problématiques de développement durable à l'échelle du territoire. De plus, l'existence d'une base de données parcellaires, disponible en Guadeloupe, est une condition *sine qua non* à la mise en place d'une démarche de prototypage de mosaïques de systèmes de culture.

Le territoire de la Guadeloupe est présenté par la suite avec la description des problématiques de développement durable et les caractéristiques de son agriculture actuelle.

1.6.Présentation du territoire guadeloupéen

Nous décrivons en détail le contexte biophysique de l'île avant de décrire l'histoire de l'agriculture guadeloupéenne qui explique, en partie, la sole actuelle des cultures sur l'île. Puis nous décrivons cette sole actuelle via le recensement agricole, et les enjeux auxquels l'agriculture guadeloupéenne pourrait répondre via des changements de pratiques de ses agriculteurs.

1.6.1. Un territoire agricole, urbain et forestier

La Guadeloupe est un archipel français de la Caraïbe composé de plusieurs îles, principalement la Basse-Terre et la Grande-Terre séparées par un bras d'eau, Marie-Galante, La Désirade et Les Saintes. La Guadeloupe a une taille de 1600 km^2 (soit 160 000 ha) dont environ 40 000 ha sont des terres agricoles, le reste étant occupé par des terrains forestiers (parc national et bois privés) sur 60 000 ha et des terrains urbanisés sur 60 000 ha. De par sa nature insulaire, il s'agit d'un territoire possédant des limites clairement établies.

1.6.2. Variabilité du contexte biophysique de l'île

1.6.2.1. Un relief variable : plat sur Grande-Terre et Marie-Galante et marqué en Basse-Terre

Le relief de l'île varie de manière importante (Cf. Figure 2) :

- La Grande-Terre est un plateau calcaire à l'Est et au Nord alors que la région centre appelée "les Grands-fonds" est une zone de mornes c'est-à-dire de creux dans le plateau qui créent des variations de reliefs importantes sur de très courtes distances.

- Basse-Terre, d'origine volcanique, est au contraire est une zone à reliefs bien plus marqués avec au Sud des chaines de montagne (la chaine septentrionale) imposantes dont le sommet le plus important, le volcan de la Soufrière, culmine à 1467 m d'altitude. A l'Est les pentes sont moyennes alors que l'Ouest est marqué par des pentes plus abruptes. Au Nord le relief est moins imposant, en raison d'une érosion plus forte liée à des formations montagneuses plus anciennes.

- Marie-Galante présente une formation géologique semblable à celle de Grande-Terre. Il s'agit d'une île d'origine corallienne avec la présence d'un plateau en son centre.

1.6.2.2. Un climat lié au relief de l'archipel

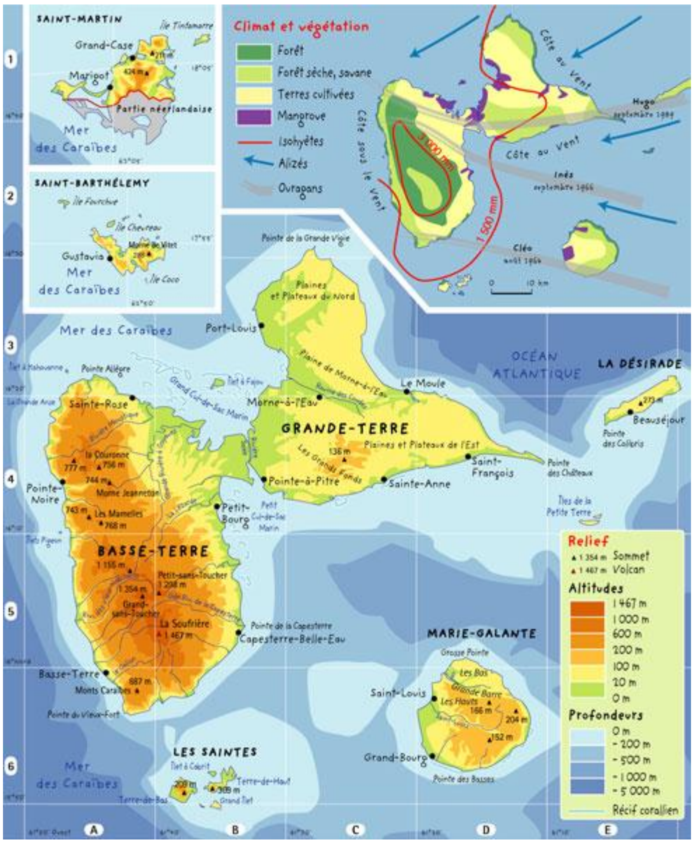

Figure 2 : Représentation du climat, de la végétation et du relief en Guadeloupe

Le climat tropical de l'île est fortement impacté par ce relief. La Guadeloupe se trouve dans la zone des alizés, vents chauds et humides soufflant d'Est en Ouest.

La Grande-Terre est un plateau très sec avec des précipitations faibles aux extrémités Nord et Est de l'île légèrement inférieures à 1000 mm.an^{-1} et en son centre et vers le Nord de la Basse-Terre, des niveaux de précipitations proches des 2000 mm.an^{-1}.

Les reliefs marqués de Basse-Terre entraînent des niveaux de précipitations annuelles beaucoup plus importants avec l'effet de foehn.

Concrètement la façade Est de la montagne est très arrosée, avec des pluies annuelles de 3000 jusqu'à 4000 mm.an^{-1}, à cause de la décharge hydrique des nuages qui se refroidissent en altitude permettant la condensation de la vapeur d'eau. Le versant Ouest de l'île connaît au contraire un trou de foehn qui correspond à une zone de réchauffement de l'air. Le versant est donc beaucoup plus sec avec des niveaux de précipitations comparables à ceux du Nord Basse-Terre, légèrement inférieurs à 2000 mm.an^{-1}. Marie-Galante présente un climat sec comparable à celui de Grande-Terre avec en moyenne des précipitations de l'ordre de 2000 mm.an^{-1}.

1.6.2.3. Des sols variables marqués par des géologies coralliennes et volcaniques et les climats

En lien avec les reliefs et climats présentés précédemment, les sols varient de manière très importante sur les 1600 km² de l'île (Cf. Figure 3). Au niveau pédologique, six grands types de sols dominent la Guadeloupe, des sols d'origine volcanique en Basse-Terre et d'origine corallienne en Grande-Terre et sur Marie-Galante.

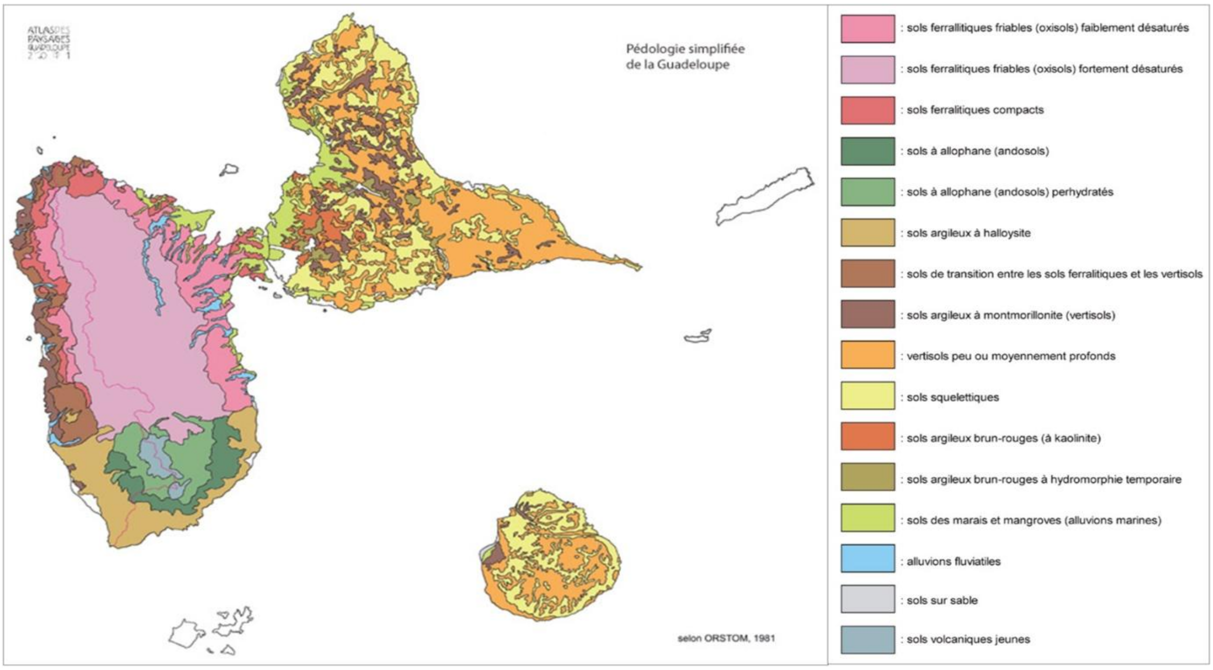

Figure 3 : Présentation de la répartition des différents sols de Guadeloupe (Chaperon, 1981)

- Les andosols composent la plupart des sols d'altitude dans le sud de la Basse-Terre. Il s'agit de sols jeunes issus du volcanisme andésitique. Ils sont composés d'allophanes. Leur teneur en matière organique est très importante et en fait l'un des sols les plus riches du monde. Ils se caractérisent donc pas une fertilité importante, une grande capacité de rétention de l'eau et des minéraux. Leur structure leur confère une porosité importante. Ce sont des sols très favorables à l'agriculture.
- Les nitisols sont des sols dérivés des andosols mais leur processus d'altération est lié à des alternances de dessication/humectation qui ont produit des argiles de type halloysites. Ils ont moins d'affinité avec la matière organique et sont moins riches en minéraux mobilisables.
- Les sols ferralitiques composent l'essentiel des sols de la zone du Nord-Basse-Terre. Ils dérivent d'un processus d'altération ancien du socle volcanique qui a conféré une profondeur et une proportion en argile importante. Ces sols sont friables et poreux donc faciles à travailler et présentent des pH très faibles. Le processus d'altération a appauvri ces sols qui présentent des propriétés chimiques peu favorables pour les cultures.
- Les sols vertiques sont plus minoritaires en Basse-Terre mais en occupent néanmoins une partie de la façade Ouest. Ils sont très compacts et ont des propriétés de gonflement importantes. Ils bénéficient toutefois d'une excellente structure lorsqu'ils sont travaillés dans de bonnes conditions.
- Les vertisols occupent la majorité des terrains de Grande-Terre. Ce sont des sols argilo-sableux peu profonds (par rapport aux sols de Basse-Terre notamment) et qui se caractérisent par une bonne richesse en éléments minéraux (calcium et magnésium). Ils peuvent être plus profonds et présenter des quantités importantes de montmorillonite.
- Les calcisols sont des sols très calcaires peu profonds où la roche affleure. Ils présentent une pierrosité élevée.

Encadré 1 : historique de l'agriculture guadeloupéenne

- -3000 av JC : des peuples amérindiens occupent la Guadeloupe.
- XVe : arrivée des Kalinagos, indiens des Grandes Antilles, qui cultivent le manioc.
- 1630 : arrivée des français et organisation de la colonisation officielle : les riches nobles s'accaparent de grandes terres en plaine, les travailleurs engagés obtiennent des concessions sur des terrains plus difficiles.
- 1643 : introduction de la canne à sucre qui demande un investissement important. Elle remplace en grande partie les cultures de cacao et tabac.
- 1650 : début de l'esclavage pour répondre aux besoins en main d'œuvre importants pour la culture de canne à sucre (93 000 esclaves en 1842).
- 1666 : mise en place du régime exclusif : la France approvisionne la Guadeloupe en échange de tout ce qu'elle produit. Les Français colonisent le Nord de la Basse-Terre et le sud de Grande-Terre.
- Début XVIIIème siècle : abandon de la canne à sucre dans les zones pluvieuses : les habitations se tournent vers les cultures de café, cacao et vanille. Défrichage dans le Nord Grande-Terre pour la culture de canne. Recours à de la petite agriculture vivrière de subsistance sur une partie des lopins.
- Fin XVIIIème siècle : la canne à sucre occupe 27 000 ha, 53% de la SAU de l'île, le café 13%, le coton 12%, les cultures vivrières, 22%.
- Début XIXème siècle : crise sucrière due au développement de la betterave en métropole et de grandes compagnies sucrières dans la Caraïbe.
- 1848 : abolition de l'esclavage : fuite des esclaves vers les terres libres, la plupart reste sur les exploitations et travaillent pour un revenu très faible et un accès à un lopin de terre dont une partie doit être cultivée en canne à sucre avec des contrats type colonat dont certains perdurent encore début 2000.
- 1850-1860 : début de l'immigration forcée de travailleurs des Indes (environ 50 000 Indiens).
- 1850 : création d'usines sucrières centrales. La baisse du prix du sucre sur le marché mondial entraîne la vente des terres de nombreux petits propriétaires aux usines.
- Fin XIXème siècle : chute des habitations et concentration foncière autour des usines.
- Début XXème siècle : fermeture des petites usines et expansion des grands usiniers sur de grands domaines : Beauport en Nord Grand-Terre passe de quelques centaines d'hectares fin XIXème à 10 800 ha en 1930.
- 1928 : introduction de la banane dans les zones montagneuses, en réponse à la demande en métropole. Etablissement d'un quota d'importation de 50 000 tonnes en 1928.
- 1930 - 1945 : remplacement du café par de la banane dans tout type d'exploitation. Premières vagues de faillite des usines sucrières.
- 1946 : départementalisation : statut identique de la Guadeloupe par rapport aux départements métropolitains. Application progressive des acquis sociaux métropolitains en Guadeloupe (emplois ; aides sociales).
- 1950 : automatisation de la production de sucre.
- 1950-1970 : consommation de biens en augmentation avec un accroissement des importations. Immigration conséquente de la Caraïbe notamment des Haïtiens, source de main d'œuvre pour les exploitations agricoles. Augmentation démographique importante, le foncier agricole disparaît au profit d'une urbanisation importante de l'île. Soutien économique aux productions d'importations au détriment des productions vivrières pour le marché local.
- 1961-1979 : réforme foncière : redistribution des terres en faire valoir-direct des usines pour la création d'exploitations agricoles familiales en 1961. En 1967, acquisition de terres par la SAFER et redistribution de 2900 ha jusqu'en 1979. En 1978, tentative de relance de la canne avec aides à la replantation et prêts bonifiés.
- 1968 : Organisation Commune du Marché du sucre : mise en place d'un quota sucrier qui protège les exportations de sucre guadeloupéen.
- 1980 - 1992 : seconde réforme foncière avec la redistribution de près de 10 000 ha pour maintenir le potentiel sucrier, préserver l'emploi et préserver le foncier agricole.
- 1990 : crise bananière face à la concurrence de régions plus compétitives et l'apparition de maladies. Les bananeraies migrent de la Côte-sous-le-vent vers la Côte-au-vent.
- 1993 : Organisation Commune du Marché de la banane qui régit le fonctionnement du marché avec des quotas et un contingent pour la Guadeloupe.
- 1993 - 2010 : libéralisation du marché de la banane accrue. Diminution des quotas et prix de la banane, disparition des petites exploitations.
- 2001 : Découverte de la pollution massive des terres due à la chlordécone.

1.6.3. Système agricole territorial actuel

1.6.3.1. Présentation des exploitations et des cultures sur le territoire

L'ensemble des statistiques présentées ci-dessous sont issues de traitements réalisés sur le recensement agricole 2010 et présentent la sole actuelle de la Guadeloupe. Un historique de l'évolution de cette sole apparaît en dans l'Encadré 1. La sole de culture par région révèle une spécialisation très forte des régions en Guadeloupe (Cf. Figure 4).

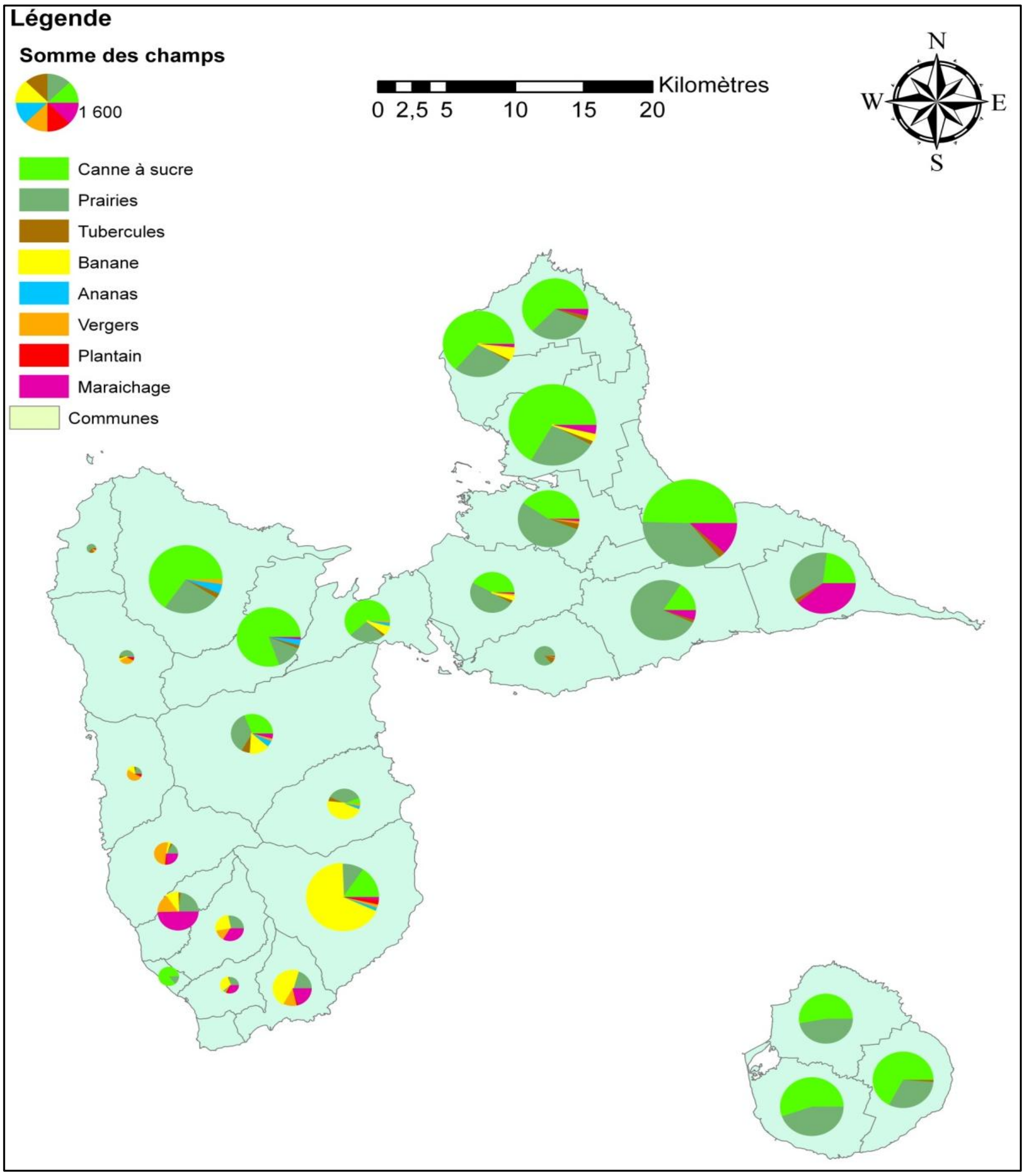

Figure 4 : Carte des assolements des communes de Guadeloupe (Recensement agricole 2010)

En Grande-Terre, le centre représenté par les communes des Abymes, de Morne-à-l'eau et de Gosier est peu agricole et dominé par les pâturages. Il s'agit de la seule région en Guadeloupe où le pâturage domine le paysage agricole. Dans l'Est de la Grande-Terre, La présence du maraîchage en forte proportion différencie cette région des autres. La région du Nord Grande-Terre est un bassin cannier important avec des surfaces importantes en pâturage et une proportion en maraîchage faible mais néanmoins significative.

En Basse-Terre, le nord est également un bassin cannier important mais avec une proportion en culture de diversification significative avec surtout des tubercules (igname, madère, manioc...) et de l'ananas ainsi que quelques terres en banane plantain. Le Sud-Est, quant à lui, est dominé par la banane cultivée historiquement dans la zone mais avec une proportion non négligeable de canne à sucre réintroduite dans cette zone dans des rotations avec la banane depuis la fin des années 1990. Des cultures de diversification apparaissent, telles que la banane plantain et l'ananas dans une moindre mesure. Le Sud-Ouest de l'île est une région arboricole avec beaucoup de cultures d'agrumes (mandarines, oranges et limes) et une proportion importante de pâturage. La banane est encore présente mais représente désormais une proportion faible.

Marie-Galante est également un bassin cannier important avec beaucoup de terres en pâturage. Les autres cultures sont très peu représentées à l'échelle de cette dépendance.

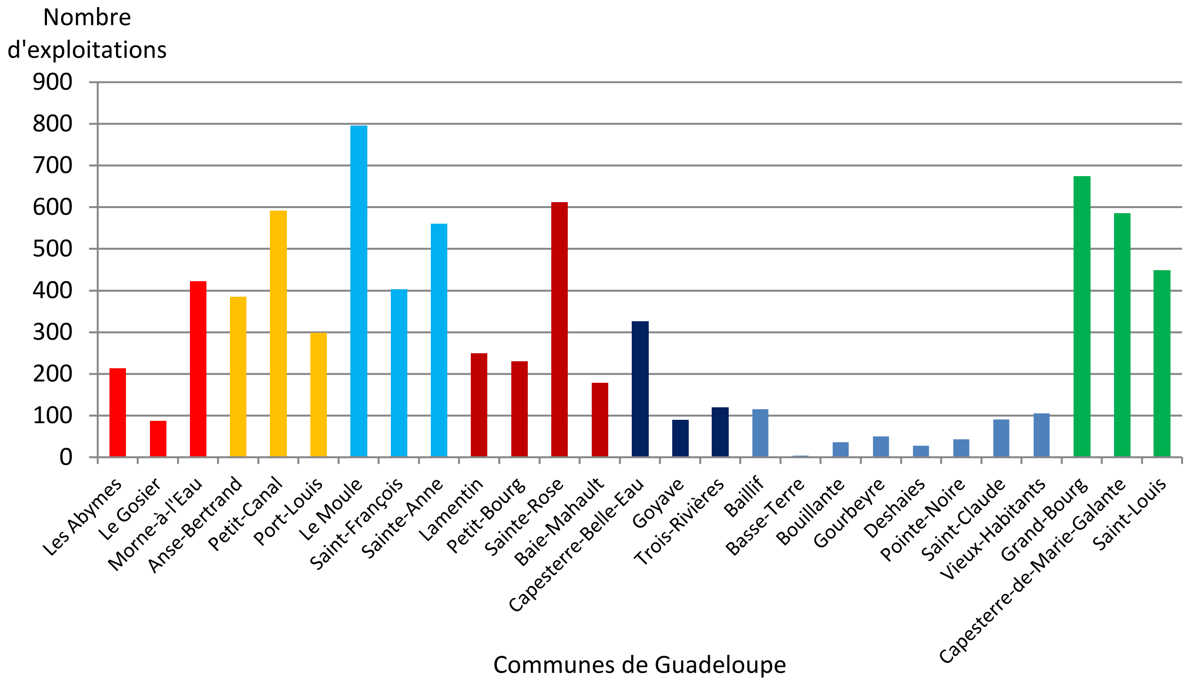

Figure 5 : Nombre d'exploitations en Guadeloupe par commune

On peut voir que les régions de l'Est Grande-Terre, du Nord Grande-Terre et du Nord Basse-Terre comportent le plus d'exploitations (Cf. Figure 5). Il s'agit en moyenne d'exploitations de faible taille, environ 3-4 hectares pour les exploitations avec des proportions importantes de canne à sucre, de pâturage et de maraîchage. Les exploitations bananières sont de plus grande taille en moyenne, autour de sept hectares (Blazy *et al.,* 2009). La taille des exploitations en revanche varie de manière importante dans chaque type de production avec des exploitations de quelques ares à plusieurs centaines d'hectares.

1.6.4. Un territoire en proie à des difficultés économiques, sociales et une fragilité environnementale

1.6.4.1. Une économie agricole faible en 2010

- *Faible contribution de la valeur ajoutée agricole au PIB de l'île*

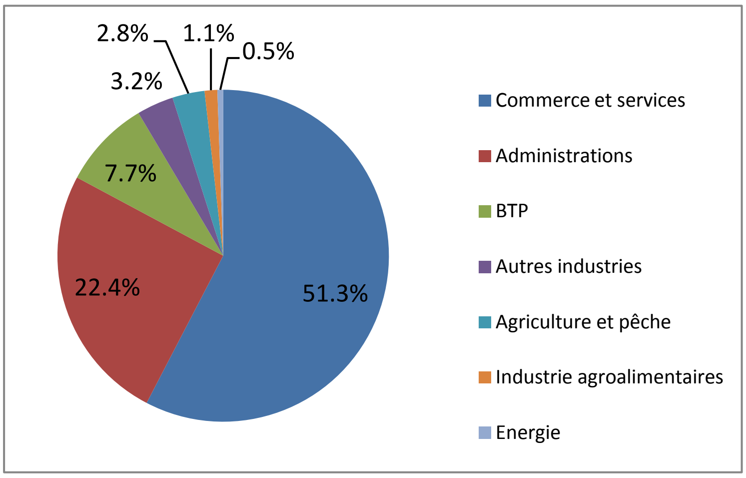

Figure 6 : Répartition de la valeur ajoutée totale par secteur

Le PIB de la Guadeloupe est de 8.1 milliards d'euros (INSEE, 2014) et sa répartition est visible sur la Figure 6. L'agriculture rapporte une valeur ajoutée agricole faible au territoire par rapport aux secteurs du tertiaire. Ce PIB est plus faible que celui de la métropole par habitant : 18 409 $ contre près de 30 000 $ pour la métropole (Agreste, 2011).

- *Dépendance aux subventions*

La dépendance du secteur agricole vis-à-vis des subventions est importante. Les subventions pour les planteurs de bananes représentent environ 20 millions d'euros annuels contre environ 30 millions pour la production de canne à sucre (Agreste, 2011).

1.6.4.2. Des enjeux sociaux liés à la dépendance par rapport à l'extérieur

- *Autonomie alimentaire*

La Guadeloupe est actuellement importatrice de denrées alimentaires. Depuis les années 1960, il y a eu une régression des productions agricoles pour le marché local, une augmentation des importations, ce qui a fait baisser le taux de couverture des importations par les exportations à 60 % en 1999 en valeur concernant le secteur agricole (Mardivirin, 2000 ; Insee, 2008). L'alimentation des Guadeloupéens est fortement dépendante du marché mondial et donc vulnérable aux fluctuations des prix (Obertan, 2009). L'agriculture de subsistance a été négligée au profit des cultures d'exportation, telles que la canne à sucre et la banane, qui à elles seules recouvrent la moitié des terres arables de l'île (Agreste, 2009). La Guadeloupe exporte des produits à faible valeur ajoutée en dehors du rhum, et importe des denrées transformées beaucoup plus chères. Il en résulte un grand déficit commercial. Les autorités politiques avec à leur tête, Michel Barnier, ministre de l'Agriculture en 2009, ont reconnu qu'un "très gros travail" devait être fait dans l'agriculture aux Antilles pour recréer "une autosuffisance alimentaire" et favoriser la production locale, alors que le département était en proie depuis plusieurs semaines à des manifestations contre la "vie chère" (AFP, 2009).

- *Autonomie énergétique*

En Guadeloupe, 92% de l'énergie primaire consommée en 2006, soit 7600Gwh, est importée (Cf. Table 1). Il s'agit essentiellement des carburants des véhicules, et des combustibles (charbon, fuel). Seulement 8% de l'électricité est produite avec des ressources locales dont la moitié par la bagasse, un sous-produit de la canne à sucre.

Table 1: Présentation des différentes sources d'énergie en Guadeloupe

Energie en Guadeloupe	
7600 GWh d'énergie primaire consommée en 2006	
➔ 92% importée (54.5% de métropole)	
72%	**Carburant pour véhicules**
	Combustibles - centrales thermiques (EDF Jarry Nord + centrale à cycle combiné Jarry)
18%	**Charbon – Centrale thermique du Moule**
➔ 8% produite localement	
4%	**Bagasse**
<1%	**Electricité géothermique**
<1 %	**Photovoltaïque**
<1%	**Eolien**
<1%	**Autres : solaire thermique ; hydroélectrique**

Seulement 3% de l'énergie totale consommée est destinée à l'agriculture (Explicit, 2007).

- *Création d'emplois*

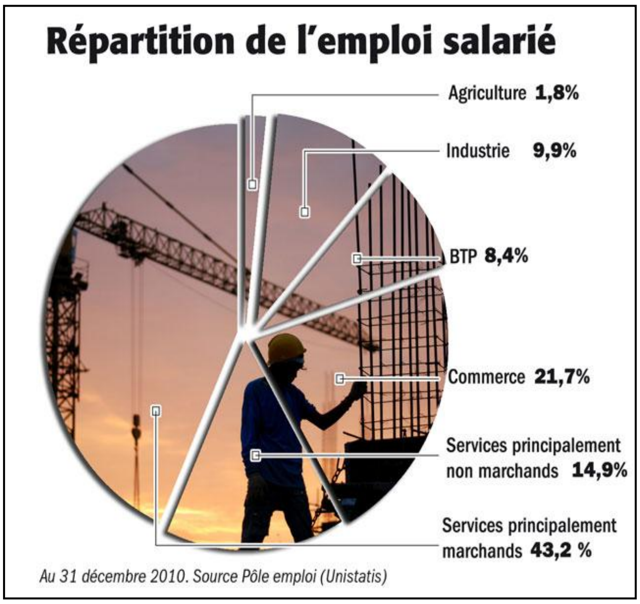

Figure 7 : Répartition de l'emploi par secteur en Guadeloupe

En 2011, il y a 57 760 demandeurs d'emplois de catégorie A. En 2011, la population active (1) guadeloupéenne s'élève à 165 771 personnes, pour une population totale de 401 730. Le taux de chômage est de 26.2% (INSEE, 2014). Le rapport population active/population totale - 41% - est le même qu'en France hexagonale. L'agriculture est fournisseuse d'emplois à la fois famílliaux et salariés avec 5341 UTA familialles et 2495 UTA salariales (Agreste, 2011), ce qui représente 1.8% de l'emploi salarié (Cf. Figure 8). Ils se répartissent dans les exploitations agricoles et dans les entreprises para-agricoles qui conseillent les agriculteurs, les fournissent en matériaux ou les aident à vendre leurs productions (les SICAs notamment).

- *Production de nourriture non contaminée par la chlordécone*

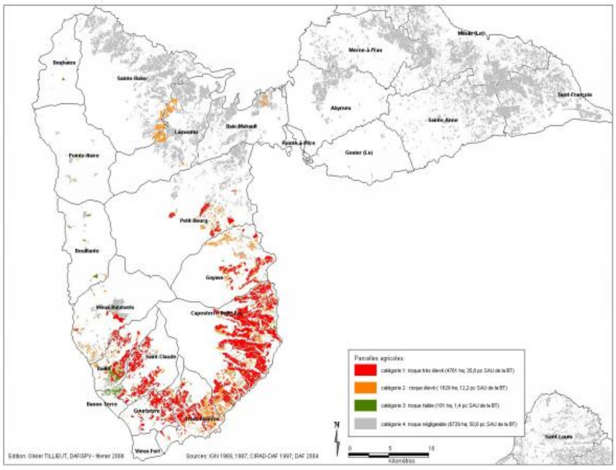

Figure 8 : Carte du risque de contamination des sols par la chlordécone

La chlordécone, l'un des pesticides organochlorés les plus persistants, a été appliquée de 1972 à 1993 sur les bananeraies de Guadeloupe ce qui a provoqué une pollution des sols, une contamination des eaux, des milieux aquatiques et des cultures très importante (Cf. Figure 9). Environ 6500 ha en Guadeloupe sont contaminés par cette pollution (Cabidoche *et al.,* 2009). De nombreux fruits et légumes sont hautement contaminés lorsqu'ils sont cultivés sur des terres dites « chlordéconées ».

Aucune plante à l'heure actuelle n'a été identifiée pour absorber le polluant en grande quantité pour pouvoir envisager une dépollution par culture (Cabidoche and Lesueur-Jannoyer, 2012). Il serait envisageable de diminuer le risque de contamination des denrées agricoles en favorisant la culture de plantes non sensibles au chlordécone sur ces terres contaminées.

1.6.4.3. Une agriculture devant s'intégrer dans un environnement fragile

- Protection des ressources en eau

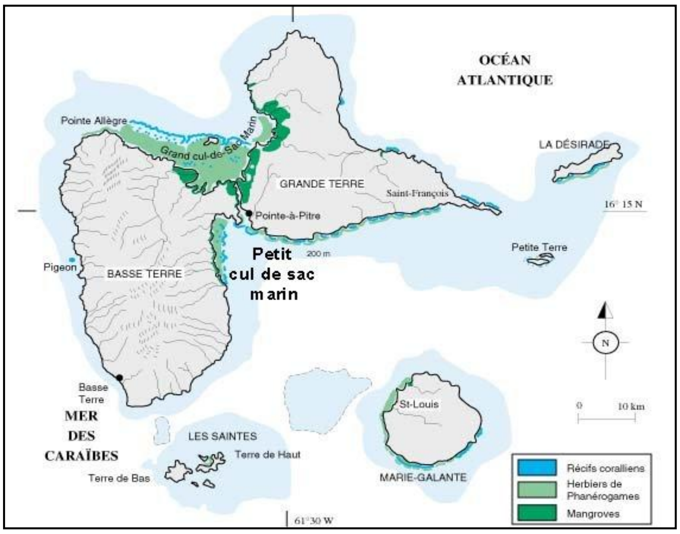

Figure 9 : Localisation des mangroves, cours d'eau et récifs coralliens

La préservation de la qualité de l'eau est importante pour la consommation humaine et pour les écosystèmes d'exception dont la conservation est un enjeu important (Cf. Figure 10). Cabidoche *et al.,* 2002) prônent une surveillance accrue des pollutions surtout dans les périmètres irrigués de Grande-Terre où de fortes pollutions peuvent être causées par des utilisations importantes de pesticides en zone sèche.

- Protection des sols

Une partie des sols de Guadeloupe est sensible au phénomène d'érosion hydrique. Il s'agit des sols vertiques du Sud-Ouest de la Basse-Terre dont l'érodibilité est importante ce qui entraîne un risque érosif important malgré une pluviométrie relativement faible par rapport au reste du territoire.

- Diminution des émissions de GES

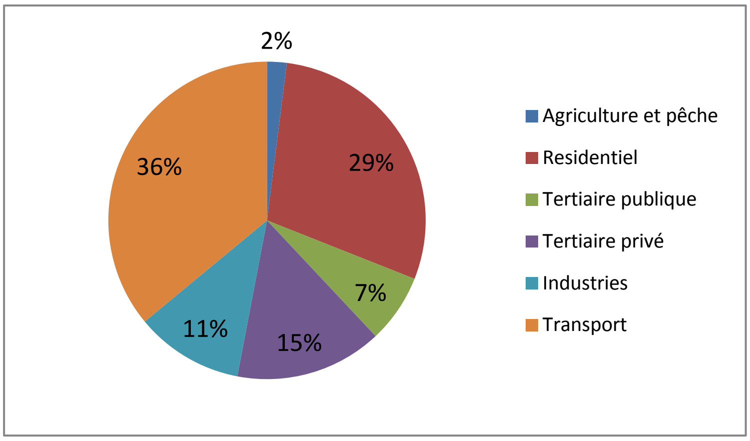

Figure 10 : Répartition des émissions de GES selon les différents secteurs d'activité

L'agriculture contribue faiblement aux émissions de gaz à effets de serre (Cf. Figure 11). Elle consomme toutefois 222 Gwh de produits pétroliers sur les 6698 consommés en Guadeloupe (Prerure, 2008). Des réductions sont possibles sur ce secteur.

1.7. Présentation de la base de données utilisée dans la thèse

1.7.1. Présentation de l'association Agrigua

Agrigua est une association créée en 2002 qui a pour objectif la mise en place d'un système d'information géographique pour le suivi des surfaces agricoles en Guadeloupe. Agrigua fonctionne avec différents instituts agricoles et opérateurs de terrains pour les déclarations de surfaces graphiques d'une part, la mutualisation des données et leur diffusion d'autre part. Chaque année, elle produit une base de données géographiques du parcellaire des agriculteurs avec l'usage agricole majoritaire pour l'année donnée.

1.7.2. Présentation de la base de données Agrigua

Nous avons récupéré en début de thèse, les bases de données de 2004 à 2010 qui comprennent un ensemble de polygones qui représentent chacun une parcelle géographiquement localisée sur le territoire. Le travail de modélisation des choix des exploitations agricole, dans le cadre de scénarios, est réalisé à partir de la dernière année (2010) qui est l'année la plus complète en termes de surfaces déclarées par rapport aux surfaces recensées.

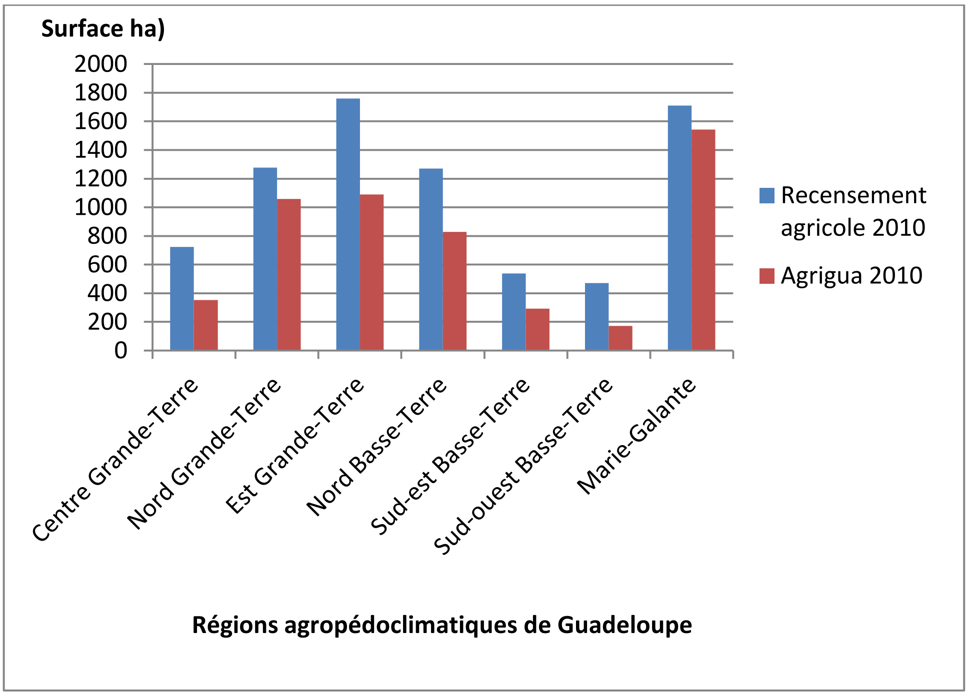

Figure 11 : Comparaison du nombre d'exploitations entre Agrigua et le recensement agricole 2010 (total RA : 7749 exploitations, contre 5336 dans Agrigua)

La base de données Agrigua rassemble près de 70% des exploitations guadeloupéennes. Le manque d'exploitations se répartit sur l'ensemble des régions de Guadeloupe avec toutefois quelques légères nuances (Cf. Figure 12). Le nombre d'exploitations à Marie-Galante est très proche du nombre total d'exploitations agricoles du recensement alors que pour les régions du centre Grande-Terre, de l'Est Grande-Terre et du Sud-Ouest Basse-Terre, le manque de données sur les exploitations agricoles est légèrement plus important que la moyenne des régions.

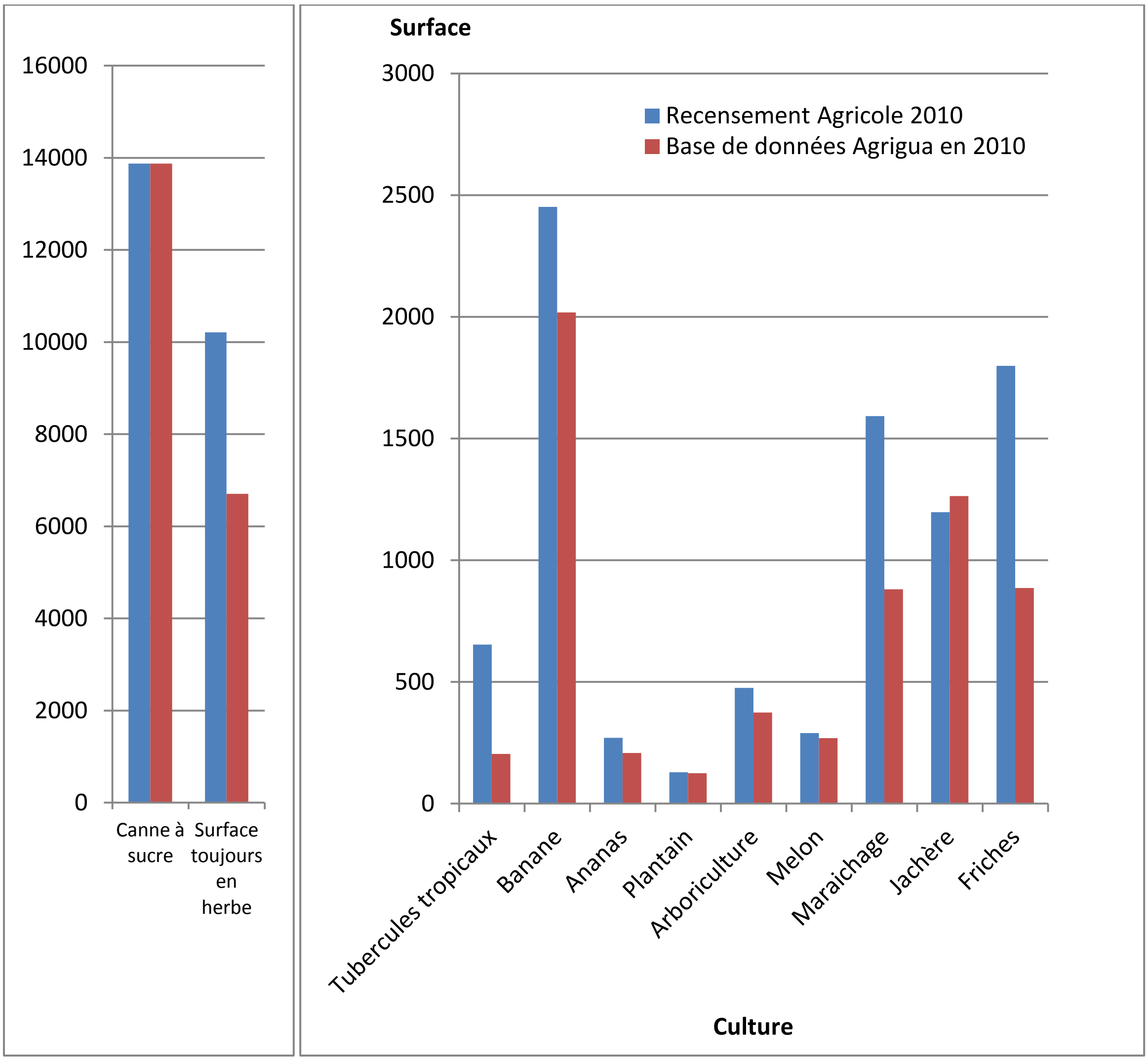

Figure 12 : Comparaison des surfaces du recensement agricole 2010 et de la base de données Agrigua 2010.

Les cultures de canne à sucre et de banane export sont particulièrement bien représentées dans cette base de données (Cf. Figure 13). En revanche les manques sont assez importants pour le pâturage, les tubercules et cultures maraîchères (Cf. Figure 13). On constate que les terres en jachère sont supérieures dans la base Agrigua par rapport aux surfaces du recensement agricole. Il s'agit d'un biais de déclaration des agriculteurs. Lorsque les surfaces sont déclarées à l'Agrigua beaucoup d'agriculteurs déclarent posséder des jachères alors qu'elles correspondent plutôt à des surfaces en gel qui devraient être renseignées sous le terme de "friche".

Table 2: Comparaison des surfaces par région des différentes cultures entre le recensement agricole et la base de données agrigua

Base de données utilisées	Régions	Canne à sucre (ha)	Surface toujours en herbe (ha)	Tubercules tropicaux (ha)	Banane (ha)	Ananas (ha)	Plantain (ha)	Arboriculture (ha)	Melon (ha)	Maraichage (ha)	Jachère (ha)	Friches (ha)
Recensement agricole 2010	Centre Grande-Terre	938	1328	89	28	9	7	32	3	27	75	74
	Nord Grande-Terre	4432	1865	131	199	0	6	43	76	51	187	531
	Est Grande-Terre	2417	3202	150	16	2	4	47	211	748	131	220
	Nord Basse-Terre	3115	1216	150	174	209	27	85	0	71	210	254
	Sud-ouest Basse-Terre	149	419	53	194	4	33	186	0	524	76	201
	Sud-est Basse-Terre	350	471	46	1836	45	52	77	0	150	456	456
	Marie-Galante	2474	1713	34	5	1	0	6	0	21	63	63
Base de données Agrigua en 2010	Centre Grande-Terre	866	668	30	30	4	6	19	0	26	46	10
	Nord Grande-Terre	4393	1402	56	163	0	6	33	194	89	311	451
	Est Grande-Terre	2240	1979	46	5	0	2	37	75	374	109	69
	Nord Basse-Terre	3134	553	28	10	143	21	54	0	72	88	178
	Sud-Ouest Basse-Terre	103	140	4	1555	60	10	157	0	155	101	24
	Sud-Est Basse-Terre	696	383	28	255	1	78	64	0	121	549	91
	Marie-Galante	2447	1580	12	0	0	2	10	0	43	59	62

Table 3: Proportions des surfaces de cultures par région présentes dans la base agrigua

	Régions	Canne à sucre	Surface toujours en herbe	Tubercules tropicaux	Banane	Ananas	Plantain	Arboriculture	Melon	Maraichage	Jachère	Friches
Proportion de culture présente dans Agrigua 2010	Centre Grande-Terre	92%	50%	34%	107%	44%	86%	59%	0%	96%	62%	14%
	Nord Grande-Terre	99%	75%	43%	82%	-	100%	77%	255%	175%	166%	85%
	Est Grande-Terre	93%	62%	31%	31%	0%	50%	79%	36%	50%	83%	31%
	Nord Basse-Terre	101%	45%	19%	6%	68%	78%	64%	-	101%	42%	70%
	Sud-Ouest Basse-Terre	69%	33%	8%	131%	25%	30%	84%	-	30%	133%	12%
	Sud-Est Basse-Terre	120%	81%	61%	85%	133%	150%	83%	-	81%	121%	20%
	Marie-Galante	99%	92%	35%	0%	0%	-	167%	-	205%	93%	98%

Les Tables 2 et 3 peuvent prêter à confusion dans la mesure où les surface du recensement peuvent être inférieures aux surfaces de la base agrigua et donc entrainer des proportions pouvant dépasser les 100% dans le Table 3. Pour ces cultures, il s'agit en fait d'une différence dans la déclaration de surface entre le recensement et la base de données Agrigua. Dans le recensement les surfaces peuvent être rattachées à une exploitation située dans une commune différente alors que dans la base Agrigua, le calcul des surfaces par commune est réalisé par un traitement SIG qui lie les parcelles aux communes auxquelles elles appartiennent géographiquement. Ainsi des parcelles peuvent être recensées sur une exploitation appartenant à une autre commune mais comptées, dans Agrigua, dans les surfaces communales où elles se situent géographiquement. C'est le cas par exemple de la banane en Sud-Ouest Basse-Terre dont la proportion est de 131%. Nous pouvons imaginer que les grandes exploitations de Capesterre-Belle-Eau en Sud-Est Grande-Terre peuvent détenir des parcelles dans le Sud-Ouest de la Basse-Terre.

Nous considérons la base d'une qualité suffisante pour pouvoir faire des simulations de nouveaux assolements. Toutefois, les scénarios testés prendront en compte ces manques dans les informations sur les possibles leviers d'action pour augmenter la contribution de l'agriculture au développement durable du territoire. Nous privilégierons les scénarios qui touchent des types d'exploitation bien représentées où des cultures bien représentées dans la base de données afin de ne pas biaiser l'analyse d'impacts de leviers d'action pour les décideurs qui pourraient conduire à des mauvais conseils de notre part en termes de leviers d'actions pour modifier les systèmes de culture des exploitations.

2. Construction d'une typologie d'exploitations et modélisation des changements de systèmes de production

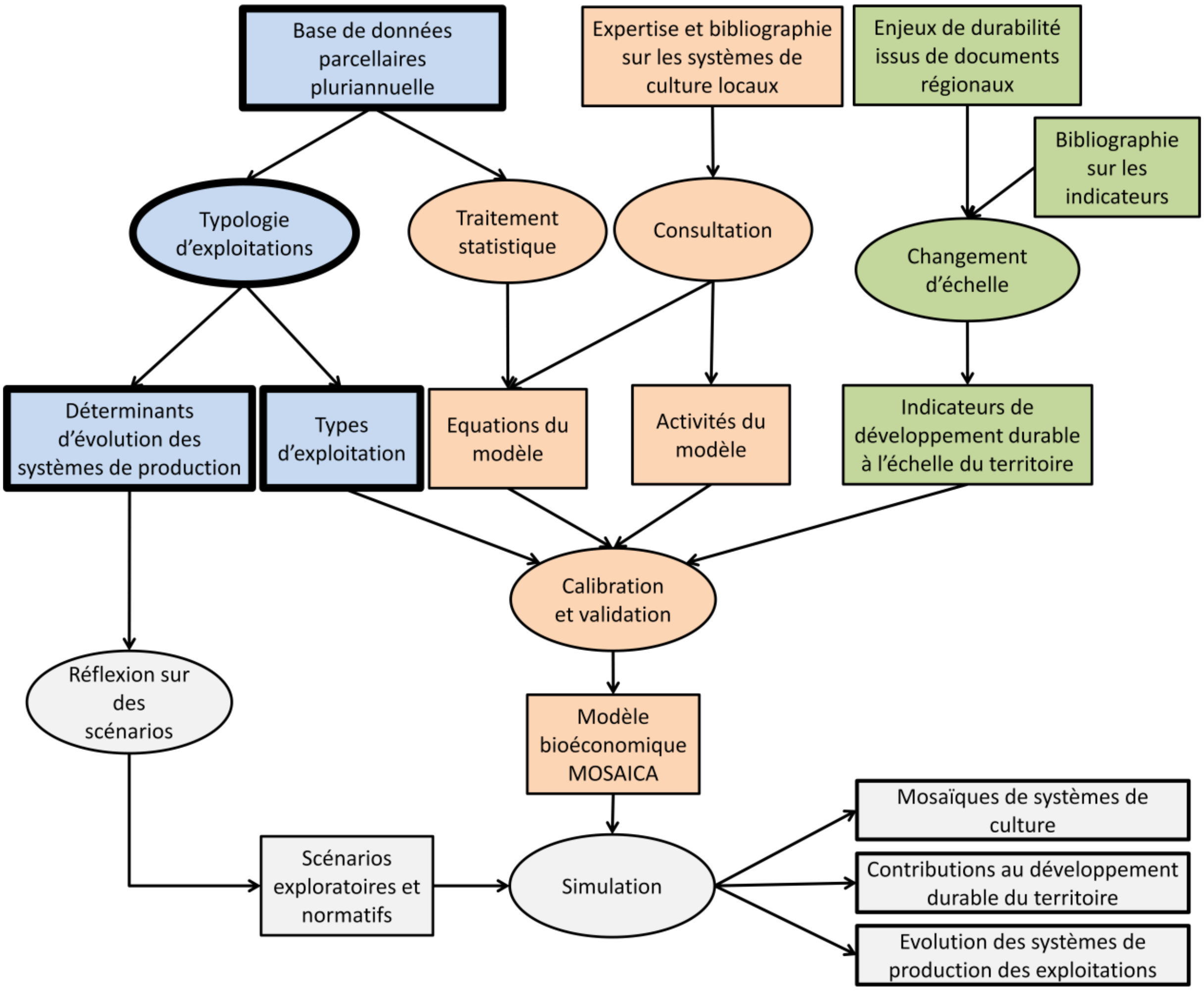

Figure 13: : Ensemble méthodologique pour la conception et l'évaluation multicritère de mosaïques de systèmes de culture: Focus sur la construction de la typologie d'exploitations

Ce chapitre correspond à la description de la première étape de la méthode (voir Figure 13).

