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Ph.D. Thesis

Spatial analysis in MuSIASEM

The use of Geographic Information Systems and Land Use applied to the integrated analysis of rural systems' metabolism

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Chapter 6

Mauritius: the idyllic sugarcane island

6 Mauritius: the idyllic sugarcane island[19]

6.1 Introduction

In this chapter I show a practical application of the MuSIASEM approach tested on a system where we integrate several dimensions and scales in order to present a more elaborated final case study. In particular, we analyse Mauritius Island and we focus on applying MuSIASEM to study some concrete problems related with the future development alternatives, integrating the lessons developed along the previous chapters. In this case we use the approach for the first time to establish the nexus among food, energy and water at different levels and scales of analysis, integrating in practice many varied sources of statistical datasets and GIS data. The goal is to implement a *diagnosis* of the current metabolic patterns of the system and, based on this first stage, elaborate a *simulation* of possible future scenarios.

This chapter is based on the results of the application of MuSIASEM to the case study of Mauritius, in the context of the GIZ-funded FAO project “Application of the MuSIASEM approach to three cases in the agrifood sector” (GCP/GLO/445/GER (GIZ)[20], in collaboration with the Energy Team of the Climate, Energy and Tenure Division (NRC) of the UN Food and Agriculture Organisation (FAO). The study of Mauritius is the result of the input from several colleagues of the research team, however I was the leader for this case study, and I will focus on presenting those parts more related with my personal contribution to the case and I will put the effort on explaining the particular methods I implemented relevant for the aims of this thesis.

As we will see in detail along section 6.1.1.2, Mauritius has big challenges regarding its immediate future due to its current specialization in sugarcane exports, which makes the whole territory dependent of various factors whose mid-term sustainability is questionable. If this system intends to maintain a similar standard of living, it is imperative for them to use robust analytical tools to be able to evaluate possible future alternatives. They could try for example to achieve a higher level of self-sufficiency on some strategic resources (e.g. food, energy, materials, and capital). The following exercise addresses the theoretical and methodological challenges related with these issues. Please keep in mind that this case study is again a mere illustration of possible analytical tools to deal with these problems, and by no means it is meant to actually guide policy development. A proper application of MuSIASEM demands the involvement of local actors and experts, a prerequisite that was not fulfilled in this project.

The overall goal of this chapter is to illustrate the use of some innovative analytical tools (focusing on geographic methods) in an empirical study applied to a system where we considered for the first time many biophysical dimensions simultaneously (food, water, energy, land and human activity), and also to explore the particular usefulness of GIS for the diagnosis and simulation processes of the analysis.

In section 6.2 I will summarize the particular way of how MuSIASEM was applied to this case study and the innovative approaches featured in this project. Section 6.3 describes part of the methodology undertaken in this case, focusing on the links among some dimensions with land use and the calculations made using GIS tools. Section 6.4 of this chapter focuses on the particular results of applying this approach to the Mauritius case study, illustrating what kind outcomes we obtain regarding the possible trade-offs at different scales of analysis.

6.1.1 Mauritius as a perfect case to test the approach

Since its independence in 1968, Mauritius has started a gradual liberalization and diversification of the economy, from an agricultural based system to a big expansion of the industrial (18% of Gross Value Added), real state (12%),

[19] This case study based on the chapter “The Republic of Mauritius” prepared for the book Giampietro, M., Aspinall, R.J., Ramos-Martin, J., Bukkens, S.G.F. (Eds) (2014) *Resource Accounting for Sustainability Assessment: The Nexus between Energy, Food, Water and Land Use*. Routledge, London.http://www.routledge.com/books/details/9780415720595/

[20] http://www.nexus-assessment.info/

financial (10%) and tourism (8%) sectors (Ministry of Finance and Economic Development, 2012f). The island is then famous for becoming a tropical touristic destination, a tax heaven, and a sugarcane exporter. Mauritius Island represents an exceptional platform for testing the MuSIASEM approach given its particular economic and biophysical conditions:

- Although it is a small State, Mauritius is a system with a fully diversified and relatively complex recent economy that can be subdivided into the most common hierarchical levels and compartments of modern socioeconomic systems. As an independent State, Mauritius also has institutional and political sovereignty, making it an autonomous territory which does not tribute for its managing options to any higher level system. In a biological simile, the Mauritian territory is a full autonomous organism, not just an organ of a larger organism with partial functions.
- It is an island, so its physical borders (the sea) make it a well geographically delimited territory. The size and identity of the metabolic system expressed by the funds is patent, as the fund land use of this system is invariable along the time. The fund human activity is also pretty stable and the possible variations are easily measurable, because exchanges with other systems (migrations and tourism) are perfectly quantifiable in this territory. Being an island is also relevant for tracing the exchanges of flows, as the imports and exports become very evident. Furthermore, these exchanges are crucial to understand the degree of openness in relation to various aspects with the rest of the world.
- Mauritius has very interesting issues to study about current dependencies on some key assets (energy and food). As a territory with limited natural resources to supply the most basic goods that its own society consumes, the choices for patterns of metabolic profile in relation with other systems have critical implications.
- Finally, as a small island, we could say that Mauritius is immediately affected by the possible actions on various dimensions. The effects of whatever decision undertaken about the future metabolic pattern will impact its own territory immediately. More specifically, the natural resources are clearly limited in this system, and the ecosystem is in a particularly delicate equilibrium. The reader may recall that the sadly famous case of the extinct dodo (Turvey & Cheke, 2008) comes from this island, a lesson that will remain in the memories of Ecological History. We could also keep in mind the lesson of what happens to Nauru, a Micronesian island that exploited its lands so much for mining extraction of phosphates that now the island is almost literally destroyed (Marks, 2008).

6.1.1.1 Geography of Mauritius

Mauritius is located in the Indian Ocean, at more than 800 km from Madagascar. Its surface covers 204,000 hectares (FAO 2013a), including the islands of Agalega, Cargados Carajos and Rodrigues, and its highest peak ranging at 828 metres above the sea. The island has a volcanic origin, so its geology is all influenced by this fact, except for some coral formations of the reef and few alluvial areas. The climate in Mauritius is humid, subtropical and maritime (Saddul, 1995; Proag, 1995), due to its tropical latitude, small size, small altitudes, and distance from continents. There are two main seasons, a warm and rainy season with 79% of the rainfall, and a more dry winter season from May to October. The temperature ranges from 16ºC to 28ºC, and humidity remains quite constant about 80% along the year. Rainfall varies into three main climatic zones (subhumid, humid and superhumid) according to the elevation, with an average annual precipitation of more than 2000 mm. Mauritius suffers occasionally from cyclones, affecting considerably the agricultural production (Proag, 1995).

Half of the surface of Mauritius is used for agricultural production (FAO, 2013a), and the urban area is quite extended covering 15% of the island (Chung Tze Cheong et al., 2011). The forests, shrubs, and rocky area represent 33% of the land (FAO, 2013a; Chung Tze Cheong et al., 2011). Sugarcane lands have lately slightly decreased, however, it remains by far the most important agricultural crop. The four major sugarcane varieties include R570, M 3035/66, M695/69 and 1658/78 (Chung Tze Cheong et al., 2011). The rest of lands for other agricultural crops cover less than 12% of the harvested land, and the pastures cover around 10% of the land under production. The non-sugarcane crops are potatoes, few vegetables and fruits, tea and tobacco. A map we created for the project from satellite imagery of the main land covers of the island is shown in Figure 33.

