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

Pierre Chopin [a,*], Thierry Doré [b,c], Loïc Guindé [a], Jean-Marc Blazy [a]

[a] INRA, UR1321 ASTRO Agrosystèmes tropicaux, F-97170 Petit-Bourg, Guadeloupe, France
[b] AgroParisTech, UMR 211 Agronomie, F-78850 Thiverval-Grignon, France
[c] INRA, UMR 211 Agronomie, F-78850 Thiverval-Grignon, France

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ABSTRACT

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

1. Introduction

Agriculture plays an active role in the provision of ecosystem services by way of ecosystem management. Recent studies have shown that the spatial organisation of cropping systems, which are called cropping system mosaics at the landscape scale, drives the provision of some ecosystem services (Thenail et al., 2009). These cropping system mosaics contribute to the protection of soils (Ronfort et al., 2011), the rational use of water (Bergez et al., 2007) and the conservation of biodiversity (Rusch et al., 2012), among others. The cropping system mosaic is also important for the provision of economic and social services, such as the provision of food and employment. Cropping system mosaics are the results of farmer cropping system choices at the field level (Dury et al., 2011).

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

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

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

* Corresponding author.
E-mail address: pierre.chopin@antilles.inra.fr (P. Chopin).

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cropping system changes in current bioeconomic models is not spatially explicit, which decreases the usefulness of the assessment for decision-makers, who want to determine the impact of the policy on the cropping system mosaics and the evolution of the contribution from these mosaics to the sustainable development of their region. Some regional models including SOLUS (Schipper et al., 2000) and Landscape IMAGES (Groot et al., 2007) take different spatial scales into account in the design and assessment of policy support for sustainable land-use options. However, SOLUS does not directly account for individual constraints at farm level (Schipper et al., 2001) and IMAGES is mostly used to optimise landscape functions to explore possible trade-offs among these functions with an evolutionary algorithm.

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

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

2. Material and methods

2.1. Area of implementation

We implemented our generic bioeconomic model in Guadeloupe as an example. Guadeloupe is a French archipelago located in the Caribbean. In this area, the climate is tropical, rainfall is positively correlated with relief, and ranges from 1000 to 5000 mm yr^{-1}. Soils in the mountain areas are acid, Andosols, Nitosols, Ferralsols and vertic soils, while flat lands have Calcisols and Vertisols. The total cultivated area of the archipelago, which is composed of the Grande-Terre, Basse-Terre and Marie-Galante islands, is 32,948 ha (PDRG, 2011), the different cropped areas and their spatial arrangement within the territory, is shown in Fig. 1. There are 7749 farms in Guadeloupe, and their sizes range from less than one hectare to more than one hundred hectares, with an average of four hectares (Agreste, 2011). This variability in the socioeconomic and biophysical context and farm resources is responsible for the variability of the cropping systems, described through typologies such as that of Blazy et al. (2009) for banana farms and Chopin et al. (2015) for farming systems.

2.2. Overview of the bioeconomic model MOSAICA

The modelling framework with the inputs and outputs of the Multi-scale model of the crOpping Systems Arrangement and Its Contribution to sustAinable development (MOSAICA) is shown in Fig. 2. The inputs of the model are i) the geographic database of fields that contain information about the biophysical context and the farm structure, e.g., the farm size and the land tenure, ii) the database of activities that describe the cropping systems and technical-economic coefficients that can be allocated to fields and iii) the farm typology and the classification algorithm for the eight farm types. The model optimises the sum of individual farmer's utilities at the regional scale, which includes expected farm revenue and the risk aversion towards price and yield variations. The allocation of cropping systems is modelled through a set of equations that model the choice of cropping systems by farmers at different scales, namely the field, farm, sub-regional and regional scales. Optimisation is performed at the regional scale because equations are implemented at this scale to constrain the overall quantity of production for some crops within the entire area of study (because of market sizes or production quotas). The outputs of the model are the cropping system mosaics and the calculation of a range of sustainability indicators.

2.3. Model inputs

2.3.1. Building the geographic databases

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

In our case study in Guadeloupe, we worked with a geodatabase of fields that was provided by the local agency that helps farmers with their subsidy applications. The initial geographic database gathered 25,057 fields, owned by 5336 farmers, and the crops grown on them in 2010. The reliability of the farm and field databases is checked by comparing the area of each crop in the database with the agricultural census data in 2010 (Agreste, 2011). We can see that the total number of farms in the database is smaller than the actual number, 5336 farms compared with the initial 7749 farms, from the statistics. This discrepancy in the database is quite homogeneously spread among the sub-regional areas, but the Marie-Galante area is better represented than the eastern Grande-Terre and the southwestern Basse-Terre. The crop areas follow trends that are linked to the number of farms. Except for the lack of data on crop-gardening and pastures, a gap that prevents us from generalising some of the trends in changes observed in these crops (Fig. 1), the database is satisfactory because it represents 80% of the agricultural area.

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