Les objectifs sont les suivants :

- Construire une typologie d'exploitations pour modéliser la diversité des exploitations en termes de systèmes d'exploitation pratiqués

- Modéliser les changements de systèmes d'exploitation et comprendre leurs déterminants.

La méthode proposée pour conduire l'analyse de l'évolution des systèmes agricoles à l'échelle de l'exploitation ainsi que les résultats de son application sur les exploitations agricoles en Guadeloupe sont présentées dans l'article suivant, intitulé **"A new method to assess farming system evolution at the landscape scale"**, qui est publié dans la revue *Agronomy for Sustainable Development*.

A new method to assess farming system evolution at the landscape scale

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Abstract

Agriculture can provide many ecosystem services to humankind such as food, fiber, clean water and sequestration of carbon. The values and flows of ecosystem services provided by agriculture are deeply linked to the crop composition and crop arrangement decisions made by farmers in agricultural landscapes. Agricultural landscape changes are mainly studied through the analysis of the crop allocation process at farm scale and rotations at field scale. However, the understanding of the farmers' decisions about the choice of crop acreages is of great importance in order to identify determinants of the evolution of farming system at landscape scale. Thus, we built a seven-step method, based on a dynamic farm typology, to 1) reveal the evolution of farm crop acreages in time and space and 2) identify the factors responsible for changes in agricultural landscapes. This dynamic typology is a multi-year classification of farmers. Steps 1 to 3 contribute to the building of the farm typology; steps 4 to 6 assess the changes in agricultural landscapes, and step 7 highlights the determinants of changes. Our method was applied to 3591 farms in Guadeloupe. We distinguished 8 farm types by means of crop acreages thresholds, allowing for the automatic classification of farms into types during the period 2004-2010. Through this classification, we found a diversification process among 111 specialized sugarcane growers breeders and mixed producers towards the production of vegetables and fruits. A spatial analysis of this diversification process revealed a relationship between it and the amount of water available from rainfall and irrigation. The method can reveal trends among the defined farm types and the determinants of changes in agricultural landscapes at the farm scale. The method can also be used as a prerequisite for assessing the trade-offs in the provision of ecosystem services or disservices associated with changes in agricultural landscapes, such as the provision of food or the pollution of water by regional agriculture.

2.1.Introduction

Agricultural landscapes account for one third of the human land use across the globe (FAOSTAT, 2008). Agricultural practices have had a wide range of harmful effects on their surrounding environment, such as the degradation of soils, the loss of biodiversity and the decrease of water quality, despite their ability to provide many fundamental ecosystem services to humanity (Tilman *et al,*. 2002). The values and flows of these services are deeply linked to the crop composition and the crop arrangement in these landscapes (Castellazzi *et al*., 2010; Benoit *et al*., 2012; Schaller *et al,*. 2012).

Both the composition and the configuration of agricultural landscapes are the result of farmer's cropping plan choices made at the farm level (Dury *et al*., 2011). A farm cropping plan is composed of 1) the crop acreages that refer to the farm area, usually devoted to one or a group of crops each year (Wijnands, 1999) (Figure 14) and 2) the crop allocation, which is the assignment of a particular crop to each plot on a given piece of land (Aubry *et al*., 1998). Crop rotation is defined as the practice of growing a sequence of plant species on the same land and is a concept that has long been used to represent the temporal dimension of cropping plan decisions (Bullock, 1992). Different rules for crop rotation decisions affect farmer's crop acreages, such as the return period of crops, the maximum number of successive years that a crop may be grown in a field, and prohibited crop sequences (Castellazzi *et al*., 2007). A farmer's cropping plan and crop rotations are often spatially explicit at the farm scale (Rounsevell *et al*., 2003). They are determined by a range of factors that impact the farmer's decision process, including biophysical factors (e.g., slope, rainfall) and socio-economic factors, (e.g., farm size, land tenure) (Leenhardt *et al*., 2010). At the regional scale, decision makers can strongly influence the provision of ecosystems services by modifying farmers' cropping plans according to agricultural policies that focus on these determining factors (Castellazzi *et al*., 2007; Valbuena *et al*., 2008).

The determinants of crop choices have been analyzed in a range of studies conducted within the "landscape agronomy discipline" (Benoit *et al*., 2012), which strongly focuses on the identification of patterns of crop rotations and the understanding of the process of crop allocations to plots. Patterns of crop sequences have been analyzed with special emphasis on the temporal and spatial evolution of the organization of crops (Benoit *et al*., 2001) and crop acreage changes at the regional scale (Mignolet *et al*., 2007) and very large scale (Xiao *et al*., 2014). The landscape regularities caused by crop rotations, in time and space, have been analyzed by Schaller *et al.* (2012) who found that they were the results of decision rules for crop allocations made at the farm scale. Sorel *et al.*(2010) noted that this crop allocation process is influenced by the farm type, the field characteristics and a range of agronomic factors. In these studies, the changes in cropping plan decisions were analyzed using an understanding of the changes in crop allocation processes as generally formalized with a set of rules (Aubry *et al*., 1998). In these studies, crop acreage choices are studied either at the regional scale, without consideration of the farmer's level of decision-making, or at the farmer's level, without observing the aggregation of changes at the regional scale. This analysis at both farm and regional scale seems to be of a great importance for understanding the determinants of crop acreage changes at the regional scale and to help decision-makers to formulate farm-scale policies intended to modify farming systems.

The most common approach to take account of crop acreages at the farm scale, when working at the regional scale, is farm typology, which categorizes farms into homogeneous groups with similar crop acreages. Comparisons of these groups are used to understand farmers' decision processes for crop choices (Iraizoz *et al*., 2006). Typologies are often built with either statistics, including principal component analysis and cluster analysis (which divide the overall farmer population into types), with expert knowledge, or with a mix of both approaches (Madry *et al*., 2013). Nonetheless, most farm typologies are static; they are made for a particular year and do not show changes over time and cannot, therefore, reveal the changes in farm cropping plans across time and space or the determinants of changes in farm cropping plans.

For analyzing the evolution of farm crop acreages over time and space, we propose a seven-step method that employs a dynamic farm typology, a multi-year classification of farmers into types : 1) to reveal the evolution of farm crop acreages across time and space and 2) to identify the determining factors of changes in agricultural landscapes. An understanding of such determinants can help decision-makers to define agricultural policies that target the cropping plans of farmers to modify agricultural landscapes and, in turn, the provision of ecosystem services by these landscapes. The method is first presented with all its steps and then is applied to a case study of farms in Guadeloupe. Special attention will be paid to the provision of food for local markets, because the weak level of food self-sufficiency is one of the main problems for decision-makers in Guadeloupe.

2.2.Material and methods

2.2.1. Description of each step of the method

The seven-step method includes the building of the farm typology in steps 1 to 3 and the assessment of changes in agricultural landscapes in steps 4 to 6, and highlights the determinants of changes in step 7.

2.2.1.1. Step 1 : building the multi-annual farm database

A geographical database of farms including data on their crop acreages, economic structure and biophysical context is built for the study period, generally at least 5 years. Surveys of farm acreages and crop allocations to fields are generally available at the regional scale through public statistics and satellite imagery. However, information concerning the biophysical context and the structure of the farms can be scarce. Then, the databases need to be completed with relevant geographical information such as altitude, rainfall, and proximity to city. These data can be compiled from geographical information systems, census data, on-farm surveys or field measures to provide a sufficient level of information about the hypothetical determinants of changes in farm cropping plans. The farms can either be mapped using the address provided in the database, by identifying farms with satellite imagery or can be represented as the centroids of fields owned by farms.

2.2.1.2. Step 2 : Building the farm typology

The typology of farms is based on some variables describing the farm crop acreage for a given year of the study period, generally the first or the last year. Principal component analysis is first used to reduce the number of variables in the sample and to avoid problems associated with multicollinearity. Then, relevant principal components are selected for the ascending hierarchical classification. After the ascending hierarchical classification, the partitioning of the population into homogeneous groups is performed using Ward's method (Ward, 1963) to minimize the intra-group variability and maximize the inter-group variability (Blazy *et al*., 2009).

2.2.1.3. Step 3 : Generating thresholds for the classification of farms

Thresholds allow the allocation of a farm to a given type. This allocation for each year of the studied period allows the modeling of the dynamics of the typology. These thresholds are generated with a regression tree. Classification and regression tree (CART) techniques are statistical tools that have been used in agronomy mainly for identifying the factors controlling yield variability (Tittonell *et al*., 2008) or farming practices (Maton *et al*., 2007). In our study, the regression tree is used to classify farms into farm types during the study period. In the regression tree, the variable to be explained is the farm type obtained from the ascending hierarchical classification, and the explanatory variables are the crop acreages of the farms.

2.2.1.4. Step 4 : Observing tendencies of farm type changes

The categorization of each farm into a farm type for each year of the multi-annual database reveals the evolution of the number of farms of each type across the period studied. These evolutions show the tendencies of the number of farms of each type to increase or decrease.

2.2.1.5. Step 5 : Generating farm transitions from type-to-type during the period

Step 5 focuses on farm types, with significant increases or decreases to determine which types of farm transition are responsible for the significant temporal trends observed. Farm transitions are generated by examining the changes of various farm types during the study period. The transitions among farm types are summarized in a graph that combines all the significant transitions among types that occurred during the study period. This generation of farm transitions among all types allows for the identification of types responsible for the temporal trends observed in the previous step. For each transition, the farms belonging to the original types are mapped on the study area. These mapped farms include those that changed to another group during the studied period and those that stayed within the same type. Hence the map identifies the areas where transitions have occurred and areas where the farm types have not changed.

2.2.1.6. Step 6 : Detection of spatial autocorrelation in transitions

The spatial influence on farm transitions is highlighted by performing spatial autocorrelation analyses on the map of farms. Spatial autocorrelation measures the degree to which a phenomenon is correlated to itself in space (Cliff and Ord, 1973). It refers to either similar values statistically clustered in space or similar values dispersed all over the area of study. Absence of spatial autocorrelation indicates that the spatial pattern observed is random. One can thus identify two types of clusters : 1) positively autocorrelated areas in which the changes in the frequency of farm type are statistically greater than that of a random pattern of farms, and 2) negatively autocorrelated areas in which the changes in farm type are statistically lower than the level of change of a random pattern of farms. A binary variable is created to identify the farms which have changed (binary variable 1) and those for which the type has not changed during the studied period (binary variable 0). Spatial autocorrelation is then performed on this binary variable. The farms for which the contribution to spatial autocorrelation, represented by the Z-score, is above +1.96 or under -1.96 are selected because these values show a pattern of farm transition that is significantly different from a random pattern, at a confidence level of 95% (Ord and Getis, 1995). These farms are then selected for regression analysis because they allow for a better identification of the determinants of changes in farm cropping plans.

2.2.1.7. Step 7 : Identifying the drivers of changes in farm cropping plans

To identify the determinants of changes in farm cropping plans, regression analysis is performed on the farms of the positively and negatively autocorrelated clusters in the studied area. The regression analysis quantifies the effects of the structural and biophysical variables of the farms on the importance of the local spatial autocorrelation, represented by the Z-score allocated to each farm. This method is similar to the one used by Chopin and Blazy (2013) to explain the origins of regional variability in crop yields by biophysical and socioeconomic determinants.

2.2.2. Application of the method to Guadeloupian farms

Figure 14: Sugarcane and pasture are an important component of farmers' cropping plans in Guadeloupe, as shown in the agricultural landscape pictured in photograph.

Guadeloupe is an archipelago located in the Caribbean. The 31300 hectares of the total farmed area are cultivated by 8000 farmers all across the territory (Agreste, 2010). Farm sizes range from less than one hectare to more than one hundred. The biophysical context of the farms varies from dry plains on calcic soils to andisols and nitosols located at high altitudes, where crops are grown on sloppy fields with high rainfall on very fertile clay soils. Rainfall in cultivated areas of Guadeloupe ranges from 800 $mm.yr^{-1}$ in the dry plains to more than 4000 $mm.yr^{-1}$ at high altitudes. According to the regional statistics, sugarcane, pastures and banana occupy respectively 14000, 10000 and 2100 hectares and the other crops, less subsidized, including crop gardening, orchards, tubers, pineapple and plantains occupy 3000, 950, 350, 300, and 300 ha (Figure 14). Guadeloupian agriculture is oriented towards the exportation of highly subsidized agricultural products, mainly bananas and sugar. Therefore, the food crop production does not meet the needs of the population and consumers must buy expensive imported foodstuffs. The Guadeloupe regional council is willing to drive the local production towards an increase from the current level of food self-sufficiency. Our application will then focus on the types that can contribute to an increase in food self-sufficiency by the production of tubers, vegetables and fruits.

2.3.Results and discussion

2.3.1. Results of the application of the method to the Guadeloupe case study

2.3.1.1. A seven-year database comprising 3591 farms

We used a geographical database of individual fields, represented by polygons, corresponding to the annual declarations of farmers for obtaining subsidies. The annual databases, covering the period from 2004 to 2010, were merged together and the 25054 fields for which the crop type was declared for the entire period were selected. As shown in the two last columns of Table 4, this multi-year database is quite representative of the regional statistics (Agreste, 2010) as regards the areas of the subsidized crops of banana and sugarcane grown by more professional farmers, but less so for fruits and vegetables. We divided the numerous initial crops of our database into eight categories, "sugarcane", "banana", "pastures", "crop-gardening", "tubers", "plantain", "pineapple", and "orchards," based on the similarity of the crop management system and the crop length cycle.

We generated the biophysical characteristics of field by using a geographical information system (GIS) and different layers of information in a shapefile or a raster format. Altitude information was obtained by using a fifteen-meter digital elevation model (DEM), a raster dataset representing the evolution of altitude over the region, which was produced with a map of altitude with contours every five meters, using the kriging tool from Arcgis 9.3 (ESRI, 2009). The rainfall layer used was obtained the same way with a shapefile of isohyets. The slope raster was obtained using the slope tool in Arcgis 9.3 with the DEM as the input. Geostatistical analysis of fields with each generated raster provided the mean altitude, mean rainfall and mean slope for each field of the database. The farm structure variables, represented by the farm size, the proportion of irrigable area and the proportion of the farm in agricultural land management, were obtained either by a simple calculation or by a geographical treatment. The total cultivated area is the sum of the field areas of the farms. The proportion of irrigable area was based on a shapefile of irrigation schemes. The proportion of the farm area under each crop was obtained by dividing the area of each crop by the total cultivated area. This biophysical, agronomic and farm structure information was up-scaled from the field level to the farm level using the means weighted by the area of each field for each farm.

Table 4: . Descriptive statistics of the eight farm types obtained from the ascendant hierarchical clustering. The values in the columns on the left of each group are the variable means and the values in parenthesis are the standard deviations of the variables. For the acreages, the mean values are weighted by the size of each farm. The mean characteristics of the total farm population are also given along with the area of each crop at the regional level. The area of crops and the total number of farms in the database are lower than the area of crops and the number of farms given in the regional statistics (3591 farms compared to the 8,000 declared farms).

Name of types	Crop-Gardeners		Mixed cane growers Breeders		Breeders		Diversified		Diversified cane growers		Specialized cane growers		Arboricul-turists		Banana growers		**Total farm population**		**Total area in the database (ha)**	**Total area of crops in the regional statistics (ha)**
Number	56		624		697		90		925		976		54		169		3591		20543	31000
Prop. in pasture	1%	(3%)	47%	(7%)	83%	(15%)	13%	(14%)	17%	(11%)	0%	(1%)	6%	(11%)	0%	(9%)	25%	(34%)	5227	10000
Prop. in sugarcane	0%	(0%)	46%	(8%)	13%	(15%)	40%	(24%)	78%	(11%)	99%	(2%)	5%	(6%)	9%	(12%)	57%	(39%)	11743	14000
Prop. in banana	0%	(3%)	1%	(1%)	0%	(0%)	1%	(8%)	0%	(1%)	0%	(0%)	2%	(11%)	87%	(18%)	9%	(18%)	1850	2100
Prop. in plantain	0%	(0%)	0%	(1%)	0%	(2%)	4%	(26%)	0%	(3%)	0%	(0%)	1%	(11%)	1%	(5%)	1%	(6%)	84	300
Prop. in pineapple	0%	(0%)	0%	(1%)	0%	(1%)	7%	(19%)	1%	(4%)	0%	(1%)	1%	(3%)	0%	(5%)	1%	(5%)	159	300
Prop. in crop-gardening	97%	(4%)	3%	(3%)	1%	(6%)	21%	(27%)	2%	(4%)	0%	(1%)	4%	(10%)	1%	(9%)	4%	(18%)	808	3000
Prop. in orchards	1%	(2%)	2%	(4%)	2%	(5%)	9%	(9%)	1%	(8%)	0%	(1%)	80%	(19%)	1%	(3%)	2%	(14%)	510	950
Prop. in tubers	0%	(0%)	1%	(3%)	0%	(3%)	5%	(18%)	1%	(4%)	0%	(0%)	1%	(6%)	0%	(3%)	1%	(6%)	161	350
Mean altitude (m)	195	(266)	20	(40)	37	(60)	55	(74)	22	(29)	22	(25)	194	(138)	197	(159)	39	(79)		
Mean slope (%)	10	(13)	3	(5)	6	(7)	7	(7)	3	(3)	3	(3)	20	(14)	15	(7)	4	(6)		
Number of fields	5	(8)	6	(4)	4	(4)	9	(6)	6	(4)	4	(8)	5	(4)	15	(17)	6	(7)		
Number of crops	1.1	(0.3)	2.3	(0.6)	1.7	(0.7)	3.2	(1.1)	2.3	(0.7)	1.1	(0.3)	2.0	(0.9)	1.5	(0.8)	1.9	(0.9)		
Total cultivated area (ha)	6	(9)	5	(5)	5	(9)	9	(14)	6	(5)	6	(35)	6	(7)	15	(25)	6	(20)		
Mean rainfall (mm per year)	1935	(1064)	1757	(425)	1651	(504)	1929	(748)	1714	(450)	1749	(456)	2626	(675)	3230	(635)	1814	(603)		
Prop. of irrigable area	74%	(44%)	31%	(45%)	41%	(47%)	66%	(45%)	44%	(48%)	33%	(45%)	27%	(43%)	59%	(46%)	39%	(47)		
Prop. of area in agricultural land management	0%	(13%)	12%	(31%)	3%	(16%)	30%	(36%)	30%	(44%)	11%	(31%)	2%	(14%)	7%	(24%)	12%	(31)		

2.3.1.2. A typology composed of eight types of farms

The variables used in our typology are the proportions of the eight types of crops in the cultivated farm area (Table 4). The principal component analysis reduced the number of dimensions in our data according to the Kaiser's criteria to four principal components that had values above one. We used these four principal components in the ascending hierarchical classification and obtained eight groups (Table 4). This partition into eight groups is the one with the highest ratio of inter-group variability to intra-group variability. However, some degree of similarity exists between the "diversified" type and the "crop-gardeners" type as well as between the "mixed cane growers - breeders" (called "Mixed" in the rest of the paper) and the "diversified cane growers," as evident in the description of their mean crop acreages (Table 4).

The inter-group variability of the farm structure and the farm biophysical context in the overall population reflects the large diversity of farms in Guadeloupe. The descriptive statistics for the eight groups revealed a high level of specialization of five groups and a diversification for the three others (Table 4). The specialized producers, " cane growers", "breeders", arboriculturists", "crop-gardeners", and "banana farms", respectively, specialized in sugarcane, beef production, perennial fruit production, crop-gardening, and banana production for exportation. "Mixed" and "diversified cane growers" represent groups with two or three main products. For the first type, sugarcane and pasture are the only production types, while these crops are grown with a diverse group of crops in the second type. The "diversified" type includes farms that produce at least three or four crops and pasture and sugarcane have the smallest acreages on the farm.

The groups "crop gardeners", "diversified", "arboriculturists" and "banana growers" are localized on a high range of physical and structure context. On the opposite the groups, "mixed", "breeders", "specialized cane growers" and "diversified cane growers" are located in the same context (Table1). "Mixed" producers, "breeders", "diversified cane growers" and "cane growers" cultivate in average four hectares, the altitude of the farm is low (around 40 meters), the fields slope is weak, around 5% and rainfalls are in average around 2000 mm per year. "Arboriculturists", "crop-gardeners", "diversified" and "banana growers" are located on a range of different biophysical contexts and their intra group structure strongly differ. The most import difference among these groups is the size of farms. "Banana grower" own large farms around 15 hectares in average, the size of "diversified" farms is also above the average size of the farm population with seven hectares while "crop-gardeners" and "arboriculturists" have the same mean size as the overall farm population. "Diversified" are located in average at lower altitudes than "crop-gardeners" and "arboriculturists", while "banana growers" are located on greater altitudes. Slopes also reflect the variability of biophysical contexts. They are quite high, between 10% and 20%, but their standard deviation in these groups is really important (15%). "Crop-gardeners" are located in average on irrigation schemes while "arboriculturists" are outside of these schemes.

2.3.1.3. Fourteen thresholds for crop acreages categorize farms into the eight farm types

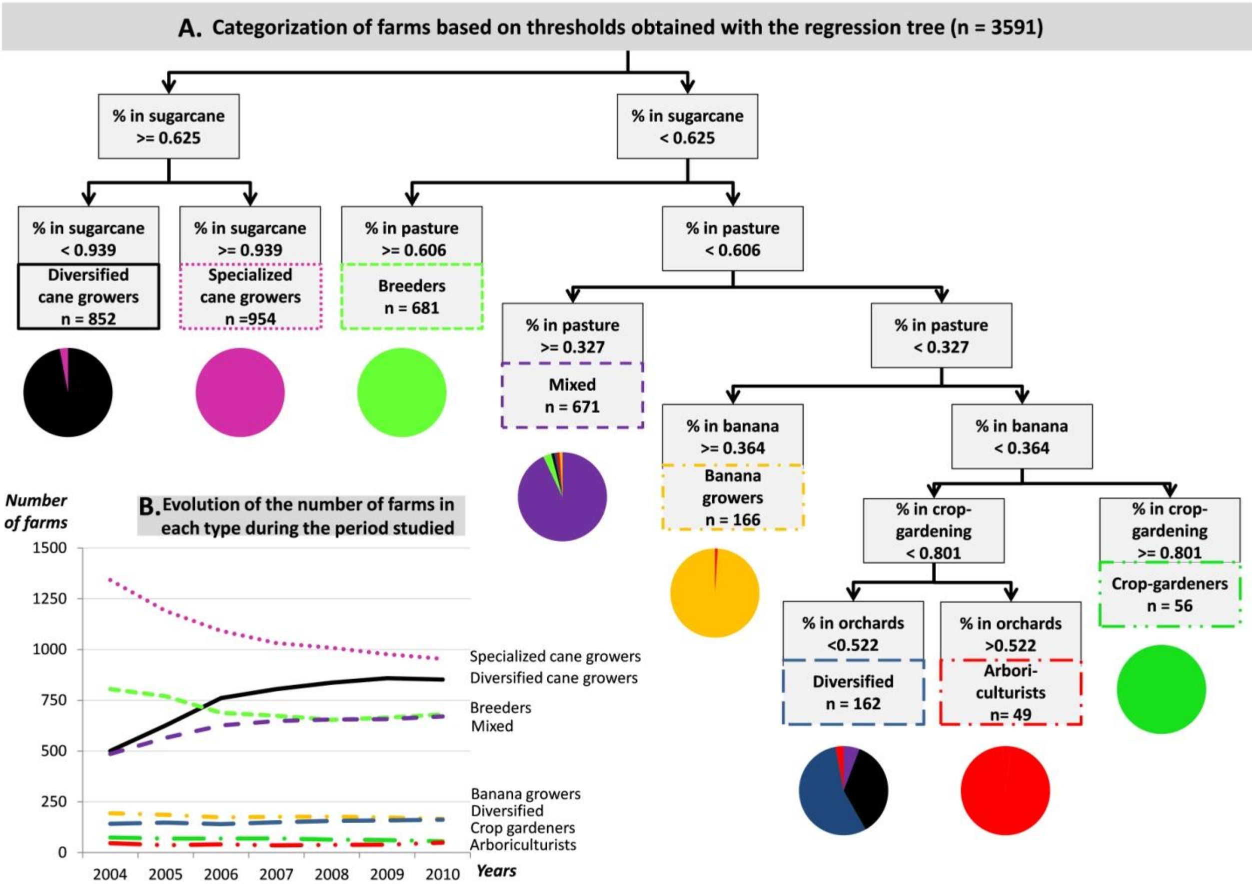

Figure 15: Figure 15 A shows the results of the regression tree for the population of farms. Thresholds for automatically categorizing farms are enclosed in light grey boxes, and the different farm types identified by the regression tree are given in the colored boxes, with their numbers. The pie charts represent the proportion of each group from the ascending hierarchical classification included in each group obtained with the regression tree. We can see that the reproduction of groups from the cluster analysis is very good for seven of the eight groups. Only the classification of "diversified" farms is average, even though more than half of the group is constituted by farms classified as "diversified" in the hierarchical clustering analysis. In the pie chart of the "diversified" farm type, we can see that one third of this type is constituted by the "diversified cane growers" farm type, which is similar to the "diversified" farm type in its description because they both included diversified farms for which the proportion of sugarcane has decreased. Figure 15 B shows the changes in the numbers of farm types from 2004 to 2010 in the selected population of farms (n=3291 farms). We can see that the number of "specialized cane growers" from 1300 to less than 1000 while during the same period, the number of "diversified cane growers" increased rapidly.

The regression tree generated fourteen classification thresholds based on the proportions of crops within the farms' cropping plans. These thresholds enabled the automatic categorization of the farms of our geodatabase into one of the eight farm types for each year of the study period (Figure 15). For each group obtained via the regression tree, the pie charts presented in Figure 15 represent the proportion of the "initial" groups built from the ascending hierarchical classification. We can see from the pie charts that the regression tree produced similar results to the ascending hierarchical classification; for 7 out of the 8 farm types, more than 90% of farms were correctly classified. Only the "diversified" group was composed of a significant proportion of farms classified differently by the ascending hierarchical classification. In this group, 30% of the farms were classified as "diversified cane growers" by the ascending hierarchical classification. However, we consider the entire classification from the regression tree as valid because the two groups "diversified" and "diversified cane growers" are similar in terms of their descriptions. Furthermore, only 5% of the total number of farms in the population were categorized incorrectly. The fourteen thresholds allowed for the automatic categorization of the population of 3591 selected farms from 2004 to 2010.

2.3.1.4. Farm-type dynamics from 2004 to 2010

We noticed a significant decrease in the number of "specialized cane growers" farm type between 2004 and 2010. In contrast, the number of "diversified cane growers" farms strongly increased (Figure 15). Thus, the population of "specialized sugarcane growers" decreased from 1400 in 2004 to less than 1000 in 2010, i.e., from 39% to 26% of the overall farm population. In contrast, the number of "diversified cane growers" farms increased from 500 to 800, i.e., from 14% to 25% of the total farm population in 2010.

2.3.1.5. Summary of the transitions of farms among types

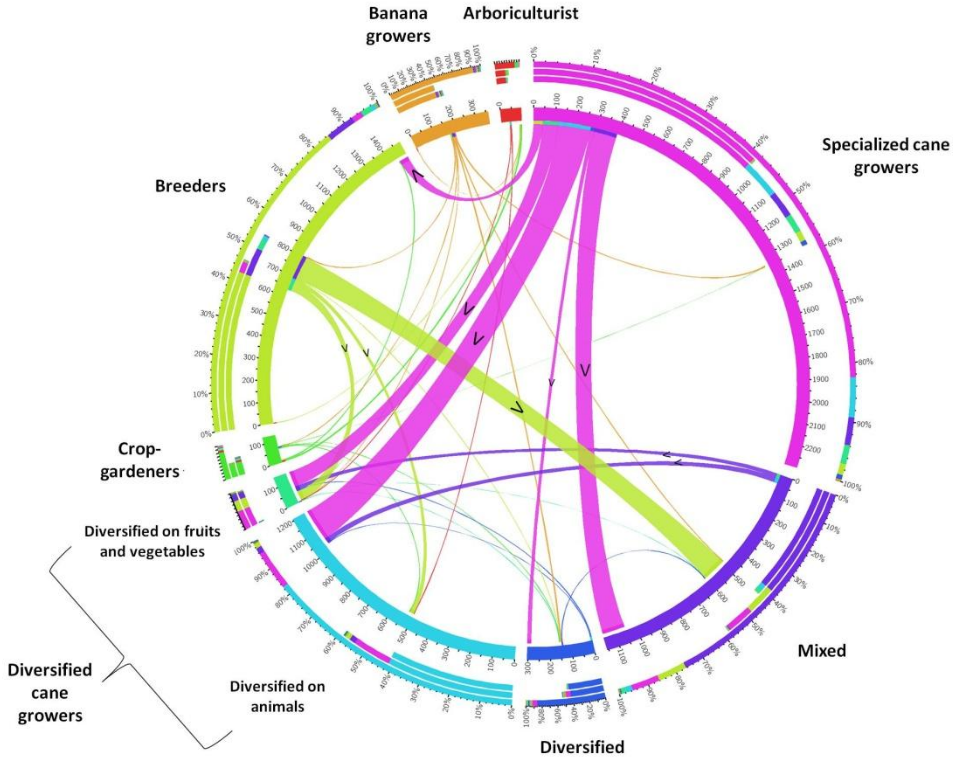

Figure 16: Circular plot of farm types in 2004 and the representation of their transition during the period 2004 to 2010 for the selected population of farms (n=3291 farms). Ribbons between types represent the transition of farms from a given type in 2004 to another one in 2010. Ribbon width represents the number of farms in transition. Direction of transitions is represented by an arrow. The angular size of circularly arranged segments represent the population of each type (with their corresponding color used in Figure 15) and are proportional to the size of farm types in 2004. 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. The "diversified cane growers" group was split into two subgroups, "the diversified on animals" and the "diversified on fruits and legumes" subgroups. The latter reflects the adoption of legumes and fruits crops by 111 farms from the "specialized cane growers", "mixed" and "breeders" farm types, represented by the flows to "diversified on fruits or legumes".

All the farm changes from 2004 to 2010 have been summarized in terms of the number of changes over the period (Figure 16). A number of "specialized cane growers" transitioned to "diversified cane growers". To test the ability of the method to explain transitions between farm types, we decided to focus on the determinants of the increase in the "diversified cane growers" farm type. This increase corresponds to the transitions of farms initially belonging to the "breeders", "specialized cane growers" and "mixed" farm types into "diversified cane growers". These transitions reflect an important change in production from pasture and sugarcane to crop-gardening and orchards. Indeed, sugarcane and pasture can be considered as more risky, more resource intensive (in terms of time, equipment and workforce) and also more profitable. The focus on these transitions revealed two different patterns among farm transitions. The first is a diversification process through the adoption of cattle breeding by farmers, while the second pattern is a diversification process associated with the adoption of vegetables or fruit production. We then decided to split the "diversified cane growers" type into two subgroups, a "diversified on animals" subgroup and a "diversified on fruits or vegetables" subgroup, according to the presence of fruits or vegetables in the farm acreage in 2010, which was 10%, on average, in 2010.

After splitting the "diversified cane growers" type into subgroups, we focused on the transitions from "specialized cane growers", "mixed" and "breeders" to "diversified on vegetables and fruits" in order to understand the process of crop acreage changes towards production of food for local consumers. An understanding of the determinants of farm cropping plan changes towards the diversification of crops is of a great importance to propose adapted agricultural policies aimed at increasing the level of food self-sufficiency in Guadeloupe. We then mapped the 2504 farms belonging to the "specialized cane growers", "breeders" and "mixed" groups in 2004. Of these 2504 farms, 111 farms changed to the "diversified on vegetables or fruits" type. This number represents a small proportion of the farms in Guadeloupe, but this transition can be used as a basis for understanding the determinants of the diversification process in Guadeloupe. A binary variable was used in the spatial autocorrelation analysis to identify the 111 farms that changed to the "diversified on vegetables and fruits" farm type.

2.3.1.6. Groups of autocorrelated farms in transitions

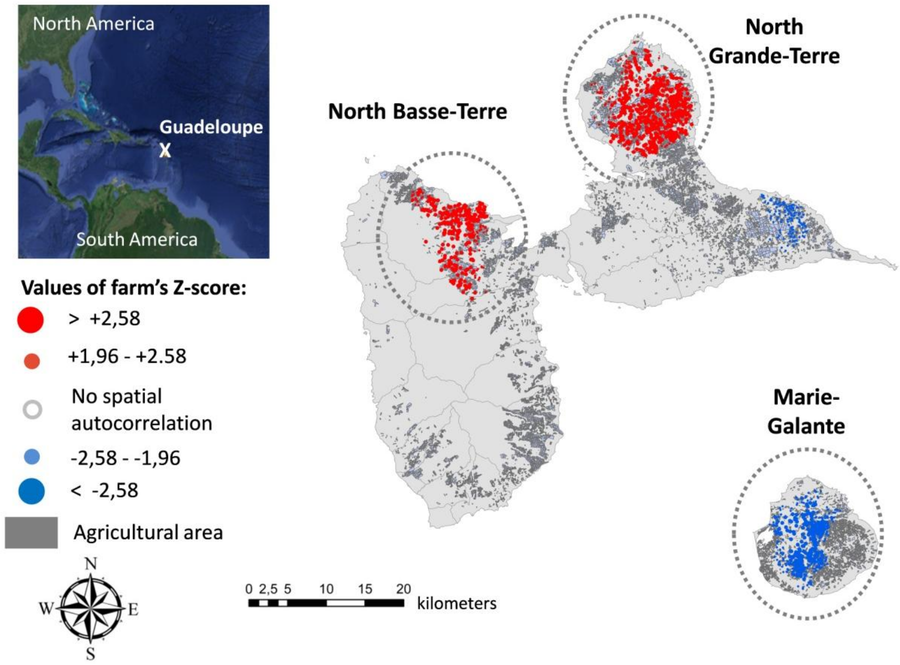

Figure 17: Map of the level of local spatial autocorrelation, highlighting the areas where farms from the "breeders", "specialized cane growers" and "mixed" groups changed to "diversified cane growers in legumes and fruits". The hot spots shown in red are farms in areas where the changes in farm type are statistically greater than those of a random pattern of farms, while cold spots shown in blue are areas where the changes in farm type are statistically lower than a random pattern. Three areas are significantly different; the "North Grande-Terre" area and the "North Basse-Terre" have a high number of changes in farm type, while in the number of changes is low in the "Marie-Galante" area.

The fourth step is the spatial autocorrelation analysis of the population of farms to identify areas where 1) statistically, more transitions have occurred from one group to another and 2) areas in which farms have, statistically, less transitions (Figure 17). The spatial autocorrelation analysis of farms based on the binary variable identified three areas, two areas of positive spatial autocorrelation and one area of negative spatial autocorrelation. We selected the 1280 farms that were highly negatively and positively autocorrelated within these three clusters for regression analysis.

2.3.1.7. Access to irrigation for crop growth explains the observed changes in farm cropping plans

$$Z.score = 5.489 + 0.568\ (slope) - 0.004\ (rainfalls) + 0.006\ (\ cultivated\ area) \\ +\ 0.833\ (\%farm\ in\ irrigation\ scheme) + 0.198\ \ (\%farm\ in\ land\ management)$$

R^2 = 0.77 and Mean rainfalls(P<0.01), Prop. farm in irrigation scheme (P<0.01)

A multiple linear regression performed on the 1280 selected farms in the three above-mentioned clusters revealed the influence of the access of farms to irrigation and the amount of rainfall on the diversification process (see the Equation 1). The presence of farms within irrigation schemes was positively correlated to the transition of farms to "diversified on vegetables and fruits", while the amount of rainfall was negatively correlated to the diversification towards vegetables and fruits. This finding can be explained by the fact that vegetables and fruits need to be irrigated in dry areas because of the lack of water from rainfall, while the amount of water is too high in humid areas where rainfalls are close to 3000 mm. This high amount of water can cause waterlogging and drive the development of pests and diseases that strongly decrease the yields of vegetables and fruits (while pasture and sugarcane are resistant to this phenomenon).

2.3.2. Discussion of the method for understanding the determinants of change in farm cropping plans

2.3.2.1. Automatic classification of farms into farm types facilitates monitoring of the impacts of agricultural policies on farms

The construction of thresholds for categorizing the farms into farm types can facilitate the identification of tendencies for decreases or increases in the number of farms of various types over a territory. This automatic classification is particularly useful for decision-makers to follow the dynamics of change at the scale of the farm in addition to the regional scale. This automatic categorization is fast because it does not require repeating a statistical analysis on databases for every survey. This automatic classification also does not require the intervention of expert knowledge for classifying farms into groups. Thus, this method is particularly useful in the context of the high frequency of farmer interviews and census that encompass a wide range of information about a farmer's activities on their farm. Using the method for several years can help local agricultural policy makers to easily follow the evolution of farmers' cropping plans and assess the effectiveness of agricultural policies aimed at changing the agricultural landscape.

Regression trees are characterized by rough discontinuity, which means that small changes in a farmer's cropping plan can generate a change in farm type. In our study, this threshold effect could be important for farms cultivating few fields. The change of a crop in one or two fields can create a significant change in crop acreages at the farm scale and thus a change in farm type. These changes in farm type could occur several times for a given farm as a result of crop rotations for instance. It is difficult to know if farm type changes are caused by crop rotation effects or a long lasting change in the activities of the farm. In our case study, this problem is minimized by the high number of farms included and by the fact that sugarcane- and pasture-based farm types, e.g., "breeders", "mixed" and "specialized cane growers", do not perform crop rotations; therefore, their inter-annual variations in crop acreage at the farm scale are minimized. This problem can also be minimized by characterizing the pattern of crop rotations at a regional scale that are common to different farms (Benoit *et al.,* 2001; Mignolet *et al.,* 2007). Instead of building a typology on crop acreages, it can be built on proportions of different crop rotations at the farm scale. Considering crop rotations directly can prevent us from over-estimating the farm type changes based on crop acreages at the farm scale. A new crop rotation in the cropping plan of a farm can then be considered as a change in farm type towards another form of crop production.

2.3.2.2. Transitions of farms among farm types

The main advantages of our method rely on its ability to assess the evolution of agricultural landscapes at the farm scale through the analysis of the changes in the number of farm types over time. Our method insures invariability in the description of types, which reveals the farm cropping plan changes by the changes in farm types. In previous studies (Iraizoz *et al*., 2007; Mignolet *et al*., 2007), farm typologies were static, and several statistical treatments were required to generate a dynamic typology. However, these multiple treatments modified the description of groups across the period studied. The study of determinants with these treatments may have introduced bias into the analysis of determinants because a farm with the same crop acreages can be categorized into different types across the study period because of the changes in the definitions of the farm types.

In our method, we can identify the farms within farm types responsible for the temporal tendencies observed. The transitions of farms from one type to another are all described for the period studied. The explicit changes in the farm types of all the farms in our case study allows for the identification of the transitions among groups. These transitions are an indicator of farm cropping plan changes across the territory. Iraizoz *et al. (*2007) realized a typology for studying the trajectories of changes in farm structure over time. The dynamic dimension of their typology was the measure of the annual percentage change of the structure variable for four years, but no change of the structure over time was presented. The indicator of changes in farm cropping plans available with our typology allows for the better identification of the spatial factors that determine the changes in farm cropping plans.

The method needs to be applied to a multi-year database in order to observe trends among farm types. The time scale of the multi-year database should be based on the availability of data for the study area and on the duration of crops in the area. In our study, the main crops, bananas and sugarcane, are grown for 7 years on average before being destroyed. Hence the use of a seven-year database seemed appropriate to see changes taking place in farmers' crop acreages.

2.3.2.3. Identifying the determinants of changes for spatially targeted agricultural policies

Transitions are defined not only by an increase or a decrease in the number of farm types but also by the location of the temporal transitions observed with the method. Focusing on the farms from positively and negatively autocorrelated clusters helps by statistically highlighting the determinants of farm changes. The residuals of the model we built to explain the transition of farms toward the subgroup "diversified on fruits or vegetables" were tested for spatial autocorrelation to reveal any bias in the estimation of parameters of farm type changes, as in Chopin and Blazy (2013). The spatial autocorrelation tests did not reveal any autocorrelated pattern of farm changes in the residuals of the regression model. This verification ensured us that the estimations of the parameters in the regression analysis were not biased.

This method enables the identification of the determinants of changes in farm cropping plans and, in turn, the changes in agricultural landscapes. In our case study, the determining effect of the access to irrigation can drive agricultural policies towards the provision of a sufficient amount of water to farms located in dry areas to reach the regional objective for food self-sufficiency.

Providing access to irrigation to the farmers is a lever of action to promote conversion from sugarcane- and pasture-based systems to fruits or vegetables. This process of diversification of cane-based farms can then be increased by an extension of the irrigation schemes in dry areas where cane-based farms are located, as has been done in the north Grande-Terre area since the beginning of the 2000's (Cabidoche *et al*., 2002). In the West-Grande-Terre area, the trend towards diversification is weak since this diversification process took place in the 1980's with the opening of irrigation schemes. In contrast, the results of the analysis demonstrated that high levels of rainfall were a constraint to the adoption of crop-gardening production in humid areas. This is particularly true in the South-Basse-Terre area, where the decrease in the banana area has not been accompanied by a significant increase in market gardening. This is due to the presence of polluted soils that prohibit the cultivation of roots and some vegetables (e.g. zucchini; see Cabidoche *et al.,* 2009) and the lack of rainfall in the dry season that cannot be corrected by irrigation due to the absence of irrigation schemes. Considering the high cost of drainage of water from a field, innovative crop gardening-based cropping systems can be designed to respond to this important constraint. Thus, crop rotations should be designed with an emphasis on the resistance of crops to waterlogging effects and high pest infestations when the rainfall levels are important. These systems can be prototyped for all the pedoclimatic areas of Guadeloupe by taking into account the biophysical and the socio-economic contexts of the farms and the objectives of farmers in these areas. This prototyping method can be based on the modeling of the adoption of innovative cropping systems by farmers, contributing to an increase in food self-sufficiency in Guadeloupe (Blazy *et al*., 2009).

Other geographical factors can explain the absence of changes in farm types towards diversification. For instance, the level of subsidies can explain the absence of transitions of banana farms towards more diversified farm types during the study period. The economic context of banana production, which is affected by the common market organization (CMO) that will lead to the end of banana quotas and taxes, will most likely threaten banana production and exportation in Guadeloupe by 2020 because of its low degree of competitiveness in the world market. Thus, other possible determinants of changes in farm cropping plans to other farm types should be investigated to identify all the levers of action towards the diversification of crops for each type of farm. The lack of data on the structure of farms and the personal objectives of farmers in the database we used makes it difficult to determine all of the determinants of changes in crop acreages at the farm scale. Complementing our study with on-farm surveys would help gather new information and data concerning the process of diversification. As proposed by Debolini *et al.* (2013), mapping the knowledge of agricultural experts would be a good step to perform before surveying farmers. These experts would most likely be able to provide a range of possible constraints to the diversification of farm types.

As we showed in Table 4, this multi-year database is less representative of the regional statistics for fruit and vegetables than for sugarcane and pasture. The number of farms geared to the production of fruit and vegetables is thus probably underestimated in our study. This lack of farms was identified in all the districts of Guadeloupe in a homogeneous way based on 2010 census data. The access to irrigation is a determinant of change from cane- and pasture-based types to "cane growers diversified on fruit and vegetables" that can be equated to the missing farms in our database. This lack of farms in our data appears as a constraint for the application of our method since it reduces the probability of identifying a trend in the number of farm types.

This method can help to assess ecosystem services provided by agriculture at the regional scale. This supply of ecosystem services is the contribution of agriculture to sustainable development. For instance, in our example, the development of fruit and vegetables in "cane growers diversified on fruit and vegetables" can enhance the provision of food, but at the same time, the use of irrigation in new areas can decrease the regulatory service of agriculture for the purification of water, with an increase in pollution due to intensive farming practices. Such ecosystem services can be appraised using indicators to measure their provision at the regional scale. These indicators use information about cropping systems e.g. the yield or the use of pesticides, and up-scale this information from field to region in order to measure these services. An assessment of different types of services from year to year can help characterize the trade-offs between the production of food and the provision of clean water by agriculture.

2.4.Conclusion

The method developed here differs from the methods currently used for examining changes in farm cropping plans because it is mainly based on the analysis of farm crop acreages in contrast to other methods that focus on the crop allocation process. The typology developed with our method ensures a dynamic and automatic representation of the evolution of farm types over several years, based on crop acreage choices. This dynamic reveals the temporal and spatial tendencies of changes in farm cropping plans during the studied period as well as the transitions among groups. This temporal and spatial characterization aids in the identification of the determinants of the changes in farm cropping plans. This method also avoids bias in the analysis of the influence of determinants by assessing spatial autocorrelation and providing a description of the farm types that remain the same over time. Furthermore, this rapid classification method is particularly useful for following the evolution of the farm population and assessing the effectiveness of agricultural policies on the changes in cropping plans that are reflected in the changes in the number of farms of each type. Using the method to examine a larger database, with more structure data and socio-economic information or would increase the number of geographical factors to be tested as possible determinants of change. The analysis would then help decision-makers to drive the changes in farm cropping plans towards a desired state, such as an increased level of food-self sufficiency in Guadeloupe, by using determinants as possible levers of action.

Our method could be used as a prerequisite for assessing the trade-offs in the provision of ecosystems services associated with land use changes. The provision of ecosystem services is a multicriteria problem and a change in farm cropping plans can provoke multiple effects on different ecosystem services. In our method, each farm type is described by the mean farm crop acreages. For each acreage, at each different location, we can derive a mean level of the provision of ecosystem services. Then, by analyzing the influence of determinants on the changes in farm cropping plans, we would be able to characterize the changes in agricultural landscape and the provision of ecosystem services. In order to measure the provision of ecosystem services and determine the trade-offs among these services, indicators can be designed. These indicators use the information on cropping practice at the field scale and up-scale this information to the regional scale in order to determine these trade-offs. Finally the method can allow for the measurement of the overall contribution of the agricultural landscape to the sustainability of a territory.

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3. Indicateurs pour l'évaluation de la contribution de mosaïques de systèmes de culture au développement durable du territoire

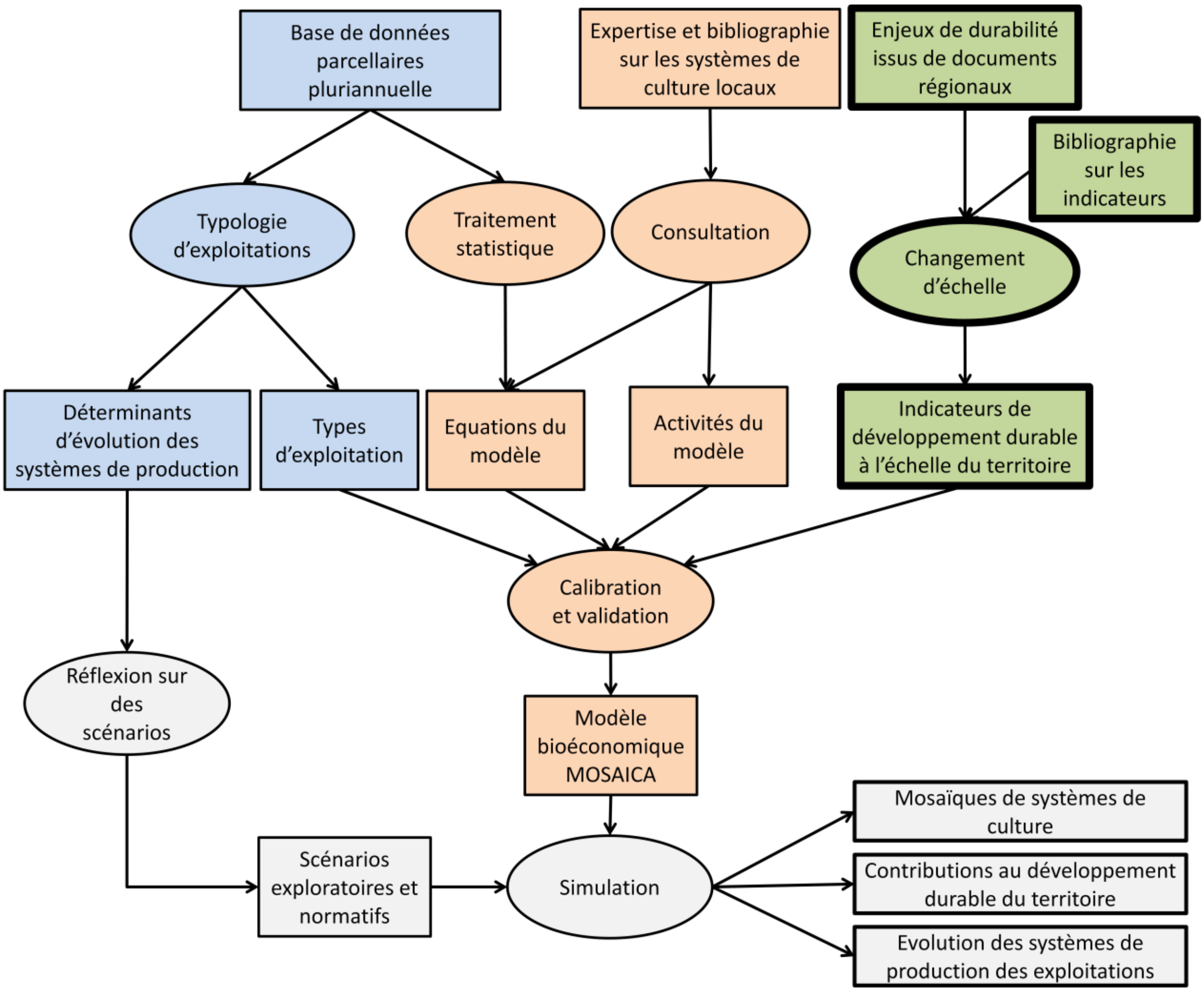

Figure 18: Ensemble méthodologique pour la conception et l'évaluation multicritère de mosaïques de systèmes de culture: Focus sur la construction des indicateurs d'évaluation à l'échelle du territoire

Ce chapitre correspond à la description de la seconde étape de la méthode (Figure 18). Les objectifs sont les suivants :

- Construire une batterie d'indicateurs permettant d'évaluer la contribution de mosaïques des systèmes de culture au développement du territoire

- Evaluer la contribution actuelle de l'agriculture guadeloupéenne au développement durable du territoire

La méthode proposée pour répondre à ces objectifs est présentée dans l'article suivant, intitulé "**Contribution of agricultural landscapes to sustainable development : a method of scaling up from the field to region and its application to Guadeloupe**", soumis à la revue *European Journal of Agronomy*.

Contribution of agricultural landscapes to sustainable development : a method of scaling up from the field to region and its application to Guadeloupe

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Keywords : Agricultural landscapes, indicators, cropping systems, scale-change, sustainable development, integrated assessment

Abstract

Many methods have been designed for assessing the sustainability of cropping systems and farming systems, but few methods exist at the landscape scale. This lack is due to the spatial mismatch between the field scale at which information of the cropping system is available and the landscape scale at which policy-makers make decisions. We propose here a method for assessing the agricultural landscape sustainability. This assessment encompasses a global score for each indicator that is calculated at the landscape scale and provides an overview of the spatial variation of different footprints of agriculture throughout the territory. In this method, we identified 1) the sustainability objectives at the regional scale, 2) the relevant indicators providing information of the impacts that are related to these objectives at the field scale, 3) a method for scaling up indicators, 4) cropping system information at the field scale to calculate indicators and 5) a database with the spatial location of fields and spatial units in order to analyze the entire territory. We used this framework to assess the sustainability of the Guadeloupian agricultural landscape. The results show that the contribution of agriculture in Guadeloupe is weak for economic and social sustainability and quite good for environmental sustainability. This method was particularly efficient for conducting a spatially explicit integrated assessment from the field to regional scale with adapted scale change procedures. This method could be used for the ex ante assessment of innovating agricultural systems at the landscape scale, aiming at improving the response of agriculture to sustainability objectives.