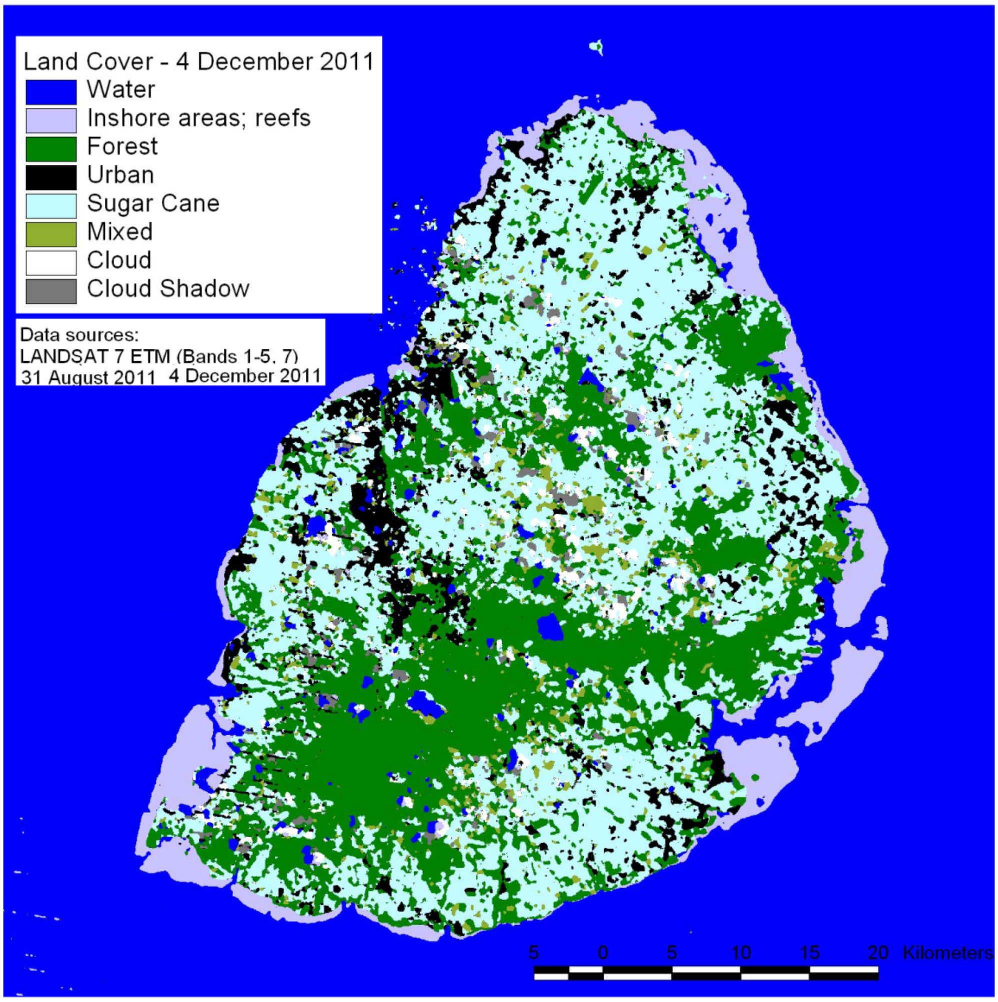


Figure 33. Main land covers of Mauritius. Elaborated by Richard J. Aspinall from LandSat 7 imagery for the book of Giampietro et al. (2014).

6.1.1.2 The issue of specializing in one single crop type

Mauritius has about half of its territory available for agriculture (FAO, 2013a). Sugarcane occupies 78% of the current land use for agriculture, so the island is clearly specialized in this crop production. Apart from dominating the Mauritian landscapes, thus occupying a large part of the territory, sugarcane is as well the activity with the highest use of water resources, using 65% of the total water consumption of the island for this single task. The sugarcane is exclusively run as an industrial crop for export, although sugar exports contribute only to 2.5% of Mauritius' GDP. A by-product from sugarcane called bagasse (a fuel made from the fibrous wastes of the sugar production) is burned in thermal plants to provide electricity.

The key issue now is that the demand of sugarcane abroad is under threat due to the change of the EU policy regarding projected use of biofuels (Harrabin, 2008; Adam and Jha, 2008; Kanter, 2008), so Mauritius urgently has to decide what to do with all the sugarcane production. At the same time, since the country is using most of its agricultural resources (land, labour, machinery, and water) only for sugarcane production, Mauritius is highly dependent on the external supply of many goods and services to maintain its current standards of living.

6.2 Analysing the nexus between water, energy and food with MuSIASEM

6.2.1 Diagnosis

For the *diagnostic* stage of the study an innovative analytical framework was developed (this is the first time we make it so elaborated) where it was possible to integrate information about:

- **Funds**: in this case study the demography, the labour force, the technical capital and the colonized land are analysed. In our approach these dimensions are formalized and accounted as human activity (in hours), power capacity (in watts) and land use (in hectares).
- **Flows**: for the first time this case study is used to introduce the analysis of the food flow in socioeconomic systems. The exosomatic energy, water and monetary flows are also considered. Different grammars were developed (shown in section 6.2.3.1) to study these flows and to integrate their analysis into a common framework.
- Finally, the **flow/fund ratios** of the dimensions previously considered in terms of density (flows/hectare) and intensity (flows/hour) are used to describe the metabolic performance of the system across different scales. These ratios can be used as benchmark values to characterize the profile of the socioeconomic system.

The diagnosis is implemented to analyse several lower-level compartments representing functional elements of the system distributed across hierarchical levels of organization. The choice of the selected functional compartments in the analytical phase depends on the aim of the study. They must also be practical for data collection (accommodate to the aggregation degrees of the statistical data), mutually exclusive, and the sum of the parts must equal the size of the total. This particular application is dividing the functional compartments of the system into two main parts: the "end-uses" compartments representing the consumption side, and the "sources" compartments, which represent the supply side. The *end-uses* are the various socioeconomic sectors that were classified as: households (HH), agriculture (AG), energy and mining (EM), rest of remunerated economic activities (PW*), and exports, which for the particular purpose of this study was divided into agricultural exports (EXP_{AG}) and the exports of the rest of the economic sectors (EXP_{PW*}). The *sources* providing the supply of flows are divided in our study into the domestic supply and the imports from abroad. A final compartment in the sources side was added to reflect some virtual imports of resources embedded in the imported goods, such as the water and agricultural land required to produce the imported food.

6.2.2 Simulation

For the *simulation* stage, we checked the feasibility, viability and desirability of some alternative scenarios of future development.

- The **feasibility** is determined by the compatibility of the flows required by the society and the sink capacity of the environment with the boundary conditions of the ecosystem. This is analysed using GIS, which provides a characterization of the demanded flows of the socioeconomic system over the information about the environmental constraints provided by the geographical configuration of the ecological features.
- **Viability** checks the congruence of the demand and supply flows across the internal different levels and compartments, and with the whole system. The scenarios are estimated with the technical coefficients obtained in the diagnosis (the "density" and "intensity" of flows over the various compartments). We also check that the total consumption of the *end-uses* must be congruent with the technical coefficients of the elements of the system in charge of the *supply* side. We arrange the information in a "Multi-level Table" where it is possible to implement both the Sudoku technique and check the results of the Mosaic effect.
- Finally, it is possible to provide a series of indicators based on flow/fund ratios of the end-uses compartments of the simulated scenarios in order to check the desirability of the proposed alternatives, by comparing them to benchmark values of those flow/fund ratios for given types of socioeconomic systems.

6.2.3 Quantitative description of the profile of the metabolic system analysed

6.2.3.1 The grammars of food, energy, and water

For this project the team developed some multi-purposes grammars to define and quantify the flows of food, energy and water. The purpose of generating these grammars is to be able to describe the relevant analytical stages associated with the supply and consumption of the flows in the system considered. As we can see in Figures 34 to 36, in particular, these multi-purpose grammars allow arranging the information to analyse the following:

- The total gross requirement and supply of flows for the system (at the left of the diagram)
- The net requirement by the functional compartments for the end-uses (at the right of the diagram)
- The fraction of the flow for internal consumption
- The losses of flows at the different stages of the network
- The degree of self-sufficiency of the system given by the internal supply
- The fraction of flows for exports and the imports required
- The internal autocatalytic investment, which consists in those flows that need to be reinvested to maintain the flow supply (such as the energy to run a power station, or the seeds required to grow more food)

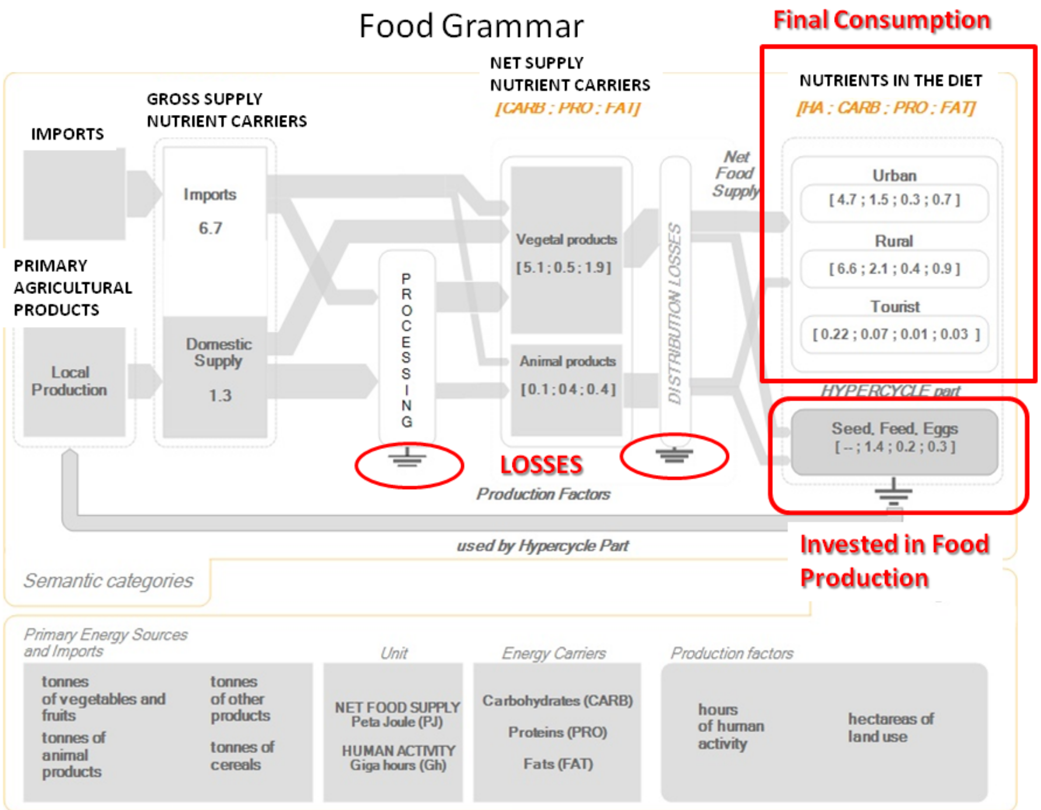


Figure 34. Food grammar of Mauritius. Elaborated by Juan Cadillo Benalcazar for the book of Giampietro et al. (2014).

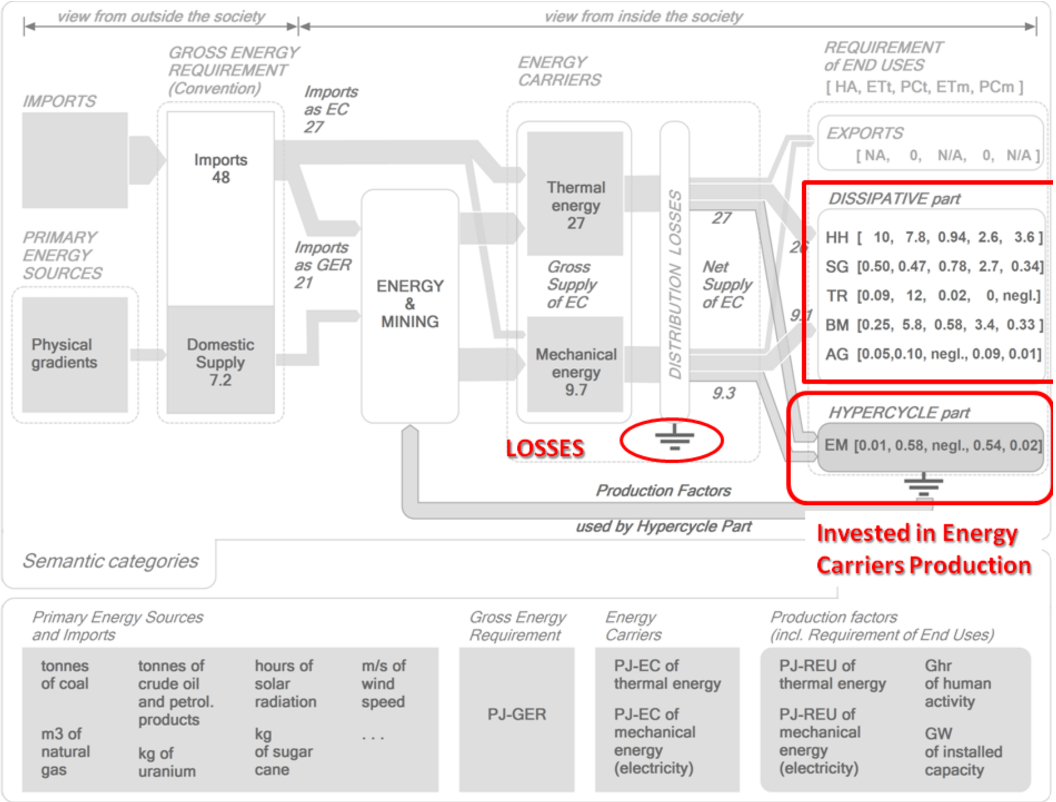


Figure 35. Energy grammar of Mauritius. Elaborated by François Diaz-Maurin for the book Giampietro et al. (2014).