3.1.Introduction

Agriculture worldwide has strongly affected the ecosystems and depleted their capacity to offer a wide range of ecosystem services to humanity (MEA, 2005). Agriculture needs to face new challenges by increasing its services to society while insuring a decrease of its negative externalities on the environment. The successful implementation of *land use* policies is often hampered by the lack of knowledge regarding their impacts on sustainable development in different contexts (Reidsma *et al.,* 2011). The assessment of agricultural systems at the regional scale is strongly required by policy-makers in order to assess the effects of the implementation of policies in favor of such development.

The study of ecosystems services provision has provided a large body of scientific papers aiming at assessing the sustainability of agricultural systems (Sadok *et al.,* 2009; Strassert and Prato, 2002; Zander and Kächele, 1999; Bachinger and Zander, 2007; Dogliotti *et al.,* 2003; Pelzer *et al.,* 2012). Most of these methods follow similar steps with the identification of the sustainability problems and the selection of criteria for the assessment of system responses to these problems (Lopez-Ridaura *et al.,* 2000). The development of approaches has focused on the multi-functionality of agriculture in which agriculture is seen as an activity that provides services to society that can be productive, economic, ecological, cultural and social (Gomez-Sal and Gonzalez-Garcia, 2007, Castoldi and Bechini, 2010). These integrated assessments are generally performed to advise decision-makers on the best practices to foster at the plot scale, but these cropping systems can have various effects at the regional scale, the level of decision at which policy-makers act (Rusch *et al.,* 2012).

At the regional scale, the contribution of cropping systems to sustainable development can strongly differ depending on their location in the territory. At the regional level, the agricultural system is composed of several plots on which a cropping system is selected based on the farmers' decision-making process. These mosaics of cropping systems or crops, also called agricultural landscapes, are the results of farmer's cropping plan decisions (Dury *et al.,* 2011), which is why the farm scale also matters in agricultural sustainability assessments. Agricultural landscapes can then be described by a crop or cropping system composition and an arrangement in space. These crop compositions and crop arrangements play an important role in the ecological processes within a territory, such as the spread of pollution (Houdart *et al.,* 2009), erosion (Joannon *et al.,* 2006) or biodiversity conservation (Castelazzi *et al.,* 2010). In the cited studies, the authors specifically focused on a given process rather than on the entire contribution of landscapes to sustainable development.

This integrated assessment is currently difficult to conduct because of the lack of indicators at the regional scale. This lack is due to the spatial mismatch between the regional scale at which information needs to be provided for decision-makers and the cropping system scale at which information is available for determining impacts (Ewert *et al.,* 2011; Niemiejer and Groot, 2008; Carof *et al.,* 2013). The cropping system scale is the scale at which externalities are produced by farming practices. This scale is the elementary brick that can be modified by farmers. The recent advances in scale change methodologies for taking information from the field and scaling it up to the regional level can help build a range of indicators (Ewert *et al.,* 2011). This methodology for scale change can then be the base for up-scaling indicators from the field to the regional scale in order to provide a global score.

In addition, the variability of the contribution of fields to sustainable development should be highlighted with adequate tools in order to help decision-makers better target their policy within their decision area (Chopin and Blazy, 2013). Some authors have demonstrated that the contribution of different areas of a given landscape can strongly vary. Dizdaroglu and Yigitcanlar (2014) showed that the variability of the parcel-scale area contributes differently to the sustainable development of the local area. Van Passel and Meul (2012) showed that the level of sustainability of farms could vary greatly within the dairy production sector in Flanders (Belgium) in a sustainability assessment. In ecology, landscape indicators are used to display the variability of ecological conditions in an area in time and space. The observation of the variability of indicators at the regional scale is then used to establish an environmental monitoring system (Olsen *et al.,* 2007). These studies demonstrate the importance of considering the variability of contribution of a landscape to sustainability issues.

We present here a method to assess the contribution of agricultural landscapes to the sustainable development of a territory. This method is based on a set of indicators at the plot scale and several procedures for up-scaling these indicators to the regional scale. This method provides i) an overall assessment of the contribution of agricultural landscapes to sustainable development and ii) a spatial emphasis of the variability of this contribution within the agricultural landscape. This method makes possible the ex-post and ex-ante assessment of agricultural landscape considering a hierarchical approach of the contribution of agricultural systems to sustainable development.

3.2.Materials and methods

3.2.1. Overview of the integrated assessment at landscape scale

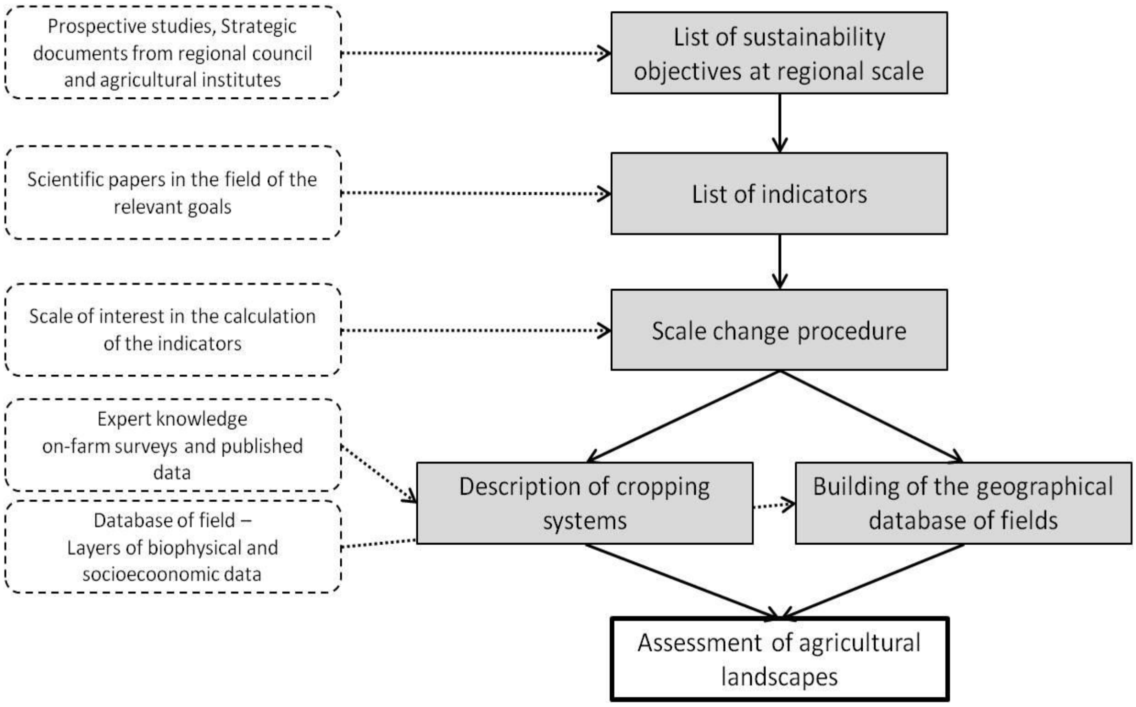

Figure 19 : Framework of our method with the five steps leading to the assessment of the agricultural landscapes.

The method that was developed for our sustainability impact assessment includes i) the definition of several sustainability goals, ii) the selection of indicators, iii) the description of scale change procedure, iv) the data collection encompassing the cropping system description and v) the building of a geodatabase of fields including the spatial units to which they belong (Figure 19).

3.2.1.1. Dimensions of sustainability

Sustainable agricultural landscapes are mosaics of crops or cropping systems that maintain or enhance the contribution of agriculture to the sustainable development of society. The value of this contribution needs to be appraised with a range of indicators.

Sustainable agriculture should be economically viable, socially desirable and environmentally sound following the definition of sustainability from the Bruntland Report (1987). Most of the methods that have been designed for the integrated assessment of agriculture are based on these three pillars, which are then divided into different categories. Castoldi and Bechini's method (2010) divided a global index of sustainability into Economy, Nutrient, Energy, Pesticide, and Soil categories. Other authors, such as Sadok *et al*. (2009), Pelzer *et al*. (2012), Mouron *et al*. (2012) and Dantsis *et al*. (2010) also divided the three pillars of sustainability into several sub themes that were approached with several indicators to provide a score for each dimension. This categorization of sustainability issues underlines the objective of assessing the multi-functionality of agriculture in an integrated way (Bezlepkina *et al.,* 2014).

Following the recommendations of Bezlepkina *et al*. (2014), we broke the environmental, economic and social sustainability into objectives. Some of these stakes are local issues that are specific to the studied area, while other issues can be considered global issues in the sense that they are global problems that need to be considered by policy-makers everywhere, such as climate change, or issues that are common to most territories, such as maintaining the quality of water bodies. In order to provide a spatial emphasis on the assessment over the landscape, a set of indicators are selected at the field scale based on their ability to provide information on the response of agricultural landscapes to the sustainability goals.

3.2.1.2. Selection of indicators

Several indicators are selected in order to provide an assessment of the different dimensions of an agricultural system. Some properties of indicators can be determined before the selection of indicators. Indicators need to (1) be relevant to the previously defined sustainability issues and objectives (Niemeijer *et al.,* 2008), (2) be measurable over space and quantifiable using simple techniques, (3) be calculable (information needs to be available for each crop of a cropping system in order to be able to calculate the indicators for a set of agricultural landscapes) (Dale and Beleyer, 2001), (4) be well-adapted to the context of the studied area (Sadok *et al.,* 2008), 5) be understandable by policy-makers who are not specialists of the landscape agronomy science (OECD, 1998), (6) be adaptable to the spatial and temporal scales of the assessment, (7) be validated scientifically (EEA, 2000), (8) avoid repeating the same information and (9) not be numerous to avoid altering the understanding of farming externalities by policy-makers (Bockstaller *et al.,* 2008). These properties are used to select the indicators that are applied in our method. Many indicators have been designed in recent decades (Jørgensen *et al.,* 2013).

The multiplicity of indicators at the field scale has been reviewed from the previously cited methods in order to be applied in our methodology. These indicators to be calculated at the field scale can then be up-scaled at the regional scale following procedures in order to provide an overall score. Their representations over the territory at a lower scale provide a graphical representation of the variability of the contribution of agriculture to the sustainable development of the region.

3.2.1.3. Scale change in the assessment of the agricultural landscape

In our method, indicators provide information at the regional scale. However, most of these indicators describe externalities of the cropping system at the field scale, after which the information needs to be scaled up from the field to the region.

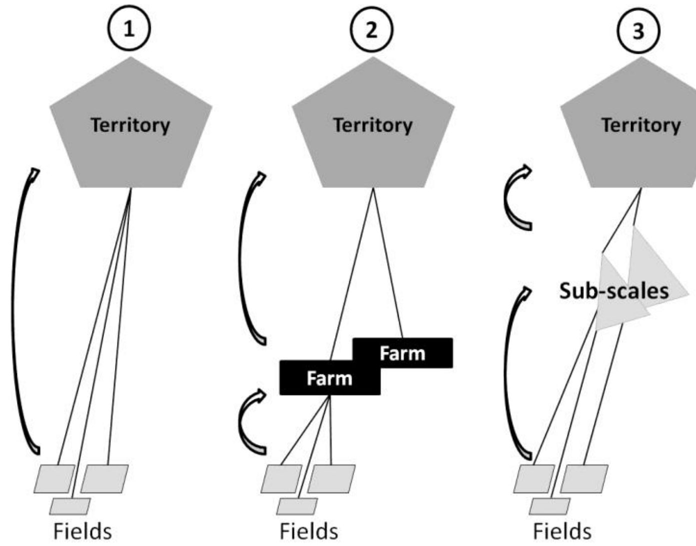

Figure 20 : Range of possible scale change to bring information 1) directly up from the field to the regional scale, 2) from the field to the farm and the landscape 3) from the field to a given subscale and then to the region.

The data at the cropping system scale must be adapted by a scaling up procedure. This scaling procedure can be either 1) directly up from the field to the regional scale, 2) from the field to the farm and the landscape or 3) from the field to a given subscale and the region, for example, the water catchment level. For each scale change, a given transformation of data is necessary from the initial scale to a greater scale (Figure 20). Thus, the field data can be summed, aggregated, averaged, weighted, extrapolated or interpolated (Volk and Ewert, 2011). Different spatial units need to be mapped in order to provide a spatially explicit assessment of the sustainability of cropping systems.

3.2.1.4. Cropping system information at the field scale

The cropping system scale is the basic scale from which information about farmer practices is provided. In order to define the cropping systems throughout the area, we used three types of information. First, published articles describing the externalities of cropping systems were recorded by the research team. Different sources of information were used to complete the description of cropping systems, for instance, economic data (e.g., prices and production costs) were provided by documentation from local agricultural institutes. Second, expertise from local advisers was used by applying the Delphi method (Linstone and Turoff, 1975). Each expert of a given crop is interviewed individually, and then a meeting is organized in order to discuss the differences that emerged from expert interviews and to agree upon these differences (Linstone and Turoff, 1975). Finally, when expert knowledge is lacking or when experts cannot agree on a given characteristic of the cropping systems, several on-farm interviews can be conducted to describe the cropping systems.

3.2.1.5. Geographical database of the fields

In our framework for the assessment of agricultural landscapes, each field is spatially located within the landscape in order to consider the crop composition as well as the crop location in the assessment. In order to ensure the measurability of the indicators, all of the fields from the landscape should have the information that is required to calculate the indicators.

Our geodatabase is composed of multiple polygons representing fields. Such geographic details are generally available at the regional scale with farmer's declarations. However, information about the biophysical context and the structure of the farms that is required to calculate some of the indicators can be scarce. Therefore, the databases need to be completed with relevant geographical information, including, for instance, altitude, levels of rainfall, distances to city, presence in an irrigation scheme, etc. Such data provide information on the relative location of fields compared to spatial units of interest and can be obtained with geographical information systems (GIS), census data, on-farm surveys or field measures to provide a sufficient amount of information to calculate the indicators. For each polygon, the parameters that are used for the calculation should also be defined. For instance, the slope and the level of rainfall need to be considered in pollution pressure indicators. This information should be available for each polygon. The owner of each field should be defined as well as the spatial unit to which the field belongs, e.g., the water catchment or the district, in order to calculate indicators involving these scales. This link between the spatial units and fields ensures up-scaling from the field to region.

When these steps have been followed, the agricultural landscape can be assessed with the calculation of indicators based on the information from the cropping system description and the parameters of different spatial units at a different scale. The indicators are then up-scaled and provide information on the sustainability goals of local agriculture at the regional scale.

3.2.2. Case study : the current agricultural landscape of Guadeloupe

We assessed the sustainability of the Guadeloupe agriculture with the framework that we previously presented. Guadeloupe is an archipelago in the Caribbean. The climate is tropical with rainfalls ranging from 1,000 to 5,000 mm yr-1. The 31,300 hectares of the total farmed area represent 20% of the island and are cultivated by 8,000 farmers (Agreste, 2011). The farm sizes range from less than one hectare to more than thousands, and most of them are specialized in a given production, such as sugarcane, banana, crop-gardening, orchards or breeding. The biophysical context of the farms varies from dry plains on calcic soils to andisols and nitosols at high altitudes where crops are grown on sloped fields with high rainfall on very fertile clay soils.

This variability in the socioeconomic and biophysical context is at the origin of the high variability in the cropping system externalities at the field scale as shown by Blazy *et al*. (2009) for banana production in Guadeloupe where, for instance, agronomic performance ranges from 10 to more than 40 tons.ha-1.

3.3.Results

3.3.1. Establishing sustainability goals in Guadeloupe

The sustainability goals are summarized in the Table 5.

Table 5 : List of indicators to be calculated.

Sustainability objectives	Indicators	Units
Improving the agricultural revenue	Overall farm revenues	€.yr^{-1}
	Repartition of revenue among the farm population	-
Increasing the autonomy from subsidies	Total amount of subsidies	€.yr^{-1}
	Mean efficiency of the farmers	%
Reaching food self-sufficiency	Ratio of produced carbohydrates over needs	%
	Ratio of produced proteins over needs	%
	Ratio of produced fats over needs	%
Producing local energy from agriculture	Potential of energy that is produced by crops	MW.yr^{-1}
Contributing to employment	Total workforce needs	pers.yr^{-1}
Insuring the safety of locally produced foodstuff	Area of risk of chlordecone contamination of food crops	ha
Improving the state of biodiversity	Percentage of area with a risk for birds in high-value ecological zones	%
Enhancing the water quality	Number of potentially polluted rivers	-
	Number of potentially polluted water abstraction sources	-
	Number of potentially polluted water catchments	-
	Amount of water that was used for irrigation	m^3
Protecting the soil quality	Percentage of the area that is potentially eroded due to farming practices	%
Decreasing the contribution to climate change	Overall emissions from farming activities in equivalent CO_2	tons $CO_2.yr^{-1}$
Improving the diversity of agricultural landscapes	Diversity of crops across the landscape	-

In Guadeloupe, economic sustainability involves the increase of benefits from the agriculture sector and the decrease of dependence from the outside. Guadeloupian agriculture is currently oriented towards the exportation of highly subsidized agricultural products, mainly bananas and sugar (Cour des comptes, 2011). Banana farms and sugarcane farms rely on a significant amount of subsidies, while other types of farms are less subsidized. Agriculture should decrease its recourse to subsidies because global banana and sugar production markets tend to decrease the permitted provision of subsidies to planters (Anania, 2010; Gotor and Tsigas, 2010). In addition, the benefits of agricultural production should be shared in a fair manner between farmers.

Social sustainability involves a better contribution of agriculture to the welfare of society, in which the majority of persons have access to sufficient and healthy food, employment and green energy. The current production of food crops barely covers the needs of the population, and consumers must buy expensive imported foodstuffs. The Guadeloupian regional council and the population are willing to drive local production towards an increase in the current level of food self-sufficiency (PDRG, 2011;Projet Guadeloupéen de Société, 2012). In addition, the production of local energy from crops, which should help reach the overall goal of 50% of renewable energy in Guadeloupe by 2020, is strongly encouraged (Région Guadeloupe, 2012). The production of foodstuff should be safe and free from contaminants, especially chlordecone. Chlordecone is an insecticide that has been used in banana fields for over thirty years and has created a long-lasting soil contamination on approximately 20% of the cultivated area in Guadeloupe (Cabidoche *et al.,* 2009). Chlordecone can contaminate human beings through the consumption of contaminated food, provoking a sustained toxicity involving the nervous system, liver and testes (Cannon *et al.,* 1978; Cohn *et al.,* 1978; Taylor, 1982; Multigner *et al.,* 2008). The Guadeloupian energy mix relies heavily on imported fossil sources (85%). The potential of agriculture to provide a deep range of local biomass for electricity production could increase the energy self-sufficiency of the island, for example, with the cultivation of energy crops. The high level of unemployment of 25% and the possibility of the development of a local agriculture with more jobs is an important challenge, which is particularly relevant for adults that are younger than 30 years, because their unemployment rate is 46% (INSEE, 2012).

For the environmental dimension of sustainable development, five challenges need to be considered. Improving the state of biodiversity is important considering the fact that Guadeloupe is a hot spot of biodiversity, with endemic birds, fishes and bats (Myers *et al.,* 2000). Current droughts make it possible for pesticide pollution to occur in water catchments, especially around water abstraction sources because the dilution effect is lower compared to that under rainy conditions (Cabidoche *et al.,* 2002). Soil protection is required in some areas because erosion might occur due to the intensity of the rainfall, especially on vertic soils (Cabidoche *et al.,* 2004). The decrease in CO2 emissions seems also extremely important for agriculture worldwide, and Guadeloupe can specifically target agricultural production to reduce greenhouse gas emissions (GHG) (Colomb *et al.,* 2014). Finally, the current homogenized landscape should be diversified considering the visual landscape quality.

3.3.2. Indicators definition and scale change procedure

Table 6 : Calculation details of the indicators.

Indicator	Calculation	Variables used
Overall farm revenues	$AAV = \sum_{p=1}^{p}\sum_{C=1}^{c}(Pb\ c - VC\ c) * X(p,c)$	**P** : plots **C** : cropping system **Pb(c)** : product of the crop selling c (€.yr^{-1}) **VC(c)** : variable costs of the crop c (€.yr^{-1})
Repartition of the AAV among the farmer population	$Gini = \frac{2 * \sum_{f=1}^{f} REV(f) * \text{rank}(f)}{Nb_f * \sum_{E=1}^{e} REV(f)} - \frac{Nbf + 1}{Nbf}$	**Rev(f)** : revenue of the farm f (€.yr^{-1}) **Rank(f)** : rank of the farm revenue in the farm population (ascending order) **Nbf** : number of farms in the population (case study 5336 farms)
Total amount of subsidies	$Sub = \sum_{p=1}^{p}\sum_{C=1}^{c} Yie(c) * Sb(c) + Sbx(c)$	**Yie(c)** : yield of the crop c (ton.ha^{-1}.yr^{-1}) **Sub (c)** : Subsidies coupled with production (€.ton^{-1}) **Sbx** : Subsidies not coupled with production (€.ha^{-1}.yr^{-1})
Mean efficiency of the farmers	$Eff = mean\ [\sum_{f=1}^{f} \frac{REV(f)}{Ch(f)}]$	**Rev(f)** : revenue of the farm f (€.yr^{-1}) **Vc(f)** : aggregation of the variable costs at the farm scale
Ratio of produced carbohydrates over needs	$GLU = \frac{\sum_{p=1}^{p}\sum_{C=1}^{c} Glu(c)*Yie(c)*X(p,c)}{GluN * popsize}$	**Glu(c)** : carbohydrate content of 1 ton of crop c (kg.ton^{-1}) **Rdt(c)** : yield of crop c (ton.ha^{-1}.yr^{-1}) **GluN** : carbohydrate needs of an average person (kg.yr^{-1}.pers^{-1}) **popsize** : size of the considered population (pers)
Ratio of produced proteins over needs	$PROT = \frac{\sum_{p=1}^{p}\sum_{C=1}^{c} Prot(c)*Yie(c)*X(p,c)}{Protneeds * popsize}$	**Prot(c)** : protein content of 1 ton of crop c (kg.ton^{-1}) **Yie(c)** : yield of crop c (ton.ha^{-1}.yr^{-1}) **ProtN** : protein needs of an average person (kg.yr^{-1}.pers^{-1}) **popsize** : size of the population considered (pers)
Ratio of produced fats over needs	$LIP = \frac{\sum_{p=1}^{p}\sum_{C=1}^{c} Lip(c)*Yie(c)*X(p,c)}{Lipneeds * popsize}$	**Lip(c)** : fat content of 1 ton of crop c(kg.ton^{-1}) **Yie(c)** : yield of crop c (ton.ha^{-1}.yr^{-1}) **LipN** : fat needs of an average person (kg.yr^{-1}.pers^{-1}) **popsize** : size of the considered population (pers)
Potential of energy that is 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 with one ton of biomass (MW.yr^{-1})
Total workforce needs	$JOB = \sum_{p=1}^{p}\sum_{C=1}^{c} Wor(c) * X(p,c)$	**Work(c) :**working demand for crop c (pers.ha^{-1})

Area of risk of contamination of food crops	$CLD = \frac{\sum_{p=1}^{p}\sum_{C=1}^{c} Cld("Risk")*X(p,c)}{Atot}$ on field with a pollution risk	**CLD(c)** : crop potentially contaminated by chlordecone (qualitative score) **Atot** : total agricultural area (ha)
Percentage of 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) ($L.ha^{-1}$) **QMA(pes)** : quantity of active ingredient (pes) ($g.L^{-1}$) **LD50(pes)** : acute toxicity of pesticide (pes) on the bird population (g)
Number of potentially polluted rivers	**RPEST(p) => Decision Tree** $RPEST = \frac{\sum_{C=1}^{c} RPEST(p,c) * X(p,c)}{X(p)}$ for RPEST(p,c) > 7	**RPEST(p)** : Decision tree from Tixier *et al.* (2006) encompassing the ➢ Quantity of active ingredients ($L.ha^{-1}$) ➢ Level of run-off based on expert knowledge for each type of soil ($m^3.ha^{-1}.yr^{-1}$) ➢ Half life of the active ingredient in the environment (days) ➢ Acute reference dose obtained from the EU pesticide database ($g.kg^{-1}$) ➢ LC50 : toxicity for fish ($g.kg^{-1}$) ➢ Groundwater ubiquity score ➢ Drainage obtained based on expert knowledge ($m^3.ha^{-1}.yr^{-1}$)
Number of potentially polluted water abstraction sources		
Number of potentially polluted water catchments		
Amount of water that was used for irrigation	$IRR (p) =\sum_{m=1}^{12}(Rain(p) - H20need(c))* X(p,c)$ $IRRI = \sum_{p=1}^{p} IRRI(p)$	**H20 needs(c)** : the water needs are determined based on the crop coefficient Kc and yearly mean evapotranspiration ($m^3.month^{-1}$) **m** : month **Rain(p)** : the rainfall is determined based on the mean levels of rainfall per month based on 30 years of data ($mm.month^{-1}$)
Percentage of the area that is potentially eroded due to farming practices	**RERO(p) =>Decision tree** $RERO = \frac{\sum_{C=1}^{c} X(c,f)}{X(f)}$ pour tout RERO(f) >7	**RERO(p)** : decision tree based on : ➢ the type of soil ➢ the crop cover (%) ➢ the number of mechanized interventions (nb.yr-1) ➢ the furrow depth (cm) ➢ the rainfall (mm.yr-1)
Overall emissions of CO_2 from farming activities	$CO_2 = \sum_{p=1}^{p}\sum_{C=1}^{c}\sum_{otk=1}^{otk} GES (p, c, otk)$	**GES (otk)** : CO_2 equivalent produced by agricultural practices (otk) (kg eq CO_2)
Diversity of crops across landscape	$ISDI (subR) = \frac{1}{\sum_{C=1}^{c} P(subR,c)^2}$ $ISDR = \frac{\sum_{SubR=1}^{subR} ISDI(subR)}{nbSubR}$	**ISDI(subR)** : Inverse Simpson's Diversity Index in sub-regions **P(c)** : proportion of crop c in sub-regions (%) **nbSubR** : number of considered sub-regions

The indicators used are listed in Table 5. The details for the calculation of the indicators are given in Table 6.

3.3.2.1. Indicators of economic sustainability

Economic sustainability encompasses the objectives of improving agricultural revenue and increasing the autonomy of farmers.

Improving agricultural revenue increases the overall farm revenue as well as a fair repartition of this revenue among the farmer population. The first indicator is the aggregation of all of the gross margins at the field scale. The gross margin of each field is calculated by the crop gross margin of each cropping system, which is aggregated from the field to the region, as shown in Figure 20-1 with a sum. The gross margin is calculated based on an average crop price and the yield of the cropping system subtracted by the cost of production (Dogliotti *et al.,* 2004). Variable costs include the cost of plantation, crop management, harvest, inputs and workforce. The distribution of the overall revenue among the farmer population is assessed using the Gini coefficient, which measures the overall inequality of a variable across a population (Gini, 1921). Revenue at the farm scale is the overall farm revenue at the field-scale. The scale transformation is the second in Figure 20. Revenue is first aggregated with a sum at the farm scale, and then the results obtained are used to calculate the Gini indicator as explained in Table 6. This index is simple to understand because its value ranges from 0, a perfect equity in the repartition of the agricultural revenue, to close to 1, producing an unbalanced distribution of revenue in the population (Ceriani and Verme, 2012). This indicator is often used to observe the distribution of household revenue and can easily be adapted to farm revenue (Severini and Tantari, 2011).

The autonomy of farmers is assessed by two indicators, one showing the total amount of subsidies that are provided to agriculture and the other one the efficiency of farmers, as Sadok *et al*. (2009) did in the MASC model (for Multi-attribute Assessment of the Sustainability of Cropping systems). The first indicator aggregates from the field to the region with a sum the overall amount of subsidies for crop production given to farmers in Guadeloupe through the common agricultural policy (Zahm *et al.,* 2008). This calculation considers banana crop production, sugarcane production and beef production, for which one part of the subsidies is coupled to production and linked to the level of yields, while another part is decoupled from production, such as the agri-environmental measures. The second indicator is a measure of the farmer's efficiency, which is the overall gross margin of the farm divided by the total amount of the variable cost of production (Bockstaller and Girardin, 2006). The measure of efficiency at the farm scale is up-scaled to the region scale with a mean to represent the mean level of farm efficiency throughout the territory.

3.3.2.2. Indicators of social sustainability

Social sustainability encompasses the objectives of reaching food self-sufficiency, producing local energy from agriculture, contributing to employment and ensuring the safety of locally produced food crops.

The self-sufficiency objective is calculated based on three indicators of provision of the main nutrients, carbohydrates, fats and proteins from the produced crops. Every cropping system and livestock system was described based on the overall production of carbohydrates, fats and proteins from crops and animals per hectare based on a mean yield. The indicator is a ratio of the overall production of each of three nutrients on the total need of the population and is calculated using the amount of required nutrients of a standard person and the total population of the island, which is 400,000 inhabitants (INSEE, 2012). These ratios express more understandable information than just a sum of the nutrients at the regional scale.

The local production of electricity is assessed based on the production of biomass for electricity. Currently, only the production of sugarcane can bring energy because one of its coproducts, bagasse, is used as source of carbon for combustion in energy industries. The energy potential of sugarcane cropping systems is described based on the potential production of $MW.ton^{-1}$ of sugarcane. This indicator is directly summed to the regional level to provide an overall measure of the potential production of biomass throughout the territory.

The contribution to employment is based on the required workforce for each cropping system (Zahm *et al.,* 2008). The total required workforce is directly summed from the field to the region without any intermediate scale. The penibility of work has not been assessed because no cropping system expert was available to characterize this indicator.

Table 7 : Decision support system that was used to assess the field risk of crop contamination by chlordecone. The black rectangles are the "presence of a risk" combinations. The type of soil "other" encompass ferralitic and nitosol.

Risk of contamination		High		Average		Low		Absence	
Type of soil		Others	Andic	Others	Andic	Others	Andic	Others	Andic
Crop category	Tubers	■	■	■	■	■	■		
	Pastures	■	■ CLD "risk"	■	■				
	Crop-gardening	■	■	■					
	Others								

The production of locally safe food crops is assessed with the risk of exposition of consumers to crops that are contaminated by chlordecone. The contamination of crop depends on the risk of chlordecone content in the fields, as mapped by Tillieut and Cabidoche (2006), the type of soil on which the crop is cultivated and the type of crop grown (Cabidoche and Lesueur-Jannoyer, 2012). This indicator considers the diversity of the characteristics of crop absorption of the molecule, soil adsorption of the pollutant and the risk of chlordecone content in the field (Table 7).

We constructed a decision tree with the four qualitative risks of chlordecone presence, four crop categories, tubers, pasture, crop-gardening and others (banana, sugarcane, pineapple, orchards, and plantain), and we divided the types of soil into two categories, high adsorption (ferralitic and nitosols) and low adsorption (andisol) based on Cabidoche and Lesueur-Jannoyer's findings (2012). This decision tree based on expert knowledge of the pollutant was applied for each field and led to a qualitative assessment of either "no risk of contamination" or "presence of a risk of contamination" (Table 7). At the regional scale, the area of the fields that were rated "presence of a risk of contamination" were summed and divided by the total cultivated area in Guadeloupe.

3.3.2.3. Indicators of environmental sustainability

Environmental sustainability encompasses the objectives of preserving water resources and biodiversity, protecting soils, decreasing the amount of GHG emissions and diversifying agricultural landscapes.

The risk of loss of biodiversity is assessed by a load index of birds (Gaudino *et al.,* 2014; Samuel *et al.,* 2012). This indicator is calculated at the field scale with a quotient of the quantity of active ingredient spread and the level of toxicity, as represented by the LC50 of pesticides. This indicator is calculated for the fields in high-value ecological zones where bird protection is a priority. We summed the load index of all of the fields in high-value ecological zones and divided this total load index by the total cultivated area in high-value ecological zones. We then obtained an average load index of the fields in high-value ecological zones representing the pressure of agricultural activity on bird diversity in the protected area. A load index greater than 1 indicates a pressure of the pesticide on bird biodiversity.

The risk of pesticide pollution is assessed using three indicators at the regional scale, but the calculation at the field scale is the same and consists of an adapted version of the Rpest indicator provided by Tixier *et al*. (2006).This indicator was designed in Guadeloupe for banana production. The Rpest indicator is determined by following a decision tree with parameters describing the field situation (run-off and drainage) and the cropping systems (dose of active ingredients, DT50 mammals, acceptable daily intake (ADI), and toxicity for fish). The information on the pesticides is obtained from the European Union Pesticides Database (European Commission, 2011). The total run-off and drainage were calculated for an entire year based on the total rainfall that was calculated per field with a shapefile of the mean annual rainfalls and expert knowledge on the proportion of rainfalls for run-off and drainage in different pedoclimatic areas. The different cropping system parameters were averaged following the proportion of each dose of pesticide on the total applied amount. The parameters were determined for an entire year, and the calculation produced a score ranging from 0 to 10 per field for the calculation of the three regional indicators :

- First, an indicator of the risk of water pollution in the water abstraction sources was assessed by aggregating the Rpest from the fields within 200 meters around water abstraction sources. Then, the overall score per water abstraction sources was calculated as a weighted mean of the Rpest score of the fields within the 200 meters around the water abstraction sources. These 200 meters were considered a perimeter of immediate protection in which recommendations were made for agricultural practices. For each perimeter of protection, an average score of Rpest was determined using a weighted mean of the surface of the fields on the total cultivated area in these perimeters. Then, an average Rpest score was obtained for each perimeter. We consider a perimeter with a score of greater than 7 as a potential polluted perimeter of protection. This threshold was selected based on the recommended value that was provided by Tixier *et al*. (2006) in their work on the Rpest indicator in banana fields.

- Second, the same process was conducted on the rivers in Basse-Terre (Figure 21). A 50-meter buffer area was generated around the rivers of Guadeloupe as in Houdart *et al*. (2009) in Martinique to assess the pressure of pesticides on rivers. This distance was recommended by agronomists based on the fact that the molecules in this area will generally enter a river without being degraded (Probst *et al.,* 2005). The thresholds we used were the same, and we determined an average level of Rpest per river and at the regional scale provided a proportion of potentially polluted river.
- Third, we mapped all of the water catchments in Guadeloupe. We determined for each water catchment a mean score of Rpest based on the score of each field. We averaged this score for each water catchment as realized, for instance, in Macary *et al*. (2014). Then, we determined for each agricultural mosaic in Guadeloupe the number of potentially polluted water catchments due to pesticides.

The risk of water shortage was assessed based on the total amount of water that was used for irrigation. This amount of water was calculated for each month. First, the irrigation dose was assessed based on the level of rainfall per month and the crop coefficients, which depend on the developmental stage of the crop. A mean evapotranspiration level was defined for both of the islands in Guadeloupe, at 3.5 $mm.day^{-1}$ in Basse-Terre and 4 $mm.day^{-1}$ in Grande-Terre (Cornet, pers. comm.). The crop coefficients were obtained using the FAO irrigation manual (FAO, 1986). Then, at the field scale, the level of irrigation was calculated only in the fields in water schemes. This amount of water per month is the difference between the potential evapotranspiration multiplied by the mean crop coefficient subtracted by the rainfall level. If the amount of rainfall is greater than the crop needs, the amount of irrigation is null. If the crop water needs are below the level of rainfall in a month, we considered that the farm has compensated for this difference using irrigation. The differences of each month were summed for each field. Then, the amount of irrigation on each field was summed to obtain a regional amount of provided water.

We assessed the erosion based on the Rero indicator that was developed by Tixier (2004). This indicator was previously adapted to the local conditions but was developed only for banana production and for one type of soil. We adapted the decision tree by multiplying the Rero from the decision tree to a coefficient depending on the type of soil. The selected coefficients were 0.8 for andisols, ferralsols and nitosols and 1.2 for vertic soils based on expert opinions. The differences between the angle of tillage and the angle of the water flow in the field were deleted from the decision tree because the farmer can perform the tillage in the direction of slope to accumulate the water flow in the same direction and redirect it toward the ditches. The indicator was only calculated for the field in Basse-Terre because erosion only occurred on this part of Guadeloupe.

The CO2 emissions were assessed using data from the CLIMAGRI tool and were previously published by Colomb *et al*. (2014). The overall amount of emissions was directly aggregated from the field to the region to provide a global amount of emissions from agricultural production in Guadeloupe. This method considers the emissions from the production up to the farm gate and includes the farm emissions and emissions from the fabrication of inputs. We also integrated emissions from exportations of agricultural products. The amount of GHG is expressed in CO_2 equivalents.

Compared to temperate areas, only CH_4 and N_2O, which are related to manure management and electricity, were adapted to our tropical context. Other coefficients were based on the references for temperate climates.The diversity of the landscape was assessed using Inverse Simpson's diversity index (Simpson, 1949). This indicator is calculated from the fields to sub-regions and then aggregated at the regional scale with an average. We assessed this indicator in 6 homogeneous areas that are groups of several districts based on their proximity in the socioeconomic and biophysical context of farms. We considered seven types of crops in the landscape composition : sugarcane, banana (plantain and fruit), pastures, fallow, pineapple, orchards and crop-gardening. The value of the indicators for each sub-region ranges from a score of 1, which is a homogenized landscape that is composed of one category of crop, to a score of 7, which is a heterogeneous landscape in which each of the seven categories of crop occupies the same area.

We described 21 cropping systems based on previously published data (e.g., Blazy *et al*. (2009) for banana production; Lebellec *et al.,* (2011) for citrus production), expertise based on the Delphi method and on-farm surveys. The description of the cropping systems was based on the required data for the calculation of the criteria (Table 8). The mean economic data were provided by expert opinion and documentation, such as an economic guide edited by the local Chamber of Agriculture, which gathers all of the crop yields, gross margins and the costs of practices. Information on the time required for crop management was obtained using BANAMARGE® (Manceron *et al.,* 2010) and IGNAMARGE® tools (Causeret *et al.,* 2012), which provide a range of technical information for banana cropping systems and yam cropping systems. For other crops, the results were extrapolated based on the similarity of practices and the crop density. Information on the food production was obtained from the FAO database on fruits and legumes (FAO, 2012). Electricity production based on bagasse was obtained by dividing the total electricity that was produced from bagasse by the total amount of sugarcane that was produced. The amount of water for irrigation was based on the crop coefficient Kc from by the FAO data (FAO, 1986), which helps determine the quantity of water required by the crop. The use of pesticides and fertilizers, which was used in the calculation of the CO_2 emissions, pollution indicators and economic objectives, were obtained based on expert surveys for melon, crop-gardening, plantain, and sugarcane. The experts were farmer advisers or farmers that were involved in the sector. The doses of considered pesticides were recommended. The active ingredients were identified based on commercial products that were used.

3.3.3. Definition of cropping systems and the geographical database of the fields

Table 8 : Description of cropping systems. The example of the intensive banana cropping system.

Indicators	Cropping system information required	Intensive banana cropping systems
Overall farm revenue	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}
Repartition of revenue among the farm population	Gross margin	10417 €.ha^{-1}
Total amount of subsidies	Subsidies	19197 €.ha^{-1}
Mean efficiency of the farmers	Efficiency of cropping system	22%
Ratio of produced carbohydrates over needs	Carbohydrate content	228 $kg.ton^{-1}$
Ratio of produced proteins over needs	Protein content	10.9 $kg.ton^{-1}$
Ratio of produced fat over needs	Fat content	3.3 $kg.ton^{-1}$
Potential of energy that is produced by the crops	MW	0 $kW.ton^{-1}$
Total workforce needs	Pers	0.9 $pers.ha^{-1}$
Area of risk of contamination of food crops	Absorption of the Chlordecone	No
Percentage of area with a risk for birds in high-value ecological zones	Quantity of active ingredient Mean LC50	7.8 $kg.ha^{-1}$ 20 $mg.kg^{-1}$
Number of potentially polluted rivers Number of potentially polluted water abstraction sources Number of potentially polluted water catchments	Mean DT50 Mean Dose of QMA Mean ADI Mean Aquatox Mean Groundwater Ubiquity Score (GUS)	20 days 7.8 $kg.ha^{-1}$ 0.025 $mg.day^{-1}$ 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 use of heavy mechanization	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 landscape	Crop category	"Banana"

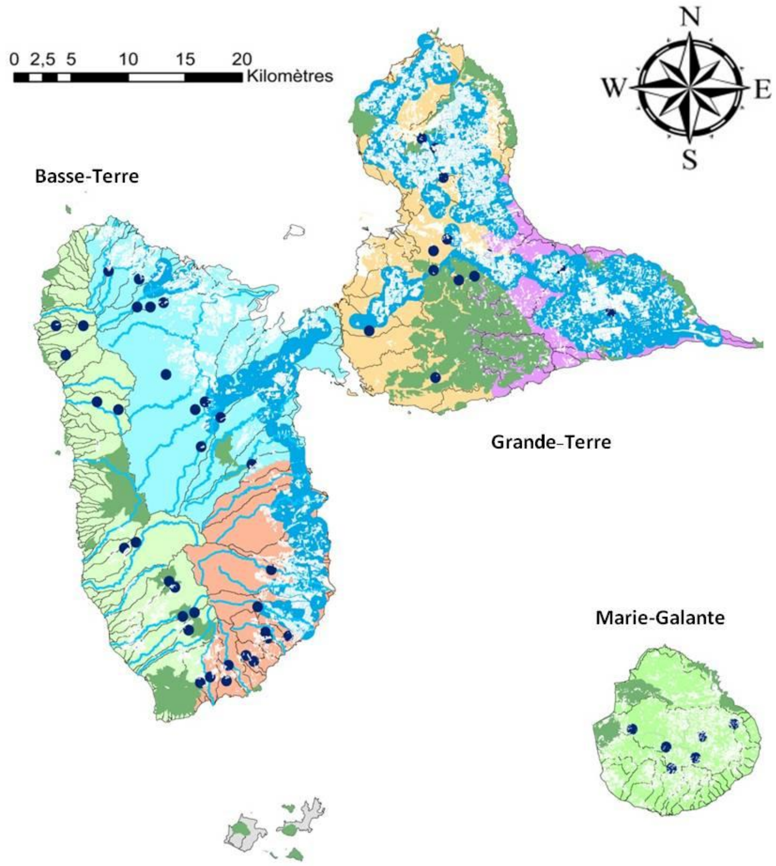

Figure 21 : Map of the different spatial units that were used to calculate the indicators. The dark blue point represents water abstraction sources, the polygons with black frames are water catchments, the blue lines are rivers, the dark blue areas are irrigation schemes, the white polygons are fields, and the dark green areas are protected areas for birds. The colored areas of the territory are pedoclimatic areas that are used for the crop diversity assessment.

In parallel, we constructed the geographical database using the required information for the calculation of indicators. The initial geographic database gathers 25 057 fields owned by 5336 farmers and the crop grown in the fields in 2010. The fields are represented by polygons for which we calculated the area and aggregated the total areas for each field, and we obtained the farm size of each farm. A geographical shapefile representing the farm location was constructed with weighted centroids of all of the farm plots. This shapefile was used to demonstrate the level of farm revenue and the use of water for irrigation throughout the territory. The fields were spatially intersected to the following spatial units : rivers with a 50-meter buffer, water catchments, water abstraction sources with a 200-meter buffer, high-value ecological zones and sub-regions (see Figure 21). This information was used, respectively, to calculate the following indicators : the number of potentially polluted rivers, the number of potentially polluted water catchments, the number of potentially polluted water abstraction sources, the load index in high-value ecological zones and the diversity of agricultural landscapes.

Geographical information was added to this database as a parameter to calculate the indicators. The rainfall was determined based on a mean level of rainfall based on a 30-year-period of data. The inter annual level of rainfall was assessed based on the monthly rainfall as 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). The types of soil were added based on an intersection with the soil shapefiles from the soil map (Colmet-Daage, 1969).

The map of the risk of chlordecone contamination was used to generate the risk of chlordecone on fields (Tillieut and Cabidoche, 2006). The irrigation schemes were intersected with the fields to provide information on the potential for access to irrigation.

The cropping systems were allocated to the farmer's plots based on if-then rules as defined by expertise (Clavel *et al.,* 2011). For instance, the intensive banana cropping system that is described in Table 8 was allocated to plots if the crop that was grown in 2010 on the given plot was "banana", if the size of the farm that owns the plot was greater than 15 hectares and if the slope of the plot was less than 15%.

3.3.4. Assessment of the current level of sustainability of Guadeloupian agriculture

The indicators were calculated with a linear programming model, which is solved by using the General Algebraic Modeling System (GAMS) software program version 23.8.2. GAMS is a high-level modeling system for mathematical programming problems (Brooke *et al.,* 1998).

The previously presented range of indicators was applied to the geographical database. The use of indicators provided a sustainability assessment of the current cropping system mosaic and offered the possibility of performing a primary diagnosis. The assessment at the regional scale provided a global assessment of the mosaic in an integrated way, encompassing every dimension of sustainability (Table 9). The indicators were also spatialized throughout the territory in order to identify the spatial variations of the contribution of fields to the sustainable development of the territory. Only three indicators, representing the economic, social and environmental dimensions, represented at different scales are shown in Figure 22. The other indicators can be found in Supplementary materials.

3.3.4.1. Economic sustainability assessment

The economic sustainability was low considering a significant amount of subsidies of 80 M€.yr-1 compared to the overall farm revenue of 75 M€.yr-1 and the high level of inequity in the revenue of agriculture among farmers that is demonstrated by the high Gini coefficient of 0.775. Farms appear to have a low efficiency on average (27.3%).

This economic sustainability strongly varies throughout the territory (Figure 22.A). Banana growers in southern Basse-Terre tend to obtain more subsidies for banana production than do other producers and have the highest revenue among the farm population. The efficiency of farmers is homogenous among the farm population. Southern Basse-Terre and northern Basse-Terre have a more significant number of efficient farms but are not numerous.

3.3.4.2. Social sustainability assessment

The social sustainability was also low considering the weak cover of food needs by local agriculture with 5% of the fat, 15% of the carbohydrates and 27% of the protein needs covered by the local production. Carbohydrates production is low due to the fact that banana and sugar are mainly exported to metropolitan France.

Table 9 : Results of the assessment of the current agricultural landscape

Dimension	Sustainability objectives	Indicators	Results
Economic	Improving the overall revenue	Overall farm revenues	75 M€
		Repartition of the revenue among the farm population	0.775
	Increasing the autonomy from subsidies	Total amount of subsidies	80 M€
		Mean efficiency of the farmers	27.3%
Social	Reaching food self-sufficiency	Ratio of produced carbohydrates over needs	15 %
		Ratio of produced fat over needs	5%
		Ration of produced proteins over needs	27%
	Producing local energy from agriculture	Potential of energy that is produced by crops	30 MW
	Contributing to employment	Total workforce needs	3240 Pers
	Ensuring the safety of locally produced foodstuff	Area of the risk of contamination of food crops	1178 / 27350 ha = 4%
Environmental	Improving the state of biodiversity	Mean quantity of toxicity in the fields in high-value ecological zones	0.694
	Enhancing the water quality	Number of potentially polluted rivers	8/36
		Number of potentially polluted water catchments	33/189
		Number of potentially polluted abstraction water sources	11/36
		Amount of water that was used for irrigation	21 Mm^3
	Protecting the soil quality	Percentage of the area that was potentially eroded due to farming practices	0.1%
	Decreasing the contribution to climate change	Overall emissions of CO2 from farming activities	130 kT Eq CO2
	Improving the diversity of agricultural landscapes	Diversity of crops across landscapes	2.97

The level of electricity production (30 MW) is not negligible but is still less than the amount of renewable energy that could be produced from crop residues, fiber cane and sugarcane throughout the territory (Prerure, 2008) if fiber cane cropping systems were adopted by farmers. Agriculture provides a relatively high level of on-field workforce, but its spatial variability indicates that most of the workforce is in the southern Basse-Terre area for the banana production. Other districts could better contribute to employment throughout the territory (Figure 22.2). The assessment of the contamination risk of food crops in the southern Basse-Terre area demonstrates a significant amount of risky area compared to the overall cultivated area in this region. This risk appears to be homogenous throughout the area of southern Basse-Terre.

3.3.4.3. Environmental sustainability assessment

The level of pressure on bird biodiversity is considered weak because the indicator value is less than 1. The amount of water for irrigation is important considering that this amount is greater than the 9 Mm3 of the water consumption of the inhabitants on the island. The Rpest indicator is aggregated at three levels. At the regional level, a small proportion of rivers are potentially polluted (Figure 22.C). The amount of potentially polluted water catchments is low despite the importance of the area of some of the polluted catchments. The number of potentially polluted water sources was also very low. Southern Basse-Terre is exposed to pesticides pollution in the rivers and water sources that are close to the sea. The center of Grande-Terre is also potentially polluted by three sources with an Rpest score of greater than 7. The risk of erosion in Guadeloupe is almost nonexistent considering the vulnerability of the fields. The number of fields on vertic soil is low, and erosion mainly occurs in fields that are cultivated with crop-gardening and with high level of rainfalls. The amount of GHG from agriculture in Guadeloupe is weak compared to the other sectors (2% from agriculture and 30% from residents) but more important in southern Basse-Terre due to the significant amount of fertilizers that are used in banana cropping systems. The diversity of crops in the landscape is low in Guadeloupe but with an important variability considering the sub regions : from 2.1 in Marie-Galante and northern Basse-Terre to more than five in southwestern Basse-Terre.

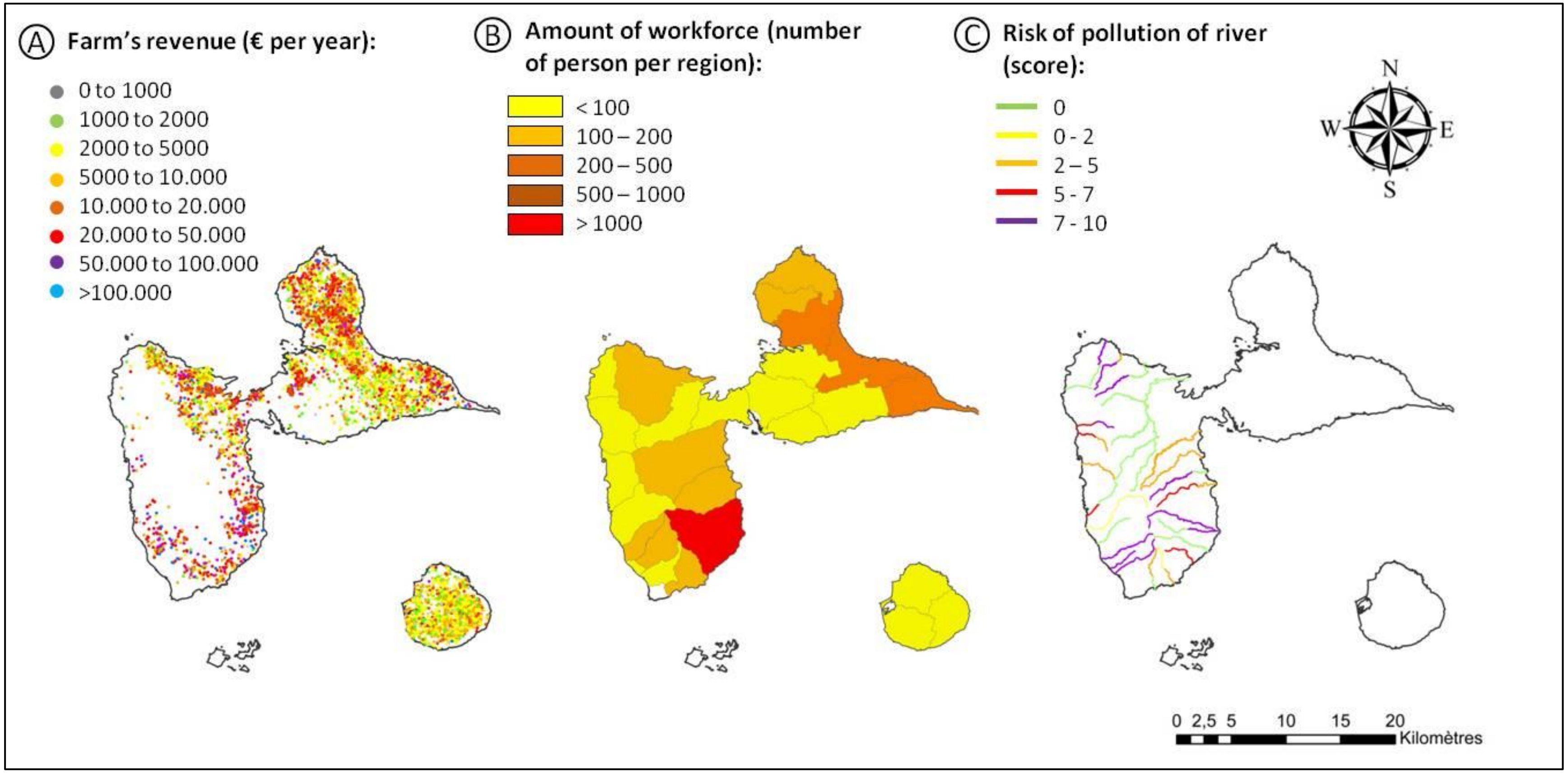

Figure 22 : Maps of the three calculated indicators. A : farm revenue mapped at the farm scale. B : indicator of the workforce needs at the district level. C : map of the risk of pollution in rivers.