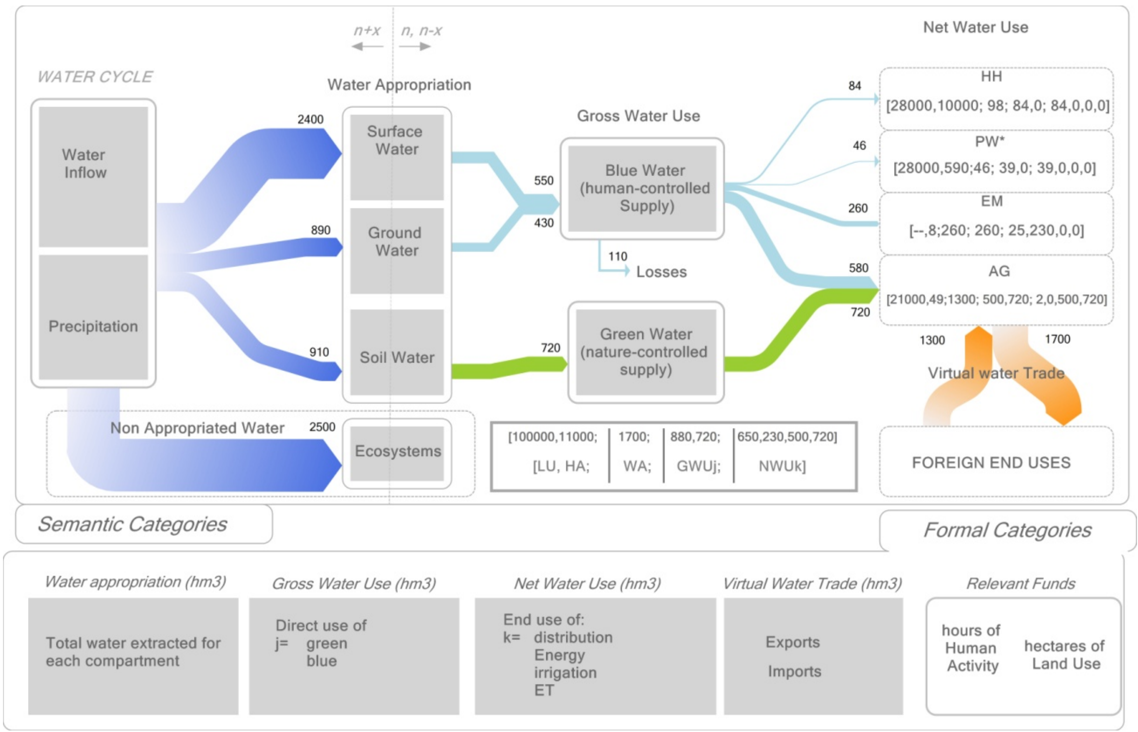


Figure 36. Water grammar of Mauritius. Elaborated by Cristina Madrid for the the book Giampietro et al. (2014).

Note that the food grammar (Figure 34) has a similar structure to the energy grammar (Figure 35). This is in part caused because the grammar of the food is in fact accounting for the endosomatic energy, whereas the energy grammar is about the exosomatic energy throughput of society. At the end they both perform similar loops, differently from, for example, how the water flows in the system (Figure 36), which has very different conceptual entry points and does not have compartments requiring water for operation (there are not relevant autocatalytic loops). For detailed information about these multi-purpose grammars and further analysis of the theoretical implications, please see Giampietro et al. (2014).

6.2.3.2 *The fund elements of the system*

As seen in previous chapters, MuSIASEM always characterizes flows in relation to funds (e.g. water per hectare of agricultural land, food consumption per year per capita), so the performance and the size of the parts composing the system can be accounted for. In this study, apart from considering the human activity and the land use, power capacity (PC) was also included. PC is the quantification of the technical capital available to perform activities where exosomatic energy is required (e.g. electronic appliances at home; machinery for the manufacturing sector; vehicles for transportation). The funds also provide information about the size of the various functional compartments across the hierarchical levels of analysis of the system under consideration.

6.2.4 The Multi-level Table

In this study we use what we have named the “Multi-level Table” (Table 3) to describe the metabolic pattern across hierarchical levels and dimensions of analysis, combining the information about the funds and flows distributed in the system among the functional compartments previously listed in Section 6.2.1.

Mauritius Diagnosis	FLOWS				FUNDS		
	FOOD (PJ)	ENERGY (PJ-GER)	WATER (hm3)	MONEY (million US$)	HA (million hr)	LU (k ha)	PC (GW)
HH	5.9	16	98	N/A	10000	28	4.5
PW*	0.8	37	44	8200	600		1.4
AG	1.3	negl.	190	220	39	21	negl.
EM	N/A	2.2	260	180	8	negl.	0.03
EXPORTS PW*	N/A	N/A	3	4900 (50%of GDP)	590	N/A	N/A
EXPORTS AG	negl.	0.36	1100	250 (2.5% of GDP)	39	54	0.02
WHOLE	8	56	1700	9800	11300	100	6
IMPORTS	6.7	49	N/A	6200 (63% of GDP)	N/A	N/A	N/A
DOMESTIC SUPPLY	1.3	7	1700	9800	11300	100	6
VIRTUAL IMPORTS	N/A	N/A	770	N/A	?	210	N/A

Table 3. Multi-level Table of the Mauritius diagnosis.

The Multi-level Table is a way to represent an integrated quantitative characterization of the metabolic pattern of the system across hierarchical levels (e.g., the whole, its compartments, and their subsectors) and different dimensions (e.g., demographic, economic, biophysical dimensions) of analysis. As a result, it is possible to obtain ratios for the flows of energy, water, food and money over three fund elements of human activity, land use and power capacity, being these ratios distributed across the functional compartments of the system. These ratios describe the performance of the compartments at their own operative scale (e.g. the water throughput per hectare in the agricultural sector, or the GDP per hour of human activity in the exports sector).

The values of the funds in the table over the different compartments also tell us about the structural relations between the functional parts and the whole. Using this information it is possible to obtain indicators to characterize the type of socioeconomic system, because the relative size of the functional compartments indicates if we are dealing for instance with an agricultural based socioeconomic system (e.g. Laos), a country which is service based (e.g. Sweden), a country specialized in manufactured exports (e.g. China), etc.

Finally, this kind of table allows the quantification of the exchanges of the system with other systems, in order to estimate the degree of self-sufficiency, dependency or openness of the system in relation with the various dimensions considered. For instance, we could check how an Arabic country could be self-sufficient in exosomatic energy, but maybe would be strongly dependent on food imports, thus requiring to export part of its oil production to get money in exchange for other key resources.

The main contribution of this sort of table is that it is possible to check in quantitative terms how the various flows and funds elements affect each other at (i) different hierarchical levels (i.e. vertically across the columns of the table) and (ii) across the dimensions involved in the analysis (i.e. horizontally across the rows of the table). This table indeed represents a practical application for both the Sudoku effect and the Mosaic effect!

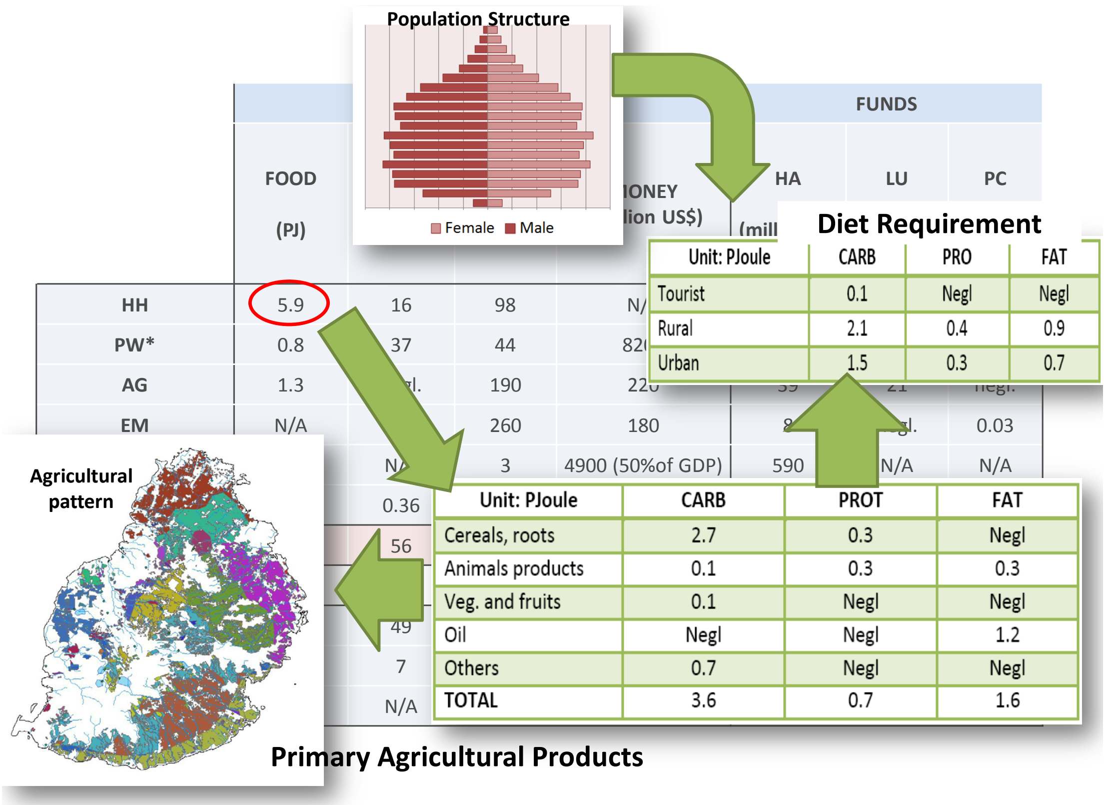


Figure 37. Example of opening a vector (food consumption by households) into its lower-level components.

Please bear in mind that the compartments of the multi-level table actually represent vectors whose values are in turn made of many other sub-compartments. For example, we can see in Figure 37 how the food consumption at household level is indeed defined by two matrices, one based on dietary requirements and one based on primary agricultural products. The diet is related with the demographic structure of the system (top of Figure 37), whereas the agricultural products depend on agronomic variables, which are in turn defined by geographic characteristics (bottom left of Figure 37). In this way we are applying a multi-level representation of vectors and matrices based again on the Sudoku effect.

6.3 Materials and methods

Data and sources for the whole analysis of the Mauritius case are very vast because they comprise many dimensions at multiple scales, so along this section I will mention only those methods which are directly related with the specific topic of this thesis: the food, water and land calculations in relation with the agriculture and the geographic analysis. Statistical data were in general obtained from the Ministry of Finance and Economic Development (2007, 2010, 2012a, 2012b, 2012c, 2012d, 2012e, 2012f) and the Ministry of Agroindustries and Fisheries of the Republic of Mauritius (2008), as well as from FAO (1995, 2001, 2009, 2010, 2013a, 2013b, 2013c). The Mauritius Sugar Industry Research Institute (MSIRI) (Chung Tze Cheong et al., 2011) also provided very useful information about land uses. All data refer to 2010 unless stated otherwise.

6.3.1 Calculating the data for food, water and land use

6.3.1.1 Analysis of the metabolic pattern of food

As seen in the food grammar (Figure 34), a quantitative link between the agricultural sector and the food flows was established. Specifically for the Gross Food Requirement we organized the information in a matrix (bottom table of Figure 37) where we set the relation among the energetic values of “nutrient carriers” (macronutrients such as carbohydrates, proteins, and fats required by human metabolism), and the categories of “primary nutrient sources” (the classes of food products that are sources of nutrient carriers, e.g. cereal, meat or oil).

6.3.1.2 The analysis of water metabolism

For households and industry, the analysis of water metabolism can be mostly covered using available statistical data. When water use statistics are not available, the estimation of water use could be calculated using benchmarks describing expected rates of consumption per typology of water uses (the specific Water Metabolic Rate–WMR), which depend on the type of industry and urban settlements.

However, for the data about the water used in agriculture according to the grammar of water (Figure 36) another type of assessment was required, as it depends on many geographical factors. The Penman–Monteith method (R.G. Allen et al., 1998) was used to get the Crop Water Requirement (CWR) and effective rain, using climatic, soil and crop data. For this calculation GIS provided the necessary information, as we will see in detail in the following Section 6.3.2.

6.3.1.3 Land use

For the detailed information about harvested land for every crop in agricultural lands, the data included in the tables of the Digest of Agricultural Statistics of the Ministry of Finance and Economic Development of Mauritius was used, the same as the source for the analysis of food flows in the diagnosis. An important land use type in the MuSIASEM approach is the urbanized land use, used to calculate the density of flows referring to those socioeconomic sectors different from agriculture (i.e. HH, and the other sectors–SG, EM, TR and BM–included all in the PW* sector). The urban area is not commonly reflected in land use statistics, so I had to look for remote sensing sources to get this information for Mauritius, in this case the Mauritius Sugar Industry Research Institute (MSIRI) had already calculated this area with remote sensing (Chung Tze Cheong et al., 2010). It is important to underline that in most of cases it is very difficult to discriminate among different land uses within the urban area belonging to the categories residential, manufacturing, services and government (the land occupied by various buildings and other infrastructures associated with these sectors) through remote sensing. Thus, for the land analysis a common category of accounting was adopted summing together all the land uses referring to all the economic sectors except agriculture (PW*), and the household sector (HH).

In relation to imports, it is possible to make an estimation of the virtual land associated with some imported goods such as food using the following protocol: (i) if the imported food is already being produced in Mauritius, then I use the land requirement per ton of the different imported products–by looking at the yields of various crops or the land requirement associated to animal products (pasture plus the double conversion of feed into animal biomass); (ii) if the imported food is not produced in the island, then I use an estimate of land requirement per ton of product using the value "hectares/ton of food product" found in the country providing the largest share of the imported product.

6.3.2 The added value of spatial analysis

6.3.2.1 Using GIS to get information for the diagnosis

As introduced in Chapter 4, it is possible to use the information given by the fund land use to estimate the characteristics of a certain geographical level in the territory (meso level) knowing the characteristics of the parts composing that level. Then, it is possible (i) to establish the rate of a certain flow per hectare (the *density*) for each land use (e.g. the food production per hectare), and (ii) using GIS, it is possible to know the distribution and extent of each type of land uses (e.g. type of crops) in that geographic entity. As a result we obtain the total amount of the flow (e.g. total food production) at that geographical level of the system. This is indeed what it is called in MuSIASEM the Mosaic Effect, in this case study it will be achieved through geographic analysis using GIS tools. This process is reflected in the following equation:

$$TF_{\text{region } j} = \sum \Phi_i \cdot x_i$$

$TF_{\text{region } j}$ = Total flow in region j, Φ_{LUi} = rate of flow/ha for land use i, X_i =area of land use i

In addition to this, with GIS is possible to find out data about flows which are not obtained through other sources (e.g. statistics) if the density of flows (rate of flow/ha) depends on geographic characteristics whose information can be obtained from maps in GIS layers. For instance, let's say we know in the first place the level of agricultural production associated to the type of soil and climatic zone. Then, with GIS we could combine the layers of the map of distribution of this crop with maps of the different soils and climatic zones. As a result, we obtain (i) the rate of agricultural production per hectare in every place, and (ii) the total production in the analysed area for this specific crop, by adding all the different ratios of flow/ha and their frequency on the map.