3.4. Discussion

3.4.1. A methodological framework for the ex-ante-/post assessment of agriculture

3.4.1.1. Overall assessment of the regional agriculture from field information

The developed method is close to some existing methodologies in the steps of sustainability assessment (Binder *et al.,* 2012; Gómez-Limón and Riesgo, 2009) but introduce novelty to the change in the scale from the field to the region. This type of assessment is scarce in scientific literature despite the important amount of agricultural sustainability assessment studies that mainly focus on a given sustainability objective, such as organic matter conservation (Bechini *et al.,* 2011). Integrated assessment with scale change allows for a synthesis of the main externalities of agriculture at the landscape scale and provides a quantitative assessment of this change based on pressure indicators. This assessment indirectly indicates the potential of agriculture to fulfill the objectives of decision-makers in terms of sustainable development. This multi-dimensional assessment allows users of the board of indicators to observe the tradeoffs among different objectives. In this framework, the calculation of quantitative indicators can easily underline the differences between the different policies with the observation of the variation of indicator values at the regional scale.

3.4.1.2. Spatial variability of the contributions of land to sustainable objectives

In addition to the values that are provided at the landscape scale, the indicators are also spatialized on the spatial units of interest and can then provide information about the variability of the contribution of fields to a given issue. The indicators can then be used as bases for establishing spatially targeted policies, such as subsidies for crop-gardening production, to increase the efficiency of farmers in their production process (Chopin and Blazy, 2013). Also using this type of analysis, agronomists can design new cropping systems that are adapted to areas where sustainability issues are the most important.

The range of indicators that we applied is useful to diagnosis sustainability but can also be useful for the ex-ante analysis of innovative agricultural systems at the regional scale. Models of farmers' decision-making processes could be constructed to simulate the choice of cropping system on the farmer's plot under different scenarios (Abadi ghadim *et al.,* 1999). A land use scenario can help define levers to increase the sustainability of the landscape (Cotter *et al.,* 2014).

3.4.1.3. A useful method for policy-makers

We designed here a short list of indicators for assessing the response to issues. This list is a tradeoff between the necessary amount of information in order to understand local agriculture and the amount of an indicator that does not deplete the accuracy of the provided information. Our indicators alone bring information of the agricultural landscape goals. For instance, we considered that the production of nutrients by agriculture meets the food self-sufficiency goal. These stand-alone indicators (in sustainability objectives) meet the goal of describing the response to the objective because these indicators are close in their description of the defined objectives.

In our method, we did not aggregate indicators as in other studies (Van Asselt *et al.,* 2014; Castoldi and Bechini, 2010; Sadok *et al.,* 2009). Aggregation introduces subjectivity to the analysis (Rigby *et al.,* 2001). Quantitative indicators become qualitative based on a qualitative scale categorizing the values of indicators into classes, such as "Bad" and "Good". This categorization is based on the values that were observed among all of the studied cropping systems or limits due to legislation constraints. However, for regional planning, it is very difficult for a given territory to define these thresholds for categorizing variables because territories are different by nature and cannot be compared as can cropping systems. Furthermore, aggregation is particularly relevant for assessment based on the need of a great number of indicators to synthesize the information that is provided by these indicators. In our assessment, the number of indicators was low compared to that of other methods, which use up to 50 indicators (Pelzer *et al.,* 2012; Guillaumin *et al.,* 2007). The number of indicators is consistent with the method's goal of providing clear information to decision-makers to help make decisions regarding local agriculture sustainability.

The objectives of this assessment framework were not to provide a ranking of landscapes to the decision-makers. In contrast, this assessment provides the decision-makers an integrated assessment with an indicator board and a map of the territory with the relevant spatial units. This double assessment helps the decision-makers understand their territory and the geographical variation of the contribution to different units to the sustainability of local agriculture.

3.4.1.4. Uncertainties in the analysis

Uncertainty relies on the typology of the cropping system that was used in the fourth step and the lack of farmed area in our geodatabase in the fifth step.

The defined cropping systems were simplified due to the high diversity of practices as highlighted in surveys and due to the availability of information. Several cropping systems were defined for a given crop because the cultivation of this crop was significantly different at the field scale in term of externalities, e.g., yield, crop management or fertilization. This variability was considered in the description step.

Indicators are models providing information on the pressure and impacts of agricultural activities on different local and global issues. The difficulty of regional assessment is that the studied process, such as pollution, needs to be understood by scientists in order to describe a precise indicator. The required information and knowledge to calculate the indicator need to be available throughout the entire area, including information of the spatial and temporal scales that are used in the analysis. For instance, pollution is difficult to assess because the process of sorption/desorption and the mobility of different types of molecules in tropical soil are still not fully understood. The variability of soil types in Guadeloupe makes it difficult to predict a pollution level, which is why we constructed an indicator assessing the potential for pollution that simplifies the values of parameters, such as the type of soil in the Rero indicator. The irrigation indicator presents the same limitations with the fact that the water storage capacity of the soils could not be assessed throughout the territory. The soil compartment is not considered in the assessment of irrigation needs. For this indicator, the comparison of values among different landscape should be prioritized over the value itself, considering the significant simplification of the process of water fluxes in soils.

Our geodatabase does not fully cover the agricultural areas in Guadeloupe. More than 4000 ha and 2500 farmers are lacking in the geodatabase. This area is mainly cultivated by small subsistence farmers for which agricultural activity is a complementary income. Their contribution to indicators that were up-scaled from the field directly to the region can be considered weak because the total area they represent is limited. The contribution of these farmers to sustainable issues for which field information is up-scaled from the field to the sub-region is significant depending on the issue. For instance, with the indicator of risk of a polluted river, some of these subsistence farmers are located close to the rivers and intensively use pesticides, which could modify the risk of pollution. This effect is minimized by the number of rivers that are assessed but could generate a non-negligible change. For the indicators that are up-scaled to the farm scale, the gap could be more important considering the significant proportion of the missing farmers in the total farmer area. This gap should be considered when interacting with stakeholders either to fulfill this lack in the database or to conduct another analysis focusing on these small farmers.

3.4.2. Understanding of the current level of sustainability at the landscape scale for the design of new cropping systems at the field scale

3.4.2.1. Contribution of the cropping system composition to the sustainability level of the landscapes

Based on our ex-post assessment, the agriculture in Guadeloupe has a low level of sustainability considering the different calculated scores of indicators. On the economic side, farmers are highly dependent on subsidies due to the production of the highly subsidized banana and sugarcane. Furthermore, farm revenues are low due to the low gross margin of sugarcane compared to that of banana and subsistence crops. At the farm level, equity is low because banana is cultivated on large farms that capture the subsidies, while small farms are oriented to diversification with no subsidies. The efficiency of farms is low on average considering the high cost of labor for cropping systems. The level of food self-sufficiency and the production of renewable energy for electricity in Guadeloupe are far from their potential. The amount of workforce in agriculture could be more important considering the total area that is covered by crops, which is explained by the low cover of crop-gardening, roots, plantain and orchards for food self-sufficiency and the source of carbon for combustion during energy production. Workforce needs are low because sugarcane cultivation occupies half of the area and does not require much workforce (approximately 60 hours of work are required per ha). The provision of electricity from renewable energy is currently far from the local goal of 50% by 2020 because only the residues from sugar production are used for electricity production. The risk of chlordecone contamination of crops could be decreased by a change in the land use of the potentially contaminated field. The pressure on the environment is low for biodiversity, while for water, the amount of irrigation water is close to that used for in water consumption of the population. The water resources are not potentially polluted in Guadeloupe, but awareness should be raised in southern Basse-Terre where water resources can be polluted due to the highly intensive banana cultivation in this area. Central Grande-Terre is also potentially polluted due to the intensity of crop-gardening in this area. The erosion in Guadeloupe is low because this phenomenon mainly occurs on vertic soils and with crops for which cover is low. In our database, few fields on vertic soil with crops, such as crop-gardening, appeared. The CO_2 emissions from agricultural production are weak due to the low mechanization of agricultural activities as well as the weak use of fertilization except in some cropping systems, such as banana, where this amount can reach up to 400 kg of nitrogen.ha^{-1}.yr^{-1}. Finally, the level of landscape diversification is low but unequal among sub-regions with a diversified landscape in southwestern Basse-Terre but with low diversity in other areas, especially Marie-Galante. In Grande-Terre, this score is low because agriculture is dominated by pasture and sugarcane, while southern Basse-Terre, the east is composed of banana, sugarcane and pasture, and the west is much more diversified, with pasture, orchards, banana, crop-gardening and sugarcane.

3.4.2.2. Recommendations for increasing the sustainability of local agriculture

From this diagnosis, several methods of improvement can be drawn for increasing the response of agriculture to local and global sustainability issues. Subsidies could be reallocated to different types of farmers and productions, especially food crops for the local market, and decreased for sugarcane and banana. This change would improve the efficiency of small farms and increase the equity in the repartition of the added agricultural value. This added agricultural value could increase with a wider adoption of food crops, especially of banana and sugarcane farms, because it would be more remunerating for these farmers. For social issues, this change could be especially relevant because the food autonomy of the island would increase drastically with changes from sugarcane and banana toward food crops. The risk of the contamination of food crops would most likely increase on polluted soils; therefore, these soils should be devoted to another type of use, such as the production of fiber cane for electricity, which would thereby increase the energy self sufficiency of the island, or the production of fruits from orchards. Employment would increase with the cultivation of crop-gardening or orchards, even with a global increase of mechanization to increase the efficiency of farmers. With the current crop-gardening-based cropping systems, the pressure of agricultural activities on natural resources would increase. Crop-gardening cropping or orchard systems would naturally increase the potential of pollution with pesticides in water catchments, rivers, and abstraction water sources. In addition, the amount of water for irrigation would most likely increase, especially in the Grande-Terre area, where the level of rainfall is too low for rainfall crop-gardening systems. On vertic soil, crop-gardening should be avoided or adapted to the sensitivity of this soil to erosion events. Finally, the amount of CO2 should be reduced by globally reducing the amount of nitrogen that is applied to cropping systems.

Agronomists in Guadeloupe should focus on prototyping crop-gardening, orchards and new agroecological cropping systems that are adapted to local pedoclimatic area issues in order to maximize the production of ecosystem services at the regional scale. Thus, for instance, in southwestern Basse-Terre, crop-gardening-based cropping systems should limit the use of irrigation and avoid the risk of erosion, which could be important in this area. In southeastern Basse-Terre, crop-gardening cropping systems should face the issues of water quality preservation because most water bodies are located in this area. The prototyped cropping system in this area should minimize its recourse to pesticides, especially close to rivers and water abstraction sources. In these two areas, roots legumes, zucchini, and cucurbits, should be avoided due to chlordecone pollution. Orchards should be prototyped for these areas by considering the above-mentioned constraints. In northern Basse-Terre, agronomists should prioritize cropping systems with rotations enhancing the quality of the visual landscape and favor the cultivation of tropical roots that cannot be produced in southern Basse-Terre due to the chlordecone pollution. In addition, beef production could be enhanced in this area with an incoming system based on pasture rotations that are still not widespread in Guadeloupe. In Grande Terre, crop-gardening should be based on low-chemical-input systems due to the potential of pollution in water abstraction sources. These systems should be based on species requiring water during the rainy season and low-water-need species during the dry season. A mechanized system would be particularly well adapted in Grande Terre due to the low slopes.

This increase in crop-gardening should come with the maintenance of a sufficient level of sugarcane area, which provides renewable energy for the production of electricity and banana that currently contribute to the production of revenue from local agriculture. These cropping system changes could not be realized at the same time. Simultaneously increasing the response to every objective would be difficult. The current agricultural system needs to be modified by agricultural policies impacting farmer's decision-making processes. Well-adapted policies should be implemented to target the correct area for crop acreage changes in order to drive agriculture towards the desire state. However, over-simplistic assumptions in the design of policy instruments as well as difficulties with predicting the behaviors of farmers should be avoided (Malawska *et al.,* 2014). A modeling tool could be used to assess ex-ante the adoption of innovations by farmers (Janssen *et al.,* 2007). A dynamic model could most likely provide information of the time gap within a farmer population to adopt the previously recommended changes. Indeed, differences among the farmer's behavior in the face of innovation, from early adopters to laggards, which is the last group to try or adopt new crop in innovation theory (Rogers, 1962), will most likely postpone the effects of targeted policies aiming to improve the sustainability of agriculture.

3.5.Conclusion

This study provides a new framework for the assessment of agricultural landscape based on a set of indicators allowing the ex-post and ex-ante assessment of the agricultural landscape from the field to the landscape. After identifying relevant sustainability objectives for agriculture in Guadeloupe, we selected and calculated a range of indicators at the field scale to demonstrate the variability of the contribution of landscape to sustainable development. We also applied a scale change procedure to obtain a global score for each indicator at the regional scale. This choice of indicators oriented the cropping system description and the generation of the field information throughout our territory. The regional values and spatialization of these indicators can help decision-makers understand the origins of the level of sustainability by studying the variability in the contribution of fields to the different sustainability issues.

In Guadeloupe, the application of this framework showed a low social and economic sustainability of the island and a fair environmental sustainability. These levels of sustainability could be enhanced with the progressive replacement of banana and sugarcane by new cropping systems. These new cropping systems should be adapted to the constraints and opportunities of the different context over the Guadeloupe in order to be adopted by farmers. Agronomists have a great role to play in prototyping these systems and interacting with policy-makers to assess agricultural policies in favor of the adoption of these relevant cropping systems for the different areas in Guadeloupe.

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4. Modélisation des décisions des agriculteurs en termes de choix de systèmes de culture à l'échelle du territoire

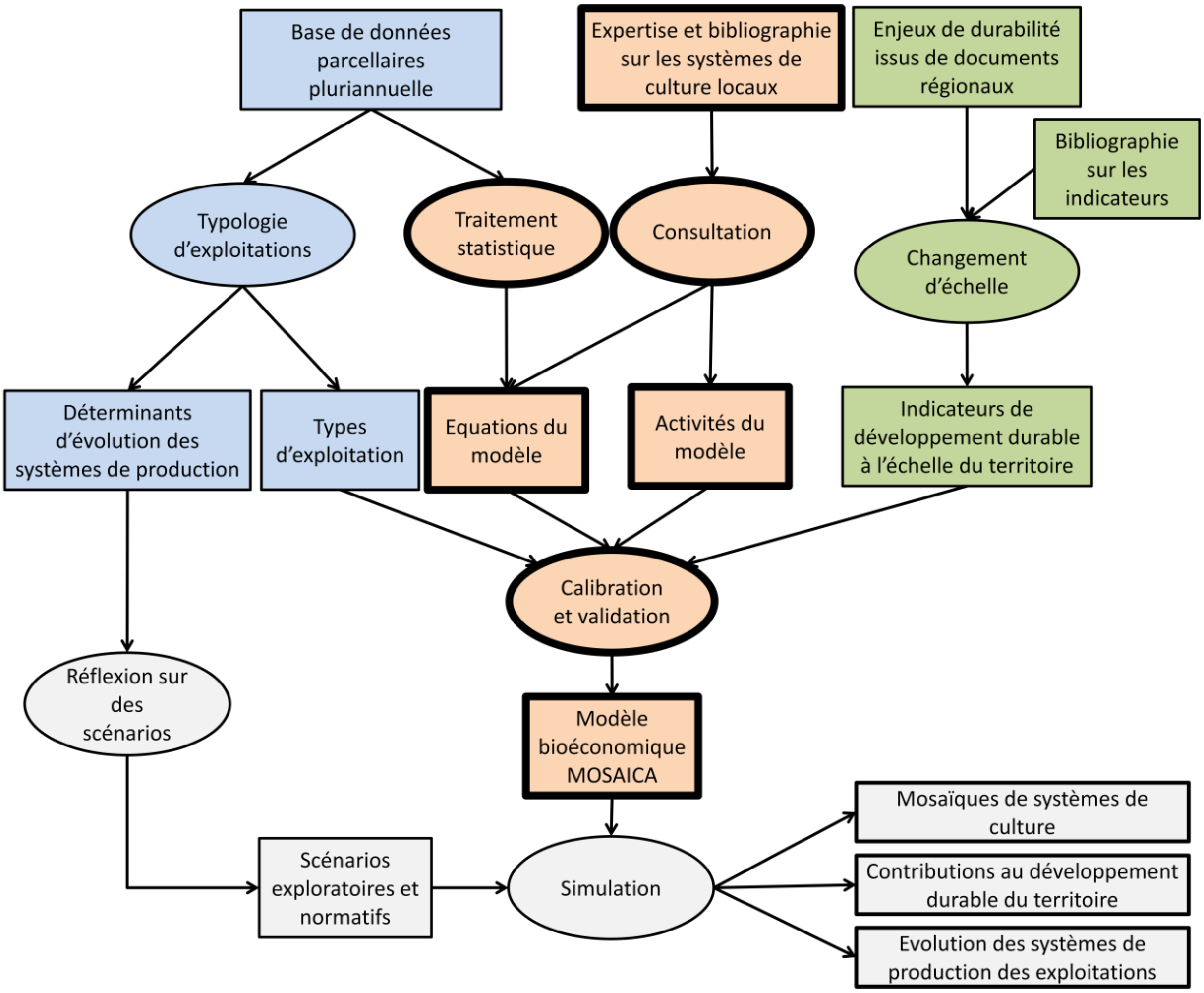

Figure 23 : Ensemble méthodologique pour la conception et l'évaluation multicritère de mosaïques de systèmes de culture: Focus sur la construction du modèle bioéconomique

Ce chapitre correspond à la description de la troisième étape de la méthode (Figure 23).

Les objectifs sont les suivants :

- Construire un modèle bioéconomique qui permet de simuler le processus de décision des exploitants agricoles en termes de choix de systèmes de culture à l'échelle du territoire

- Valider le modèle en évaluant ses performances aux différentes échelles spatiales introduites dans la méthode de conception.

La méthode proposée pour construire, calibrer et valider le modèle est présentée dans l'article suivant, intitulé "**A multi-scale bioeconomic model of farmer's cropping plan choices: from the field to the regional scale**", soumis à la revue *Agricultural Systems*.

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

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Keywords: land use change, scenarios, ecosystem services, sustainability indicators, farm typology, agricultural landscapes, Common Agricultural Policy

Abstract

Agriculture plays an active role in the provision of ecosystem services by way of cropping systems. cropping system choices by farmers are driven by a range of biophysical, socioeconomic and environmental factors that impact their location in a territory and thereby the provision of ecosystem services. To understand the effects of policy changes on cropping system mosaics and their contribution to the sustainable development of given regions, we built up a regional and spatially explicit multi-scale bioeconomic model called MOSAICA. The model inputs are a geographic database of fields, a database of cropping systems and a farm typology. The allocation of cropping systems is performed with the optimisation of the overall farmer's utilities at the regional scale with a risk coefficient that is defined at the farm level. The farm typology that is introduced within the model helps to follow the evolution of farming systems over the area of study. The allocation accounts for a set of equations defined at the field, farm, sub-regional and regional scales. The model generates new cropping system mosaics with this allocation process and assesses their contribution to sustainable development with a set of indicators that take into account the location of cropping systems over the region. To create an example of model use, three scenarios for changes in the agricultural subsidy regimes are tested in Guadeloupe. These three explorative scenarios produce new cropping system mosaics that decrease the area of cultivation of sugarcane and banana at the regional scale. The percentage of each farm type changed within the territory with the disappearance of banana growers and the decrease of sugarcane-based types. The scenarios were informative because the mosaics of modelled cropping systems improved agricultural contribution to the sustainable development of the studied area. The model structure is generic and can be reused in territories with data on farms and cropping systems are available. Finally, the MOSAICA model can be useful for scenario analyses to identify a promising combination of levers of change at different spatial scales and to assess changes in the cropping system mosaics and their correlative contribution to sustainable development.

4.1.Introduction

Agriculture is actively involved in the provision of ecosystem services by the management of ecosystems. Recent studies have shown that the spatial organization of cropping systems, called cropping system mosaics at the landscape scale, drive the provision of some ecosystem services (Thenail *et al.,* 2011). These cropping system mosaics contribute to the protection of soils (Ronfort *et al.,* 2011), the rational use of water (Bergez *et al.,* 2007) and the conservation of biodiversity (Rusch *et al.,* 2012) among others. The cropping system mosaic is important as well for the provision of economic and social services, such as the provision of sufficient food and the provision of employment. Cropping system mosaics are the results of farmer's cropping system choice at the field level (Dury *et al.,* 2011).

Cropping system choice is driven by a different range of parameters acting at the field, the farm and the regional scale (Aubry *et al.,* 1998). Biophysical drivers (e.g. the slope, the rainfall), social factors (e.g. the age of farmer), economic factors (e.g. the investment capacity), farm structure and resources (e.g. the size of farm, the amount of workforce), farmer's objective and risk aversion can highly drive the choice of farmer's cropping system at different spatial scales. At the field scale, biophysical factors can constrain the adoption of new cropping systems (Chopin and Blazy, 2013), while the change in production quotas at farm scale and the personal objectives of farmers affect the choice of farming systems (Bureau *et al.,* 2001). At the regional scale, the implementation of agricultural policies (Flichman *et al.,* 2011) and protected environmental areas drive the choice of crops and agricultural practices. Some of these parameters are spatially explicit and can then affect farmer's choices in a different way depending on their location on the territory. The location of cropping systems is directly responsible for the values of ecosystem services provided by agriculture. Thus, in order to manage ecosystem service provision at the regional scale, decision-makers should implement well adapted multi-scale spatially explicit policies aiming at organizing the landscape for increasing the provision of services in the desired direction.

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

However the interrelations between the field, the farm and the regional scales have scarcely been integrated in bioeconomic models despite their influence on the decision process of farmers (Delmotte *et al.,* 2013). Moreover, assessment of consequences of cropping system changes in current bioeconomic model are not spatially explicit, which decreases the usefulness of the assessment for decision-makers, who want to know the impact of policy on the cropping system mosaics and the evolution of the contribution of these mosaics to the sustainable development of their region.

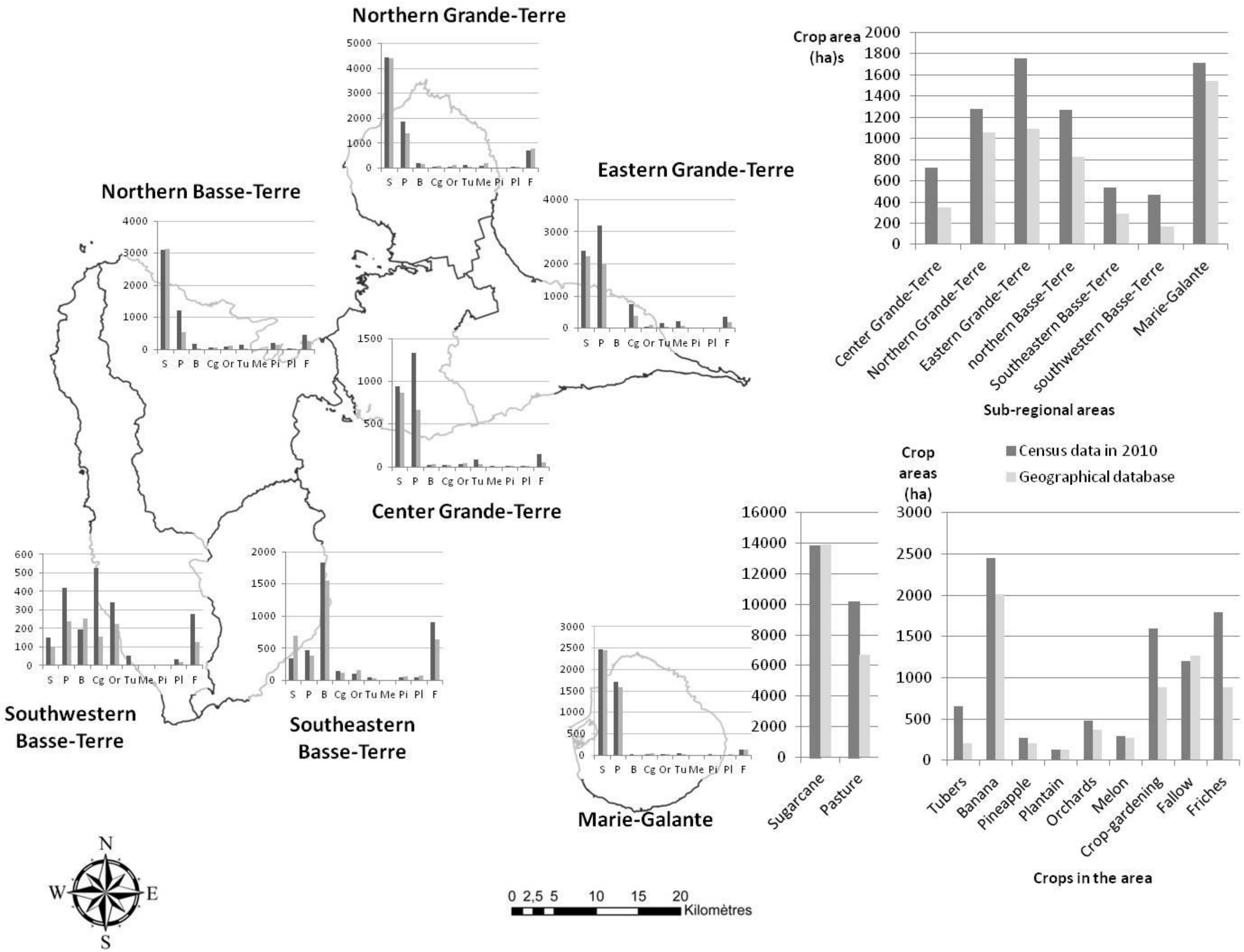


Figure 24 : Repartition of crops at the district scale and comparison of the census data in 2010 with the geographical database used in the study in hectares. On the map S stands for sugarcane, P for pasture, B for banana, Cg for crop-gardening, Or for orchards, Tu for tubers, Me for melon, Pi for pineapple, Pl for plantain and F for fallow.

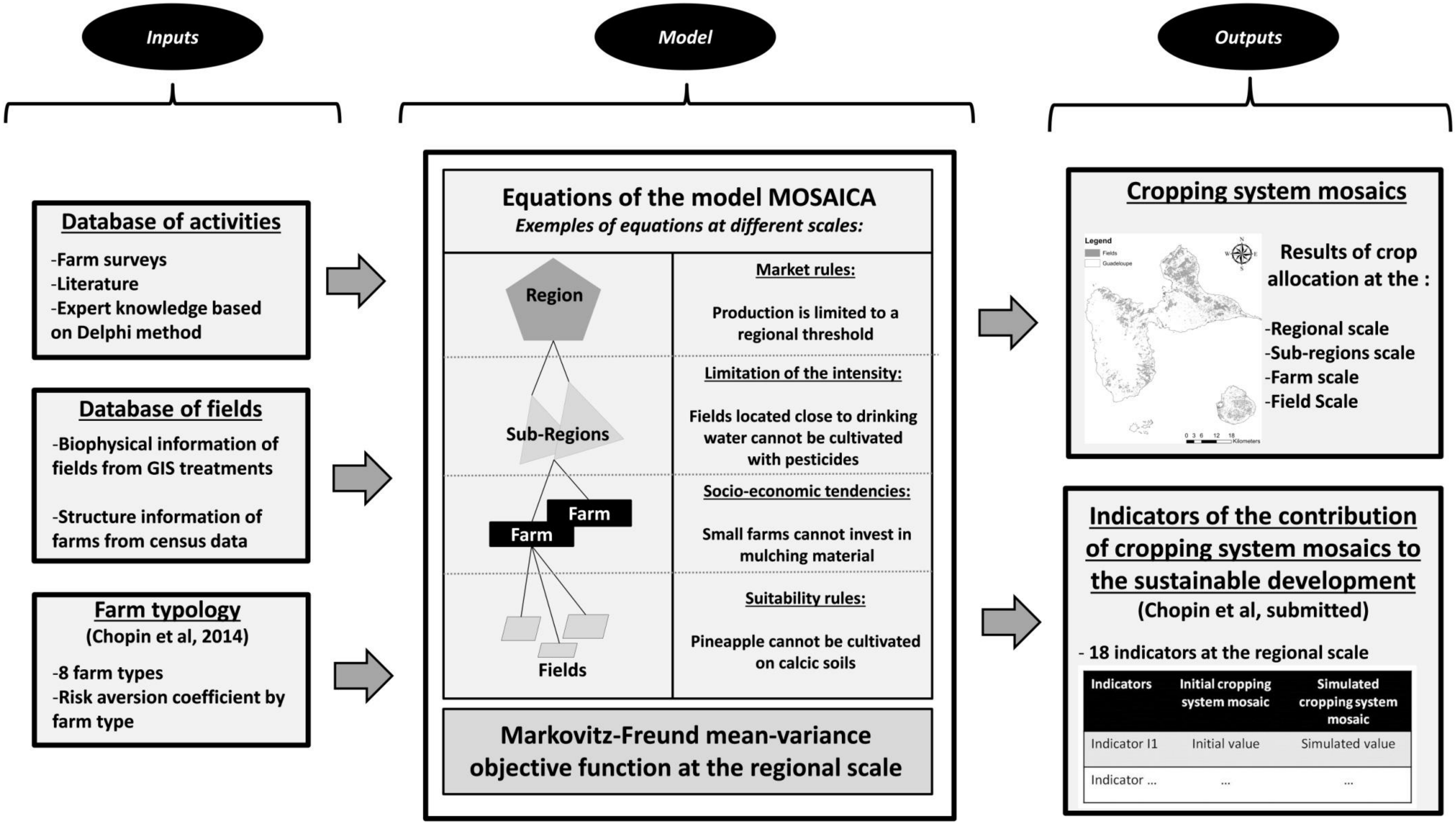


Figure 25 : Presentation of the modeling framework based on Multi-scale model of the crOpping Systems Arrangement and Its Contribution to sustAinable development (MOSAICA)

In order to assess the effects of policies on the contribution of cropping systems to the sustainable development at the regional scale, we built a regional spatially-explicit multi-scale bioeconomic model of farmer's cropping system choice at field scale. This model can optimize regionally the allocation of cropping systems at field scale by taking into account the constraints and opportunities at field level, the availability of production factors at farm scale, farmer's attitude toward risk, the policy implemented or the availability of resources (e.g. water for irrigation) at the regional scale. This model allows the simulation of the effects of scenarios of policy changes at different scales on the organization of cropping systems and their contribution to sustainable development.

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

4.2.Material and methods

4.2.1. Area of implementation

Our spatially explicit multi-scale bioeconomic model is a generic model for scenario analysis at the regional scale. We implemented it in Guadeloupe as an example. Guadeloupe is a French archipelago located in the Caribbean. In this area, climate is tropical with rainfalls positively correlated to the relief ranging from 1000 to 5000 mm yr -1. Mountainous areas are located on acid soils, andosols, nitosols, ferralsols and vertic soils and flat lands on calcisols and vertisols.

The total cultivated area of the archipelago, composed of Grande-Terre, Basse-Terre and Marie-Galante islands, is 32 948 hectares which encompass sugarcane, pastures, banana, crop-gardening, tubers, orchards, melon, pineapple and plantain (Figure 24). Their acreage is respectively 13 875, 10 214, 2452, 1592, 653, 476, 290, 270 and 129 hectares while the area of fallow and waste land are 1198 and 1799 hectares (Recensement agricole, 2010). Crops are spatially arranged as follows: sugarcane and pasture are located all around the island; banana is located in the southeastern part of Basse-Terre mainly with some areas in the southwestern part and in the northern Grande-Terre. Crop-gardening and tubers are located on the eastern Grande-Terre and on the southwestern of Basse-Terre. Orchards are in the southwestern of Basse-Terre as well. Pineapple areas are mainly located in the northern Basse-Terre, while melon cultivation takes place in the northern Grande-Terre. Plantain is mainly located in the south-east of Basse-Terre with some areas in the north (Figure 24).

The number of farms is 7749 and their size ranges from less than one hectare to more than hundred and in average four hectares (Agreste, 2010). This variability in socioeconomic, biophysical context and farm resources is responsible for the variability in cropping systems. This variability has been described in the island through typologies in diverse studies such as the conditions for the adoption of innovative banana cropping systems (Blazy *et al.,* 2009), the prototyping of new citrus based cropping systems (Le Bellec *et al.,* 2011) and the variability of farming systems (Chopin *et al.,* 2014).

4.2.2. Overview of the bioeconomic model MOSAICA

The modeling framework with the inputs and the outputs of the Multi-scale model of the crOpping Systems Arrangement and Its Contribution to sustAinable development (MOSAICA) appears in the Figure 25. The inputs of the model are i) the geographic database of fields spatially located all over an area of interest that needs to contain information about the biophysical context of fields and the farm structure, e.g. the farm size and the land tenure, ii) the database of activities that describes cropping systems that can be allocated to fields and iii) the farm typology and the algorithm of classification to the eight farm types. The model optimizes the overall farmer's utility which is composed of the revenue and a risk aversion coefficient. The allocation of cropping system is modeled through a set of equations that guide the adoption of cropping systems by farmers at different scales: the field, the farm, the sub-regional and the regional scale. The optimization is realized at the regional scale because equations are implemented at this scale for constraining the overall quantity of production of some crops within the entire area of study. The outputs of the model are cropping system mosaics and the calculation of a range of indicators based on the mosaic structure and the location of cropping systems within this mosaic.

4.2.3. Inputs of the model

4.2.3.1. Building of the geographical databases

Firstly, a geographical database of fields needs to be used in order to design and assess cropping system mosaics. This type of database can either be obtained from agricultural uses declared by farmers or can be drawn from aerial or satellite images. This geographical database needs to be composed of fields represented with polygons that are spatially located within the territory with the agricultural use on each field for the year of declaring. Secondly, a shapefile of farms is built with either information obtained on the location of farms or with the centroids of fields owned by a same farm, using for instance the geostatistical tool in ArcGis (ESRI, 2009). Thirdly, the reliability of these database has to be checked, for scenario analysis at the regional scale, by comparing the crop areas in statistics and crop areas in the geographical database to provide some limits on the use of the database for regional scenario analysis. Fourthly the farm and the field databases are completed with the required information for describing the allocation factors of activities.

The Figure 25 provides some examples of information that appear in equations of the model and that needs to be integrated within the databases through geographical treatments with shapefiles of information.

In our case study, we first obtained a database of fields from the local agency that gathers farmer's declaring of crop areas for subsidy demands. The initial geographic database used gathers 25 057 fields, and the crops grown on them in 2010 are owned by 5336 farmers. Some additional information are provided such as the land tenure. Afterwards, a shapefile of farms is constructed with centroids of fields and the reliability of the field database is checked by comparing the areas in local statistics (Agreste, 2010) and the areas in the geographical field database. The Figure24 shows the repartition of farms over the Guadeloupe territory and the area of each crop in the database compared to the agricultural census data in 2010. We can see that the total number of farms in the database is below the actual number with 5336 farms compared to the initial 7749 farms in statistics.

This lack of farms in the database is quite homogeneously spread among the sub-regional areas but the Marie-Galante area is better represented than the eastern Grande-Terre and the southwestern Basse-Terre. The crop areas follow tendencies linked to the number of farms. The crop-gardening and tubers that are cultivated in the southwestern Basse-Terre and the eastern Grande-Terre are lacking in an important proportion and the total area of pasture is also below the current level in the census data. The lack of crop-gardening and pasture should prevent from generalizing some tendencies of change observed in these crops.

In the fourth step,areas of fields were calculated and aggregated to obtain the size of each farm. Rainfalls were calculated based on a mean level of rainfalls from 30 years of data on rainfall. The inter-annual level of rainfalls were assessed based on monthly rainfalls determined with a shapefile from Meteo France which provides results from meteorological stations and where interpolated using the kriging tool from ArcGIS 9.3 (ESRI, 2009). Types of soil were added based on an intersection with the soil shapefiles from map of soil (Colmet-Daage, 1969). In Guadeloupe, 20% of fields are contaminated by chlordecone, a pesticide that was spread in banana fields and that caused a long term pollution of soils (Cabidoche *et al.,* 2009). In this area some crops cannot be grown due to their absorption capacity of the pollution, mainly tubers, some vegetables such as zucchini. The map of risk of chlordecone content was used to generate the risk of chlordecone on plots (Tillieut and Cabidoche, 2006).

Irrigation schemes were intersected to fields in order to provide information on access to irrigation. Altitude was calculated from a digital elevation model (DEM) built by using the kriging tool as well. The slope raster was determined from this DEM using the slope tool. Fields within mangrove areas were determined based on a shapefile localizing these areas, provided by the Guadeloupe Department of public works, land use and housing. Fields were spatially intersected with sub-regions determined based on their similarity of soil and climate conditions.

Thus, the interrelations between scales were explicitly defined considering the fields like entities owned by farmers, belonging to a sub-region and within Guadeloupe.

4.2.3.2. Building of the database of activities

The basic element of the bioeconomic modeling approach is the production process, or the production activity (Flichman *et al.,* 2011). One activity is defined by the technical coefficients that represent the use of inputs needed to produce different outputs. Products are outputs and can be produced by several activities while one activity can have several outputs (e.g CO_2 emissions, yield, gross margin, use of pesticide active matter). Activities can be defined in different ways, by expertise, by using crop models, with on-farm-surveys, considering the objectives of the study, the availability of biophysical models and the presence of expertise on the area of study.

Table 10 : Description of some activities entered in the Multi-scale model of the crOpping Systems Arrangement and Its Contribution to sustAinable development (MOSAICA)

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

Mosnier *et al., (*2009) defined activities as a combination of a crop variety x input level x soil type from the local chamber of agriculture. Surveys can also be used in order to define the range of activities performed by farmers on a given area as Belhouchette et *al.* (2011) did with a description of yield of the different crops in rotations in activities using the CropSyst model. Crop models are often used in order to define the characteristics of activities especially in temperate areas where crop models can be adapted. Description of the cropping systems has to be based on required data for the optimization process, (e.g. the average gross margin, the cost of production, yield, working demand, price of selling...) and the information required to calculate the indicators in outputs. For instance, Belhouchette *et al.,* (2011) particularly focused the description of activities on nitrogen application since the aim of the study was to investigate the effects of policy changes on the level of nitrogen leaching at farm scale.

In our case study, We described 36 cropping systems based on i) previously published work, ii) expert-knowledge and iii) on-farm surveys. We presented some activities with their technical coefficients in Table 10. Previously published work encompass scientific publications, such as Blazy e*t al.,* (2009) for banana production or Lebellec *et al.* (2011) for citrus production and technical guides from agricultural institutes and agricultural cooperatives, describing cropping systems with quantitative data. Experts were first interviewed individually and gathered together in order to come to an agreement on the characteristics of cropping systems following the principle of the Delphi method (Harold and Murray, 2002). On farm-surveys were realized to complete data that were lacking.

Mean economic data were provided by experts and documentation such as economic guide edited by the local Chamber of agriculture which gathers all the crop yields, gross margins and the costs of practices. Information on the time needed for crop management were obtained using BANAMARGE® (Manceron *et al.,* 2010) and IGNAMARGE® tools (Causeret *et al.,* 2012) that provide a range of technical information for respectively banana cropping systems and tubers cropping systems. The use of pesticides and fertilizers were obtained based on expert interviews. We applied the Delphi method for determining the crop gardening cropping systems, we individually met four farmer advisers of crop-gardening in Guadeloupe and we gathered them later. For plantain, our results were based on a 56 farm surveys. Doses of pesticides considered are recommended doses. Active ingredients were identified based on the main commercial products used.

4.2.3.3. The farm typology

Typology are used to group farmers over a territory based on the similarity of their decision process. Typology can be made in different way either from expertise or from statistical analysis (Madry *et al.,* 2013). Statistical analysis can be performed on the farm database for clustering farmers based on their decision process. Statistical analysis based on multivariate analysis are often used. They encompass principal component analysis or canonical analysis for simplifying variables used for splitting the farmer's population, and hierarchical trees for categorizing farmers (Köbrich *et al.,* 2003; Blazy *et al.,* 2009; Gaspar *et al.,* 2007). Since crop acreages are the results of farmer decision process (Aubry *et al.,* 1998; Dury *et al.,* 2011), these variables should be included in the statistical analysis that may also include biophysical variables, structure or socio-economic variables (Andersen *et al.,* 2007).

In our case study, we used a farming system typology realized in Guadeloupe on 3591 farmers that were categorized in eight farm types: "arboriculturists", "banana growers", "specialized cane growers", "diversified cane growers", "diversified", "breeders", "crop-gardeners" and "mixed cane growers-breeders". Chopin *et al.* (2014) performed a regression tree on the classification in order to obtain an algorithm of automatic classification of farms into farm types. This algorithm, composed of several thresholds of proportion of crop acreages at farm scale, has been implemented in our bioeconomic model as a set of if-then-else rules in order to provide i) a classification of farms in types at the initial state of the mosaic and ii) a post-optimization classification that shows the evolution of farming systems from the initial cropping system mosaic to the simulated one after scenario analysis. This change in number of farms in types is an indicator of farming system changes that can help understanding the drivers of farming system changes at the territorial scale.

4.2.4. The model description

4.2.4.1. Equations of the model

Equations are mainly implemented in bioeconomic model as constraints to the adoption of cropping systems by farmers. These equations impact the allocation process of cropping system at different scales. They can be defined based on statistical analysis for determining the location factors of cropping systems (Leenhardt *et al.,* 2010) or can be defined also based on expertise on the variables driving the location of cropping systems (Clavel *et al.,* 2011).

In our case study, we mixed expertise and descriptive statistics to highlight thresholds of variables describing the location of cropping systems. These thresholds were then implement in the model with a range of equations to drive the choice of cropping systems by farmers. Since different parameters at different spatial scales can impact the cropping system adoption by farmers, we implemented a range of equations from the field scale to the regional scale.

At the field scale, we implemented a set of equations linking cropping systems to altitude, slope, area of field, the type of soil and the land tenure depending on the nature of cropping systems. For instance, plantain cropping systems were limited to an altitude of 400 meters due to the fact that above this altitude its growth duration greatly increases. A slope value above 25% limits the adoption of mechanized cropping systems. Mechanized sugarcane in Guadeloupe has to be cultivated in plots with a minimum size of 0.3 hectare in order to be mechanically harvested by a farm work firm. Pineapple cannot be grown on calcic soils (vertisols and calcisols). Long duration crops such as banana, sugarcane, plantain, orchards, and citrus cannot be grown in plots in indirect tenure.

At farm scale, the size of farm, a maximum proportion of crop at farm scale based on agronomic reasoning, production quotas and workforce resources are the main constraints for the adoption of cropping systems. Intensive banana cropping systems can only be cultivated in large farms exceeding 10 hectares due to the amount of area needed for managing this cropping system (Blazy *et al.,* 2009). For banana production, production quotas are allocated to farms, and then banana farms cannot produce more bananas than their production quotas. These quotas are calculated based on the observed cropping systems allocated for the year 2010. A maximum proportion of some crops at farm scale was determined based on maximum return frequency of crops. It was for example set to 0.66 for tubers and pineapple cropping systems considering that they can be grown for two years in a row with a return period of one year (one year gap before they can be cultivated again). The amount of workforce, determined based on the observation of cropping systems allocated to field in 2010, was considered as a limited resource for farmers.

At the sub-regional scale, soil, climate, environmental and geographical protected indications constraint the adoption of cropping systems. Thus, sugarcane cropping systems cannot be grown outside their predetermined sub-regional areas, e.g northern Grande-Terre for the activity called "Northern Grande-Terre sugarcane". Irrigated cropping systems cannot be performed outside irrigation schemes while the amount of rainfalls is not sufficient. Long duration cropping systems cannot be grown on mangrove areas due to the risk of flood. Melon cultivation for exportation is restricted to several districts due to a geographical indication.

At the regional scale, we defined maximum thresholds for limiting the quantity of crops produced, which represents the crop yield multiplied by the area of crops. We limited the production of sugarcane and banana based on the contingent of production that can be subsidized, provided by the European Union to the local producers with 107 000 tons of sugar and 77 877 tons of bananas (PDRG, 2010). We also defined for non exported crops, pineapple, tubers, citrus, a threshold at the regional scale which is the level of the current consumption based on the sum of the local production in addition to the importation from other countries. For example, plantain production is around 4500 tons and the importation is 150 tons, we then set the threshold for plantain production at the regional scale to 4650 tons.

4.2.4.2. Objective function

The objective function of our regional bioeconomic model is a Markovitz-Freund mean-variance function (Equation 1). The optimal acreage at the regional scale is the maximum total gross margin balanced with an expected variability of gross margin, multiplied by a risk-aversion coefficient at farm-scale. This utility function is similar to the one used by Mosnier *et al.*(2009).

In our case study, positive and negative variations were difficult to determine due to the lack of data on the crop yields and prices variability in our case study. The coefficient of variability is determined for each activity based on agro economic expertise and encompass both an agronomic risk (yield variability due to climate conditions, pest attacks or diseases), commercial outlet risk (due to the variability of selling price across the season of selling) aggregated together. We applied to each activity a variability coefficient Δ based on a qualitative appraisal of this risk since qualitative formulation of risk is known as generating good results in bioeconomic model (Arriaza *et al.,* 2003). For sugarcane and banana this variability coefficient is for example 10%, due to the low commercial risk and a low variability in crop yield. Moreover in the case of high decrease in crop yield loss of gross margin is covered by additional subsidies. For pasture, we considered the variability as null since beef production is an extensive production with low frequency of beef selling. The variability of orchards, citrus, plantain, tubers and pineapple were set to 40%. Their commercial risk is high but their inter annual yield variation is average. The risk of crop-gardening was set to 70% since its inter annual yield variability is very high and its commercial risk is high as well.

$$MAX\ \sum_F\ (\sum_P\ \mathrm{X_a}\ (\sum_A \overline{m}_a -\ \phi_{\mathrm{F}}\ (\mathrm{Z_a})\ )\qquad (1)$$

$$\text{With } Z_a =\ \Delta_a\ \overline{m}_a \qquad (2)$$

$$\overline{m}_a = (\ \bar{y}_a\ p_a +\ subsidies_a) -\ cost_a \qquad (3)$$

Where $\boldsymbol{m_a}$ is the average gross margin of activity a based on a mean yield ***y***, a price ***p*** and a given level of variable cost "cost" (Equation 3). ***Z*** is the mean variability ***Δ*** of the mean gross margin of activity a (Equation 2). The area of activity a is symbolized by ***X*** and ***φ*** is the risk aversion coefficient used as a calibrating parameter of the model (Equation 1). In our model, the notation are as followed: ***X(f,a)*** represents the vector of decision variables, that is to say the area covered by each activity ***a*** (cropping system in our case study) on field ***f*** (Farmer can choose one or several cropping systems on the same plot).

4.2.5. Calibration procedure

Table 11 : risk aversion coefficient by farm type used for the calibration based on iterative improvement of MOSAICA's outputs

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

The calibration procedure is based on the allocation of several sets of risk aversion coefficients φ to farm types. Several iterations are realized until 80% of farming systems are well calibrated. After reaching this threshold, the model can be considered as satisfying.

In our case study, we tested several sets of risk aversion coefficients φ per farm type as calibrating coefficients of our model. The same risk aversion coefficient was allocated to each farm belonging to the same farm type (Table 11). We established a range of hypothesis on the level of risk aversion of farm type in order to start the iteration of calibration. After running 100 iterations, we managed to obtain a set of risk aversion coefficients that provided satisfying results at farm scale in term of crop areas cultivated. The coefficient φ has a value from 0, a risk neutral farm type, here crop-gardeners, to close to 3, a very risk adverse farm type like breeders in this example (Acs *et al.,* 2009).

4.2.6. Evaluation of the model

The outputs of base year in bioeconomic model should match the reality. Authors have been validating their models in different ways and no consistent and widely accepted model evaluation procedure has been recognized for validating model outputs (Janssen and van Ittersum, 2007). Several methods can be used in order to test for the validity of model outputs. For instance, Mosnier *et al.*2012) used the ratio of the number of crops simulated on the number of crop observed and the percentage of acreages misallocated. The percentage of absolute deviation (PAD) between the observed and the simulated acreages (Hazell and Norton, 1986; Leite *et al.,* 2014) or income (Schilizzi and Boulier, 1997; Osaki *et al.,* 2014) is widely used. The best calibration is reached when PAD is close to 0.

$$PAD\ (\%) = 100 * \frac{\sum_{Gwad} |(X_i(a) - X_a)|}{\sum_{Gwad} X_i(a)} \quad (4)$$

Since the purpose of our model is to ensure a sufficient prediction quality of the location of cropping systems at various spatial scales, we checked the outputs of our model at multiple scales: the regional scale, the sub-regional scale, the farm scale and the field scale with this PAD, which reveals the distance from the calibrated mosaics to the observed in term of cropping system areas (Equation 4).

4.2.7. Sustainability indicators at the regional scale

The impact of agriculture on the society at the regional scale depends on the state of the cropping system mosaic, that is related to i) the technical coefficients of farmers' cropping system allocated at field scale, ii) the location of fields within the region and iii) the properties of fields (e.g. the level of rainfall, the field area...). The indicators consist of a quantitative assessment of the externalities of farmers' cropping plan choices at the regional scale. The score of the indicator then varies depending on the cropping systems allocated in the whole cropping system mosaic. The indicators are categorized in economic, social or environmental pillars of the sustainability issue that are broken down into several sustainability objectives that local decision makers try to fulfill.

In our case study, for each objective, one to three indicators have been designed in Chopin *et al., submitted*). These indicators provide information on the contribution of mosaics to the sustainability objectives.

All the economic indicators and most of the social indicators are not spatially explicit and are calculated based on the composition of the cropping system mosaic and do not take into account the spatial organization. The total agricultural added value is calculated based on an aggregation of gross margins of cropping systems. The repartition of revenue among the farm population is the Gini indicator and measures the equity in the repartition of farm revenue (Ceriani and Verme, 2012). The total amount of subsidies is the aggregation of every subsidies provided to farmers for agricultural production. The mean efficiency is based on the ratio of the gross margin on the variable costs. Three ratios of food nutrients produced over needs are calculated based on the nutrient contents of each crop and the needs calculated for the total population in Guadeloupe and average person needs.