In the case of Mauritius, as we introduced in the previous methodological section 6.3.1.2 about water, this technique allowed the calculation of the total water consumption for agriculture, which depended on some physical characteristics associated with different geographic areas of the island (Figure 38). In particular, for the calculation of the agricultural water consumption in Mauritius, we made a discrete analysis and used data from the FAO's Climwat database (FAO, 2013c).

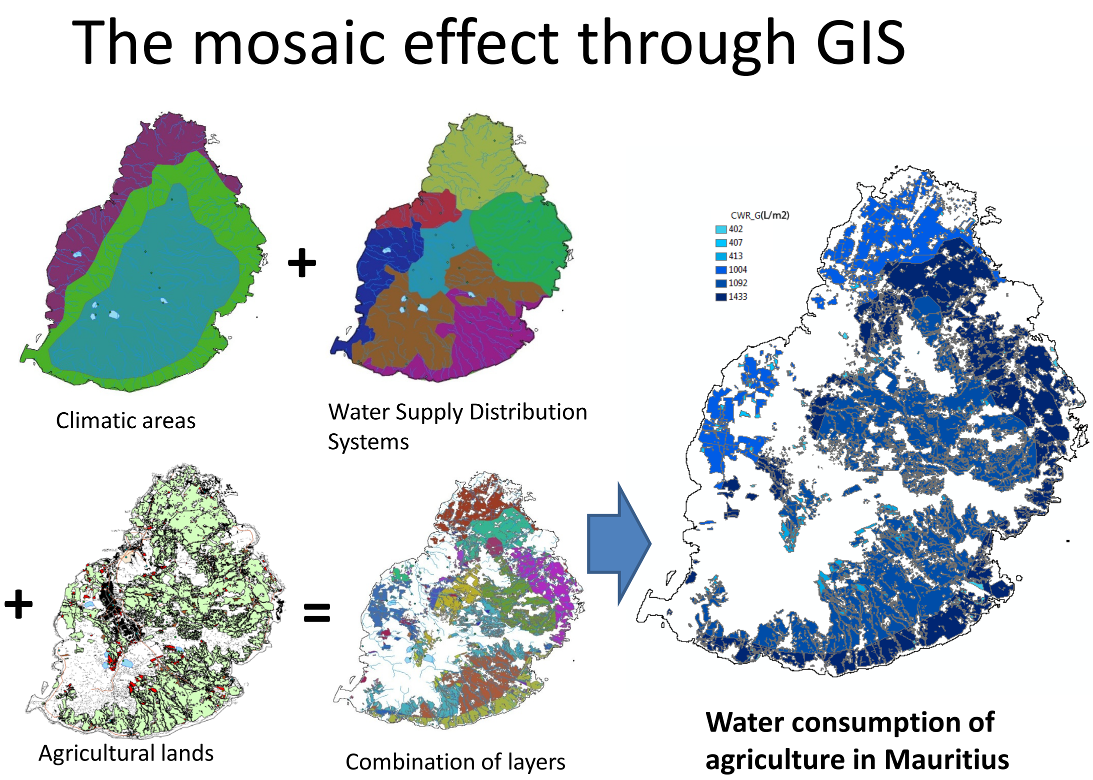


Figure 38. Calculating the agricultural water consumption of Mauritius.

It is possible to provide useful information for the ecosystem analysis by establishing the location of the water resources, which are given by natural divisions like the river basins. River basins can be easily obtained from a Digital Elevation Map (DEM) at various degrees of accuracy depending on the quality of the DEM. However, for sake of simplicity, in the Mauritius case study we organized this information using known “water supply systems” (second map of Figure 38), because in our case this existing classification was already considering water availability and population to be supplied, and because those “water supply systems” in fact follow the natural limits of water availability.

Moreover, using expected rates of flow/ha by type of land use is possible to estimate the specific use of water on those areas where data about the specific use of water per supply system was not available.

6.3.2.2 The use of GIS to simulate scenarios

The main power of GIS for the MuSIASEM approach is that it can handle information about the individual realizations of the metabolic profile of the system. This feature makes GIS a very useful instrument to build accurate scenarios that can additionally be expressed in a specific geographic arrangement and visualized in a map. It is possible to imagine the extreme relevance of this feature for example for the inhabitants of the population under consideration, because the different agents affected by the study use different geographic zones of the system. Expressing the results of the simulated scenarios on a map, different actors inside the system could check *how* the proposed scenarios are affecting differently each area of their territory, and thus affecting in a particular way to each of them.

The geographic information based in map layers was used to simulate scenarios in the case of Mauritius mainly for two purposes: (i) for the calculation of suitable lands for an alternative pattern of agricultural production (e.g. scenario 2a), and (ii) the estimation of resulting pattern of water consumption of the new scenario 2a.

GIS tools allowed checking the option space for a different mix of agricultural crops in Mauritius. For this purpose, after selecting the new mix of crops for the proposed scenario, we had to generate and cross the information given by maps describing (i) the current distribution of crops in the island, (ii) reject the areas obtained from a Digital Elevation Map (DEM) with too much slope for these crops, and (iii) discard those lands with inappropriate soil for the specific crops we have in the mix. The result of the combination of all this information is illustrated in Figure 39.