The potential of electricity production measures the energy that can be produced from crop or crop residues, mainly bagasse from sugarcane cultivation and biomass from fiber-cane. The total needs of workforce aggregate the need of workforce from each cropping systems. The area of risk of contamination is spatially explicit and measures the area for which the risk of contamination for crops by chlordecone, a pollutant in soil from former pesticide application in banana fields; this risk considers the type of soil, the crop grown and the level of pollution (Cabidoche and Lesueur-Jannoyer, 2012).

Most of environmental indicators are spatially-explicit. The mean quantity of toxicity in fields located in ZNIEFF areas (areas for the protection of birds in Guadeloupe) depends on the level of toxicity of cropping systems in ZNIEFF areas. The ratio of rivers, water abstraction sources and water catchments potentially polluted are based on the intensity of cropping systems within a buffer area for rivers and within perimeters for water catchments and abstractions sources. The amount of water needed for irrigation is based on crops needs and mean rainfalls in the area monthly. For each month a need of water is calculated and all the needs from each field and each period are aggregated for fields located in irrigation perimeters. The area potentially eroded due to farming practices depends on the type of soil, the slope and the soil cover by crops. The overall emission of CO_2 from farming practices is not spatially explicit and only represents the aggregation from farm to region of the emissions of CO_2 of the inputs of cropping system from cradle to farm gate. The diversity of crops across landscape is based on the Inverse Simpson's Diversity index which calculates the diversity of crops in each sub-regions and the mean level of diversity at the Guadeloupe scale (Simpson, 1949).

4.2.8. Policy scenarios

The current policy and the scenarios developed are summarized in Figure 26. The simulated cropping system mosaic from the calibration procedure is used as the base year in the scenario analysis in the next sections.

4.2.8.1. Current agricultural policy in Guadeloupe

The current agriculture in Guadeloupe is highly subsidized by several agricultural policies. The main policy in favor of outermost regions are i) the POSEI ("Program of specific options for isolation and insularity") arrangements, ii) the rural development program of Guadeloupe 2007-2013 that encompass the less favored area measures, the agri-environmental measures and the structural measures to sectors and iii) national subsidies (Figure 26). These policies are mainly impacting banana and sugarcane:

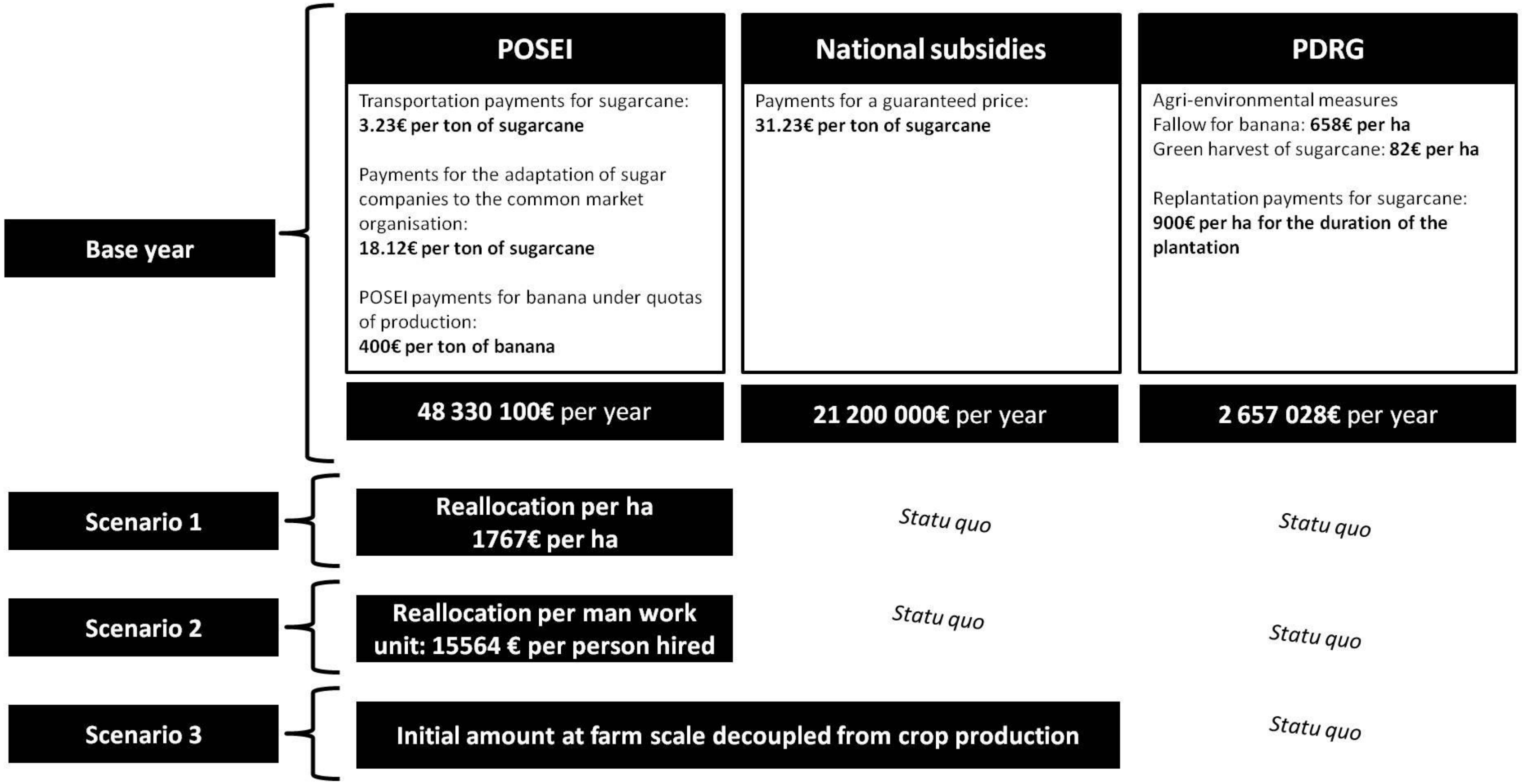


Figure 26 : Description of the current agricultural policy in Guadeloupe and the modification to be tested in the scenario analysis phase

- POSEI arrangements are subsidies that take into account the geographical and economic handicaps of outermost regions, the remoteness, the insularity, the small size, the topography and climate and the economic dependence on a few products (POSEI France, 2012). POSEI measures are funded under the first pillar of the Common Agricultural Policy, and fall into two categories, specific supply arrangement and measures to support the local agricultural production. For sugarcane, the POSEI provides a subsidy to the sugar companies and a transportation subsidy to the farmers. The subsidy towards the industry is 14 M€.yr-1and this amount is used to increase the sugarcane payment to farmer's from 14.22 €.ton-1 to 32.34 €.ton-1 in average with a subsidy of 18.12 €.ton-1 depending on the saccharine richness of the sugarcane in sub regions. The other subsidy is for helping farmers to pay the transport of sugarcane from the farmer's fields to the nearest collective point. This amount depends on the area where the field is located and vary from 2.75 €.ton-1 in the eastern Grande-Terre, the northern Basse-Terre and Marie-Galante, to 3.23 €.ton-1 in the center of Grande-Terre, and 4.76 €.ton-1 in other areas. For banana production, the POSEI provides a protection subsidy which is 400 €.ton-1 based on an historical quota of production allocated to banana farms. This subsidy is provided at farm scale but its amount depends on the production of banana by farms compared to the farm historical reference of banana production. A production of 80% of the farm historical reference insures 100% of subsidies while below 80% the decrease in production decreases proportionally the amount of subsidies. This subsidy can then be compared to a payment coupled to production.

- The rural development program of Guadeloupe (PDRG) is financed by the European Union and national subsidies that are provided for agri-environmental measures, replantation of sugarcane, fallow and production in less favored areas. The agri-environmental measures are also compensatory measures of the reduction of yield obtain after applying a set of management practices willing at protecting the environment. Payments for banana were around 658 €.ha-1 for banana farm using fallow in their rotation to manage the population of nematodes, 82 €.ha-1 for harvesting the sugarcane without burning it due to the loss of leaves for soil protection. Payments for orchards, crop-gardening, plantain, pineapple are null (PDRG, 2011). The rural development program also provides a subsidy for the replantation of sugarcane fields for the duration of the sugarcane plantation. This amount is 900 €.ha-1 for seven years in average. Compensatory payments for guadeloupean farmers located in mountainous areas are not integrated in the amount of subsidies currently considering the small number of farmer's that received this subsidy, around 50, in 2010.

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

Sugarcane farmers are also remunerated for providing bagasse, a remnant from the sugarcane pressing, for the electricity production. The amount of this payment is 10 €.ton^{-1} of sugarcane and is null for the farmers in Marie-Galante in that the bagasse is directly used by the sugar factory instead of being sold to a power plant, like in Grande-Terre and Basse-Terre.

4.2.8.2. Expected changes in agricultural policy in Guadeloupe

The current policy towards outermost regions is going to change due to the pressure of the World Trade Organization for liberalizing the sugarcane and banana market (European Union, 2012). This liberalization impacted the Common Market Organization in the past on both sugar and banana and it will probably keep on modifying the mosaics of cropping systems at the regional scale. For sugar, the national subsidies are going to disappear by 2017 while the contingent of banana from RUP may disappear by 2020.

French sugar and banana production are poorly equipped to cope with the liberalization of the European sugar market planned for 2017 and the banana market for 2020. The change in farm aid is also an objective of local decision-makers that want to improve, the self-sufficiency of Guadeloupe in energy and food, the contribution of agriculture to local employment and the rural development (PDRG, 2011). However, in the same time, ending support of the sugar sector will harm production in France's overseas departments. Many people in Guadeloupe benefit from sugarcane and banana cultivation that is present in nearly 75% of the guadeloupean farms (Chopin *et al.,* 2014). We will then test the impact of three scenarios of changes in the subsidies level and characteristics on the cropping system mosaics at the regional scale and the effects of these mosaics on the contribution of agriculture to sustainable development of society.

4.2.8.3. Scenarios of agricultural policy changes

In scenarios 1 and 2, the direct payments to crop production from the first pillar of the Common Agricultural Policy towards sugarcane and banana production are reallocated while in scenario 3, subsidies are decoupled from production (Figure 26).

- In scenario 1, the entire amount of subsidies from the first pillar, 48.34 M€.yr^{-1}, is reallocated to each crop equally with an amount of 1768 € per hectare of production, including sugarcane and banana.

- In scenario 2, the amount of subsidies from the first pillar is also reallocated, but for each unit of hired workforce the subsidy is 15 569 € per year. Then the reallocation of subsidies is more important for cropping systems with a high use of workforce.

- In the scenario 3, current level of payments from the national subsidies and POSEI payments at farm scale, that represent 69.8 M€.yr^{-1}, are maintained but completely decoupled from agricultural production. Then farms are subsidized with the amount that they obtain in the base year but the production of crops is not subsidized anymore by the POSEI or national subsidies like the decoupling of CAP in Europe.

4.3. Results

4.3.1. Consistency of the results from the calibration procedure

4.3.1.1. Consistency of results at the regional scale

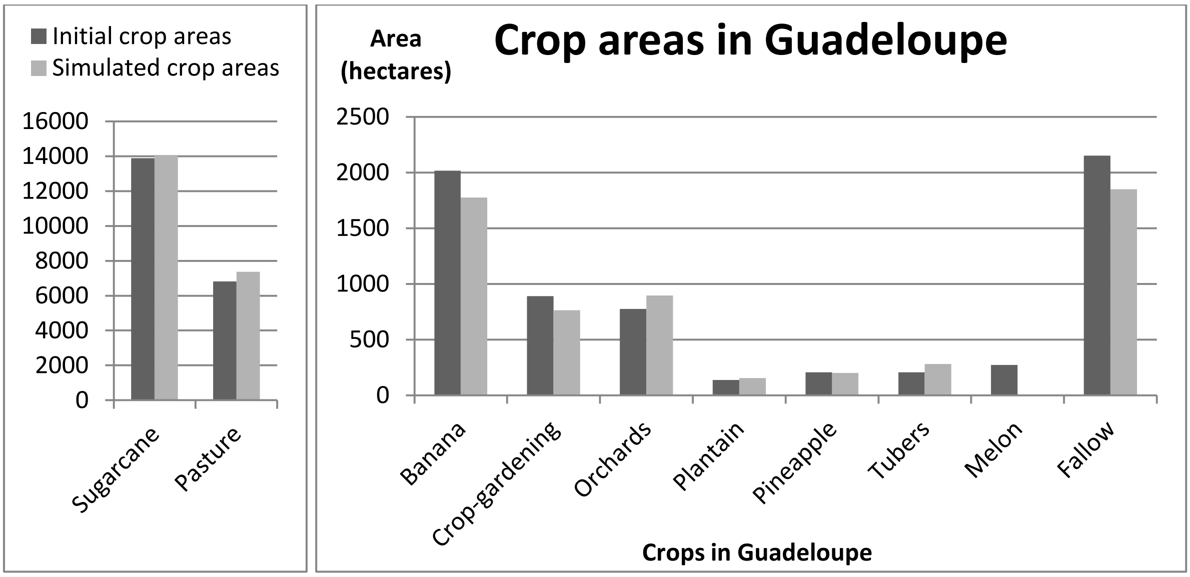


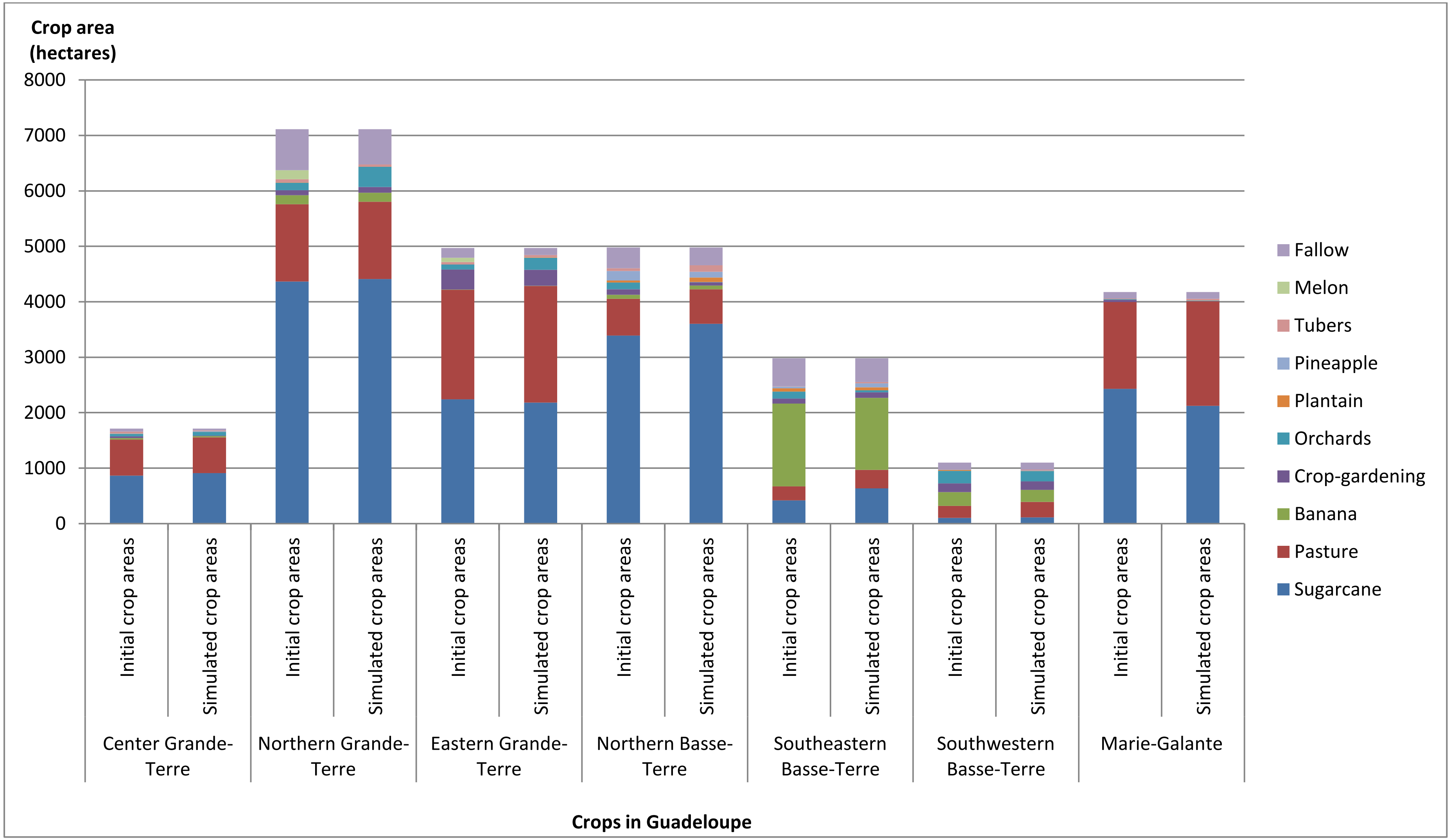
Figure 27 : Comparison of the regional crop areas between the observed situation and the simulated one after the calibration step

We first compared the simulated acreages allocated to different crops to those observed in Guadeloupe in the geographical database. The calibration procedure used in the modeling framework resulted in a good match for 8 out of 10 agricultural uses over the territory (Figure 27). We considered that the results were good when the percentage of absolute deviation (PAD) was below 15% for the main crops at the scale of the region and 20% in sub-regions as recommended by authors assessing the reliability of bioeconomic farm models (Janssen and van Ittersum, 2007; Hazell and Norton, 1986).

We observed that the total crop areas of sugarcane and pasture were very close to the initial level, with both a PAD of 1% and 8% respectively. Results were also satisfying for banana, crop-gardening, orchards, plantain, pineapple and fallow with a PAD of respectively 12%, 14%, 15%, 13%, 3% and 14%. For melon the PAD is 100% since melon cropping system was not adopted by farmers in the calibration procedure. This is due to the fact that farmers rent their land to a society that produces melon for exportation. This renting activity is not taken into account in the model that is why results are not satisfying for melon.

We consider that at this scale the model provides a reliable information despite some deviations compared to the initial state of the system for two minor crops.

Figure 28 : Comparison of the sub-regional crop areas between the observed situation and the simulated one after the calibration step



4.3.1.2. Consistency of results at the sub-regional scale

At the sub-regional scale, comparing the initial and simulated acreages can reveal if the model captures the diversity of agricultural landscape at this scale (Figure 28). Our aim was to reproduce the agronomic specificities of each sub-region that significantly differ. We then compared the outputs of the model for the main crops of each sub-region.

In the center Grande-Terre, sugarcane and pasture were well simulated with a PAD of respectively 5% and 1%. This measure becomes non significant while the crop area is low, which is the case for most of the other crops in the center Grande-Terre for which level of PAD are higher.

For the northern Grande-Terre, the pasture and sugarcane are also well represented with a PAD value of respectively, 1 and 0%. Banana is also well-represented with a PAD of 1%. For the east of Grande-Terre, the level of crop-gardening is quite under-estimated but acceptable with a PAD of 20% while sugarcane and pasture are closer to the initial state as shown by the PAD of 3% and 7% . For Basse-Terre, the northern part is well simulated with PAD of 6% for sugarcane and pasture and 7% for banana. In the southeastern part, banana and fallow are well represented with a PAD of 14% and 15% but the level of sugarcane is over-estimated in this area probably due to conflict in simulation between sugarcane and fallow. In the southwestern part, the results of simulation are good for orchards, banana, crop-gardening, sugarcane and fallow with respectively, 17%, 13%, 2%, 8% and 0%. PAD of pasture is less good with a PAD of 28%. In Marie-Galante, PAD is good for sugarcane and pasture with 13% and 20%. Other crops are negligible in this area.

MOSAICA model accurately reproduces the agricultural landscape characteristics of the sub-regions.

4.3.1.3. Consistency of results at the farm scale

At the farm scale, based on the farm type algorithm implemented in MOSAICA, we can compare the evolution of the number of farms in the types from the initial geographical database to the simulated one from the calibrated procedure (Table 12). We observed an overall good level of simulation at the farm scale with around 81% of the farm classified in the right type. This percentage is different depending on the type. For "breeders", "specialized cane-growers" and "crop-gardeners", the percentage is very good with respectively, 98%, 93% and 92% of farm from these type well-classified while the reproduction of farm type from "banana growers" and "mixed cane-growers breeders" is average with 78% and 68% and average for "diversified cane-growers", "arboriculturists", and "diversified" with 63%, 50% and 52%. However for the farms misclassified, we can see that most of them were classified in groups really close to their initial type in term of crop areas. For instance, 35% of "arboriculturists" initially are in the "diversified" group in the simulation. These two groups are very similar in that they have a low level of sugarcane, pasture and banana. Furthermore, they are really close in the classification algorithm (Chopin *et al.,* 2014). A large number of "diversified cane-growers" were classified within the "specialized cane growers" type and a high number of "mixed" producers were classified as "breeders". At the farm level, the model proved to have a good quality for reproducing current farming systems.

Table 12 : Comparison of the number of types correctly modeled with the calibration procedure

Number of farms in types at the regional scale Initial \ simulated	Arboricul turists	Banana growers	Sugarcane growers	Diversified cane growers	Diversified	Breeders	Crop gardeners	Mixed	**Total (initial)**	**Matches**
Arboriculturists	60	0	0	14	37	3	0	7	121	50%
Banana growers	2	159	0	7	15	3	0	19	205	78%
Sugarcane growers	0	0	1473	50	0	53	0	1	1577	93%
Diversified cane growers	14	0	257	665	24	71	0	19	1050	63%
Diversified	17	0	0	73	150	17	11	18	286	52%
Breeders	0	0	0	1	0	1072	0	16	1089	98%
Crop gardeners	0	0	0	0	13	0	141	0	154	92%
Mixed	0	1	0	35	1	235	0	582	854	68%
Total (simulated)	93	160	1730	845	240	1454	152	662	129	81%

4.3.1.4. Consistency of results at the field scale

Table 13 : Comparison of crop areas at the field scale between the initial state of the crop mosaic and the calibrated one

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

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

We compared the results at field scale between the initial state of the cropping system mosaics and the one obtained after calibration (Table 13). We observed that at field scale we correctly represented the crop grown on 66% of plots over the territory. However, while we calculate the overall area represented by this 66% of field we obtained 77% of the area for which the crop grown are correctly allocated. This percentage can be considered as satisfying considering the multiple possibilities of crops at the field scale for each farm. This level of precision is homogeneous among 6 out of 7 of the sub regions but is lower for the southeastern Basse-Terre for which only 56% of areas were correctly modeled. This lower level of precision is due to the fact that observed areas in fallow and banana are allocated respectively with banana and fallow at farm scale due to the change in spatial crop organization with this crop-rotation.

To sum up, the model reproduced the initial state of the cropping system mosaics in a good way. The accuracy of the model outputs were very good at the regional scale and decrease from the regional scale to the field scale but remains good in terms of prediction of cropping system at the field scale. The model is then appropriate for the production of cropping system mosaics and for their spatially explicit assessment based on the cropping system location.

4.3.2. Analysis of the scenarios

4.3.2.1. Cropping patterns changes under scenarios

The general tendencies observed through the three scenarios are a sharp decrease of sugarcane production and banana over the island with their total disappearance in scenario 1 and in scenario 3 only for banana (Figure 29). At the opposite, the areas devoted to pasture and fallow increase and the area devoted to crop gardening and orchards increase more progressively as well. Areas of tubers increased very weakly while the areas of pineapple, plantains and melon remains at the same level.

- In scenario 1, the area of sugarcane and banana greatly decreases from respectively 14 000 hectares to less than 6000 and from close to 2000 hectares to 0. In parallel, the area of pasture increases from close to 7000 to 12 000 hectares and fallow from 2000 to close to 6000 hectares. Areas of crop-gardening doubles from 900 hectares to 2000, while the area of orchards slightly increases from 1000 to 1200.

- In scenario 2 trends observed are not as significant as in the scenario 1. Sugarcane areas decrease from 14 000 to more than 8000 hectares while banana remains in Guadeloupe with 600 hectares. In parallel, the increase of pasture, fallow, crop-gardening areas are weaker. In this scenario, pasture reaches 10 000 hectares, fallow 4000 hectares, and crop-gardening 1 500 hectares. However the increase of orchards is greater than in the scenario 1 with an increase from 1000 hectares to 2000.

- In the scenario 3, sugarcane and banana disappear while the area of pastures is at the same level than in scenario 1 with 12 000 hectares. The area of fallow greatly increases from 2000 initially to more than 10 000 hectares. The level reached by crop-gardening in this scenario is the highest with 2500 hectares while orchards are close to their level in scenario 1 with 1500 hectares.

Area of tubers weakly increases in scenario 1 and scenario 2 to reach 300 hectares and remains at the same level in scenario 3.

4.3.2.2. Cropping system mosaics changes

The new organization of cropping systems in sub-regions are described below (see Figure 30):

- In scenario 1, sugarcane in center, northern and eastern Grande-Terre decreases and is replaced by pasture mainly. Banana disappeared from the northern and center Grande-Terre and is replaced by fallow and sugarcane. In Basse-Terre, the northern part follows the same tendency than the eastern Grande-Terre with a significant decrease of sugarcane replaced by pasture. In the southern part of Basse-Terre, banana disappears from the landscape and is replaced in the southeastern part by crop-gardening, pasture and orchards and crop-gardening in the southwestern part. In Marie-Galante, sugarcane disappears completely and is replaced by pasture and fallow.

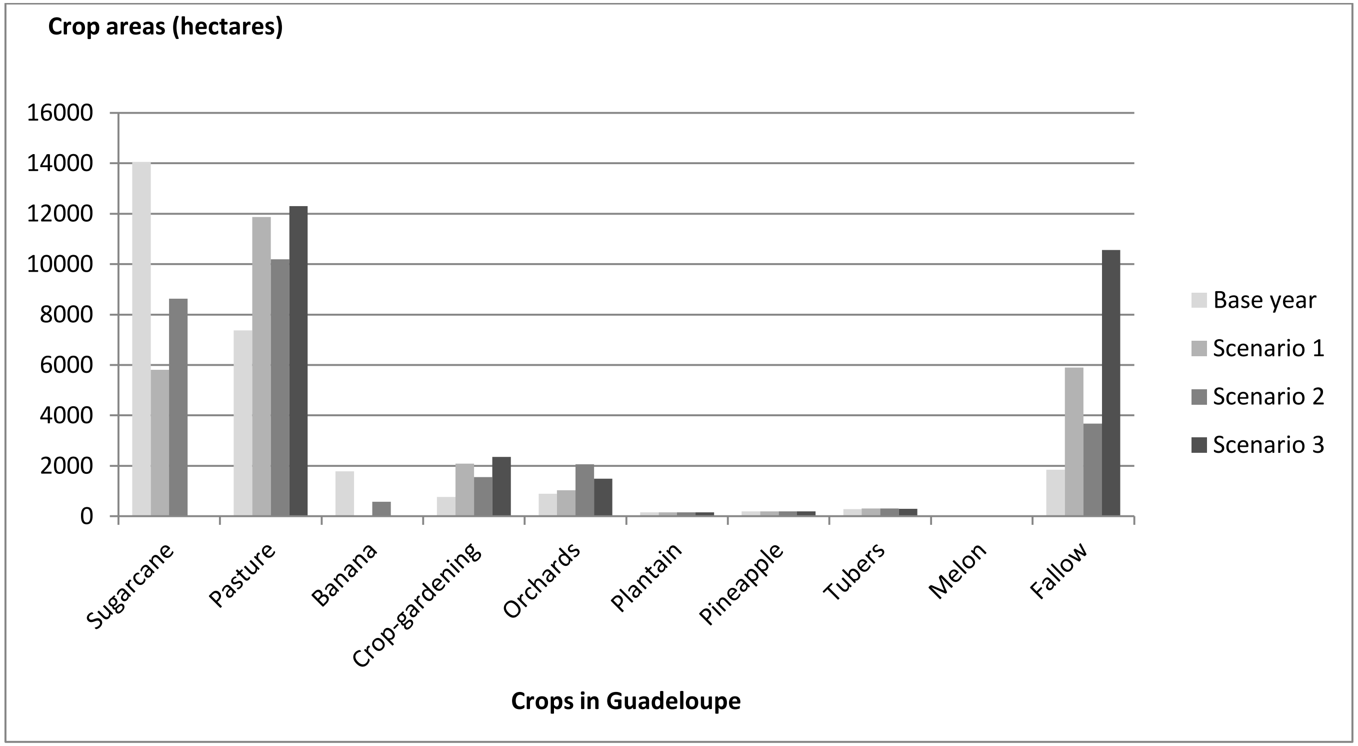


Figure 29 : Acreages evolution among the base year and the three scenarios at the Guadeloupean scale

- In scenario 2, in Grande-Terre trends observed are the same than in scenario 1 but with a higher level of sugarcane compared to scenario 1.In the northern Basse-Terre the mosaic obtained is similar to the base year. Main changes are also in the Southern part, with in the southeastern part a decrease of banana compared to the initial level which is replaced mainly by sugarcane but also by plantain, orchards and tubers while in the southwestern part, it is mainly replaced by orchards and crop-gardening like in scenario 1 but with a weaker decrease of banana in this area. For Marie-Galante, there is no difference with scenario 1; sugarcane is entirely replaced by pasture and fallow.

- In scenario 3, sugarcane cultivation in Grande-Terre and northern Basse-Terre is completely replaced by pasture and fallow. In southern Basse-Terre, the banana in the eastern part is replaced by crop-gardening and pasture mainly with some areas in orchards and fallow. The western part is mainly replaced by pastures and crop-gardening.

4.3.2.3. Farm type changes

Farm type changes appear in Figure 31:

- In scenario 1, main trends are the decrease of "specialized cane growers", "diversified cane growers" and "mixed" and the important increase of "breeders". "Banana growers" disappear while in the same time "arboriculturists", “crop-gardeners" slowly increase. The number of "diversified" decreases slightly.

- In scenario 2, trends for the «specialized cane growers» are exactly the same. The decrease of "diversified cane-growers" as well as "mixed" is less important than in the scenario 1 and they reach almost 500 farmers. The increase of "breeders" is still important but weaker compared to the scenario 1 and reaches 3000 farmers. Around 50 "banana growers" remain in this scenario; the number of "diversified" is at the same level as in scenario 1 and "arboriculturists" on the contrary increase to 250. The number of crop-gardener remains at the same level as in the base year.

- In scenario 3, "breeders" are very important with more than 4500 farmers so 85% of the total farmer population. The "specialized cane growers", the "diversified cane growers" and the "banana growers" types disappear completely. The "mixed" type is at the same level as in scenario 1. "Diversified" type are as less numerous as in scenario 1.

4.3.2.4. Changes in sustainability levels

We examined the values of the indicators of the contribution of the cropping system mosaics to the sustainable development in the three scenarios (Table 14).

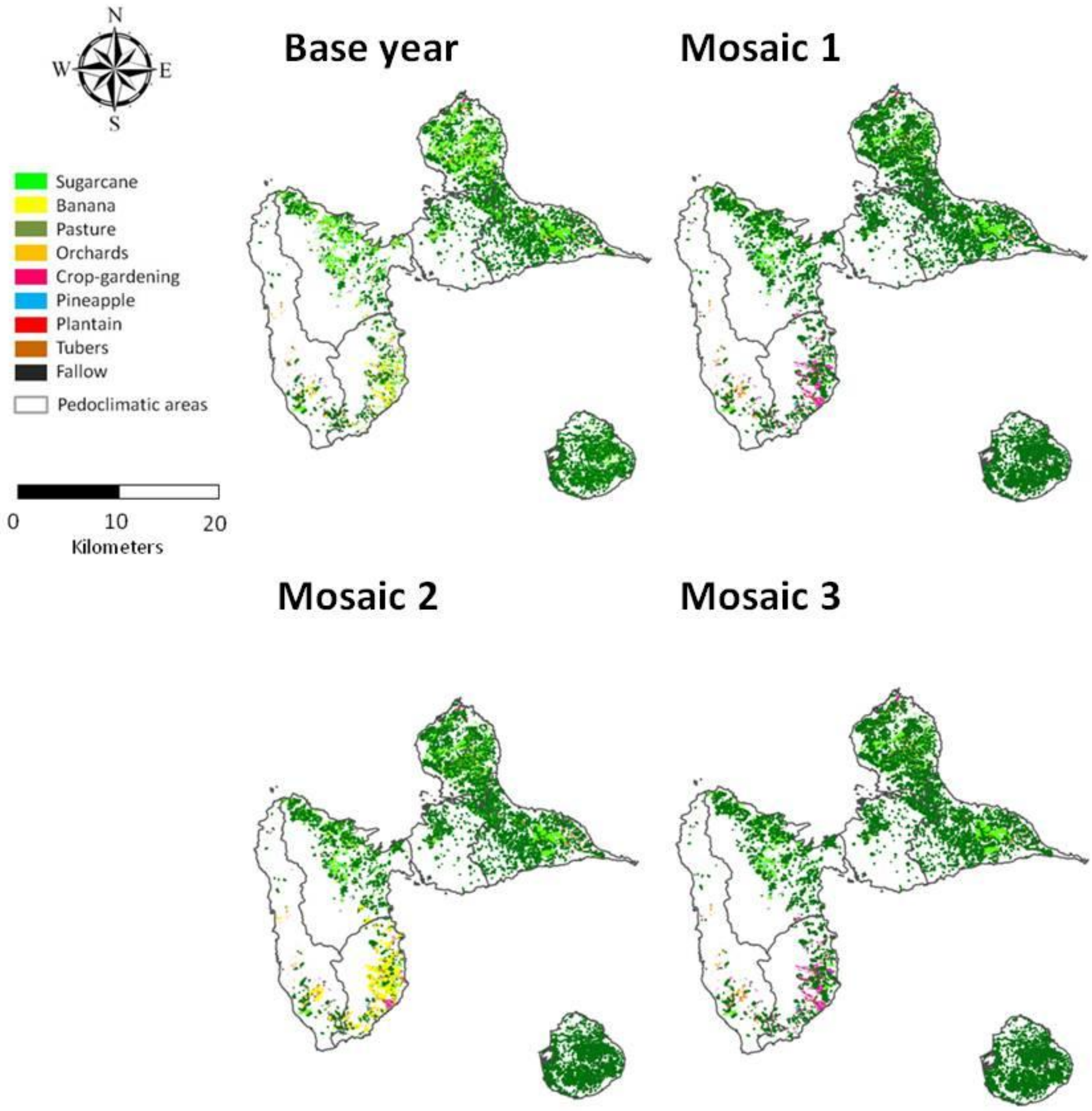


Figure 30 : Cropping systems mosaics from the base year and the three scenarios

For the economic sustainability, the three scenarios improved the level of agricultural added value by improving the overall amount especially for scenario 3, from 98 M€ in the base year to 125 M€ in scenario 2, 138 M€ in scenario 1 and 161 M€ in scenario 3 due to decoupling and also by improving its repartition from 0.64 to 0.74 in scenario 2 and 0.71 in scenario 3. This increase of agricultural added value is due to the increase in the cultivation of crop-gardening and orchards. Scenario 1 and 2 have the less important amount with 60 M€ and 62M€ while this amount is more important in scenario 3 with 72M€. This decrease in subsidies level is due to the decrease in banana and sugarcane while decoupling maintain the initial amount The mean efficiency of farmers is different among the scenarios from 83% in the initial state the mean efficiency vary from 180% in the scenario 1 to 95% in scenario 2 to 112% in scenario 3.

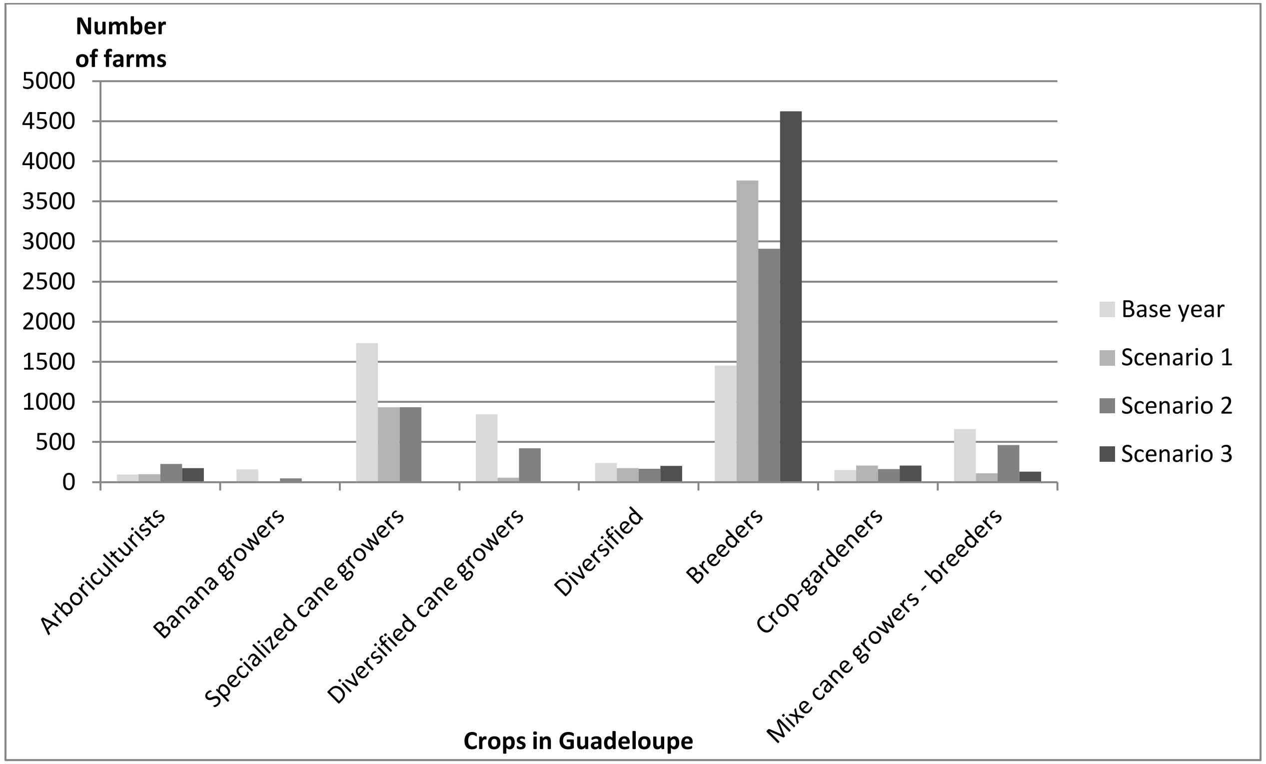


Figure 31 : Farm type evolution across the base year and the three scenarios at the Guadeloupean scale

Table 14 : Evolution of the provision of ecosystem services in the base year and the three scenarios developed

Dimensions	Sustainability objectives	Indicators	Base year	Scenario 1	Scenario 2	Scenario 3
Economy	Improving the agricultural added value	Agricultural added value ($M€.y^{-1}$)	96	138	125	162
		Repartition of the revenue among the farm population	0.65	0.65	0.74	0.71
	Increasing the independence from subsidies	Total amount of subsidies ($M€.yr^{-1}$)	75	60	62	72
		Mean efficiency of farmers	83%	180%	95%	112%
Social	Reaching food-self-sufficiency	Ratio of fats produced over needs	9%	13%	19%	16%
		Ratio of carbohydrates produced over needs	15%	20%	22%	22%
		Ratio of proteins produced over needs	22%	28%	27%	29%
	Producing local energy from agriculture	Potential of electricity produced by crops ($MW.yr^{-1}$)	33	16	24	0
	Contributing to employment	Total needs of workforce (persons)	3105	2566	2928	2772
	Insuring safety of locally produced foodstuff	Area of risk of contamination of food crops	1170	2013	1529	1843
Environment	Improving the state of biodiversity	Mean quantity of toxicity in fields located in ZNIEFF areas	1.0	0.5	0.7	0.1
	Enhancing water quality	Ratio of rivers potentially polluted	39%	8%	30%	22%
		Ratio of water abstraction sources potentially polluted	36%	22%	30%	22%
		Ratio of water catchments potentially polluted	30%	12%	20%	11%
		Amount of water needed for irrigation	17.7	14.7	19.6	15.1
	Protecting soil quality	Area potentially eroded due to farming practices	33.0	33	32.7	31
	Decreasing the contribution to climate change	Overall emissions of CO2 from farming practices (kT eq CO_2)	158	142	149	135
	Improving the diversity of agricultural landsc apes	Diversity of crops across landscape	3.0	3.1	3.4	2.7

For the social sustainability, the production of nutrients from crops varies for fats, carbohydrates and proteins. For lipids only 9% of needs is covered in the base year while the proportion increases to13% in scenario 1, 19% in scenario 2 and 16% in scenario 3. The cover of carbohydrates needs follows the same tendency and increases from 15% in the base year to 20% in scenario 1 and 22% in scenario 2 and 3. The protein cover of needs also follows the same tendency among the base year and scenarios with a slight increase from 22% in the base year to 28% in the scenarios due to the low productivity of livestock systems. The production of electricity among the scenarios strongly decreases from 33 MW to 16 MW in scenario 1, 24 MW in scenario 2 and 0 MW in scenario 3 due to the reduction in bagasse production from sugarcane. The total need of work force is 2900 person in the base year and tendencies of change vary among scenarios. In scenario 1 this amount is 2600 person, in scenario 2, 2950 persons and in scenario 3, 2770 persons. The risk of contamination of food crops by chlordecone strongly increases in the 3 scenarios. While the level was already important in scenario 1 with 1170 hectares, it increases greatly to 2000 in scenario 1 and less importantly in scenario 2 and 3 by reaching 1528 and 1843 hectares respectively.

Focusing on the environmental sustainability, the pressure on biodiversity and water resources decreases over the three scenarios. This is especially true for the scenario 1 for which the pressure of pesticides in water abstraction sources, water catchments and rivers was twice less important than the base year. Results are less good for scenario 2 with a decrease from 35% to respectively 26% and close to scenario 1 for scenario 2 with 15% in average for the three resources of water. The amount of water for irrigation decreases from the base year in scenario 1 and 3 by 3 Mm3 and 2 Mm3 while in scenario 2 the water irrigation increase by 2 Mm3. Area potentially eroded due to farming practices did not vary at all. Emissions of CO_2 decrease from 158 millions of kg of CO_2 to 142 in scenario 1, 149 in scenario 2 and 135M kg Eq CO_2 in scenario 3. Diversity of crops increased from base year to scenario 2 from 3 to 3.4, remains the same in scenario 1 and decreases in scenario 3 to 2.7.

4.4.Discussion

The main strengths of MOSAICA are i) its ability to model the consequence of scenario on the structure and properties of cropping system mosaics and ii) its structure allowing the assessment of these mosaics with spatially explicit indicators.

4.4.1. Ability of the model to design new cropping system mosaics

The regional bioeconomic model MOSAICA presented here has the ability of designing cropping system mosaics resulting of the integration of different information at multiple scales. Indeed, the model integrates field, farm, sub-regional and regional information all linked together. Then a change at one given scale modifies the farmer's choice and then the entire cropping systems mosaic. The modelling of farmer's cropping system choice and the in fine creation of cropping system mosaics resulting from the modification of a set of rules at different spatial scales is innovative for the creation of landscape mosaics. This landscape mosaics were previously mostly designed based on modelling either the farmer's allocation process of cropping system at plot scale with no representation of the regional scale (Aubry *et al.,* 1998; Sorel *et al.,* 2010) or with the representation of the regional scale without taking into account the farmer's decision process (Schaller *et al.,* 2012).

In bioeconomic models, this spatial scale chain has scarcely been implemented due to thew lack of field data and farm data. Most works either link the field scale with the farm scale (Chavez *et al.,* 2010) or the farm scale with the regional scale (Louhichi *et al.,* 2010) but the chain field-farm-region has to our knowledge never been represented before on an entire region. This inter-relation of scales can help designing and assessing innovation at multiple scales and their impact at the regional scale. This multi-scale modeling is important especially to deal with sustainability issues, such as food security or biodiversity preservation, that require multi scale relevant strategies in order to be solved (Spiertz *et al.,* 2012; Cunningham *et al.,* 2013). The lacks revealed in the database should be taken into account while performing scenario analysis because these lacks are at the origins of inconsistencies in the analysis of the impact of scenario on cropping system changes (Schaldach and Alcamo, 2006), especially when dealing with ecosystem services assessment (Hou *et al.,* 2013).

4.4.2. Ability of the model to assess new cropping system mosaics

The model allows the ex ante assessment of new cropping system mosaics with a set of indicators that provide information on the impacts of the new cropping systems in a spatially explicit way. Our set of indicators can even assess the trade-offs in the provision of services by displaying the direction of change of the indicator value between the base year and the scenarios. Bioeconomic models have historically been designed and applied in order to assess the impact of policy changes on economic, environmental and social indicators of agricultural systems but most of these models were not spatially explicit and indicators were mostly calculated at farm-scale in bioeconomic farm models.

MOSAICA has the ability to reveal the trade-offs among the sustainability objectives at the regional scale. For instance, in our case study, the scenario 3 is very good in terms of provision of agricultural added value but the risk of contamination of crops due to chlordecone is higher due to the development of crop-gardening cropping system in the southeastern part of Basse-Terre which is very polluted (Cabidoche *et al.,* 2009). The study of scenario 2 reveals, on the opposite, a decrease of the total agricultural added value and the decrease of the risk of contamination of crops by chlordecone. The model highlighted a negative correlation between these two objectives at the regional scale.

The spatially explicit assessment with the model is useful in order to assess the sustainability of cropping systems mosaics more precisely. Thus, in scenario 2 the amount of area of intensive cropping systems, crop-gardening and orchards is lower than in scenario 3 but its environmental impact is generally higher than in scenario 3. This is the results of the presence of intensive cropping systems close to environmental areas in scenario 2 despite being less present on the territory. The allocation at field scale of cropping systems spatially located on the territory proved to be relevant for dealing with the ecosystem services provision issue.

In order to allow an easier understanding of the trade-offs of ecosystem services with a quick assessment of several mosaics, aggregation tools should be developed at the regional scale. This type of tool has been developed mainly at the cropping system scale (Sadok *et al.,* 2009; Pelzer *et al.,* 2012) and now needs to be implemented at the landscape scale in bioeconomic models directly or as a separate tool like the DEXi tool from Bohanec *et al.*(2006).

4.4.3. Scenario analysis for policy impact assessment

The good result of MOSAICA's calibration procedure provides the ability of using it for the ex ante assessment of the impact of changes in policies on the contribution of agriculture to the sustainable development of territories. In Guadeloupe, the test of three exploratory scenarios of change in the current agricultural policy raises the awareness of the great impacts that this type of change could have on the agricultural areas, farm cropping plan and in fine on the provision of ecosystem services.

Through scenario analysis, the model can predict the evolution in crop areas at the regional scale and the locations on the territory where the crop areas are going to change. In the three scenarios we developed, sugarcane and banana were directly impacted by the decrease of subsidies since they are highly subsidized by POSEI and national subsidies. The decrease of banana was in all sub-regions while the decrease of sugarcane was important in Marie-Galante and the northern Basse-Terre while the decrease was less sharp in the eastern Grande-Terre. The important increase of fallow in scenario 3 shows that the disappearance of sugarcane and banana due to the deletion of current subsidies could drive the development of fallow. This important increase would eventually lead to the increase of the switch of agricultural land towards urban land in the eastern and the northern Grande-Terre where the area of fallow is very important.

The use of the farm typology is particularly useful in order to visualize the evolution of farms within the territory from the base year to different situations. This evolution is an indicator of farmer's cropping plan change within the territory and provides then information on the trajectories of change and the inner reorganization of farms. In scenario 1, the decrease of banana and the increase of crop-gardening are directly connected since the farm type "crop-gardeners" increases in this scenario due to the presence in banana farms of large amount of workforce for managing crop-gardening cropping systems.

The provision of ecosystem services strongly varies in fine depending on the cropping system mosaics. Agricultural policies tested with MOSAICA provided cropping system mosaics that could be relevant in order to enhance the contribution to sustainable development of society and to cope with the future expected liberalization of banana and sugar markets. Scenario 3 is particularly relevant in order to preserve ecosystems, while scenario 2 was socially more acceptable except for the area with a risk of contamination of crops by chlordecone which increases compared to the base year. The effects of decoupling were very similar to the decoupling effect observed in different areas such as in tobacco farms in Argentine with the decrease of subsidized tobacco area in farms and the cropping plan diversification towards others crops (Manos *et al.,* 2010). Moreover, the analysis of the contribution to sustainable development of the different mosaics could reveal the trade-offs in the response to sustainability issues. For instance, the increase of agricultural added value is positively correlated to the increase of food self-sufficiency and CO_2 emissions due to the large cultivation of crop-gardening. These services are negatively correlated to the energy food-self-sufficiency since the cultivation of sugarcane is replaced by crop-gardening, orchards and fallow. For the employment, conclusions are difficult to draw since workforce is a resource at farm scale that is calculated from the base year. Then the base year level is the maximum and workforce needs can either stay at the same level of decrease in scenarios. The other relationships among services are difficult to highlight based only on three scenarios.

Despite being able to provide a possible image of futures from this exploratory predictive scenarios (Borjesön *et al.,* 2006), the model does not reveal the transition from the base year to these possible futures. MOSAICA is static but could be turned into a dynamic model by characterizing the multi-year cropping system, such as sugarcane, banana, orchards, for which gross margin in the first year of production is low or negative, in a more precise way. It could be useful to generate the transition from one given cropping system mosaic to another one (Acs *et al.,* 2007). Other elements should be included such as the attitude towards innovations, skills, formation, investment capacity that are not taken into account here with the use of statistic on local farmers. Moreover, fixed costs as well as transaction costs that can decrease the gross margin of new activities at farm scale were not included in the study. Market of lands possibilities for off farm labor and structural changes are usually issues exogenous to the system definition of bioeconomic models. Bioeconomic model should be linked to other modeling tool that account for market and sector level changes. Technical coefficients were implemented in an empirical way and do not differ between farm types or between the different biophysical conditions. In our case study, the model incorporates average technologies and average economic performance that can strongly differ among farms. Coupling MOSAICA with crop models adapted to the different soil and climate conditions would permit to have a higher variability of performance of system and then better reproduce the possible change in the cropping system mosaic.

The MOSAICA model can now be used to simulate the changes in the cropping system mosaics emerging from a wide range of scenarios encompassing not only economic changes, tested in this paper, but also environmental changes, e.g. the implementation of protection areas, technological changes, e.g. innovative cropping systems among. These changes can be spatially targeted for one given area within the area of study, a set of farms or a set of fields.

4.4.4. Genericity of the model

The model MOSAICA we presented in this paper is generic and can then be transferred easily in many regions. The databases of activities as well as the geographical database are independent from the model like in the FSSIM model (Louhichi *et al.,* 2010). Moreover the calibration procedure can be reused since the typology of farm can be built directly from the geographical database of field and their use for a given year following the method in Chopin *et al.* (2014). We did not consider that the PMP approach (Howitt, 1995), usually used to perfectly calibrate bioeconomic models, should be implemented considering i) the satisfying results from our calibration with risk, ii) the difficulty of revealing the determinants of change in the cropping system mosaic due to the non linear costs implemented with the PMP in the objective function that combine different unknown parameters, iii) the difficulty of implementing it due to the different hard constraints at the multiple scales set in our model.

In MOSAICA, equations can be modified at the different spatial scales to modify the allocation procedure of cropping systems at field scale. The indicator database is also flexible and allows the deletion or addition of new indicators site specific like the one we used to assess the risk of contamination of food crops by chlordecone which is an important issue in our area of first implementation of the model. Nevertheless, the model implementation requires some conditions before being transferred.