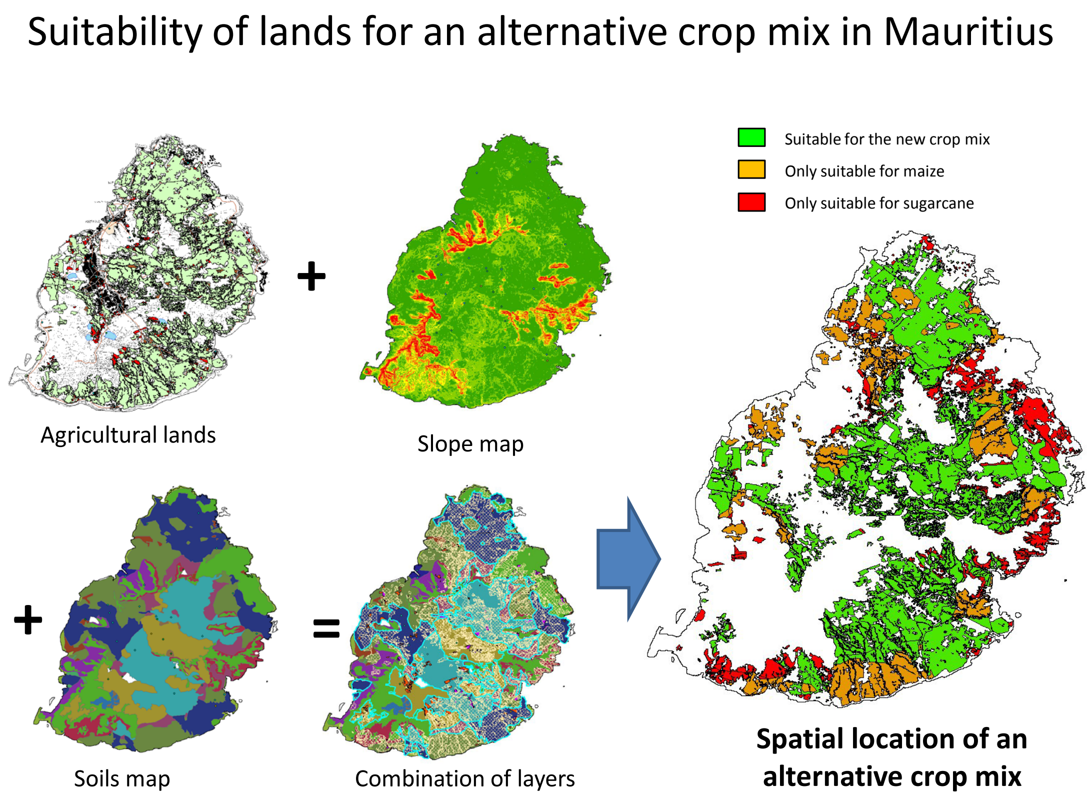
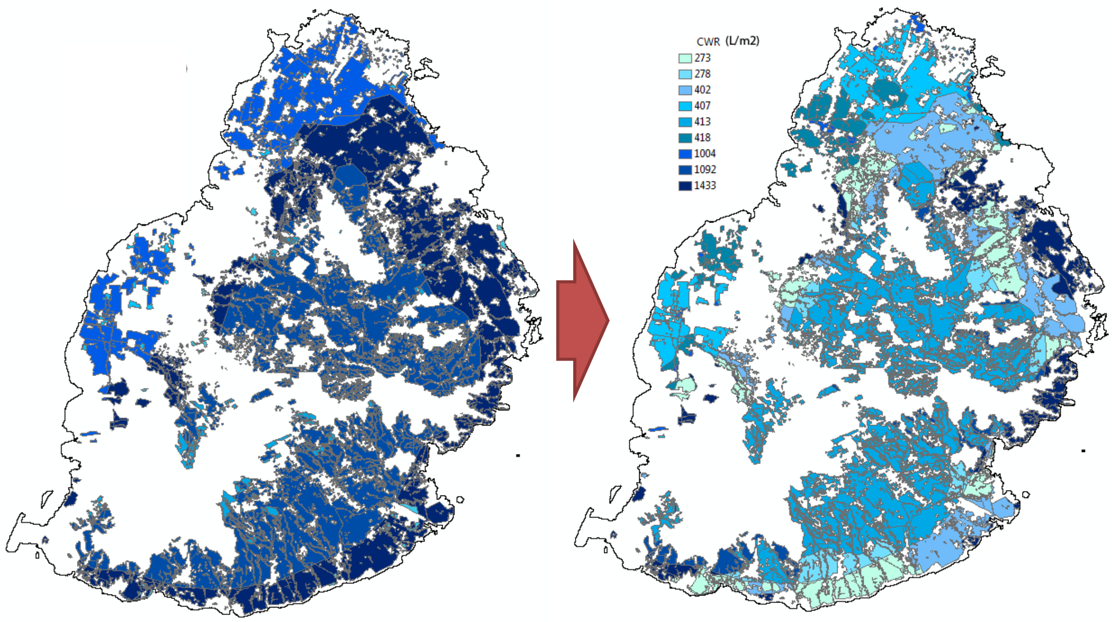


Figure 39. Estimation of the suitability of agricultural lands for an alternative crop mix in Mauritius.

Similarly to the previous section, where the example of calculation of the agricultural water consumption of Mauritius was explained, it is also possible to simulate the resulting pattern of water consumption in the new scenario, introducing the information provided by the map calculated in the previous step (Figure 39). In this case, the great difference in the pattern of water consumption for agriculture of the resulting distribution along the different areas of the island is evident (Figure 40). This figure at the same time represents a clear example of how using maps to express the different results of the simulated scenarios in the territory allows a detailed visualization that might be very useful for the different actors of the system considered in the analysis.

Estimating the geographical distribution of the new pattern of water metabolism



Current pattern of CWR

Scenario 2a pattern of CWR

Figure 40. Comparison of the resulting pattern of agricultural water consumption in the scenario 2a.

As we can see in Figure 40, using maps one could easily appreciate in a single snapshot both the overall change for the considered system, and at the same time one could zoom in and check the specific values at one particular location. For example, the farmers with lands in the southern coast of Mauritius could quickly check how this scenario changes dramatically the water consumption of their lands, as opposed to some farmers of the eastern coast that would retain a similar water consumption on the new scenario. Furthermore, since this method of expressing the results allows identifying heterogeneities in the system, one can focus the possible policies on those particular geographic places of the system which require more attention. This is just one example of the power of maps for expressing heterogeneous, complex, accurate and location-dependent results of an analytical approach such as MuSIASEM.

6.4 Results

6.4.1 Diagnosis of Mauritius

Looking again at the current situation of Mauritius shown in the multi-level table (Table 3), first some particularities about the choice of definition of compartments for the Mauritius case must be explained. We distinguished between the exports generated in the agricultural sector (sugarcane and sugar production) and the other economic sectors in PW*. MuSIASEM is an adaptable approach to the aims of each research project, and in this case we preferred to differentiate the exports to see separately the effects on the agricultural sector of Mauritius when considering the proposed scenarios. Exports compartments require production factors (funds and flows, such as labour, capital, land, energy, water) to generate products that are not finally consumed within the system considered, so these sectors use production factors but do not generate local supply. Evidently the exports generate monetary revenues, which can in turn be used to buy other products (e.g. those ones that Mauritius does not produce). In this case the agricultural exports were analysed separately because these type of products in particular consume an enormous amount of land and water while generating small value added, especially when compared to the Economic Labour Productivity (ELP) of other economic sectors.

In Table 3 we can see on the first place the box for the internal food demand of HH (5.9 PJ of food energy), representing the final food consumption of the people in Mauritius. The losses observed in the food grammar (Figure 34), are now represented in PW*, because these loses are taking place in the processing and distribution stages of the food chain, which pertain to the services, transportation and manufacturing sectors. The share of food that has to be reinvested (the hypercycle) into food production (i.e. seeds, feed, eggs and breeds) can be visualized in the corresponding compartment of agriculture (AG).

In Mauritius, it is possible to observe a clear dependence on imports for the food provision of the country when looking at the share of domestic supply. This is due to the fact that most of the agricultural land is used for sugarcane production, and the food crops grown locally represent only a small fraction (13%) of the total harvested land. Moreover, they basically grow fresh vegetables, fruits, tea and tobacco, and since the food grammar is in this case limited to the accounting of the energy contents of the nutrient carriers, these crops do not contribute with many calories to the overall food flow, given their particular nutritional composition. In this sense, in Table 3 we can see that in Mauritius they have to import most of the high energy content agricultural food products consumed in the country (such as grains, meat or oil).

It is possible to see a similar situation of dependence for the exosomatic energy. Mauritius is a country that has to import most of the energy (basically fossil fuels) required for its activities, as the island does not have exploitable deposits of any fossil energy form. With their own resources they just produce marginally some electricity from hydropower (3.7%) and wind (0.09 %). The bagasse mentioned before represents 20% of the gross energy for electricity production, but after transformation and losses, the bagasse becomes a scant contribution of 5% of the total net energy consumed in Mauritius.

Regarding the water issue, Mauritius has on average enough water from local natural resources for cultivating its crops, although there are important variations of precipitation levels depending on the three main climatic zones (subhumid, humid and superhumid). It is possible to see in Table 3 that, given that the sugarcane production is the most water demanding activity by far, Mauritius is virtually exporting most of the water resources consumed on the island. However, as it was seen in the water grammar (Figure 36), about half of the water consumed by agriculture is Green Water, that is, water available from the nature that is not inside the supply controlled by humans. In any case, agriculture is consuming 60% of the Blue Water, the water from the human water supply systems. Another remarkable feature is that since Mauritius is importing so much food, the virtual water imports are also really high compared to the domestic water supply for the food crops (770 hm^3 and 190 hm^3 respectively).