Firstly, a database of fields needs to be available and representative of the agricultural area in order to allocate the cropping systems to plots and perform a spatially-explicit assessment of the contribution of the mosaics of cropping system to the sustainable development. The low representativeness of farms or areas restricts the analysis of some trajectories of change in farm types, in cropping system and the impact in some areas. For instance in our example, the modelling of southwestern Basse-Terre is particularly limited compared to the statistic data on this area, then impact should be carefully analyzed. The population of "arboriculturists" is low due to the low level of orchards compared to regional statistics then the effects of scenario analysis could be over-estimated such as the replacement of the orchards by another use or the trajectories of change of farmers in this area towards another farm type. The lack of data in this area also impacts the ecosystem services analysis by either under or over estimating the impact of farming activities in this area. For instance, the erosion indicator we built is particularly relevant in this area for the vertic soils but the low number of fields in this soil type that should be more important considering the regional statistics, decrease the usefulness of this indicator for which the value across scenarios did not vary in our analysis. The area of study should be geographically well limited since the impact will be measured in this area and flows need to be known or assessed. For example the assessment of the emissions of CO2 can be difficult since agricultural product can be produced in a given area and then transport outside this area which would make difficult the overall calculation of emission. This is the reason why insular areas, such as Guadeloupe, are "ideal laboratories" for this type of study since they have easily discernible limits and defined flows (Spilanis *et al.,* 2009).

Secondly, the implementation requires characterizing the cropping systems and the parameters impacting their location on the territories. Sufficient expertise or the collection of data in the area of study is required, that can lead to an important workload in areas where cropping system descriptions are scarce. Fuzzy expert knowledge on the location of cropping system can also be checked with multivariate analysis of the location of the different agricultural uses within the area of study.

Thirdly, before being used for scenario analysis MOSAICA needs to be well-calibrated and to reproduce the agricultural use because the mis-representation of agricultural use can come with a mis-interpretation of the consequences of changes on the cropping system mosaics. The risk adverse coefficient allocated to farm types is a simplification of farmer's decision process in term of cropping system choice. However, the coefficient attributed to farmer's followed our hypothesis on farmer's behavior. "Breeders" have an important risk aversion coefficient following their way of managing beef production very extensively and sell the beef when the farmer's has a specific need of cash for its family or for investments. Crop-gardening is risky then "crop-gardeners" are not risk averse.

"Diversified cane growers" have diversified on beef mainly so their coefficient of risk aversion is high while the mis-represented part of this “diversified sugar cane growers” type was probably the one who is diversified on legumes and fruits. For "arboriculturists", results are only quiet good for the outputs models. "Banana growers" were considered as risk averse due to the fact that they produce really secure crops from the commercial and financial point of view. "Diversified" farms could be considered as risk averse but they are diversified on only risky crops from an agronomic and financial aspect, then this diversification process does not reveal a risk averse behavior. This coefficient could be validated by proceeding to a range of survey in order to elicit the level of farmer's risk aversion (Charness *et al.,* 2013; Gomez-Limon *et al.,* 2003).

Although this qualitative risk integration in bioeconomic model has been recognized as a good estimation of farmer's risk (Arriaza *et al.,* 2003), the different objectives of farmer's could be individually integrated in this model (Sumpsi *et al.,* 1997) to better reproduce farmer's behavior. This last solution has also some drawbacks in term of computational requirements.

The quality results of the calibration process can help defining the limits of interpretation of results. For instance, in our example, the area of sugarcane was overestimated in the southeastern Basse-Terre with 800 hectares compared to the initial 400. However in our scenarios the almost complete disappearance of sugarcane in the southeastern Basse-Terre was probably not underestimated considering the fact that in scenario its evolution was correlated to the disappearance of banana that are really linked in reality due to banana cropping system in rotations with sugarcane in some important farms.

4.5.Conclusion

This article presented a model for the design and the ex ante assessment of cropping system mosaics. The bioeconomic model MOSAICA integrates the different scales involved in the decision process of farmers and policy makers, *id est* the plot, the farm, the sub-regional and regional scale. This integration allows the test of multi scale change of policy and parameters involved in agricultural production and the assessment of this change on the provision of ecosystem services with spatially explicit indicators.

Our model could be relevant in order to test spatially targeted policies aiming at improving the contribution of agriculture to sustainable development. This model could be the base for a scenario analysis mixing normative scenarios in order to know what is possible in term of provision of services and what could be possible based on the exploratory scenarios modifying parameters of production at different scales. It can also be used in order to understand the possible adoption of innovative cropping systems and their possible impacts on the provision of ecosystem services.

Acknowledgements

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5. Conception de paysages agricoles innovants et évaluation de leur contribution au développement durable du territoire

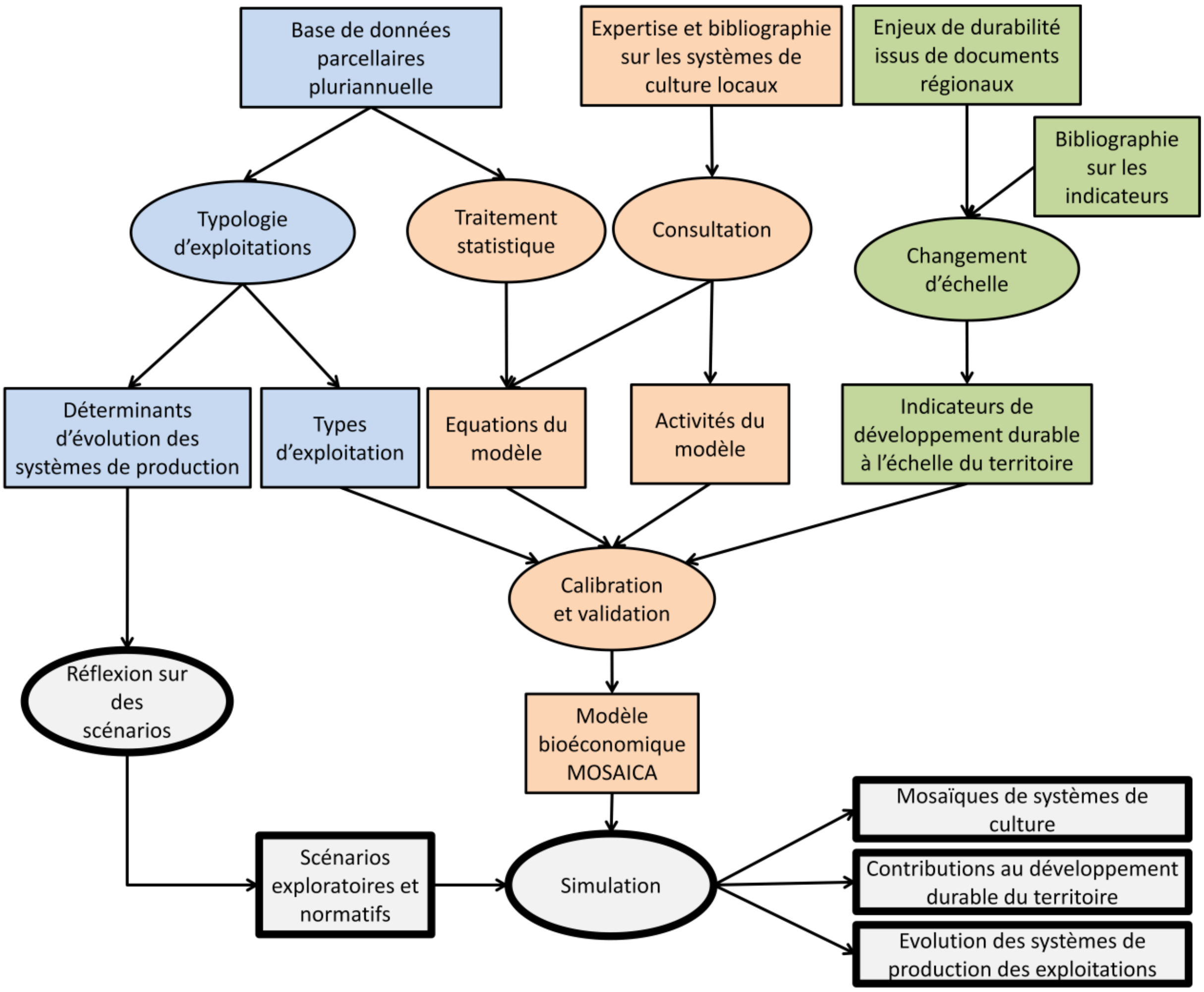

Figure 32 : Ensemble méthodologique pour la conception et l'évaluation multicritère de mosaïques de systèmes de culture: Focus sur la construction du modèle bioéconomique

Ce chapitre correspond à la description de la quatrième étape de la méthode (Figure 32). Les objectifs sont les suivants :

- Définir un itinéraire de scénarios à tester avec le modèle comme exemple d'utilisation de l'ensemble méthodologique de la thèse
- Evaluer les mosaïques de systèmes de culture, créées par les scénarios, en termes de contribution au développement durable

L'utilisation du modèle bioéconomique et des indicateurs de développement durable pour l'évaluation de scénarios de changement de la sole agricole en Guadeloupe est présentée dans l'article suivant, intitulé "**Building smart agricultural landscapes satisfying multiple sustainability goals: Application to Guadeloupe**", à soumettre dans la revue *Global Environmental Change*.

Building smart agricultural landscapes satisfying multiple sustainability goals : Application to Guadeloupe.

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Abstract

In order to build innovative smart agricultural landscapes satisfying multiple sustainability goals, agronomist have to adopt a landscape perspective by jointly simulating 1) scenarios at the landscape scale, 2) farmers' decision process for cropping system choice, and 3) cropping system performances at the field scale. We here propose a modeling framework, based on a scenario approach coupled to an optimization model to prototype smart agricultural landscapes. The framework uses a regional bioeconomic model which integrates farmer's decision process on the adoption of cropping systems at field scale based on spatially explicit biophysical conditions of field, socio-economic information of farm and current farming system to design and assess these agricultural landscapes. The scenario approach encompass normative, exploratory and optimized scenario to assess the potential of levers to improve the response of landscape to sustainability goals and asses the relevance of these levers to achieve target values defined with optimized scenarios. The implementation of this method in Guadeloupe proved to be relevant by defining a set of scenarios testing a wide range of agronomic, technical, economic and social levers to improve the contribution of landscapes to sustainable development. The set of scenarios leads to the definition of a combination of levers tested in an exploratory scenario that increases the food and energy self-sufficiency, the employment and decreases the risk of pollution in water bodies and the risk of contamination of crops due to polluted soils. Our framework integrates a range of agronomic and economic information on cropping system and farm functioning in a spatially explicit way to provide a sustainable assessment of landscapes. This assessment helps reveal the trade-offs in the provision of services by agriculture. It can be used to understand the potential of response to sustainability issues to help local decision-makers in the implementation of policies.

5.1.Introduction

Agricultural landscapes account for one third of the human land use across the globe (FAOSTAT 2008). While agriculture has constantly increased the production of food, it has also been recognized as responsible for other environmental, economic and social, positive or negative, impacts at the global and local scales (Tilman *et al.,* 2002). Agriculture is actually deeply questioned for the sustainability of Human development. Whereas agriculture has the ability of insuring production of food, energy, materials and services to society, it has also to preserve its surrounding social, economic and natural environment for future generations. The responsibility of agriculture is indeed pointed in several sustainability issues, like climate change, water and soil depletion, human diseases, etc. In order to insure the provision of food and services by agriculture while limiting these negative impacts, innovative smart agricultural landscapes satisfying multiple sustainability goals have to be designed.

Agronomists have been designing new agricultural systems at different spatial scales, but few approaches have been implemented at the landscape scale. At the field and the farm scales, the design of innovative agricultural systems has shown some limits in addressing local and global issues. Cropping systems prototyped were not adapted to the local conditions or to current farming systems especially with "one size fits all solution" for sustainable land management (Antle and Stoorvogel, 2006). Some cropping systems fail to reach the objectives addressed at the regional scale due to the low scaling integration of the spatial heterogeneity of regions (Dale *et al.,* 2013). Design methods did not integrate the crop composition and the crop arrangement in agricultural landscapes that are responsible for the provision of services (Castellazzi *et al.,* 2010; Benoit *et al.,* 2012; Schaller *et al.,* 2012). Agronomists then need to integrate a landscape perspective for the design of new agricultural systems adapted to local context and facing the challenges at the regional scale (Dale *et al.,* 2013, Benoit *et al.,* 2012).

Prototyping of cropping system mosaics at the landscape scale can help respond to the multi-objectives of agriculture by modifying the composition and the organization of crops and cropping systems within territories. These cropping system mosaics are spatially explicit allocations of cropping systems to farmer's field (Vasseur *et al.,* 2013). Many studies have analyzed the possible contributions of regions to sustainable development (Swart *et al.,* 2004; Walz *et al.,* 2007; Wei *et al.,* 2009; Carmichael *et al.,* 2004; Gutzler *et al.,* 2015: Cotter *et al.,* 2014, Gibreel *et al.,* 2014). These studies use scenario analysis to explore possible future developments by using, for instance, a comparative analysis of alternative drivers of change (Gutzler *et al.,* 2015). In spanning a range of options they help to explore rather than predict possible developments (Milestad *et al.,* 2014). These approaches provide images of landscapes that could meet societal goals (Wachs 2002; Hulse *et al.,* 2000; Opdam *et al.,* 2002). Some authors provided methods for agricultural landscape planning (Lu *et al.,* 2004; Groot *et al.,* 2007), but these studies focused on particular issue or developed a limited number of scenarios. We lack for methods aimed at building multi-purpose smart agricultural landscapes and quantifying the contribution of agriculture to sustainable development of territories.

In order to ascertain whether a particular lever can achieve sustainability goals or has any unexpected adverse outcomes, a scenario analysis with an integrated comprehensive model of agricultural landscape is required (Wei *et al.,* 2009; Carmichael *et al.,* 2004). Agricultural science has been using scenario analysis and integrative modeling approaches for analyzing sustainability problems (Heckelei *et al.,* 2001; Kropff *et al.,* 2001; Van Ittersum and Donatelli, 2003; Arfini, 2005; Verburg *et al.,* 2006; Bryan *et al.,* 2011). Scenarios with integrated assessment tools can highlight drivers of agricultural land use change by mean of iterations of change while an optimization approach can help decision makers gaining knowledge on the potential way of response of agriculture to given issues. This analysis could be an answer to the increasing need to "view agro-ecosystems and to identify the remedial management practices to sustainability issues in a holistic way" (Pacini *et al.,* 2004).

Whereas several methods have been proposed to design new agricultural landscapes, we lack for holistic integrated modelling frameworks that jointly simulate 1) scenarios of policies, markets and sustainability issues at the landscape scale, 2) farmers' decision process for crop and cropping system choice, and 3) cropping system performances at the field scale.

In this paper, we propose such a modeling framework, based on a scenario approach coupled to an optimization model which prototypes cropping system mosaics and assesses their contribution to sustainable development. The finality of the modeling framework is to i) gain knowledge on the possible futures of agricultural landscape organization and ii) identify levers for building smart agricultural landscapes enhancing the contribution of agriculture to targeted goals of sustainable development in territories. The aim of the paper is to present our methodological framework and its application in Guadeloupe, a small tropical island in the Caribbean. We first present the structure of this integrated agricultural landscape model called MOSAICA, which is the tool used for prototyping and assessing new cropping system mosaics. Then, we define the different types of scenarios used in our method and their parameterization in our optimization model. We explain the different steps of the method developed for the scenario building and analysis, leading to the design and assessment of sustainable cropping system mosaics. Before presenting the results of the application of the methodological framework in Guadeloupe Island, we introduce the background of this study area. We finally discuss the extent, the genericity and the requirements of our modeling framework in building more sustainable agricultural landscapes for the future.

5.2. The methodological framework and its application

5.2.1. Presentation of the integrated model MOSAICA for prototyping and assessing cropping system mosaics

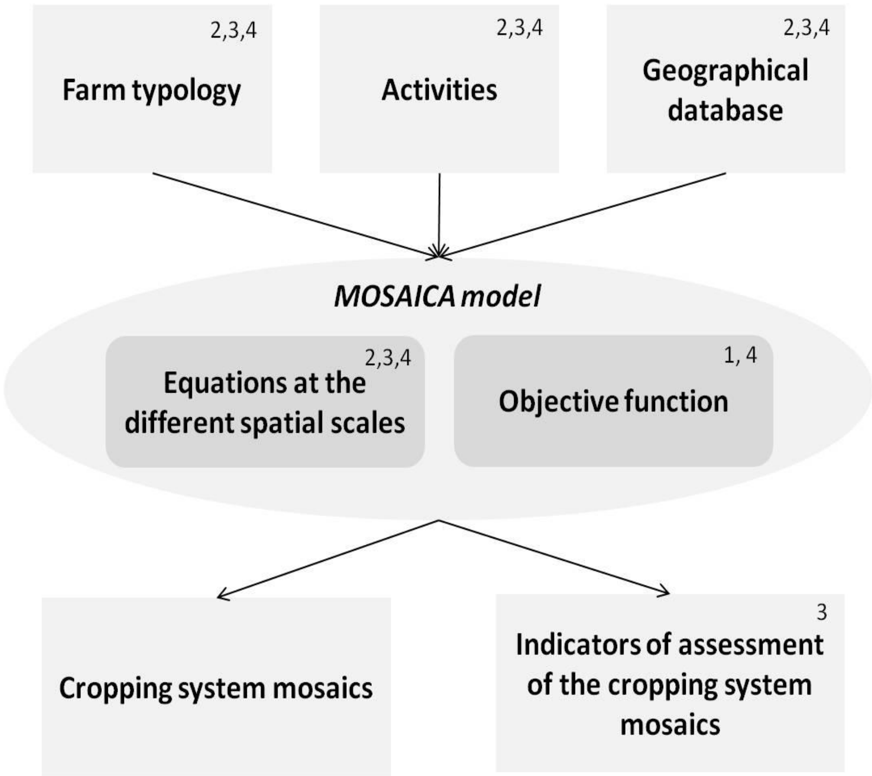

Figure 33 : Inputs and outputs of the regional bioeconomic model MOSAICA and the necessary modifications to simulate the different types of scenarios aiming at providing cropping system mosaics and assessing them. Possible modifications of the inputs, the model, or outputs for simulating scenarios appear in the figure as number in boxes: optimized scenario "1" (1) ; exploratory scenarios (2) ; normative scenario (3) ; optimized scenario "2" (4). For instance, mosaics from normative scenarios are obtained by modifying the farm typology, activities, the geographical database or equations and adding a constraint to the value of the indicator that bring information on the response of the mosaic to the targeted issue.

The structure of the MOSAICA model appear in Figure 33.

We used the MOSAICA model which is a generic regional bioeconomic model (Chopin *et al.,* submitted). Bioeconomic models are economic model that link farmer's decision process in terms of cropping system choice to a set of parameters that drive their decision (Janssen et van Ittersum, 2007). This type of model can be used for the ex-ante assessment of the impacts of policy, technological, agronomic, economic changes among others. MOSAICA simulates the farmer's allocation process of activities which are here cropping systems at farm scale by integrating the interrelations between scales in this allocation process. Biophysical, economic, structure parameters at either field, farm, sub-regional or regional scale drive the adoption of cropping systems by farmers.

These parameters can be for instance, at field scale, the type of soil, the slope or the field area, at farm scale, the size of the farm, the workforce resources, at the sub-regional scale, the access to irrigation or the presence in a labeling area and at the regional scale, the quota of production of some crops (banana, plantain, tubers and pineapple).

These forcing variables, at the different scales, are introduced within the geographical database of the fields of the landscape after data compilation and geographical information added through GIS treatments. The allocation process simulated is spatially explicit since cropping systems are allocated to spatially located plots within the territory following the set of equations implemented at different spatial scales within the model. Changes of parameters at multiple scales can then drive the change of cropping system at field scale, the change of farming system at the farm scale and then the change of the overall cropping system mosaic.

Table 15 : Presentation of the sustainability issues and the indicators used in the approach.

Sustainability issues selected	Indicator	Description of cropping systems
Increasing the production of crops for the local market (PDRG, 2011)	*Agricultural added value of local foodstuff (M€)*	Sum of the gross margins of local food crops
Increasing the production of biomass for electricity production (Prerure, 2008)	*Potential production of electricity (MW)*	Potential production of energy of sugar cane and fiber cane
Decreasing the risk of contamination of crops by chlordecone (Cabidoche *et al.,* 2009)	*Area of food products potentially contaminated (ha)*	Contamination potential of soils, absorption capacity of crops (Cabidoche and Lesueur-Jannoyer, 2012), pollution risk of soils (Tillieut and Cabidoche, 2006)
Limiting the pollution of water bodies (Cabidoche *et al.,* 2002)	*Mean pollution of water resources (score)*	Indicator of risk of pollution at field scale based on pesticides characteristics and climate parameters (R-pest indicator, see Tixier *et al.,* 2007) and proximity of fields to water bodies
Improving the overall agricultural added value (POSEI, 2011)	*Total Agricultural added value (M€ per year)*	Sum of the gross margins of all the crops
Increasing employment (PDRG, 2011)	*Workforce needs (persons per year)*	Sum of workforce needs for all the cropping systems
Reducing greenhouse gas emissions (Colomb *et al.,* 2013)	*Quantity of emissions of CO2 (kT eq CO2)*	Sum of the emissions of cropping systems considering inputs and outputs of agricultural production

The allocation process results from the optimization of farmer's resources allocation impacted by the set of constraints. The calibration of the model has been realized based on the optimization of the sum of farmer's utilities at the regional scale. Farmer's utility has been implemented as the sum of cropping system gross margin minus the expected decrease of gross margin depending on a risk coefficient. This risk coefficient is attributed to farms depending on their current farming systems. This farming system diversity has been assessed by Chopin *et al.* (2014).

From this typology, eight types of farmers emerged with different farming systems, arboriculturists, banana growers, breeders, crop-gardeners, diversified cane-growers, diversified, mixed and specialized cane-growers. An algorithm of classification of farms in types is implemented in MOSAICA and can then classify farms within a type in the new cropping system mosaics.

The contribution of the cropping system mosaics to the sustainable development of territories is also assessed with MOSAICA. This assessment is based on a set of indicators at the regional scale that measure the overall response of the cropping system mosaics to local and global sustainability issues (presented in paragraph 5.2.5.2). These indicators are calculated based on the parameters describing the cropping system externalities (Table 1). Cropping systems are defined with diverse information such as yield, pesticides and fertilizers that can be used for the calculation of indicators. 30 cropping systems have been integrated in MOSAICA and they describe the production of process of several crops, including sugarcane, banana, pasture, crop-gardening, orchards, pineapple, melon, plantain and tubers. The indicators take into account the location of plots in their calculation. This calculation provides a spatially aggregated index, a score at the regional scale, and the indicators can also be spatialized within the territory in order to display the variability of contribution of fields, farms or sub-regions within the territory for decision-making aid.

5.2.2. Definition of the four types of scenarios developed

The scenario method can be considered as a pre-modeling phase that lead to the parameterization of several scenarios to be implemented within our optimization model called MOSAICA which is presented in the paragraph 2.2. The MOSAICA model can be used in several different ways for prototyping cropping systems from scenarios.

Two types of scenarios are built within the scenario method: normative scenarios and exploratory scenarios. The normative approach targets a set of values of indicators, that bring information on the contribution of mosaics to the response of sustainability issues, in order to obtain a desired impact of the cropping system mosaic. The second type of scenarios are exploratory. They are used in order to explore the different states of a system based on the modifications of the parameters that compose the system (Borjesön *et al.,* 2006; Van Notten *et al.,* 2003). Different declinations of these scenarios are successively integrated to compose our itinerary of cropping system mosaic design in our study (see Figure 33):

- Optimized exploratory scenarios "1": This first type of scenario is implemented in the model in an explorative and strategic way to find out the optimal values of certain objectives without changes in the current system by optimizing one given sustainability goal. This approach can be used to define target values and provides potential development of the cropping system mosaic without providing the mean to reach this image. This type of scenario is useful to know the potential of the system to reach a certain level of sustainability for a given objective.

- Exploratory scenarios: explorative external what-if scenarios respond to the question: ‘’What will happen, under some new conditions ?’’. They are based on the same optimization as the initial cropping system mosaic (optimization of farmer's utilities) but they focus on analyzing the response of landscape to well specified external events, like change in policies regime. They provide some information on the effects of either individual driver of change or combination of drivers that can be modification of agronomic, economic, environmental, social factors and the direction of change of the landscape for a given objective.

- Normative scenarios: The model can be used in a normative way to reach the targets defined in the optimized scenarios 1 with the modifications of drivers integrated in the exploratory scenarios. The task is to find out how the target defined in the exploratory scenarios can be met as efficiently as possible.

- Optimized exploratory scenarios "2": The model can also be used to find out the optimal values of certain objectives with specific changes of the current system. This scenarios provide some information on the evolution of the cropping system mosaic potential to reach a given objectives with the addition of drivers of changes. With the exploratory scenario, it helps show the relevance of levers of change to drive the cropping system mosaic towards a better level of sustainability in a long-term.

These four scenario are built for targeting each sustainability objective of interest. These scenarios are modeled in our bioeconomic model MOSAICA to obtain new cropping system mosaics satisfying multiple objectives.

5.2.3. Parameterization of scenarios in MOSAICA for prototyping cropping system mosaics

The different scenarios are parameterized in different ways within MOSAICA (see Figure 33):

- Optimized scenarios 1 : in MOSAICA, the cropping system mosaics from this type of scenario are obtained by the optimization of the indicator related to the sustainability objective targeted without any change in the model equations, the geographical database or activities.

- Exploratory scenario : this type of scenario can be explored with MOSAICA by modifying the current parameters responsible for the adoption of cropping systems at the different spatial scales and also the combination of these changes at multiple spatial scales. The cropping system mosaics to be obtained from this type of scenario will be the results of the optimization with MOSAICA of the overall farmer's utility with a modification of activities, equations and/or the geographical database in the models.

- Normative scenarios : the cropping system mosaics from this type of scenario are obtained by the optimization of the overall farmer's utility functions with the changes in parameters defined in the exploratory scenario and as a constraint the target value obtained from the optimization scenario 1 to be reached by the model.

- Optimized scenarios 2 : the cropping system mosaics from this scenario are obtained by the optimization of the indicators related to sustainability objectives targeted and the modification of parameters implement in the exploratory scenarios.

The implementation in MOSAICA of these combination of scenarios is the basis of our method.

5.2.4. Steps of the methodological framework

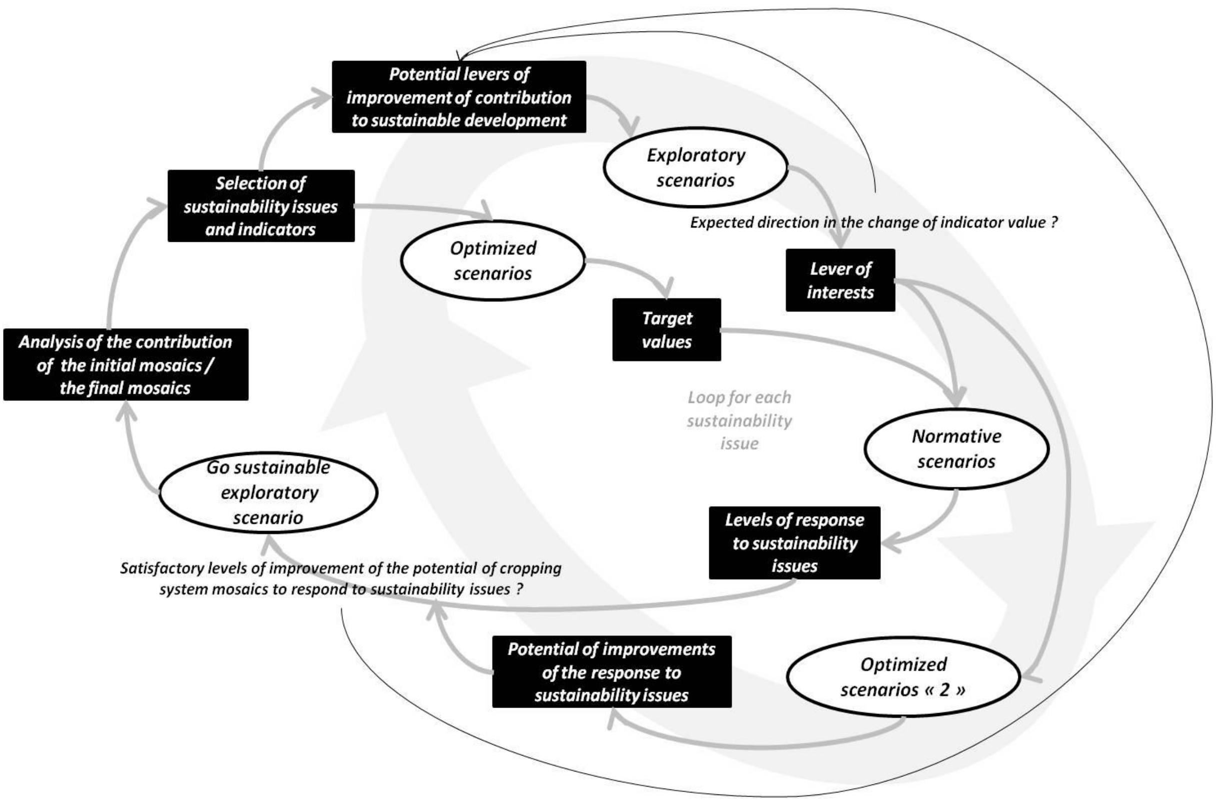

Figure 34 : Framework for the generation of different cropping system mosaics from scenarios implemented in MOSAICA. Black boxes represent inputs or outputs from mosaics obtained with the scenarios represented by the ellipses.

The method built to i) understand the potential levels of sustainability that can be reached by the cropping system mosaics and ii) gain knowledge on the potential levers of change of the cropping system mosaics, is presented in Figure 34. It is made of seven steps:

- The first step of the scenario analysis is a diagnosis of the current contribution of agriculture to sustainable development with the assessment of the initial mosaic. This assessment provides the initial values of the indicators that assess the contribution of the mosaic to the local or global issues. The diagnosis then highlights the main issues that should be targeted in order to enhance the overall contribution of agriculture to sustainable development. Then potential levers of improvement of each sustainability objectives are sought in order to be tested in the third step.
- The second step is the simulation of the optimized scenarios that aims at revealing the potential of the cropping system mosaics in terms of response to specific issues, it means the ability of the landscape to reach targeted sustainability goals. This step is performed by optimizing separately indicators, which provides information on the potential of response of the cropping system mosaics to the sustainability issues. The optimized values obtained are considered as target values.
- The third step is the test of several levers of change of the cropping system mosaics that can be i) change at the field scale, like giving access to irrigation ii) introduction of new cropping systems defined from experimental trial or expert knowledge iii) change in farms resources, iv) modification of policy regimes, and v) change in markets, like prices and quota evolution. These levers are targeted to respond to specific issues. Through iterative simulation, the levers that improved the value of the targeted indicator compared to the value of the initial mosaics as expected are kept while levers that did not improve the response of the mosaic to the targeted issue are deleted from the analysis.
- The fourth step is the setting of targets defined in the second step in normative scenarios for improving the response of the mosaic to sustainability issue while reaching the target value. Normative scenarios can help visualize if levers can be effective in both reaching the target value and improving the response to the other sustainability issues.
- The fifth step is the test of optimized scenarios 2 in order to see if the levers tested could improve the potential of the cropping system mosaic in terms of response to sustainability issues.
- In the sixth step of the scenario building, levers that proved to be relevant by i) improving their response to the sustainability issue targeted in exploratory scenarios, while ii) improving other objectives in the normative scenario, are combined in a "Go sustainable" scenario.
- In the seventh step, the cropping system mosaic (called "Go sustainable" mosaic) resulting from the "Go sustainable" scenario is assessed. The values of indicators from the "Go sustainable" mosaic are compared to the initial state of the system. If the results are not satisfying then an iteration can be done to restart the selection of levers of change with either new levers or new values associated to these levers. Results are analyzed in order to understand the changes in the cropping system mosaic that lead to better values of indicators compared to the initial cropping system mosaic. The indicators are spatialized over the territory in order to observe the variability of contribution of the mosaics to the sustainability issues. The "Go sustainable" mosaic is compared to the current one in terms of cropping system areas and arrangement of cropping systems within the territory from a map of the location of cropping system and trajectories of farming systems changes are drawn to visualize changes in cropping system choices at farm scale.

5.2.5. Application to the design of smart agricultural landscapes in Guadeloupe

5.2.5.1. Characteristics of the study area

Our scenario method for the design of cropping system mosaics enhancing the contribution of agriculture to sustainable development is performed in Guadeloupe, a small island of 1600 km². This territory presents suitable conditions for implementing the methodological framework for several reasons. First, due to insularity, the limit of the system are well defined. Flows of agricultural products are recorded at the entrance or exit of the territory such as the importation of vegetables or the exportation of agricultural products, like bananas and sugar (Agreste, 2011 ; Insee, 2012). Secondly, Guadeloupe gathers many local issues that decrease the economic, environmental and social sustainability of the territory and can be linked to agriculture (PDRG, 2011). Third, the agricultural landscape, widespread all over the territory, is heterogeneous, with rainy mountainous areas on volcanic soils and flat lands on dry calcic soils, which is interesting for testing the capacity of the framework to take into account the variability of farm biophysical conditions and socio-economic context. Fourth, geographical data on fields and farms are available.

5.2.5.2. Sustainability issues

In Guadeloupe, the diagnosis of sustainability at the regional scale has already been performed (Chopin *et al.,* submitted). The Guadeloupian agriculture has to contribute to several issues in order to enhance its contribution to the sustainable development of the territory. Guadeloupian agriculture is oriented towards the subsidized exportation of bananas and sugar from sugarcane cultivation and its local production does not cover the food needs of the local population. Thus, local population must buy expensive imported food stuff. Energy is mainly imported and rely heavily on fossil resources while the decision-makers want to improve the production of renewable and local energies. Soils are polluted due to the application of chlordecone in banana fields for over 30 years (Cabidoche *et al.,* 2009) that can cause adverse effects observed on humankind such as liver and kidney abnormalities, neurological sign on development affects (Seurin *et al.,* 2012, Bucher *et al.,* 2013). Guadeloupe is an hot spot of biodiversity with fragile ecosystems such as mangrove that have essential ecological functions at the global scale and should be protected. The sustainability goals for Guadeloupian agriculture is to i) increase the production of crops for the local market, ii) increase the production of biomass for electricity production, iii) decrease the risk of contamination of crops by chlordecone, iv) limit the pollution of water bodies especially in rivers and abstraction sources and v) improve the overall agricultural added value. The provision of employment was also assessed because it is considered an important stake but we did not include it in the analysis since workforce cannot increase beyond the limit set at farm scale in the model. The contribution to CO2 emissions is also assessed considering this issue as being a global one important for providing solutions in a climate change context. Indicators selected to assess the response of cropping system mosaics to these issues were i) the agricultural added value from local food crops, ii) the production of electricity from biomass, iii) the total area with a risk of contamination of crops by chlordecone, iv) the mean level of pollution within water bodies assessed and v) the overall agricultural added value (Chopin *et al.,* submitted).

5.2.5.3. Levers of change tested in scenario analysis

For the increase of agricultural added value of local foodstuff, several changes are combined, the increase in quota of production at the regional scale, the decrease of variability in crop gross margin due to better advising to local producers and more efficient for selling fruits and vegetables, the increase of workforce availability by 1000 persons at the regional scale and a doubling of the overall availability of water for irrigation. These changes are tested separately and the most relevant are combined for improving their overall individual effects in the last step:

- The first exploratory scenario is the combination of the relevant levers for improving the agricultural added value of local foodstuff.

- The second exploratory scenario is the combination of the introduction of fiber cane for electricity production with a price of 45 € per ton and a yield potential 25% greater than sugarcane combined with the end of subsidies support for sugarcane cultivation in order to increase the production of biomass for electricity production.

- The third exploratory scenario is the ban of the cultivation of vegetables, pasture and tubers on potentially polluted soil by chlordecone in order to decrease the risk of contamination of crops by chlordecone.

- The fourth exploratory scenario is a combination of introduction of new organic cropping systems for which agronomic performance have been prototyped based on agronomic expertise in order to decrease the pressure of pesticides on water resources. Yield has been decreased by 50% and the workforce need increases by 20% and prices by 25%. Yield variability has been increased compared to conventional crop-gardening. In parallel, crop-gardening cropping systems were taxed based on their average treatment frequency index (TFI) by 500 € per point of TFI. Subsidies were provided as an help for commercializing organic product with 1000 $€.ton^{-1}$ of vegetables or fruits from these new organic cropping systems (POSEI, 2011).

- The fifth exploratory scenario was the deletion of POSEI payments towards banana and sugarcane and the decoupling of farm subsidies from agricultural production in order to improve the agricultural added value.

5.3. Results

5.3.1. Analysis of the scenarios and the prototypes of landscape designed

The results from the steps 2 to 5 for all the sustainability issues are presented in the Table 2.

The levers of change selected to respond to the "improving food-self-sufficiency" objective were tested separately and all showed a positive effect on the agricultural added value of local foodstuff compared to the initial value. This value is 52 M€, 84 M€ and 77 M€ respectively for the levers "increase of production quotas", "decrease of crop-gardening variability" and "increase of the regional workforce availability". We then decided to select all these levers in our analysis. The optimization of the current situation on the agricultural added value of local foodstuff helps reach the value of 104 M€. The combination of levers for improving the agricultural added value was then more effective than individual levers. This value of 104 M€ was then used as a target value. The optimization on the cropping system mosaic with the combination of the three levers in the exploratory scenario exceeded the optimized value from the initial cropping system. This combination is then relevant for improving the response of the mosaic to the food-self sufficiency issue.

For the increasing of the energy self-sufficiency, the combination of the "introduction of the fiber cane activity" in database of activities and the "deletion of subsidies towards sugarcane" increased the production of electricity from 33 MW in the initial mosaic to 52 MW in the mosaic from the exploratory scenario, which is below the optimized value obtained of 56 MW. However, the normative scenario tested by the optimization of farmer's utility function under the constraint of producing at least 56 MW was feasible and showed good results for the other objectives compared to the initial cropping system mosaic. Moreover, the optimization of the new system with "introduction of the fiber cane activity" and the "deletion of subsidies towards sugarcane" showed a high potential of electricity production from fiber cane. These two levers of change proved to be relevant for improving the energy self-sufficiency in Guadeloupe.

For the reduction of the risk of crop contamination by chlordecone, we tested the lever "strict ban of the cultivation of crop-gardening and tubers on areas with a risk of contamination". This ban was effective since the area with a potential risk of contamination of food stuff drops from 592 ha in the initial cropping system mosaic to zero in the exploratory scenario. The ban of crop-gardening and tubers on risky areas proved to be an efficient strategy to completely reduce the risk of contamination of crops by chlordecone while maintaining the values of others objectives close to the value achieved in the initial state.

For the reduction of pesticide pollution of water bodies, the current value of 4.5 for the mean potential pollution of water bodies is quite significant. The potential of reduction of pollution is important from 4.5 to 1 but with a major decrease of the achievement of other sustainability goals such as the increasing of employment, food self-sufficiency and energy self-sufficiency which respectively fall from 2905 to 652 persons.yr-1, from 45 to 19 M€ and from 33 MW to 2 MW. The "introduction of organic crop-gardening activities" and "the taxes on the use of pesticides" in the exploratory scenario did not permit to reach the optimized value but the decrease of pollution in water bodies was significant with a value going from 4.5 to 3.5. The second optimized scenario on the new system with "the tax on pesticides use" and the "introduction of organic crop-gardening activities" proved to be relevant to decrease the potential of pollution.

For improving the agricultural added value, the decoupling of subsidies prove to be relevant since the agricultural added value is 96 M€ in the current system and 162 M€ in the exploratory scenario which exceeds the optimized value of 143 M€.

Most of the levers help reach or even exceed the target value fixed by the optimized scenarios of the initial situation. These levers were then considered as relevant for increasing the contribution of agriculture to the sustainable development of territories. All this levers of change were then combined in a last scenario called the "Go sustainable scenario" which is the optimization of the overall farmer's utility with the following levers of change implemented : the lever "increase of production quotas", "decrease of crop-gardening variability", "increase of the regional workforce availability", "introduction of a fiber cane activity", " deletion of subsidies towards sugarcane", " ban of crop-gardening and tubers in the area potentially polluted", " introduction of organic crop-gardening cropping systems", "taxes on the use of pesticides " and "decoupling of subsidies from production".

This exploratory scenario revealed a major improvement of the contribution of the cropping system mosaics to all the sustainability issues in the analysis. This is the only one scenario tested that improved its contribution to the response of the seven issues in table 2. The agricultural added value of local production changed from 45 M€ to 120 M€, the production of electricity from 33 to 35 MW, the area with a risk of crop contamination from 592 to 0 ha, the mean level of pollution of water bodies from 4.5 to 4, the total agricultural added value from 96 to 206 M€, the provision of employment from 2905 to 3866 persons and the emissions of CO_2 from agriculture from 157 to 150 $Kton^{-1}$ of CO_2 equivalent.

The contribution to the different sustainability issues is presented in Figure 35 and can help analyze the relationships among sustainability issues. We can see that the increase in the food-self sufficiency is important for the mosaics obtained with the combination of levers 1 and 5 and the "Go sustainable" mosaic and null for combination 2,3 and 5 while the increase in energy self-sufficiency is negative for combination 1, 5, almost null for the combination of levers 3, 4 and the "Go sustainable" mosaic and positive for the combination 2. The increase in food self-sufficiency is then negatively correlated to the increase in energy self-sufficiency. The decrease of the risk of contamination of crops by chlordecone is negative for combination 1,4 and 5 and positive for combination 3 and the mosaic from the "Go sustainable scenario". Then the decrease of risk of contamination of crops by chlordecone is negatively correlated to the increase in food-self-sufficiency. The decrease of risk of pollution of water resource is positive for the mosaics from combination 1, 4,5 and the "Go sustainable" mosaic while the decrease of the risk of pollution of water is negative for the mosaic from combination 3.

The decrease of pollution of water resources is then positively correlated to the increase in food self-sufficiency. The structure of correlations appears as follow: the increase of food-self-sufficiency and overall agricultural added value and the decrease of risk of pollution in water resources are positively correlated all together and are negatively correlated to the increase in energy self-sufficiency and the decrease of the risk of contamination of crops by chlordecone.

Targetted objectives	Scenario number	Type of scenarios	Sustainability goals to be reached: Improving food self-sufficiency — *Agricultural added value of local foodstuff (M€)*	Increasing Energy self sufficiency — *Potential production of electricity (MW)*	Reducing the crop contamination by chlordecone — *Area of food products potentially contaminated (ha)*	Decreasing the pesticide pollution of water bodies — *Mean pollution of water resources (score)*	Improving the agricultural added value — *Total Agricultural added value (M€ per year)*	Increasing employment — *Workforce needs (persons per year)*	Reducing CO2 emissions — *Quantity of emissions of CO2 (kT eq CO2)*	Combinations of changes to be tested: Combination 1: ▪Quota (1) ▪↘ of crop-gardening variability (3) ▪↗ regional workforce availability (3) — 1 2 3	Combination 2: ▪Introduction of fiber cane activity for producing electricity*45 € per ton ▪Yield 25% higher than sugarcane, same variable costs ▪End of POSEI for sugarcane in 2017	Combination 3: ▪Cultivation of crop gardening pasture and tubers is forbidden on potentially polluted soils	Combination 4: ▪New organic crop gardening cropping systems ▪Taxes of 500€ per point of TFI ▪Trade payments for organic croppnig systems 1000€.ton-1	Combination 5: Decoupling of subsidies from agricultural production
	-	Initial	45	33	592	4.5	96	2905	157	0	0	0	0	0
Improving food self-sufficiency	1	Levers from combination 1 tested separately	52	33	629	4.5	103	2914	155	1 0 0	0	0	0	0
	2		84	35	802	4.3	124	2917	123	0 1 0	0	0	0	0
	3		77	31	612	4.5	126	3905	158	0 0 1	0	0	0	0
	4	Optimized 1	104*	0	1115	2.7	106	3005	143	0	0	0	0	0
	5	Exploratory	165	15	1601	3.3	173	3856	184	1	0	0	0	0
	6	Normative	165°	15	1601	3.3	173	3856	184	1	0	0	0	0
	7	Optimized 2	183*	0	986	3.0	183	4000	222	1	0	0	0	0
Increasing Energy self sufficiency	8	Optimized 1	6	56*	246	4.3	57	372	44	0	0	0	0	0
	9	Exploratory	47	52	511	4.5	85	2904	172	0	1	0	0	0
	10	Normative	46	56°	456	4.8	85	2884	165	0	1	0	0	0
	11	Optimized 2	6	93*	215	4.6	32	365	43	0	1	0	0	0
Reducing the crop contamination by chlordecone	12	Optimized 1	22	3	0*	1.9	29	747	5	0	0	0	0	0
	13	Exploratory	44	34	0	4.9	97	2901	152	0	0	1	0	0
	14	Normative	44	34	0°	4.9	97	2901	152	0	0	1	0	0
	15	Optimized 2	22	3	0*	1.9	29	747	5	0	0	1	0	0
Decreasing the pesticide pollution of water bodies	16	Optimized 1	19	2	552	1*	25	652	11	0	0	0	0	0
	17	Exploratory	45	26	1200	3.4	71	2783	183	0	0	0	1	0
	18	Normative	90	26	1017	1°	107	2902	141	0	0	0	1	0
	19	Optimized 2	23	1784	392	0.9*	29	909	8	0	0	0	1	0
Improving the agricultural added value	20	Optimized 1	94	45	310	4.7	143*	2997	58	0	0	0	0	0
	21	Exploratory	90	0	965	2.9	162	2772	135	0	0	0	0	1
	22	Normative	90	0	965	2.9	162°	2772	135	0	0	0	0	1
	23	Optimized 2	104	0	1013	2.6	176*	3006	143	0	0	0	0	1
Go Sustainable Scenario	**24**	**Explorative**	**120**	**35**	**0**	**4**	**206**	**3866**	**150**	**1**	**1**	**1**	**1**	**1**

Table 16 : Results from the scenario analysis in terms of response to local and global sustainability issues

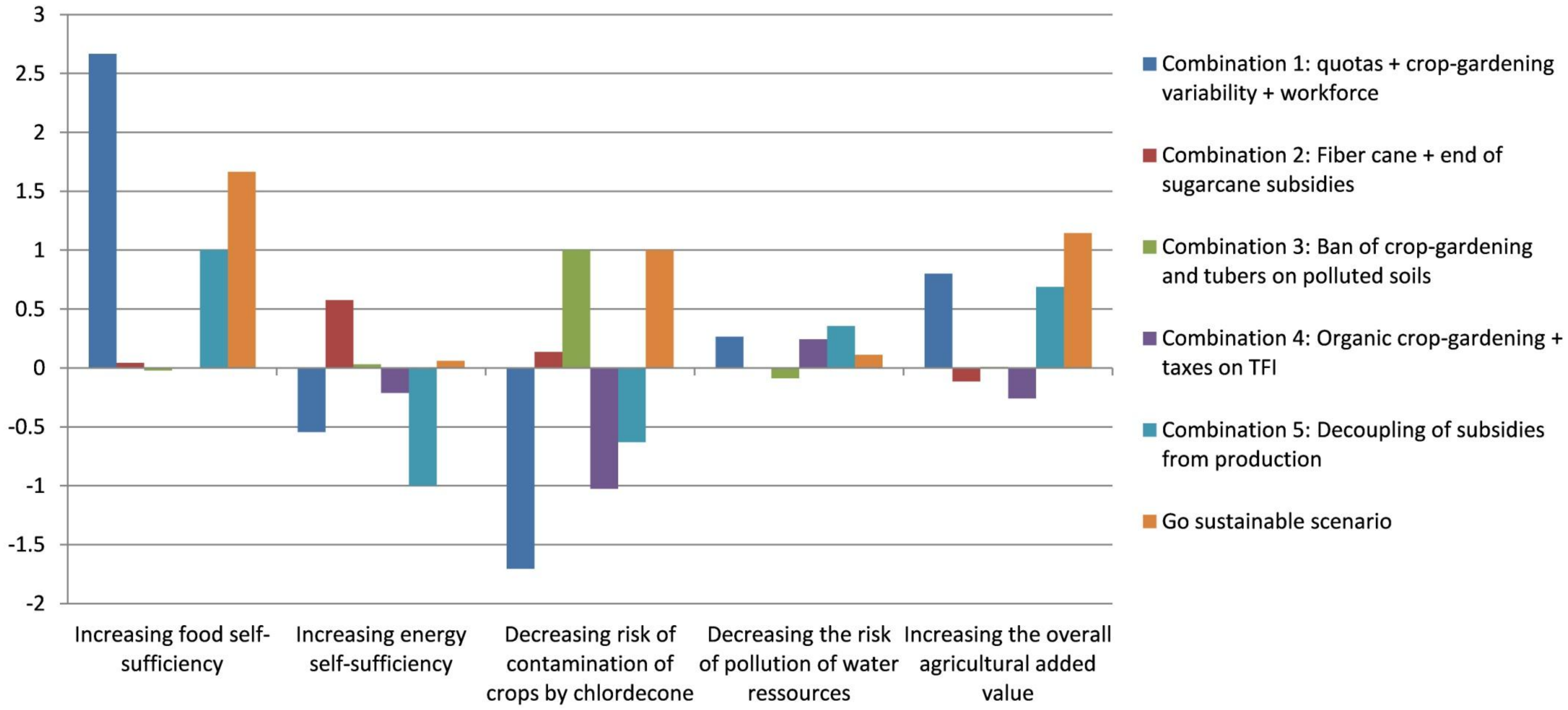

Figure 35 : Evolution of the contribution of each mosaic from exploratory scenarios compared to initial values from the current cropping systems mosaic assessed with deviations to the initial values. Positive deviational values are an improvement of the generated mosaic to respond to sustainability issues.

5.3.2. Analysis of the crop composition and arrangement in the mosaic from the "Go sustainable scenario"

The Figure 36 presents the evolution of crop areas from the initial cropping system mosaic to the final one obtained from the "Go sustainable" scenario.

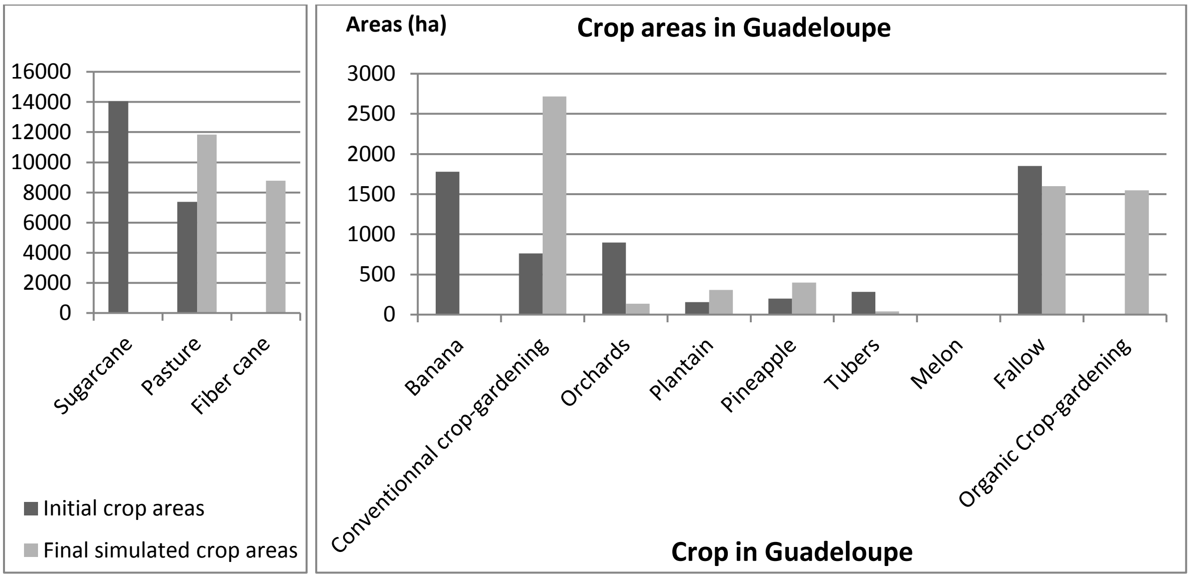

Figure 36 : Evolution of the crop areas at the regional scale between the initial situation and the cropping system mosaics from the "Go sustainable" scenario

The main tendency of change is the disappearance of sugarcane and banana in Guadeloupe and an increase of crop-gardening as well as pasture and fiber cane for electricity production. Pasture increases from 7000 to 12 000 hectares, the fiber cane from 0 to 8000 hectares, the conventional crop-gardening reaches 2500 hectares while the organic crop-gardening reaches 1500 hectares. Orchards areas decreased from 1000 hectares to 250 as well as tubers from 300 hectares to 50 hectares. The areas of plantain and pineapple increase from 200 to respectively 350 and 450 hectares.

The spatial arrangement of cropping systems changed within the territory as a result of crop acreages changes in farms (see Figure 37). It occurs mainly in the northern Grande-Terre, with the emergence of organic crop gardening and in the southeastern 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 area as well as the cultivation of fiber cane. In the northern Basse-Terre, the high proportion of cane was replaced by fiber cane mainly while the area of pineapple increase as well as conventional crop-gardening at the border of the southeastern part of Basse-Terre. The southwestern part is turned into a sub region with more crop-gardening and plantain that replaced the cultivation of banana for exportations.

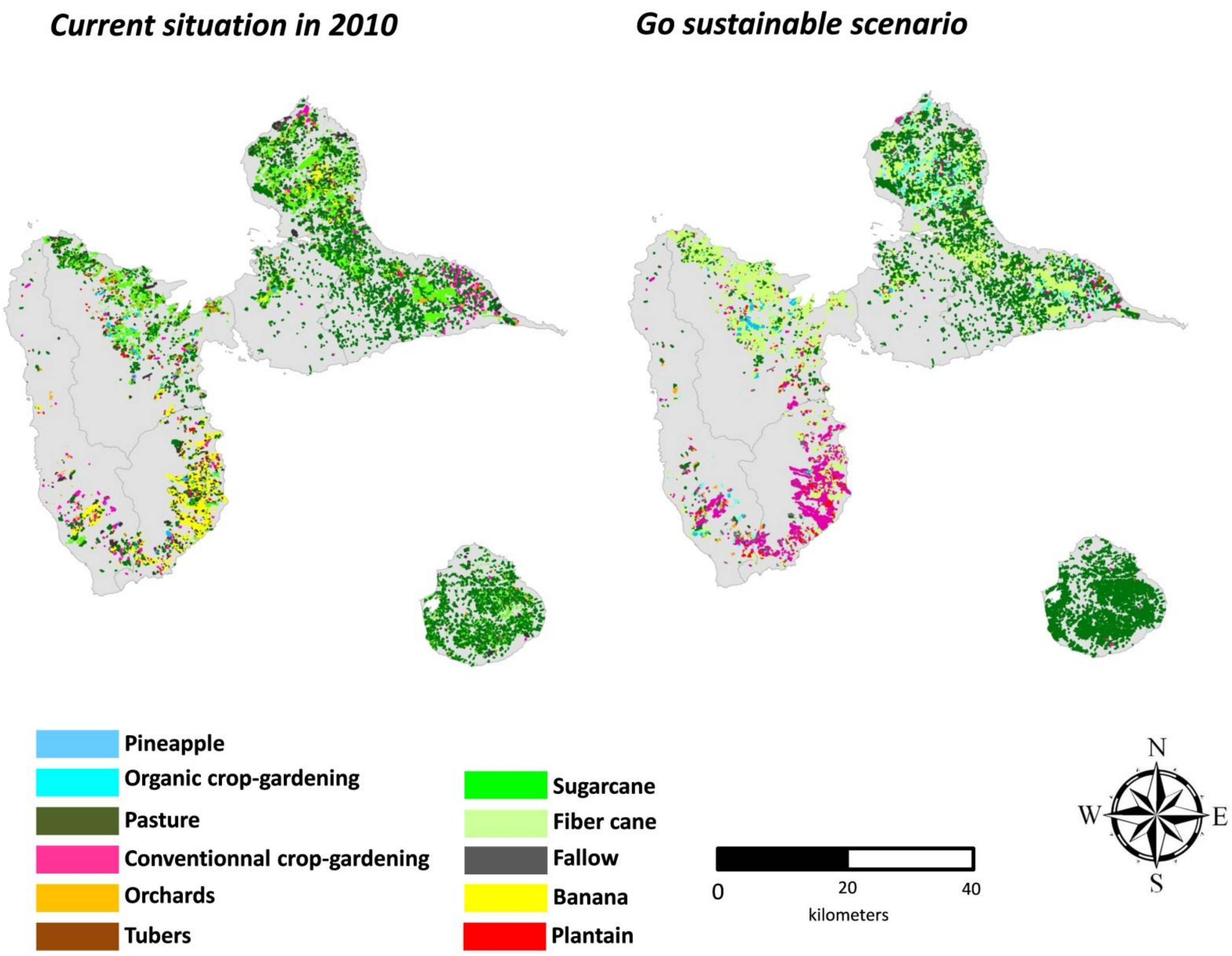

Figure 37 : Evolution of the crop arrangement in Guadeloupe at the regional scale between the initial situation and the cropping system mosaics from the "Go sustainable" scenario

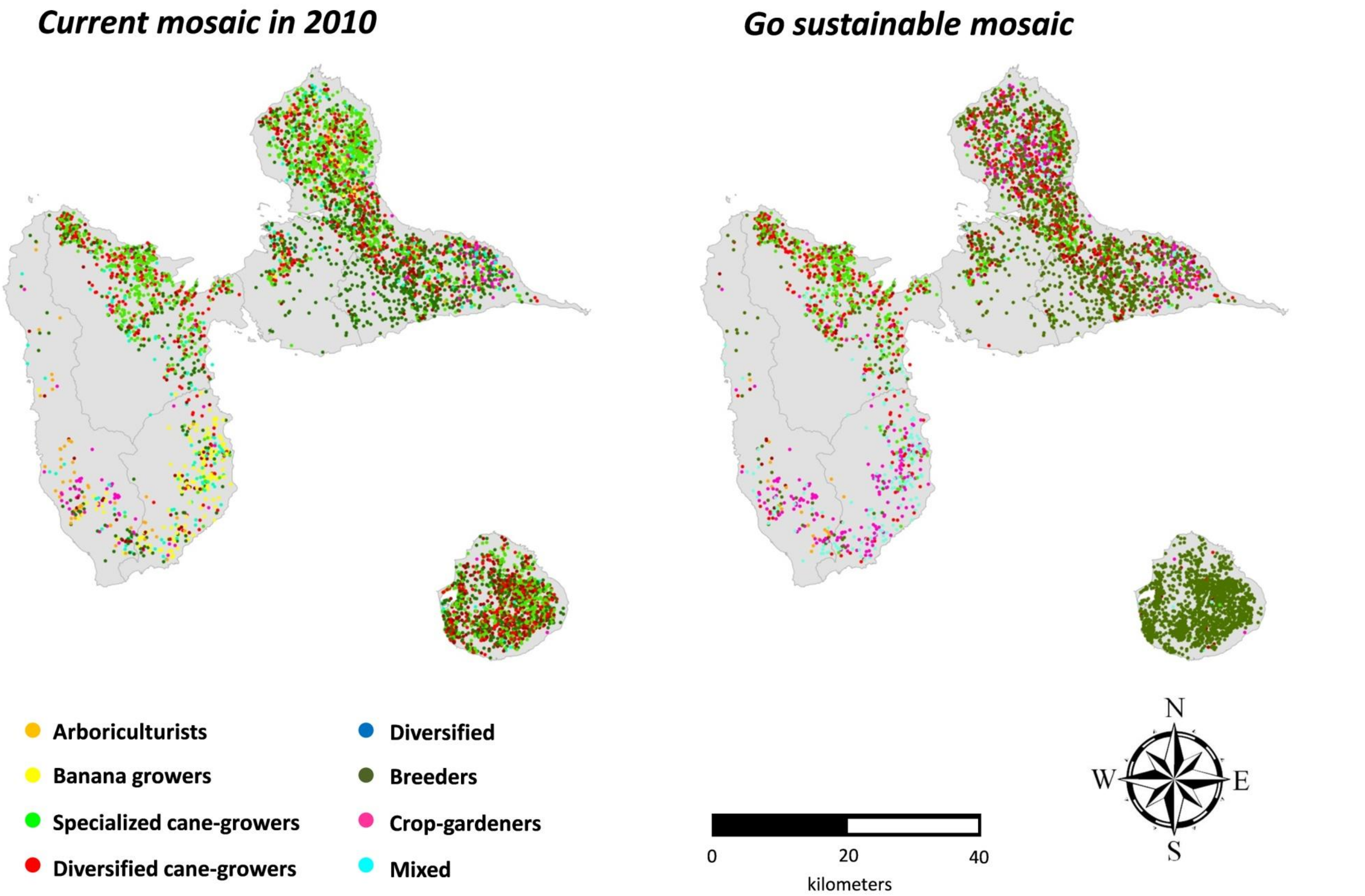

Figure 38 : Evolution of the farm types in Guadeloupe at the regional scale between the initial situation and the cropping system mosaics from the "Go sustainable" scenario

5.3.3. Analysis of changes in farming systems

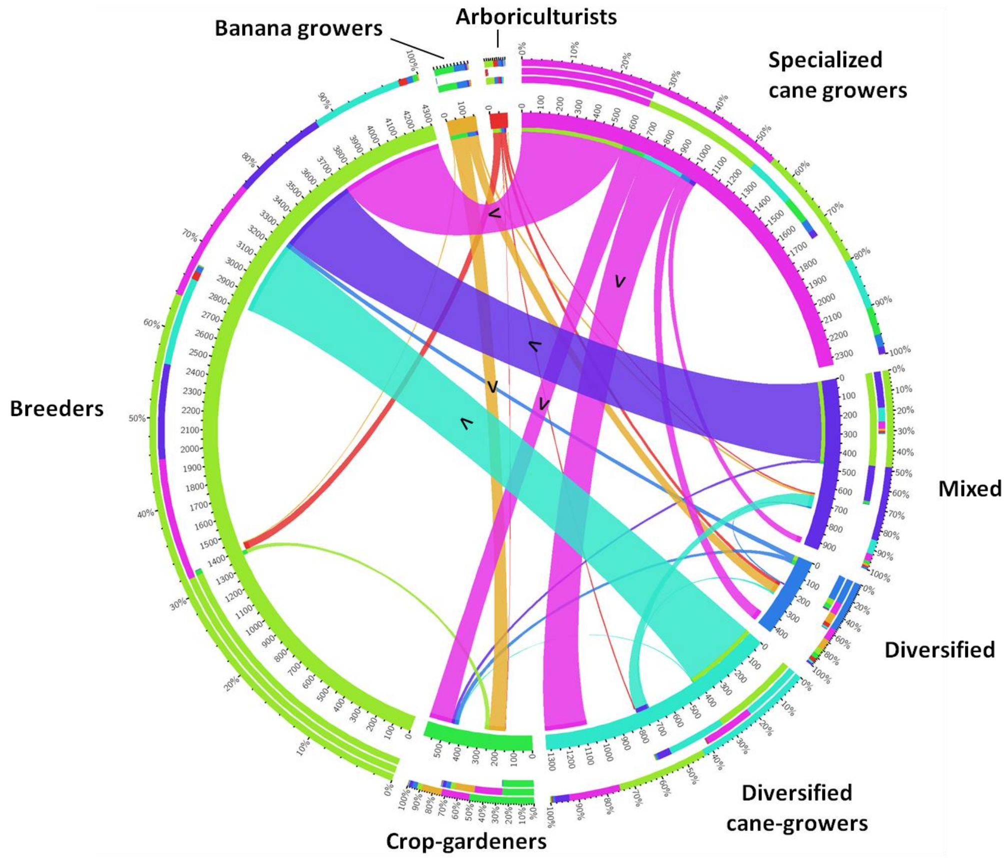

Figure 39 : Trajectories of farming system changes within the territory. Arrow represents the trajectories from the initial to the "Go sustainable" mosaic. Ribbons between types represent the transition of farms from a given type in the current cropping system mosaic to another one in the mosaic obtain with the "Go sustainable" scenario. Ribbon width represents the number of farms in transition. Direction of transitions is represented by an arrow. The angular size of circularly arranged segments represent the population of each type and are proportional to the size of farm types in 2004. 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.

The change of farm types can be observed in the Figure 38 and the trajectories of change in Figure 39. We can see that the main tendencies of change are changes from "mixed", "diversified cane-growers" and "specialized cane-growers" towards "breeders". This is especially true in Marie-Galante area where no industry, in our scenario, can produce electricity from fiber cane. However a smaller proportion of farmers within the "specialized cane-growers" type changed to the "crop-gardeners" type and the "diversified cane-growers" type. This is especially true in the northern and eastern Grande-Terre.

We can see that most farmers growing banana turned their banana based farming systems towards a crop-gardening based one and they become either "crop-gardeners" or "diversified" while "specialized cane-growers" remained in the same type within all the island due to their cultivation of fiber cane for electricity production. The population of arboriculturists that decrease in the southwestern Basse-Terre turned their multi-annual farming systems to breeding. The farming systems in the north of Basse-Terre remained almost alike.

5.3.4. Spatial heterogeneity in the contribution of the cropping system mosaics to the sustainable development of the territory

In the Figure 40, we can observe the change in the spatial variation of the contribution of sub-regional areas to the food and energy self-sufficiency issue and the increase of both the overall agricultural added value and the agricultural added value from local foodstuffs. In Figure 41, the spatial variability of contribution of the cropping system mosaics to local issues is observed at sub-regional scales and the field scale in order to respectively observe the decrease of water pollution and abstraction sources and the decrease of the risk of food contamination.

At the sub-regional scales, the production of agricultural added value from local foodstuff increases in most sub-regions except in the southwestern Basse-Terre due to the decrease in orchards. The greatest increase are in the northern and eastern Grand-Terre and the southeastern Basse-Terre due to the increase in both conventional and organic crop-gardening. The electricity production in the southwestern Basse-Terre did not increase due to the low implantation of fiber cane in this area. Otherwise the production of electricity increased in the whole territory due to the replacement of sugarcane by fiber cane which is more efficient for producing electricity and more productive. For the overall production of agricultural added value, the increase is very important in the north Grande-Terre as well as in the south of Basse-Terre. This increase is due to the expansion of crop-gardening in these areas.

For the decrease of the pollution risk in water resources, we can observe the evolution of the pressure from pesticide applications within rivers and water abstraction sources. For rivers, we can see that, in the initial cropping system mosaic, most rivers in the south of Basse-Terre are potentially polluted due to the banana cultivation and intensive crop-gardening/orchards production in the southwestern Basse-Terre. The scenario decrease the pressure of pesticides on water resources in the south of Basse-Terre but increase the pressure of pesticides in a river in the middle east of Basse-Terre due to the important development of pineapple cultivation in this water catchment.

Results are similar for the risk of pollution of the abstraction sources. The risk of pollution decreases from the initial to the "Go sustainable" cropping system mosaic. Pollution decreased in all the initially risky abstraction sources but increase in some areas especially the southern Basse-Terre due to the important amount of crop-gardening next to abstraction sources.

The issue reduction of risk of contamination of crops by chlordecone has been reached, we can see that all the area potentially contaminating from the very south of Basse-Terre has been transformed into an area free of risk of contamination due to the change from pasture in this area to non-contaminating crop-gardening or plantains.

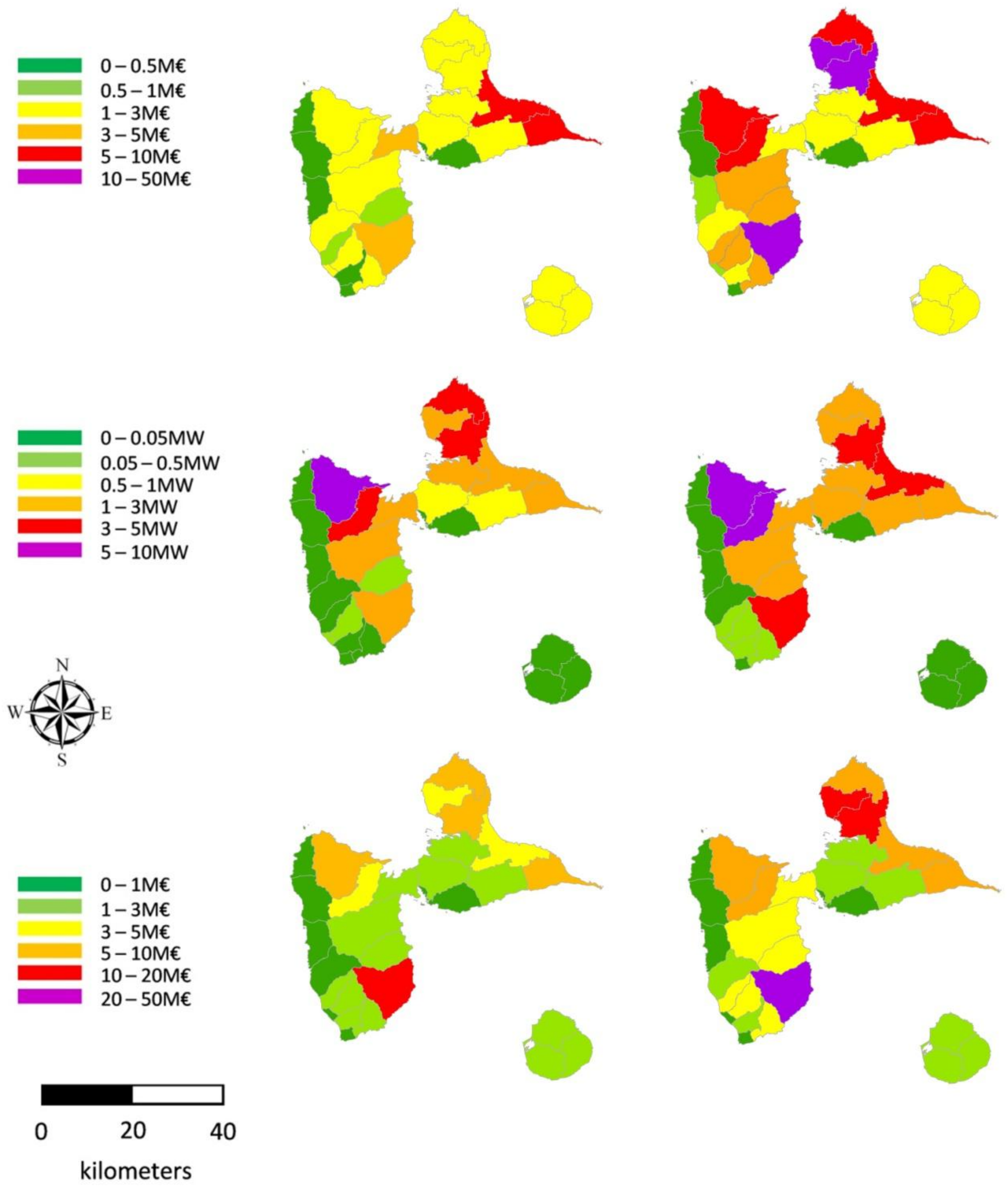

Figure 40 : Comparison of the evolution of the contribution of cropping system mosaics to the increase of agricultural added value of local food stuff (top of image), to the contribution to the production of electricity (middle of the image) and to the production of the overall agricultural added value (bottom of the image) between the current mosaic (on the left) and the one from the "Go sustainable" scenario (the right).

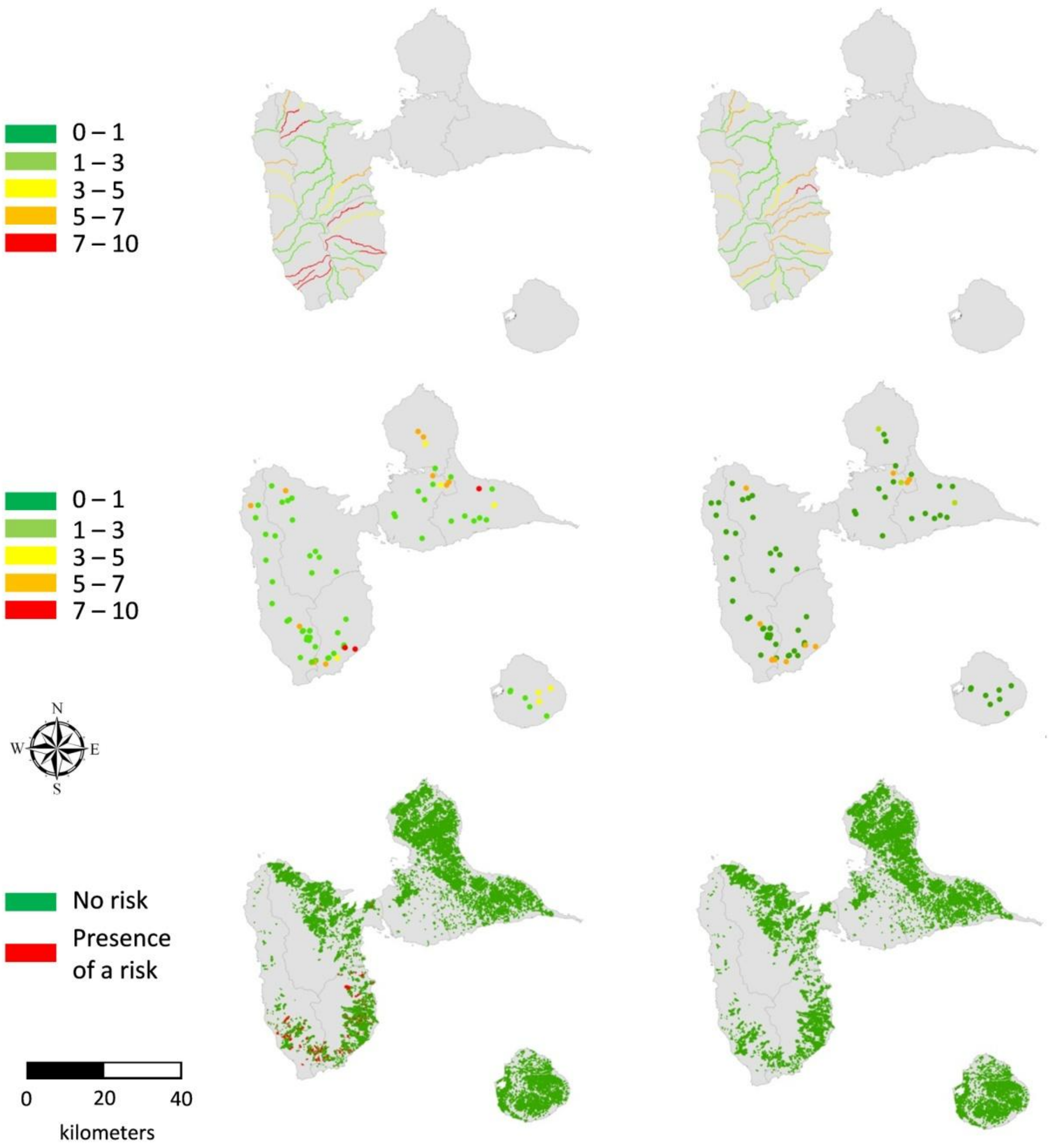

Figure 41 : Comparison of the evolution of the contribution of cropping system mosaics to the decrease of pollution in rivers (top of image), to the decrease of water abstraction source (middle of the image) and to the decrease of the area of risk of contamination of crops by chlordecone (bottom of the image) between the current mosaic (on the left) and the one from the "Go sustainable" scenario (the right).

5.4.Discussion

5.4.1. A method for integrating knowledge for scenario analysis

The model used integrates a range of knowledge on cropping system performance and potential allocation based on spatially explicit information. This spatially explicit information encompass biophysical conditions as well as information on the current farming system of farmers and their level of resources in order to adopt new activities and their decision process that vary according to the farming system. The externalities of cropping systems defined vary across the territory according to their location and then participate in the building of smart sustainable agricultural landscapes responding to multiple sustainability goals. This integration of a diverse range of information makes it particularly relevant for simulating a wide range of scenarios for decision-support on a given territory.

5.4.2. A method for drawing an itinerary of scenarios

Our method combines exploratory, normative and optimized scenarios for understanding the potential of agriculture to respond to local and global issues and the levers that can help responding to these sustainability issues. The targets defined from optimized scenarios help bring information on the conceptual distance of the current cropping system mosaic to optimal state of the cropping system mosaic for a given objective (Acosta-Alba *et al.,* 2012; Bryan *et al.,* 2011). Targets are an effective and widely used tool in regional environmental planning (Bryan *et al.,* 2011). The normative approach provides an answer on the evolution of potential of response of the cropping system mosaics to sustainable issues compared to the optimized scenarios. The normative approach can help policy-makers to know what constitutes a plausible scenario (Nassauer *et al.,* 2004). The strategic exploratory approach with a set of modifications of parameters can bring information to stakeholders on the possible levers for action that can help reach the targets defined and improve the overall system (Herrero *et al.,* 2014). The entire method has allowed the identification of optimum combination of measures and 'policy mixes' for sustainable land management.

5.4.3. Spatially-based scenario analysis for decision-support

The linear programming-based approach to build smart agricultural landscape is particularly useful for informing regional planning because it produces optimal outcomes at regional scale and give information on the spatial organization of crops and the impacts at the different spatial scales. These organizations are analyzed across scales for understanding the transitions between cropping systems, and the evolution of farming systems and their impacts (Seppelt *et al.,* 2013). This analysis helps in representing changes across scales. The scenario analysis provides information on the consequences of levers of change at different spatial scales that can be modified by decision-makers and then drive the design of new cropping system mosaics. Modifications were parameterized at different spatial scales such as the farm scale with the decoupling of subsidies, at the regional scale with the increase of workforce availability or at the field scale with the ban of tuber and crop-gardening cultivation from potentially polluted soils. In addition, we tested the implementation of innovative activities within the model with the integration of the organic crop-gardening and fiber cane cropping systems. The consequences of parameter modifications within the model are spatially explicit within the territory and can help decision makers understanding the potential of response to sustainability issues throughout the territory. For instance The "Go sustainable" scenario provided a mosaic for which the pollution within water bodies in the southern of Basse-Terre was nearly null. This mosaic revealed through this combination of changes the potential to deeply decrease the pollution in water bodies in some parts of an area of interest. This information on the potential of the different parts of a territory to a response to sustainable issues can guide decision-makers in their implementation of spatially targeted measures to drive the territory towards its potential of response.

Changes across scales can help decision-makers preparing the transition from the initial states to the desired ones. Typically, the farming systems trajectories of change modeled do not represent the same transitions costs. Some transitions can deeply modify the organization of work as well as the investment required for cropping systems management. Transitions from the "specialized cane growers" towards "crop-gardeners" imply a change in the farmer's skills for growing new species but also a higher cost of investment and new strategies for selling productions to consumers. These transaction costs are not implemented in MOSAICA but should be taken into account by decision-makers while implementing new policies. This analysis across scales can help prepare transitions of change in the local agriculture despite the fact that MOSAICA is a static model and do not model transitions from the current cropping system mosaic to mosaics from scenarios.

5.4.4. A method to assess trade-offs in sustainability goals

The method can be used for assessing the trade-offs in the response to sustainability issues. For example, the scenario analysis in Guadeloupe showed that the increase of food self-sufficiency is negatively correlated to the provision of biomass for electricity production and the decrease of the risk of contamination of crops by chlordecone. For instance in the explorative scenario with the "introduction of organic crop-gardening cropping systems activities" within the model the average level of pollution from the cropping system mosaic drops from 4.5 in the initial situation to 3.6 while in the same time the production of electricity decreases. This type of results can guide decision-makers on the tradeoffs that can cause antagonist effects that may arise while implementing new policies to target a specific sustainability issue.

5.4.5. Limits of the optimization approach for scenario analysis

The scenario analysis of the generation of optimal cropping systems mosaics also has limitations. First, the policy option/scenario approach lacks of flexibility (Gutzler *et al.,* 2015). There may be cropping system mosaics under a given spatial policy that are only slightly sub-optimal but which are much more feasible or favorable for decision-makers. To improve flexibility, multi-goal linear programming could be used to reach more realistic solutions. Also, decision-makers could prioritize the targeted issues according to society preferences. This hierarchy of goals could contribute to important modifications in the design of mosaics.

The cropping systems mosaics and related impacts from scenario parameterization can be used by regional decision-makers to decide which levers, or combination of levers, provide the relevant responses to the different sustainability issues. Since decisions depend fundamentally on stakeholders, the outcomes of such model can be useful for supporting transparent participatory decision-making processes. However, participatory based modeling with optimization tools require special attention in order to be performed since the parameterization of the different scenarios within the model and the run of simulations is a long-lasting procedure (Delmotte *et al.,* 2013).

Despite these limits that have to be overcome, we believe that the proposed methodological framework is generic and opens pathway toward designing desired scenarios of sustainable development.

5.5.Conclusion

In this paper we proposed a methodological framework to build smart agricultural landscapes. It is based on the prototyping of sustainable cropping system mosaics with a bioeconomic model that simulates explicitly farmers' decision process, in a spatially heterogeneous territory, under market and policy scenarios. This framework combines optimized, normative, exploratory scenarios to help provide knowledge to decision-makers on the potential levers of change that can help reach multiple local and global sustainability goals. Finally, it can help to identify most appropriate levers to increase sustainable development. This holistic approach provides analysis of changes that occur at the regional, the farm and the field scale, and highlights the spatial externalities of cropping system mosaics. This can help decision makers, farmers and the society in understanding pathways to transition towards a more sustainable future.

6. Discussion générale

Dans ce chapitre, nous allons discuter les points suivants :

- L'apport scientifique de l'ensemble méthodologique proposé dans la thèse par rapport aux méthodes existantes pour la conception et l'évaluation de systèmes agricoles à l'échelle territoriale ;
- La généricité de cet ensemble méthodologique ;
- Les limites et améliorations possibles ;
- Les pistes de développement pour favoriser sa mobilisation pour l'aide à la décision.

6.1. Une contribution à la recherche sur la conception et l'évaluation de mosaïques de systèmes de culture

Les objectifs définis en début de thèse étaient les suivants :

i) simuler des scénarios de changements économiques, sociaux, techniques, agronomiques et environnementaux modifiant les choix d'assolement des agriculteurs, décrits individuellement, en modélisant l'évolution de leurs systèmes de production de manière spatialement explicite ;

ii) évaluer l'impact de ces changements d'assolements par des indicateurs spatialisés qui apportent de l'information sur la contribution de l'agriculture au développement durable du territoire.

A travers l'ensemble méthodologique exposé dans la thèse, l'ambition de créer et d'évaluer des mosaïques de systèmes de culture a été atteinte dans la mesure où dans les chapitres 4 et 5 nous avons développé plusieurs ensembles de scénarios aboutissant à la création de mosaïques de systèmes de culture nouvelles, que nous avons évaluées. Dans le chapitre 4, les scénarios exploratoires simulés sont des modifications des politiques économiques et dans le chapitre 5, les scénarios sont de différentes natures : ce sont des scénarios exploratoires et normatifs très contrastés, constitués de multiples changements économiques (taxes sur l'utilisation de pesticides ; diminution de la variabilité de marge brute des cultures maraîchères), agronomiques (nouvelles activités : canne fibre et maraîchage sans intrants chimiques), techniques (augmentation de la fourniture en eau pour l'irrigation) et sociaux (augmentation de la main-d'œuvre disponible à l'échelle du territoire) à différentes échelles spatiales.

L'ensemble méthodologique est donc tout à fait pertinent pour créer de nouvelles mosaïques de systèmes de culture en réponse à des changements de contexte.

6.1.1. Une démarche intégratrice de connaissances existantes pour produire des visions du futur

La démarche développée a permis d'intégrer de nombreuses connaissances en agronomie et en économie :

- Performances des systèmes de culture
- Localisation des systèmes de culture
- Impact des systèmes de culture à l'échelle du territoire
- Processus de choix de systèmes de culture par les exploitants
- Fonctionnement des exploitations agricoles

Tout d'abord, la démarche s'appuie sur la définition de systèmes de culture en intégrant des connaissances agronomiques et socio-économiques mobilisées de différentes manières à travers la lecture de publications ou documents techniques, la sollicitation d'expertises ou des enquêtes auprès d'agriculteurs. Les différents moyens mobilisés répondent à des disponibilités en données différentes. Ces données sont utilisées pour décrire les systèmes de culture en termes d'externalités sociales, économiques et environnementales et pour décrire la localisation des systèmes.

Le modèle permet d'intégrer des processus économiques d'adoption des systèmes de culture par les agriculteurs. Ces processus d'adoption sont simulés de manière individuelle sur des exploitations réelles par une maximisation de l'utilité représentée par le revenu à l'échelle de l'exploitation et l'intégration du risque, en tenant compte des ressources principales de l'exploitation, telles que les ressources en main-d'œuvre et en terre. Il prend en compte également le type de système de production conduit par l'agriculteur en attribuant un niveau d'aversion au risque aux exploitants, fonction de ce système de production. De ce fait, les trajectoires de changement d'un système de production à un autre ne requièrent pas les mêmes leviers agronomiques, techniques, environnementaux et socio-économiques, selon le type d'exploitation considéré. Nous avons par exemple constaté, lors de l'application de l'ensemble méthodologique proposé dans la thèse, qu'un "éleveur" aura besoin de leviers économiques avantageux (subventions, diminution du risque commercial) et de nouvelles opportunités agronomiques, techniques et organisationnelles (par exemple des nouveaux systèmes de culture ; l'accès à l'eau ; de la main-d'œuvre disponible) pour pouvoir adopter des systèmes de culture plus risqués comme les systèmes de culture maraîchers, et de fait passer d'un système de production "éleveur" à "diversifié" ou "maraîcher".

6.1.2. Un exercice de conception et d'évaluation multi-échelle et spatialement explicite

La démarche de conception et d'évaluation de mosaïques de système de culture permet d'intégrer les processus agronomiques et économiques décrits ci-dessus à différentes échelles, et de manière spatialement différenciée.

Dans cette démarche de conception, du fait d'une modélisation explicite et mécaniste des processus biophysiques et socio-économiques régissant les choix de systèmes de culture, nous pouvons tester de nombreux leviers de changement des mosaïques de systèmes de culture. En comparaison des approches fondées sur des modèles statistiques ou empiriques (Schaller *et al.,* 2012 ; Sorel *et al.,* 2010 ; Salmon-Monviola *et al.,* 2011 ; Dury *et al.,* 2010), bornées de fait par un domaine de validité plus restreint, le champ des leviers de changement possibles à explorer est d'une envergure supérieure dans notre ensemble méthodologique. Le modèle bioéconomique que nous proposons nous paraît en adéquation avec la réalité des situations décisionnelles auxquelles sont confrontés les décideurs politiques locaux ou nationaux en matière de développement agricole et rural : la démarche permet en effet d'introduire des changements de facteurs internes et externes au système (van der Horst, 2007 ; Wunscher *et al.,* 2008 ; Crossman and Bryan, 2009), éléments utiles pour l'analyse de scénarios (Shearer, 2005 ; Walz *et al.,* 2007 ; Bryan *et al.,* 2011). Ces changements sont opérés à plusieurs échelles spatiales, le champ, l'exploitation et la région. De plus, notre démarche permet d'introduire des changements dans les systèmes de culture du territoire sous forme de nouvelles activités, ce qui est impossible avec certains modèles statistiques ou empiriques. Ces changements sont pourtant nécessaires pour provoquer des scénarios de rupture forte dans des contextes d'évolution radicale des objectifs de l'agriculture. C'est le cas par exemple à l'échelle nationale avec le programme Ecophyto (sa déclinaison en Guadeloupe est ECOPHYTODOM), qui vise à la réduction de 50% des pesticides utilisés par rapport à 2008, ou le programme « Ambition bio 2017», qui vise notamment à doubler la surface consacrée à l'agriculture biologique d'ici fin 2017 en France.

En termes d'évaluation, les apports de la modélisation multi-échelle et spatialement explicite sont importants pour mieux caractériser les impacts des changements de systèmes de culture. L'évaluation de la durabilité des systèmes de culture ne prend généralement pas en compte d'aspects spatiaux (voir par exemple Carof *et al.,* 2013) ou de manière limitée en incluant des variables du contexte pédoclimatique par exemple. L'ensemble méthodologique mis en œuvre permet de caractériser les externalités des systèmes de culture et de production et ce, de manière spatialement différenciée en fonction de la localisation des systèmes de culture et de production dans l'espace territorial. Ces valeurs sont agrégées à l'échelle du territoire mais leur spatialisation permet de révéler la variabilité de la contribution des parcelles aux enjeux de développement durable (Mahmoud *et al.,* 2009). Cette prise en compte de la localisation des impacts des activités agricoles est particulièrement utile pour les décideurs pour mettre en place des solutions spatialement différenciées pour atteindre leurs objectifs (Cunningham *et al.,* 2013). Les futurs paysages peuvent ainsi informer les décideurs sur les possibles bénéfices liés à une réorganisation des systèmes de culture et les coûts nécessaires pour aboutir à ces nouvelles organisations.

L'usage de l'ensemble méthodologique proposé dans cette thèse permet la définition de scénarios de changement de mosaïques de systèmes de culture fondés sur l'identification des leviers pertinents pour atteindre des objectifs de durabilité visés. Il permet également d'explorer le potentiel de réponse de l'agriculture actuelle aux enjeux de développement durable. Ces deux types de finalités permettent *in fine* i) de connaître le potentiel d'atteinte d'un objectif, ii) de tester des changements permettant d'atteindre cet objectif (Bryan *et al.,* 2011) pour l'aide à la décision publique.

6.1.3. Un apport de la démarche pour de l'aide à la décision

Notre ensemble méthodologique peut être utilisé à des fins de prospective agricole à l'échelle du territoire. Dans le cadre du présent travail, nous nous sommes concentrés sur sa construction et non sur ses usages, mais il a vocation à être utilisé pour l'aide à la décision. Typiquement, la mosaïque "Go sustainable" générée dans le chapitre 5 n'est pas une prescription de l'équipe de recherche mais constitue ni plus ni moins qu'une "preuve de concept". Ce scénario correspond à des préoccupations particulières, orientées par différents projets de recherche en lien avec l'évolution du territoire Guadeloupéen (projet REBECCA - mise en place d'une filière canne fibre en Guadeloupe (Région Guadeloupe, 2011)- Programme de recherche AgriBio pour la conception de systèmes de culture en agriculture biologique - (voir http://www6.inra.fr/comite_agriculture_biologique/Les-recherches/Par-programme/Inra-AgriBio) ; d'autres préoccupations auraient, bien sûr, débouché sur d'autres mosaïques. L'itinéraire de développement de scénario décrit dans le chapitre 5 constitue une illustration de l'utilisation possible du modèle, et les scénarios utilisés un exemple de jeu de scénarios débouchant sur un exemple de mosaïque.

L'intégration de connaissances agronomiques et économiques dans le modèle en fait un outil d'aide à la décision utile pour les décideurs. Le modèle produit des visions holistiques du territoire agricole et il permet par là même de dépasser les limites cognitives des acteurs en simulant les conséquences de combinaisons de leviers difficiles à imaginer compte tenu de la somme de connaissances à prendre en compte (Cf. 6.1.1). Le modèle renvoie des résultats sur les changements d'usages sur l'ensemble du territoire ce qui apparaît également comme un avantage du fait des zones d'action des acteurs qui se limitent généralement à une partie non exhaustive du territoire (Debolini *et al.,* 2013). Les connaissances fragmentaires des acteurs sur l'ensemble des externalités des systèmes de culture en lien avec les différents objectifs de durabilité des acteurs sont un obstacle dans les démarches qualitatives. La quantification des impacts de nouvelles organisations de systèmes de culture par le modèle permet de dépasser cette limite. Le modèle constitue également un support pour la production de nombreuses visions qui sont difficiles à faire émerger dans les démarches qualitatives du fait de processus de changements d'usages non mécanistes contrairement au modèle MOSAICA. Le modèle permet donc de générer de nombreuses mosaïques résultant de scénarios et donc de générer plus de connaissances sur les futurs possibles et l'effet de leviers de changements.

Bien que le modèle présente ces avantages par rapport aux méthodes plus qualitatives, son utilisation pour de l'aide à la décision nécessite toutefois que quelques conditions soient satisfaites. Compte tenu du formalisme actuel du modèle et de l'absence d'interface utilisateur, le transfert du modèle directement aux décideurs n'est pas possible. Le modèle, développé sous le logiciel GAMS, requiert des compétences en programmation, pour pouvoir tester de nouveaux leviers. L'aide à la décision avec ce modèle pourrait se matérialiser par des demandes des décideurs locaux de test de scénarios. Ces demandes pourraient s'effectuer à travers un exercice collectif de réflexion sur l'élaboration de scénarios dont les résultats, les mosaïques et leur évaluation, pourrait faire l'objet d'une restitution collective aux décideurs par l'équipe de recherche.

6.2.Généricité de l’ensemble méthodologique

Dans le chapitre 4 nous avons évoqué la généricité du modèle bioéconomique pour un usage sur d'autres territoires. Nous élargissons ici la discussion sur la généricité de l’ensemble méthodologique en évoquant les principales conditions d’application de l’ensemble méthodologique et les modalités d'utilisation du modèle par d'autres équipes de recherche.

6.2.1. Besoin en données

Les principales conditions d’application de l’ensemble méthodologique sont la définition des limites du territoire, la disponibilité **de données géographiques sur les parcelles**, de **statistiques sur les surfaces des différentes cultures et les exploitations**, et l’accès à de l'**information sur les performances des systèmes de culture**.

- La disponibilité des données géographiques et des données statistiques peut être une première limite pour la mise en œuvre de cette méthode. Les données parcellaires sont nécessaires dans l’algorithme d’allocation des systèmes de culture. Ce type de données peut être obtenu auprès de l'Agence de Services et de Paiement (ASP) en France et à l'échelle européenne auprès des établissements chargés des déclarations surfaciques pour l'obtention des subventions par les agriculteurs. Toutefois, les territoires pour lesquels ces données ne seraient pas existantes, peuvent faire l'objet d'une reconnaissance des parcelles par télédétection ou par le dessin des contours parcellaires depuis des photographies satellites lorsque les parcelles ont des limites claires et identifiables. Les différents usages peuvent être identifiés via télédétection ou renseignés directement dans la base de données parcellaire.

- Un second besoin vient de l'identification des flux de marchandises ou d'intrants, nécessaire pour calculer par exemple les indicateurs d'autosuffisance alimentaire du territoire. La démarche requiert donc d'avoir de l'information sur la population du territoire. La caractérisation du territoire est importante pour définir des contraintes régionales dans le modèle bioéconomique sur les quantités de productions agricoles maximales (par exemple : volume de la demande) mais également pour évaluer le modèle.

- La disponibilité de données et d'informations sur les systèmes de culture (litterature et experise locale) est nécessaire pour définir les activités du modèle bioéconomique. La présence de filières bien structurées sur le territoire et d'instituts agricoles permet d'obtenir des informations sur les performances agronomiques, économiques et environnementales des systèmes de culture.

6.2.2. Modalités d'utilisation du modèle

Nous avons précédemment évoqué les possibilités d'utilisation du modèle pour l'aide à la décision dans différents contextes. Nous évoquons ici les modalités de transfert et d'adaptation du modèle.

Le modèle MOSAICA V1.0 fera l'objet d'un dépôt à l'Agence de Protection des Programmes courant 2015. Son acquisition sera autorisée pour utilisation et modification par d'autres équipes de recherche et il sera accompagné d'une notice d'utilisation et d'adaptation au contexte d'étude. Ce dépôt marquera également la stabilisation du modèle qui a constamment évolué pendant la thèse ce qui explique les valeurs différentes des indicateurs d'emplois, de risque de contamination par la chlordécone des denrées entre le chapitre 4 et 5 lors de l'évaluation de la mosaïque initiale.

Les modifications des entrées sont faciles du fait d'une structure modulaire. Les variables des entrées du modèle, activités, base de données géographiques et typologie d'exploitations sont regroupées dans des bases de données, externes au modèle, et peuvent donc faire l'objet de modifications rapides via l'utilisation de logiciels de gestion de base de données. Les sorties spatiales, mosaïques de systèmes de culture et cartes des indicateurs spatialisés, nécessitent l'utilisation d'un système d'information géographique tel que le logiciel ArcGis (ESRI, 2009) pour traiter les sorties numériques du modèle.

Seule la modification des équations et de la fonction objectif du modèle nécessite une modification du code du modèle, écrit en langage de programmation GAMS sous le système de modélisation du même nom (voir www.gams.com). Sur le plan scientifique l'utilisation de MOSAICA est donc facile pour des tiers, puisqu'elle ne requiert qu'un minimum de modifications pour des adaptations locales.

6.3. Limites de l'approche développée

Nous répertorions ici les limites des éléments constitutifs de la démarche, c'est-à-dire la typologie d'exploitations, les indicateurs d'évaluation des mosaïques, le modèle bioéconomique et finalement les limites de l'articulation de ces trois éléments pour la démarche de scénarisation présentée dans le chapitre cinq. Nous proposons aussi des éléments d'amélioration qui permettraient de mieux répondre aux objectifs scientifiques visés.

6.3.1. Limites des éléments constitutifs de l'ensemble méthodologique

6.3.1.1. Utilisation de la typologie

Une première limite vient du fait que les types d'exploitation sont fondés uniquement sur des proportions de cultures dans la SAU, ce qui ne rend pas compte de l'hétérogénéité des pratiques et des performances des systèmes de culture dans les exploitations. Les groupes agrègent des exploitants qui ont le même assolement mais pas les mêmes contraintes et/ou les mêmes opportunités et de fait de processus décisionnels qui peuvent différer.

La seconde limite vient de l'algorithme de classification des exploitations. Cet outil est utile pour suivre l'évolution du nombre d'exploitations dans les types mais le caractère très strict de l'approche de classification avec des seuils peut provoquer un changement de type de système de production consécutif à un changement minime dans l'assolement des exploitants.

Le nombre de types définis dans la typologie est constant, il n'y a pas de redéfinition de nouveaux types. Il s'agit d'un défaut de l'ensemble méthodologique. Seule la répétition de nouveaux traitements statistiques sur les assolements des exploitations en sortie du modèle permettrait de faire émerger de nouveaux type d'agriculteurs.

6.3.1.2. Utilisation des indicateurs

La conception des indicateurs souffre de limites qui restreignent la précision dans l'évaluation des mosaïques de systèmes de culture : le manque de connaissances sur certains processus évalués, l'absence de prise en compte des interactions spatiales entre systèmes de culture et le pas de temps annuel utilisé pour décrire les systèmes de culture et enfin, le manque d'agrégation des indicateurs.

Des processus ne sont parfois pas pris en compte. Typiquement les éléments non agricoles devraient figurer dans l'évaluation du risque de pollution des bassins versants, rivières et captages. Par exemple une bande enherbée entre deux champs permet de freiner le ruissellement des matières actives épandues (Emma Ligdi and Morgan, 1995). Une caractérisation des éléments non agricoles entre les parcelles pourrait être utile via un système d'information géographique. Plus généralement, il serait nécessaire d'intégrer un ensemble de connaissances sur ces processus pour pouvoir améliorer la caractérisation du risque de pollution.

Le modèle ne prend pas en compte les interactions spatiales entre les systèmes de culture sur le territoire. L'évaluation de la mosaïque est spatialement explicite dans le sens où elle tient compte de la localisation des systèmes de culture sur le territoire par rapport aux écosystèmes et aux sous-régions. Toutefois, la localisation des systèmes de culture les uns par rapport aux autres n'est pas prise en compte. Des travaux comme ceux de Wohlfahrt *et al.* (2010), permettent d' évaluer le risque de pollution des cours d'eau en intégrant des variables décrivant l'agencement spatial des systèmes de culture les uns par rapport aux autres. Cela permet de différencier l'impact de la localisation d'un système de culture alloué sur une parcelle par rapport à un autre système de culture localisé sur une parcelle voisine. Cet élément est important à prendre en compte dans certains processus qui doivent être réfléchis en fonction des usages de l'ensemble des parcelles comme l'érosion ou la diffusion des pollutions à l'échelle d'un bassin versant.

Le calcul des indicateurs sur un pas de temps annuel est pertinent pour les indicateurs économiques ou sociaux tels que la valeur ajoutée agricole ou le risque de contamination des cultures par la chlordécone, mais il l'est moins pour certains indicateurs environnementaux qui décrivent des processus pouvant avoir un impact à des pas de temps plus petits. Concernant le risque de pollution des ressources en eau, il est par exemple très simplificateur d'estimer ce risque sur une année compte tenu de la variabilité intra-annuelle de la pluviométrie qui conditionne le processus de ruissellement et donc le risque de pollution des eaux. Toutefois le manque de données sur les périodes de traitements phytosanitaires, assez aléatoires pour certaines cultures, rend l'indicateur peu précis. Ces données annuelles sur les systèmes de culture ne sont pas en phase avec les processus évalués. De même, la description simplifiée des systèmes de culture diminue encore la précision de tels indicateurs. Le potentiel d'aide à la décision du modèle sur ces aspects environnementaux est donc moindre.

Toutefois en l'état actuel de description des systèmes de culture, nous pouvons considérer cet indicateur comme apportant des connaissances aux décideurs sur les pressions qui s'exercent sur leur territoire et sur les pratiques susceptibles d'augmenter les risques environnementaux.

Les indicateurs pourraient bénéficier d'une méthode d'agrégation des différentes dimensions de la durabilité, comme dans le cas des modèles MASC ou DEXi-PM (Sadok *et al.,* 2009 ; Pelzer *et al.,* 2012), pour faciliter la comparaison des mosaïques entre elles. Malgré le nombre restreint d'indicateurs dans notre analyse, la comparaison des contributions des différentes mosaïques au développement durable du territoire est parfois peu aisée.

L'ensemble des indicateurs développés permet de rendre compte des externalités des systèmes de culture et de production à l'échelle du territoire. Toutefois, ces indicateurs rendent peu compte de la durabilité des systèmes de production à l'échelle de l'exploitation agricole. Se posent alors de nouvelles questions autour du lien entre durabilité à l'échelle du territoire et durabilité à l'échelle de l'exploitation. Peut-on, par exemple, avoir une durabilité faible à l'échelle de l'exploitation et une durabilité élevée à l'échelle du territoire ?

6.3.1.3. Utilisation du modèle

Les limites du modèle sont le manque de diversité et la simplification opérée dans la définition des activités, la simplification de la prise en compte du consentement des exploitants à adopter de nouvelles activités, l'absence de simulation de la transition entre la mosaïque des systèmes de culture initiale et les mosaïques simulées.

Les activités du modèle sont décrites comme des systèmes moyens agrégés qui ne rendent pas compte de la diversité des pratiques, qui peut être grande comme le notent par exemple Le Bellec *et al.*(2010) pour l'utilisation de pesticides chez les arboriculteurs dans le sud-ouest de la Basse-Terre. Les activités du modèle ne prennent pas en compte les coûts fixes et les coûts d'entrée pour la pratique d'un système de culture nouveau (le défrichage pour la mise en culture d'une parcelle en jachère, la mise en place d'un verger qui produit peu les premières années...) et les coûts de transaction, coûts liés aux changements structurels dans le système de production tels que le changement de stratégie de commercialisation (Pingali *et al.,* 2005). Ces manques sont reflétés par des coefficients techniques fixes pour tout type d'exploitation alors qu'en réalité, ces coefficients diffèrent selon le type d'exploitant. Nous pourrions considérer par exemple qu'il est moins coûteux pour une exploitation bananière d'adopter des systèmes de culture à base de plantain par rapport à l'organisation actuelle des exploitations ou au matériel déjà présent sur la ferme que pour une exploitation maraîchère pour laquelle ces éléments ne sont pas présents, ce qui viendrait diminuer de fait les performances économiques de l'activité les premières années.

Les activités sont définies de manière experte essentiellement. Faute de moyens suffisants, nous n'avons conduit que peu d'enquêtes chez les exploitants pour différencier les systèmes de culture et leurs performances selon le type d'exploitant et sa localisation sur le territoire. Cette simplification des systèmes de cultures entraîne donc des effets de basculement importants de la mosaïque de systèmes de culture d'un usage à un autre lorsque les conditions d'adoption sont similaires (besoins en main-d'œuvre proches et contraintes biophysiques similaires entre les deux activités), ce qui entraîne la disparition totale de certains usages dans nos scénarios. Par exemple, pour la mosaïque du scénario "Go sustainable", conçue dans le chapitre 5, la canne fibre remplace de manière complète la canne à sucre. La définition de plus de systèmes de culture dans notre cas d'étude pose problème du fait d'un manque important de données agronomiques sur les systèmes de culture, surtout pour les sept zones pédoclimatiques. Ce travail de définition des systèmes de culture et de leurs performances de manière plus différenciée est un travail de plusieurs années requérant mesures de terrain, enquêtes sur les pratiques et suivis de parcelles. Ce travail permettrait ensuite de développer ou d'adapter des modèles de culture aux différentes zones et de coupler ces modèles à MOSAICA comme dans certaines approches (Belhouchette *et al.,* 2008 ; Blazy *et al.,* 2010 ; Delmotte, 2011). Le travail de définition des systèmes de culture avec des techniques comme l'observation de rotations à travers le traitement statistique de la base de données (comme réalisé par Leenhardt *et al.,* 2010) de 2004 à 2010 avec l'outil TeruTiMiner n'a pas permis de révéler des rotations types statistiquement plus pratiquées que d'autres successions culturales apparaissant dans la base de données. Seules les rotations banane-canne et banane-jachère, déjà connues à travers les travaux de Blazy *et al*. (2009) et intégrées dans les activités du modèle MOSAICA ont pu être identifiées via cette approche.

La simplification du processus d'adoption des agriculteurs est liée au manque d'informations sur les exploitations. Seules quelques variables sont disponibles à l'échelle de l'exploitation dans notre base de données. Aucune information ne nous permet de connaître le consentement des exploitants à adopter de nouvelles activités. Selon les cinq catégories de facteurs régissant l'adoption de systèmes techniques mentionnés par Edwards-Jones (2006), les caractéristiques des agriculteurs, les caractéristiques du foyer, le milieu social, la structure de l'exploitation et les caractéristiques des systèmes de culture, seules les deux dernières sont prises en compte dans notre modèle. De plus l'attitude personnelle des agriculteurs face à l'innovation n'est pas prise en compte alors qu'elle peut conditionner la probabilité d'adoption et de diffusion des innovations (Roger, 1962). Les autres éléments pourraient être intégrés par des techniques d'évaluation du consentement à l'adoption comme les expériences de choix (Birol *et al.,* 2006 ; Blazy *et al.,* 2011) ou les processus d'analyses hiérarchiques (Reed *et al.,* 2014) qui permettent de révéler les facteurs qui orientent – ou pas – les choix vers de nouveaux systèmes de culture. Ces techniques pourraient être mises en œuvre sur une typologie d'exploitations plus désagrégée (avec plus de diversité). Cette typologie pourrait être enrichie de données sociodémographiques comme l'âge, la taille du foyer de l'exploitant, la double activité, en liant les variables d'assolement des exploitations utilisées dans notre base de données spatiales et les données d'assolement du recensement utilisé. Les processus de diffusion des systèmes de culture qui sont conditionnés par exemple par la proximité entre les différentes exploitations agricoles (Ward and Pede, 2014) ne sont pas simulés dans le modèle. A terme le modèle pourrait intégrer des paramètres spatiaux dans la fonction d'utilité des agriculteurs dont les valeurs pourraient être déterminées par des modèles d'adoption spatiaux.

La prise en compte de plusieurs objectifs autres que la maximisation du revenu pourrait être intégrée à la fonction objectif comme la minimisation du besoin en main d'œuvre ou la minimisation des coûts d'investissement. Le poids de ces différents objectifs dans la fonction d'utilité des exploitants pourrait être élicité avec la méthode développée par Sumpsi *et al*. (1997), qui a pour avantage de définir des poids individuels par exploitant sur la base de l'observation des choix actuels des exploitants en termes de système de culture.

Le modèle est statique, il ne permet donc pas de générer les états transitoires de la mosaïque de systèmes de culture entre l'état initial et l'état simulé. Rendre le modèle dynamique permettrait de générer ces états transitoires de la mosaïque de systèmes de culture et donc d'évaluer si le passage de la mosaïque actuelle à une nouvelle mosaïque comme celle obtenue avec le scénario "Go sustainable" dans le chapitre 5 n'est pas une transition qui ferait chuter transitoirement certains indicateurs comme la valeur ajoutée agricole totale, avec l'implantation de cultures pluriannuelles ou l'augmentation du risque de contamination des denrées agricoles par le chlordécone. Cette transition pourrait alors apporter de l'information sur la nécessité de soutenir les exploitations par des aides financières et techniques au cours de la conversion de système de production. L'organisation tactique des activités culturales dans les exploitations n'est pas prise en compte dans la modélisation, du fait du pas de temps annuel de description des systèmes de culture. A terme, le modèle pourrait intégrer des modèles d'exploitation fonctionnant à un pas de temps hebdomadaire qui rendraient compte de l'organisation du travail dans l'exploitation et donc de la capacité d'une exploitation à intégrer un nouvel atelier dans son système d'exploitation.

6.3.2. Limites de l'ensemble méthodologique

L'ensemble de ces limites individuelles vient impacter la qualité des sorties de l'ensemble méthodologique conçu dans la thèse. Les limites principales de l'ensemble méthodologique sont au nombre de trois.

Une augmentation de l'incertitude dans l'évaluation des impacts à l'échelle territoriale, résultant des imprécisions aux différentes échelles spatiales : le concept même de modèle qui est une représentation simplifiée du fonctionnement d'un système entraîne un certain nombre d'incertitudes dans les sorties du modèle. Dans notre démarche, il s’agit du manque de précision dans la définition des systèmes de culture, leur description annuelle, et le manque d'information sur les exploitations. Toutefois pour mieux caractériser l'incertitude spatiale dans la localisation des systèmes de culture et l'incertitude dans l'évaluation de l'impact des mosaïques, une analyse de sensibilité pourrait être conduite (Verburg *et al.,* 2013). Cette analyse de sensibilité pourrait aider à identifier les paramètres dont des changements mineurs dans les valeurs en entrée du modèle (par exemple le rendement des activités ou les contraintes d'adoption de systèmes de culture) entraînent des modifications majeures dans la structure de la mosaïque de systèmes de culture et les impacts de cette mosaïque.

Manque de validation des valeurs du modèle et des indicateurs en sortie du modèle : la démarche souffre d'un manque de validation du modèle bioéconomique et des indicateurs. Pour le modèle bioéconomique, la comparaison des sorties de la calibration aux différentes échelles spatiales a permis de rendre compte de la capacité prédictive du modèle. Le modèle bioéconomique pourrait bénéficier en plus d'une évaluation par des acteurs du territoire qui pourraient discuter la qualité des sorties du modèle, des règles de localisation des systèmes, de leur impact et de la pertinence des indicateurs en termes d'aide à la décision. Les indicateurs pourraient également bénéficier d'une validation suivant les méthodes développées par Bockstaller *et al.* (2003) ou Qureshi *et al.* (1999) comme la présentation des valeurs des indicateurs à des panels d'experts des différents processus évalués. Un test de validation peut également être conduit pour connaître les opinions des utilisateurs concernant le degré d'utilité ou de compréhension des différents indicateurs.

Un manque de participation des acteurs locaux : la démarche pourrait bénéficier d'une implication plus importante des acteurs locaux à la fois pour l'évaluation du modèle (Andrieu *et al.,* 2012) mais également pour mettre en place une démarche de scénarios et d'échange autour des leviers de changement de l'agriculture. Dans le chapitre 5, les leviers proviennent uniquement de recommandations de chercheurs formulées lors du diagnostic de contribution de l'agriculture guadeloupéenne au développement durable dans le chapitre 3. Toutefois, la modélisation participative avec un modèle bioéconomique est particulièrement difficile du fait d'un paramétrage et d'un temps de fonctionnement très long pour produire une mosaïque (environ quinze minutes pour la Guadeloupe), ce qui rend difficiles les interactions autour de la conception et de l'évaluation de mosaïques (Delmotte *et al.,* 2013) dans des démarches participatives.

6.4. Pistes de développement

Le principal usage que nous avons fait de l'ensemble méthodologique est un usage pour l'aide à la décision. Mais la démarche peut être utilisée pour guider l'acquisition de connaissances, pour identifier les déterminants de changement des systèmes de culture.

6.4.1. Guider l'acquisition de connaissances sur l'agriculture locale et sur les processus

Le modèle MOSAICA permet, en l'utilisant pas à pas, d'identifier des manques de connaissances sur des variables qui régissent les processus évalués et pour lesquelles il faudait plus de connaissances analytiques. Le modèle pose par exemple des questions sur le comportement des polluants épandus au champ et leur capacité à rejoindre des masses d'eau en Guadeloupe. Il est nécessaire d'engranger des connaissances sur ces processus et de les intégrer au modèle MOSAICA pour une meilleure caractérisation des risques de pollution des masses d'eau.

6.4.2. Identifier les déterminants spatiaux des changements de la mosaïque des systèmes de culture

L'ensemble méthodologique développé ici permet d'identifier les déterminants d'évolution de la mosaïque de systèmes de culture, comme nous l'avons fait dans le chapitre 2. Afin de mieux caractériser l'effet des leviers de changement de la mosaïque, il pourrait être intéressant d'utiliser la méthode d'autocorrélation spatiale décrite dans le chapitre 2 pour trouver les déterminants responsables des changement observés sur le territoire lorsque les scénarios combinent beaucoup de leviers à différentes échelles spatiales (Chopin and Blazy, 2013).

6.4.3. Identifier des prototypes de systèmes de culture d'intérêt pour répondre à des problématiques de développement durable

Il est particulièrement intéressant avec le modèle MOSAICA de tester de nouvelles activités pour connaître leurs potentiels d'adoption, les conditions nécessaires à leur adoption. MOSAICA peut permettre de répondre aux questions suivantes : ce prototype de système de culture est-il potentiellement diffusable sur le territoire compte tenu des contraintes et ressources des exploitants ? Ce prototype est-il intéressant pour répondre aux problématiques de développement durable ? Le modèle peut donc montrer l'intérêt de proposer des systèmes de culture innovants sur un territoire. Ce modèle à l'échelle régionale pourrait constituer un préalable intéressant à la conception de systèmes de culture innovants en testant un système de culture idéal avec des caractéristiques qui sont les objectifs de conception vers lesquels les équipes de recherche veulent tendre (par exemple : prototypage de systèmes de culture à base d'ignames biologiques avec une performance économique proche du système conventionnel mais des performances agronomiques correctes et des performances environnementales meilleures).

Conclusion générale

Cette thèse présente un ensemble méthodologique pour la conception et l'évaluation multicritère de mosaïques de systèmes de culture en vue d'augmenter la contribution de l'agriculture au développement durable du territoire.

L'ensemble méthodologique développé comporte un modèle bioéconomique qui permet la conception de mosaïques de systèmes de culture, et qui intègre une typologie et des indicateurs qui permettent d'évaluer la contribution au développement durable des mosaïques de systèmes de culture. Ce modèle est utilisé dans une démarche de simulation avec un ensemble de scénarios exploratoires et normatifs permettant d'identifier des leviers d'action qui améliorent la contribution au développement durable de l'agriculture.

Cet ensemble intègre des connaissances agronomiques à l'échelle du champ sur la localisation des systèmes de culture, leurs performances à l'échelle de la parcelle et l'impact de leur localisation sur le territoire en termes de fourniture de services. Parallèlement, la démarche intègre des connaissances sur les processus d'adoption des systèmes de culture des exploitations agricoles par la prise en compte de leurs ressources, contraintes biophysiques et socio-économiques et de leurs systèmes de production. Ces éléments permettent de modéliser les systèmes de culture mis en œuvre à l'échelle parcellaire par les agriculteurs et leur évolution sous différents scénarios.

Notre démarche se différencie des travaux existant par la prise en compte des interrelations entre les échelles du champ, de l'exploitation et du territoire et la localisation des systèmes de culture. Cette prise en compte des interrelations entre les échelles autorise une exploration de changements variés, d'ordre agronomique, économique, technique, organisationnel, sociaux aux différentes échelles spatiales qui sont susceptibles d'orienter les processus agronomiques et économiques modélisés. Le caractère spatialement explicite de l'approche confère à la démarche une précision dans l'évaluation des changements de système de culture et de leurs conséquences sur la contribution de l'agriculture au développement durable.

L'implémentation de cette démarche sur le territoire de la Guadeloupe a montré sa pertinence pour concevoir des mosaïques issues de différents types de scénarios qui permettent de rendre compte des conséquences des leviers testés sur l'agriculture locale. En dépit de ses nombreuses limites actuelles, la démarche apparaît comme un outil utile pour aider à la décision sur le devenir du territoire et permettre également d'évaluer les synergies et antagonismes entre les différents services rendus par l'agriculture. L'utilisation du modèle dans le cadre de travaux prospectifs permettrait de co-concevoir des scénarios et de guider l'acquisition de connaissances sur les effets possibles de ces scenarios sur l'agriculture des territoires.

Le travail mené l'a été sur un territoire insulaire aux limites bien définies, ce qui présente des avantages pratiques évidents. Il engendre toutefois des pistes de réflexion et propose des outils dont l'usage peut bénéficier à des territoires continentaux. L'insularité devient alors une propriété simplificatrice du territoire, permettant le test de méthodologies en conditions simplifiées. En ce sens, notre travail ouvre la voie à un nouveau regard sur les territoires insulaires, pris comme prototypes d'avant-garde pour les nécessaires travaux à mener sur les territoires, et en particulier les territoires agricoles du monde.

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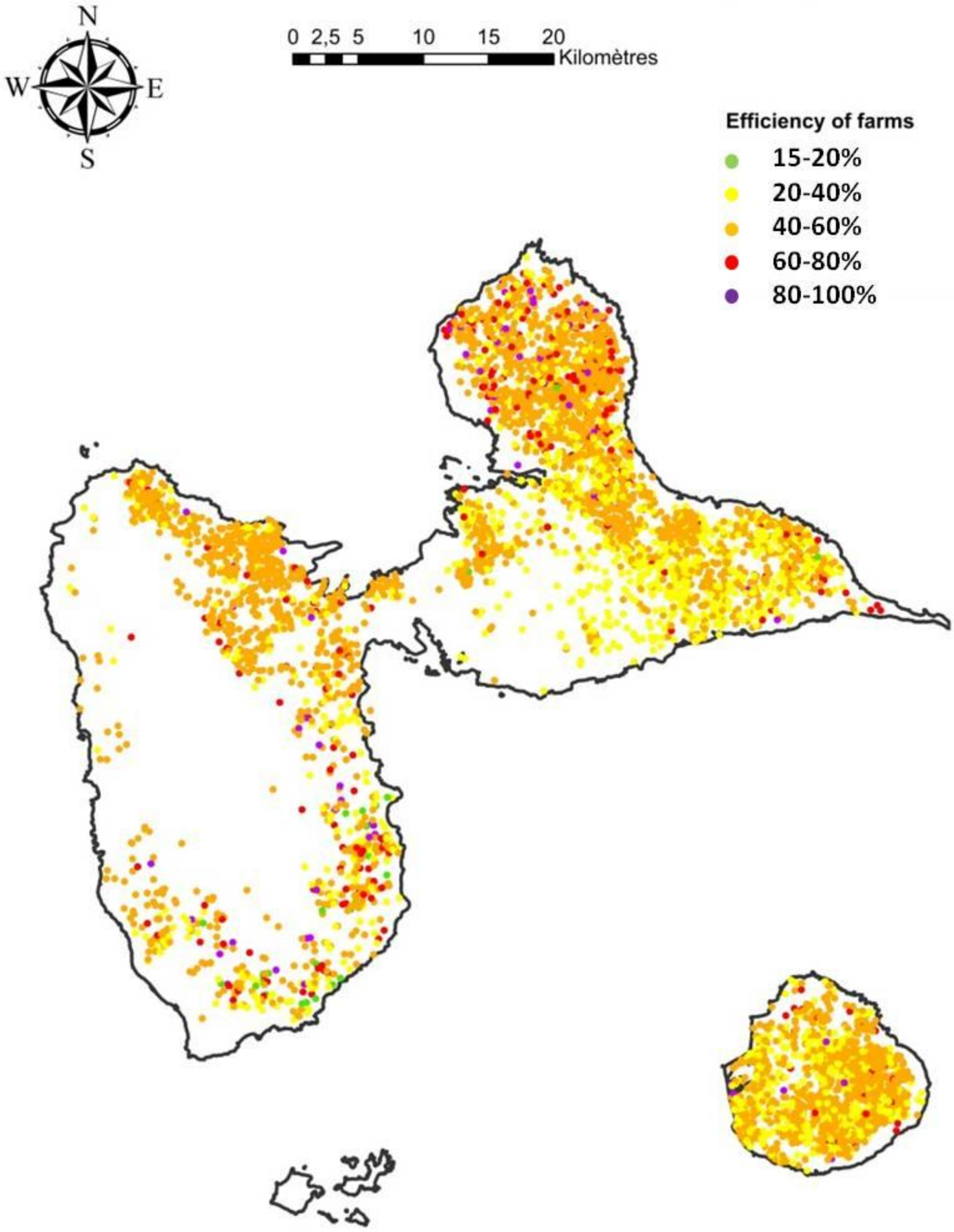
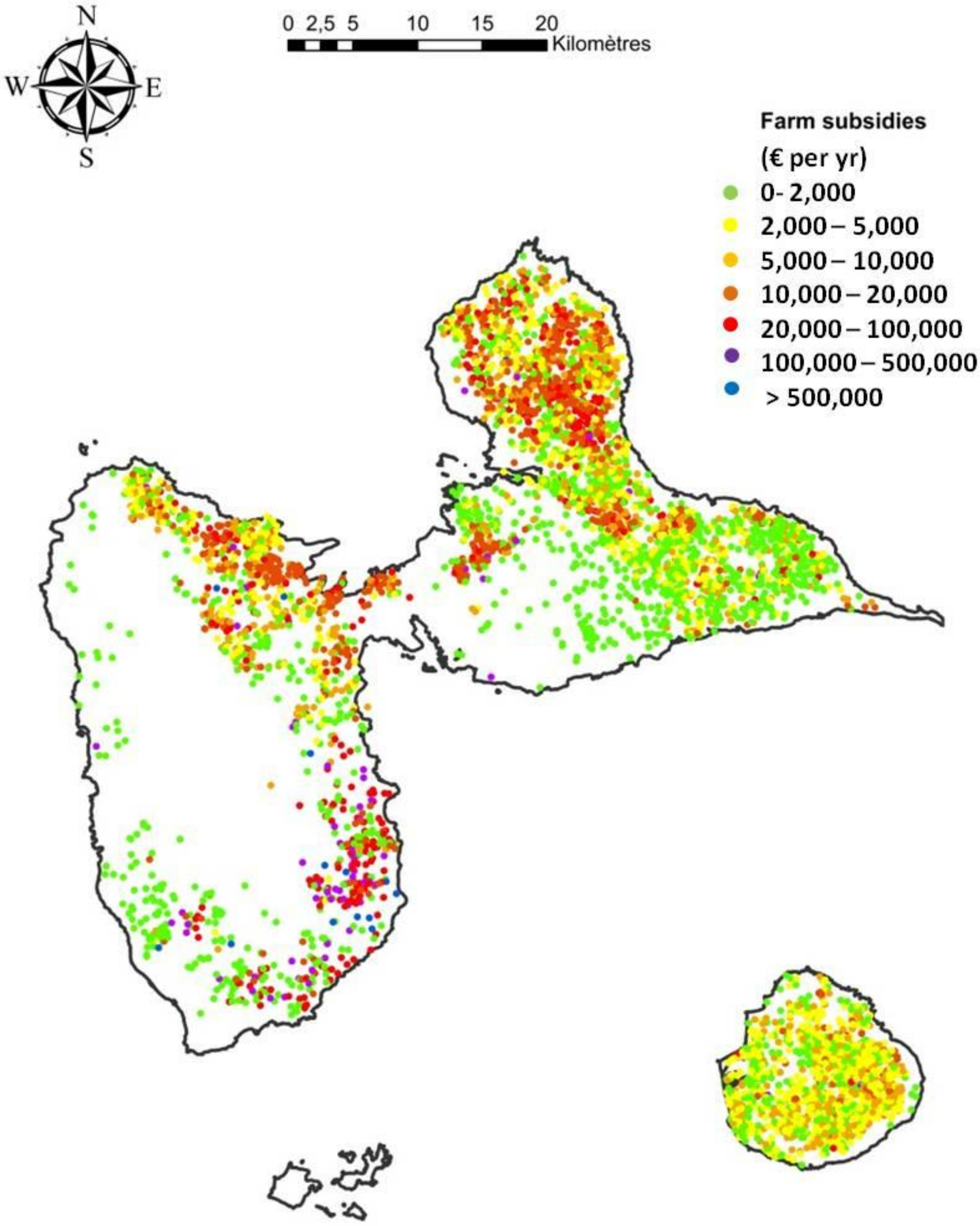
Supplementary Materials / Annexes

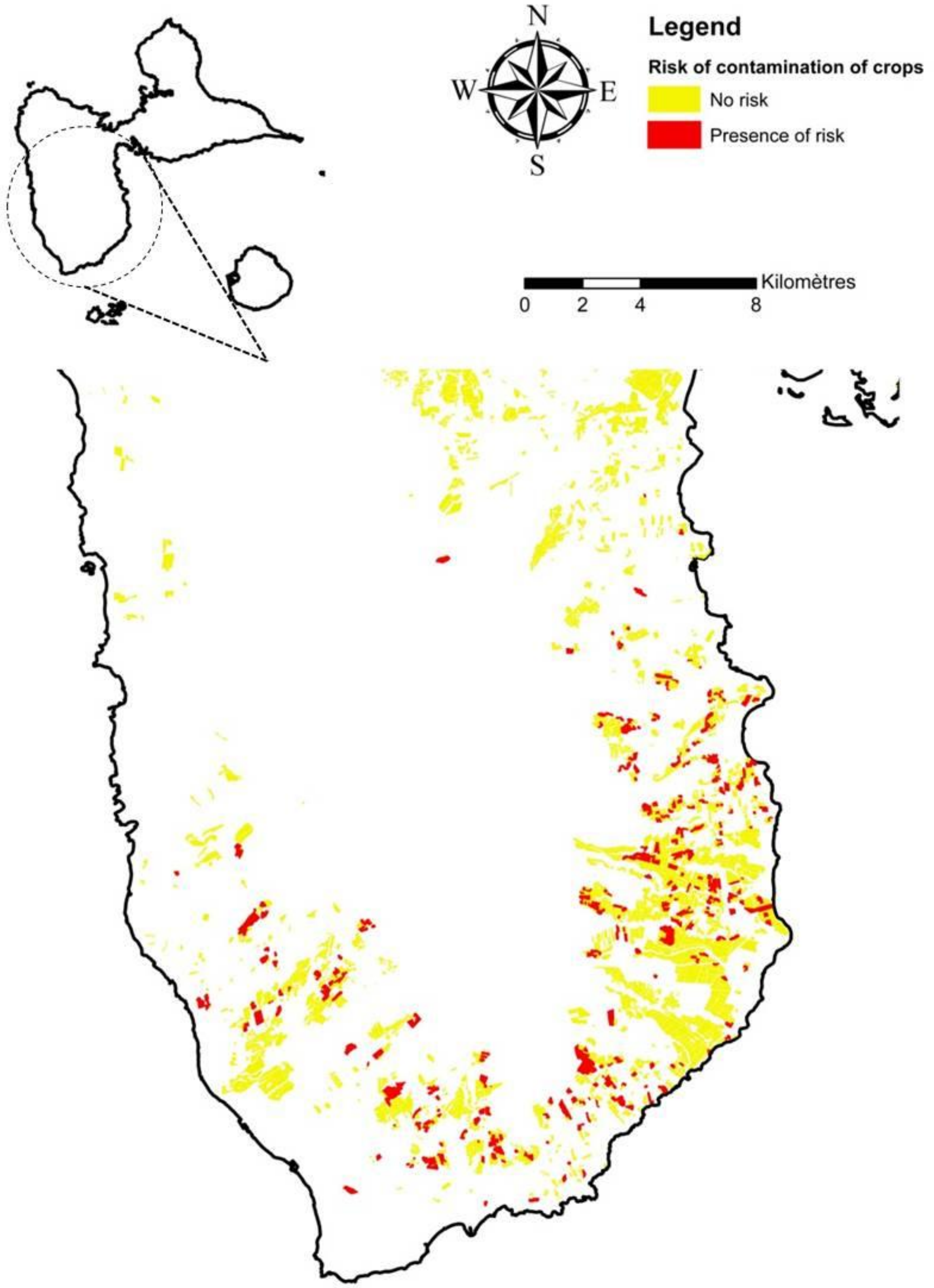
- 1 : Efficiency of farms.
- 2 : Amount of subsidies of farms.
- 3 : Risk of contamination of crops by chlordecone at field scale.
- 4 : Production of electricity at the district level.
- 5 : Water used for irrigation at farm scale.
- 6 : Risk of pollution of water abstraction sources.
- 7 : Risk of pollution of water catchments.
- 8 : Risk of erosion on vertic soils.
- 9 : Emissions of greenhouse gas at the district scale.
- 10 : Landscape diversity at the district scale.



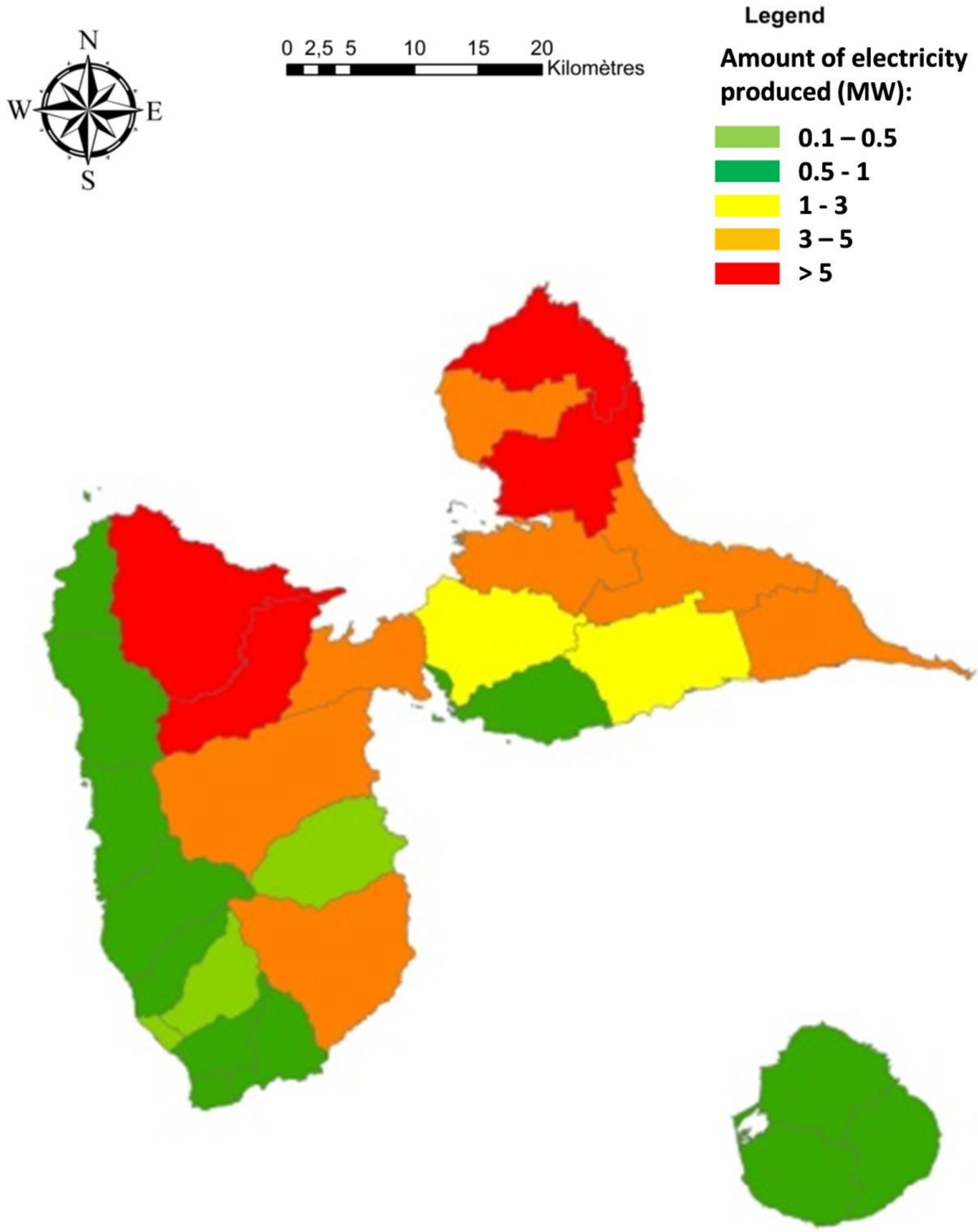
➢ 1 : Efficiency of farms.



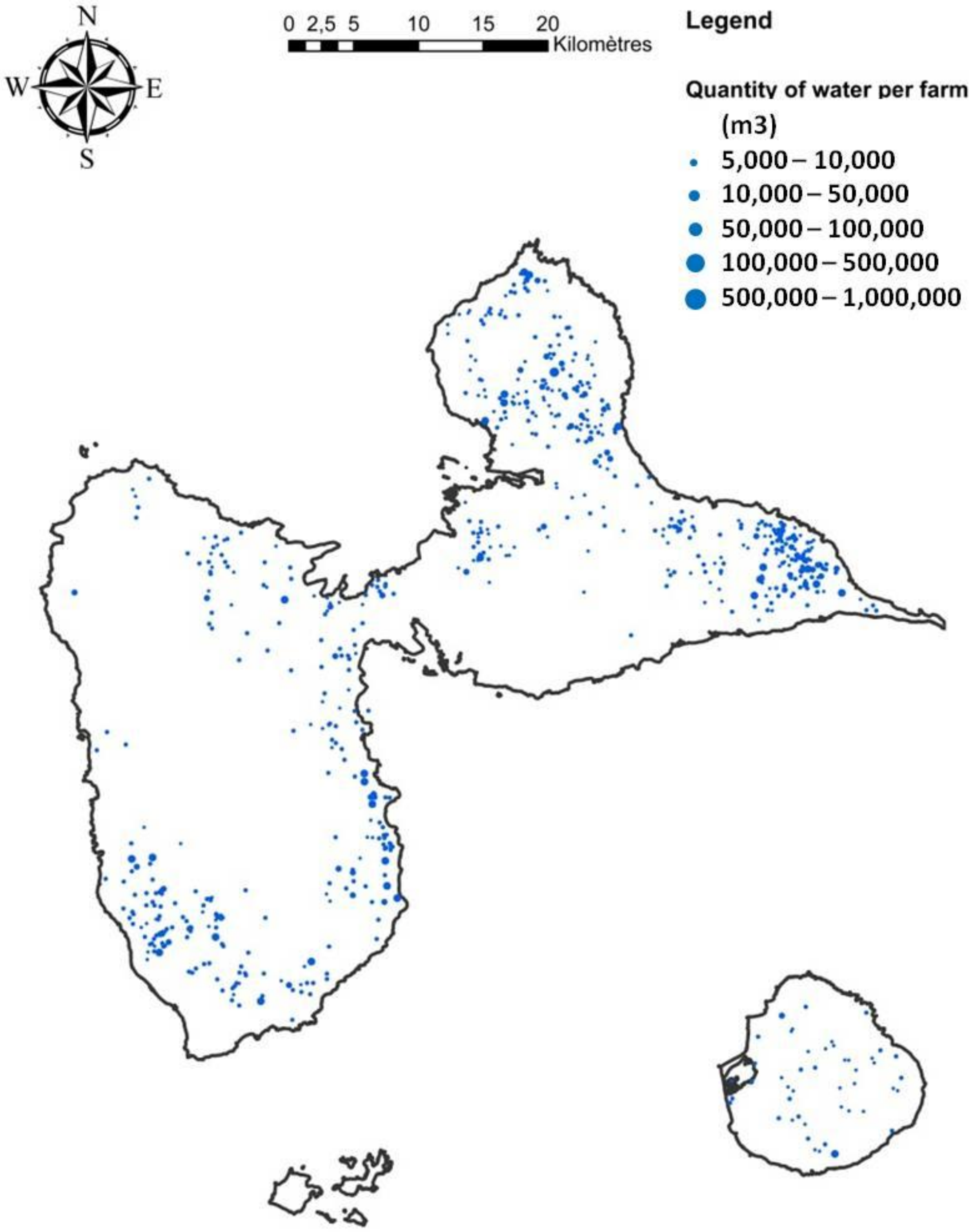
➢ 2 : Amount of subsidies of farms.



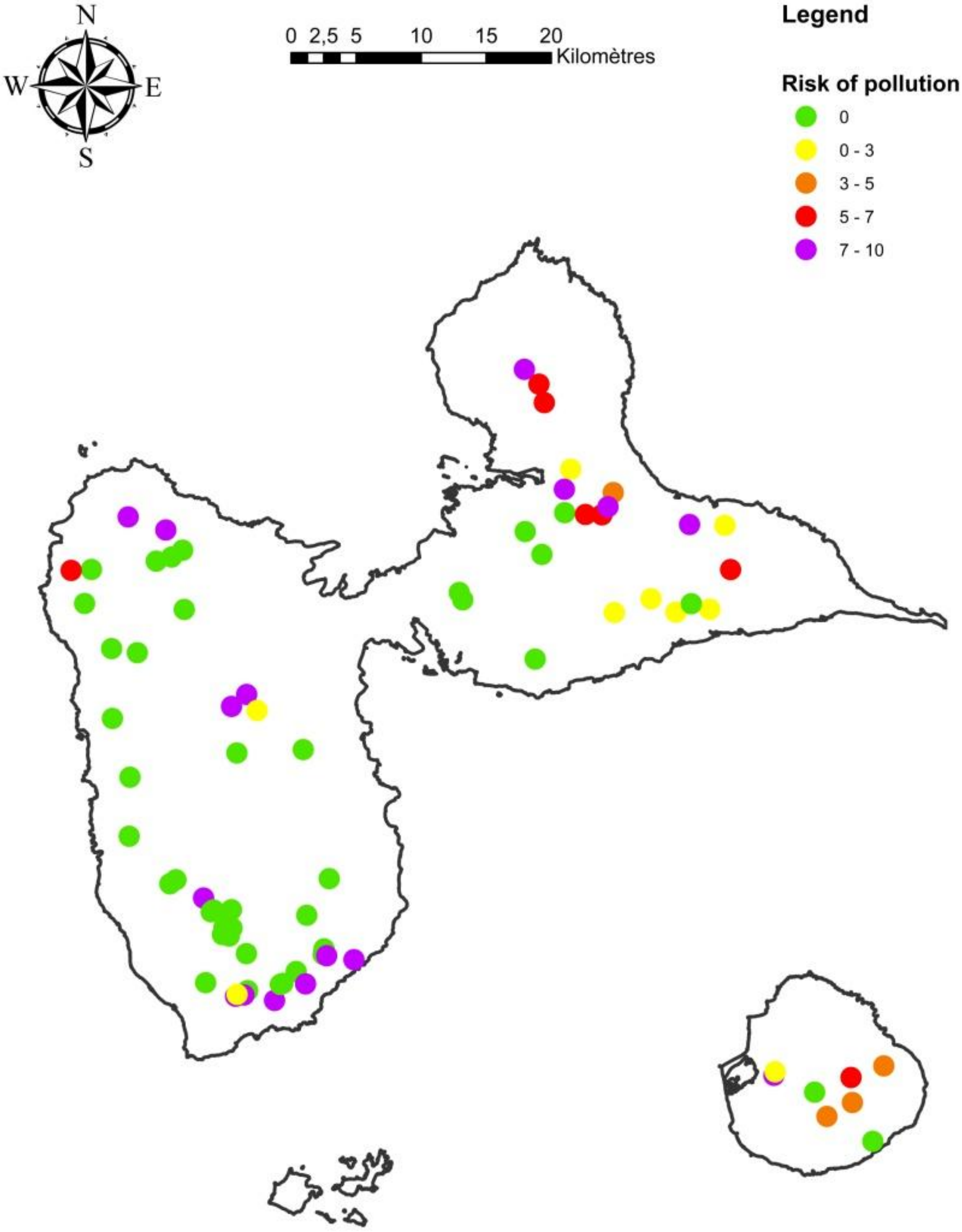
➢ 3 : Risk of contamination of crops by chlordecone at field scale.



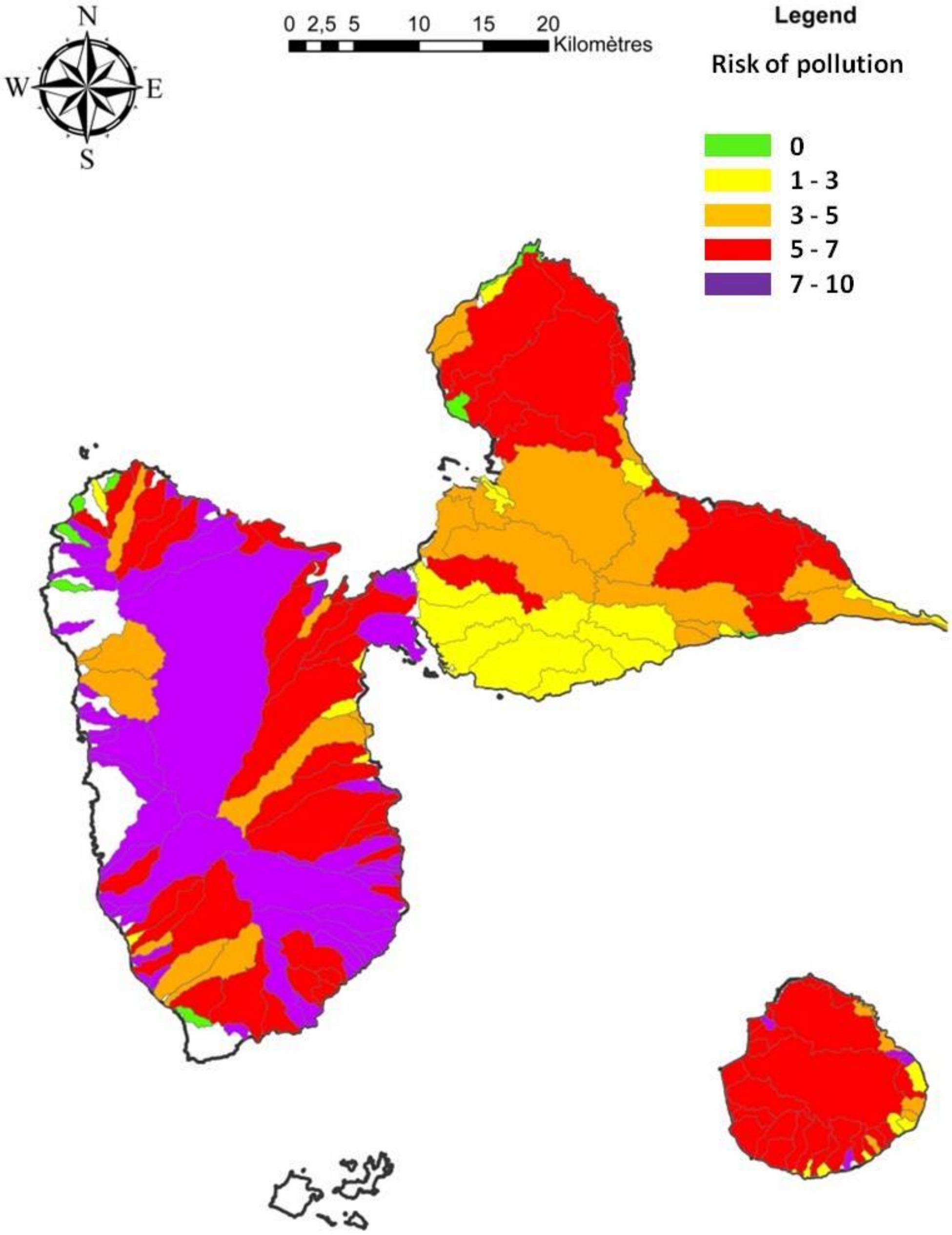
➢ 4 : Production of electricity at the district level.



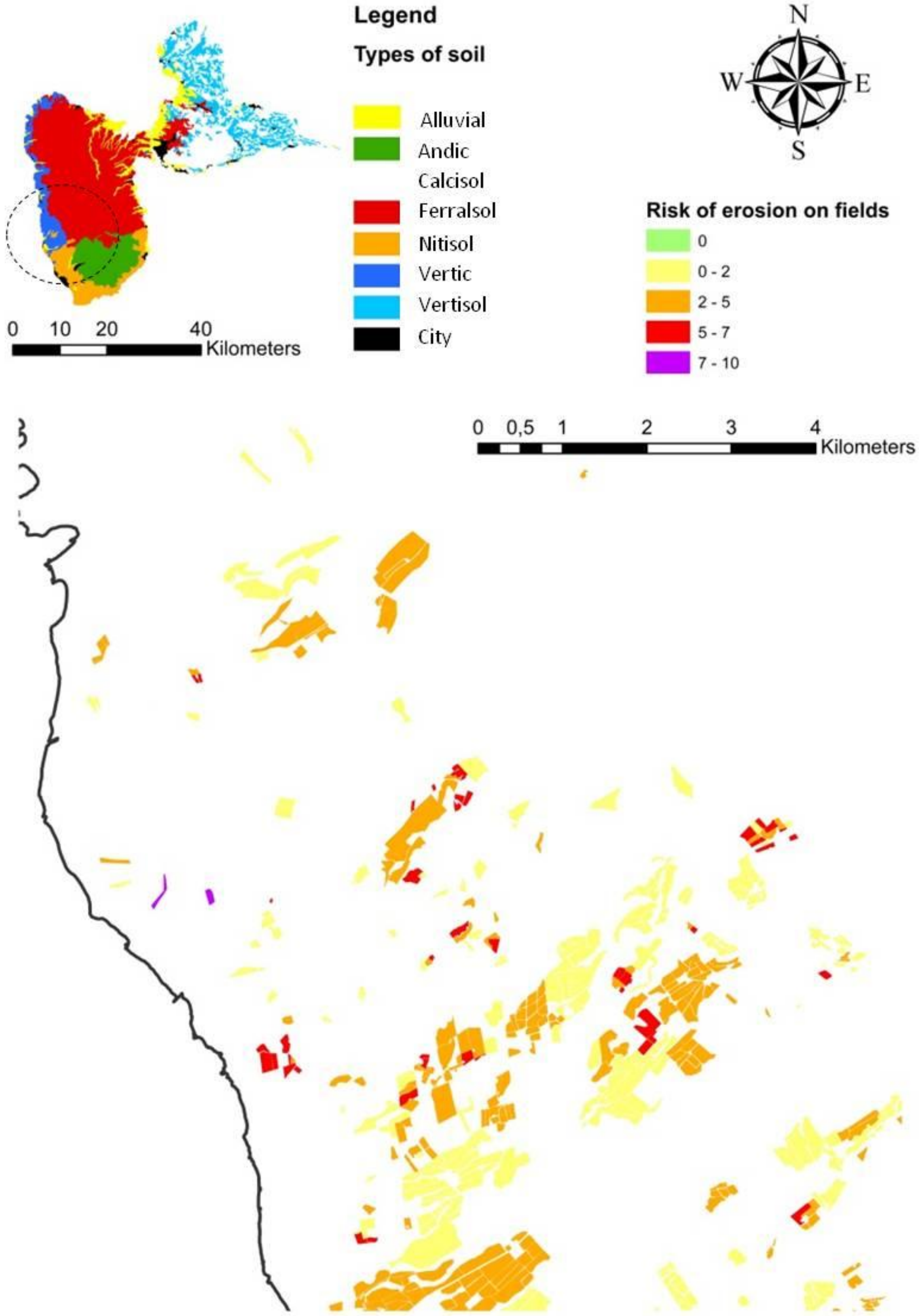
➢ 5 : Water used for irrigation at farm scale.



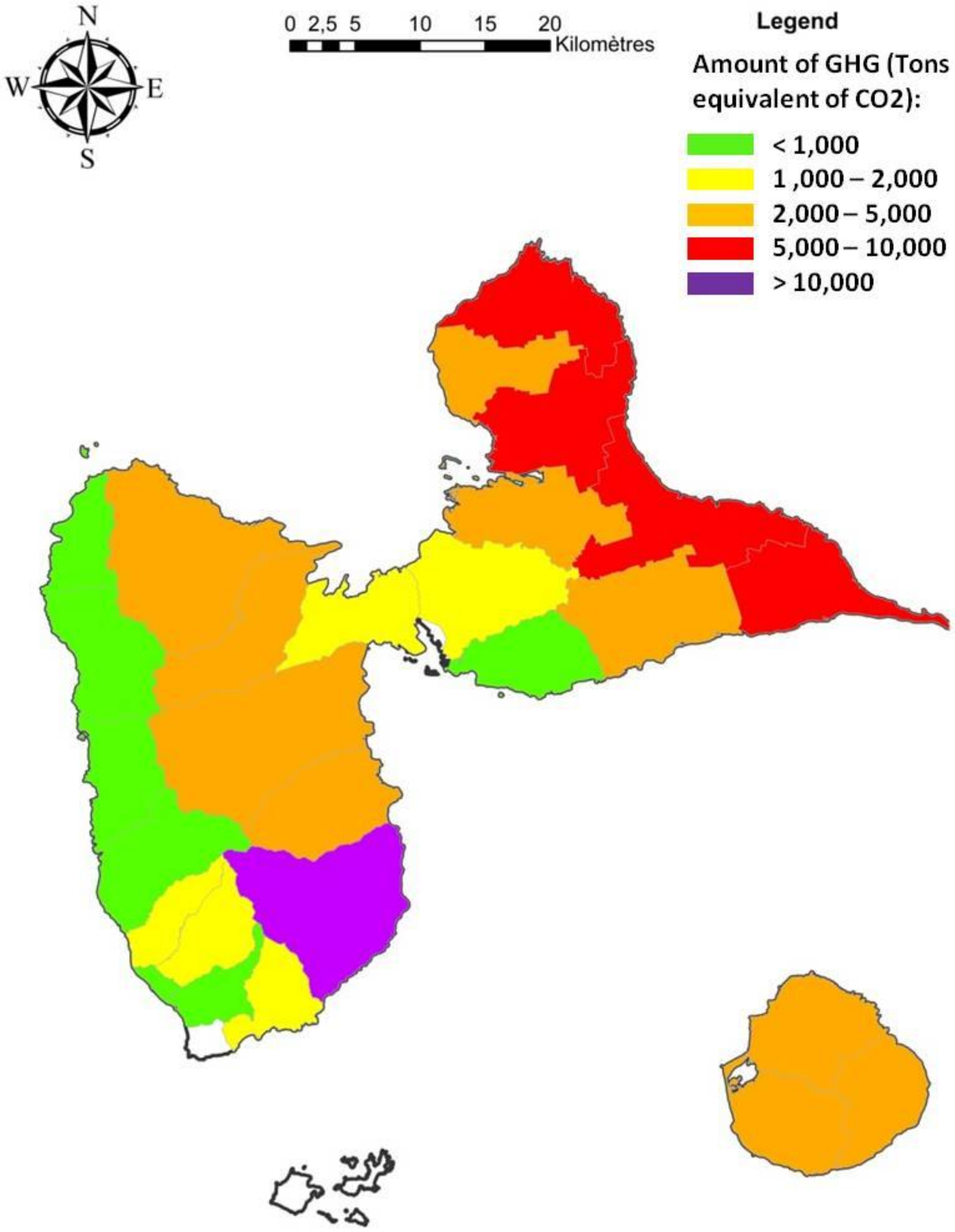
➢ 6 : Risk of pollution of water abstraction sources.



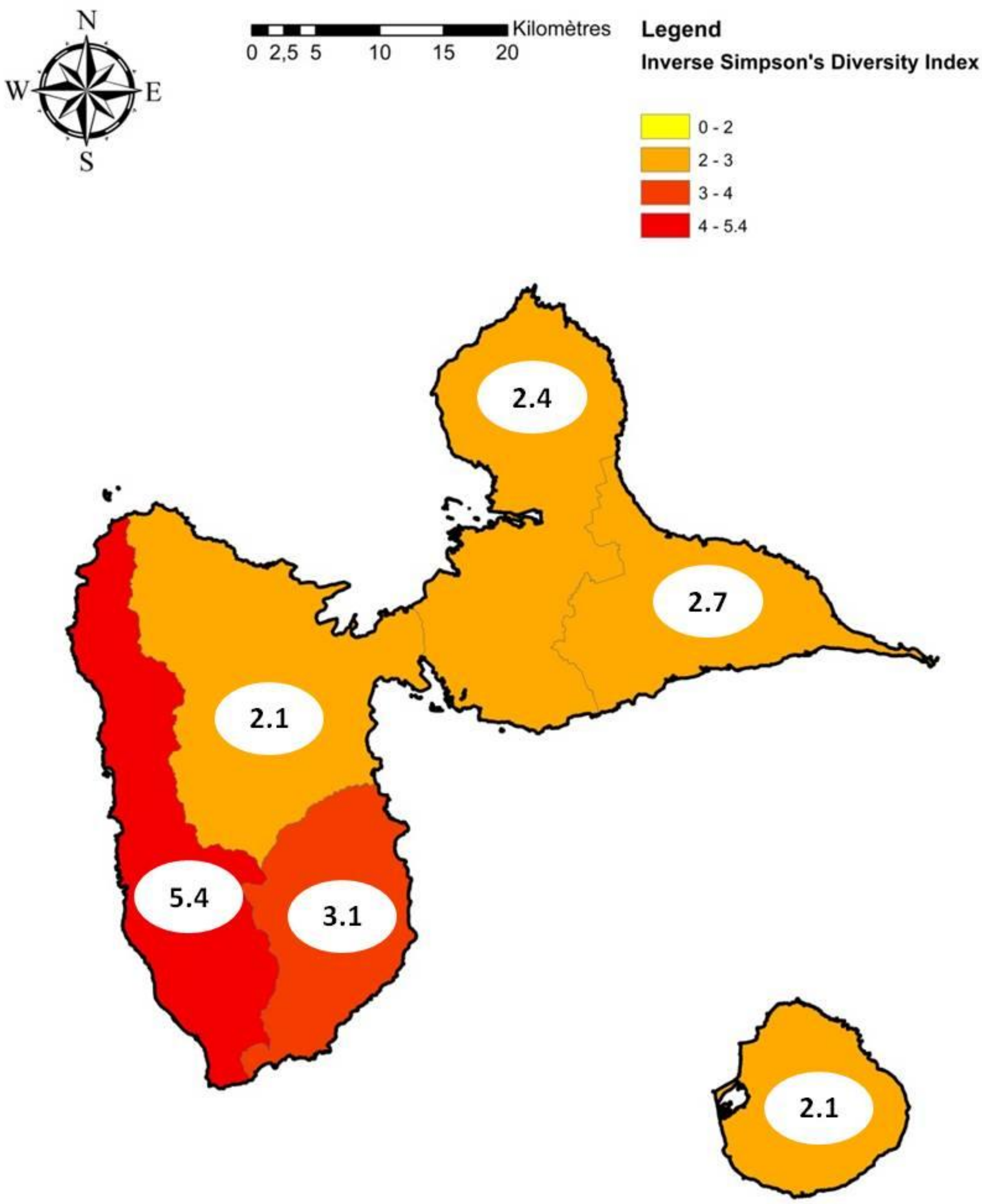
➢ 7 : Risk of pollution of water catchments.



➢ 8 : Risk of erosion on vertic soils.



- 9 : Emissions of greenhouse gas at the district scale.



➢ 10 : Landscape diversity at the district scale.