The urban area represents quite a large part of the colonized land (27%)on the island. In this category we include the residential area and all the built area for the industry, transport and services, as the surface used for these activities normally overlaps and it is not easy to distinguish among them. The rest of the colonized land is used for agriculture, mainly for the sugarcane production. We can see in Table 3 how the land of the sugarcane is allocated to exports (EXPORTS AG). Therefore, Mauritius has to “import” a lot of virtual agricultural land embedded in the food that they are not producing but they are consuming from imports. The amount of hectares virtually imported through food is calculated by taking into account the yield (tons/ha) for every crop of the main exporting country. The result of this current dynamic is that due to the food imports they are virtually consuming more than double the land they are currently exploiting on the island. This is a critical feature on an island, because land is clearly a limited resource. As we will see in the next part, scenarios are exploring what happens when they attempt to use their own resources to grow the food they consume.

Mauritius is an island where the economy is quite focused on trading, importing, exporting and re-exporting varied goods and services. In Table 3 is possible to see how the labour force is allocated to the activities related with exports and trading, while the non-agricultural exports represent 50% of the GDP of the island. This is probably explained in part due to the condition of Mauritius as a tax heaven. However, the most remarkable feature is that sugar exports represent finally only 2.5% of the GDP, although this crop was using much of the productive resources of the island (water, land and labour). This means that the sugarcane sector does not represent a major impact in the overall economy of Mauritius, although the only current purpose of this crop is exporting it for cash revenue, without contributing significantly to the island food nor energy self-sufficiency.

In conclusion, considering the condition of Mauritius as an island, with the multi-level table shown in Table 3 is possible to get an idea of the subsequent implications for the levels of self-sufficiency of the system regarding the current metabolic performance of consumption, uses of resources, and exchanges with other systems.

6.4.2 Scenarios of Mauritius

Along the following section I will explain the resulting output of the simulations undertaken by this case study. Two main scenarios were generated to check the trade-offs of different alternatives when attempting to change the situation regarding the current sugarcane production on the island. The scenario 1 proposes to use all the sugar production to produce agro-fuels (ethanol) to supply part of the internal consumption of fuels in the country. The second scenario presents the substitution of sugarcane production with an alternative crop mix providing food for the Mauritian population. The second scenario consists of two versions: the first one (scenario 2a) looks at the geographical constraints of expanding the alternative crop mix in the agricultural lands of the island, and the second one (scenario 2b) is based on the information regarding the available agricultural labour force in Mauritius to check how much of the alternative crop mix could be produced.

Scenario 1: Using the present sugarcane output for local ethanol production

Mauritius Scenario 1	FLOWS				FUNDS		
	FOOD (PJ)	ENERGY (PJ-GER)	WATER (hm3)	MONEY (million US$)	HA (million hr)	LU (k ha)	PC (GW)
HH	5.9	16	98	N/A	10000	28	4.5
PW*	0.8	37	44	8200	600		1.4
AG	1.3	negl.	190	220	39	21	negl.
EM	N/A	2.9	1400	?	47	54	0.04
EXPORTS PW*	N/A	N/A	3	4900 (50% of GDP)	590	N/A	N/A
EXPORTS AG	negl.	negl.	0	0	0	negl.	negl.
WHOLE	8	56	1750	9800	11300	100	6
IMPORTS	6.7	41	N/A	6000 (61% of GDP)	N/A	N/A	N/A
DOMESTIC SUPPLY	1.3	15	1750	9800	11300	100	6
VIRTUAL IMPORTS	N/A	N/A	770	N/A	?	210	N/A

Table 4. Multi-level table of the scenario 1 in Mauritius.

This scenario is conceptually quite simple: they stop exporting the sugar and they use it to produce ethanol for consuming it inside the island to try to improve their level of self-sufficiency of exosomatic energy. Looking at Table 4, we can see that for this simulation we simply need to move to the sector of energy and mining (EM) all of the production factors–the area planted to sugarcane for export purposes (72% of agricultural land), the power capacity and human labour involved in its production–as well as the relative input flows (water, energy, and food) presently allocated to the sector of agricultural export. As we can see with the type of arrangement of information shown at this multi-level table (Table 4), we just need to move the vectors currently in the compartment of EXPORTS AG to the EM compartment. Then, using the energy grammar is possible to make the pertinent calculations about the internal loops and energy losses related with the supply of ethanol, to get the final net supply of this energy source for the system. As a result the net supply of energy carriers to society from the local production of biofuels is obtained, which is only 8 PJ. This contribution will reduce energy imports by only 30%, but it still claims for the 72% of the agricultural land and would even increase the consumed share of the water-use in Mauritius to 80%! This scenario also presents some inconveniences in economic terms. It was not possible to calculate the GVA of the production of ethanol since there was no reliable estimate of the production costs, but it is possible to calculate the money saved by reducing the amount of energy imported due to the local production of ethanol, that is: 5.5 USD/hour. Comparing this value to the average ELP in the non-agricultural economic sectors (PW*)–that is 13.9 USD/hour–, it can be concluded that this activity does not look very attractive in economic terms.

Scenario 2a: Replacing sugarcane with food crops using all the suitable lands

In this scenario the goal was to look at the geographical constraints to check how much food for internal consumption could be produced on the island. For this task I firstly need to select the composition of the alternative crop mix that would be cultivated. I selected a list of the 20 first agricultural products with the highest consumption by the Mauritian population, in order to use the mix of nutritional components that the population is already consuming in their current diet. To be able to simulate the scenario, it is necessary to know the characteristics of the production rates (tones/ha) of the crops of the new mix, so I had to use only those products which were already being grown in the island. As I mentioned in Section 6.3.2.2, the expansion of the alternative crop mix is subject to geographical constraints such as soil type, slope, and hydrological characteristics. Then, knowing the requirements of the new crop mix, we needed to implement a spatial analysis (as described previously in Figure 39) to check their limitations for expanding throughout the territory.

Mauritius Scenario 2a	FLOWS				FUNDS		
	FOOD (PJ)	**ENERGY (PJ-GER)**	**WATER (hm3)**	**MONEY (million US$)**	**HA (million hr)**	**LU (k ha)**	**PC (GW)**
HH	5.9	16	98	N/A	10000	28	4.5
PW*	0.8	37	44	8200	600		1.4
AG	1.4	0.11	900	960	170	92	0.02
EM	N/A	0.62	260	180	8	negl.	0.01
EXPORTS PW*	N/A	N/A	3	4900 (50% of GDP)	590	N/A	N/A
EXPORTS AG	negl.	negl.	negl.	?	0	negl.	negl.
WHOLE	8.1	54	1300	?	11400	120	6
IMPORTS	5.4	53	N/A	6100 (62% of GDP)	N/A	N/A	N/A
DOMESTIC SUPPLY	2.7	1.4	1300	?	11400	120	6
VIRTUAL IMPORTS	N/A	N/A	840	N/A	?	230	N/A

Table 5. Multi-level table of the scenario 2a in Mauritius.

I estimated (with a certain approximation) that the new crop mix could only be expanded on 64.6% of the current agricultural area. Since the imports of grain to feed livestock (poultry) in Mauritius are very high, in this simulation I decided to grow maize for feed where possible, and I left sugarcane production in the remaining agricultural lands that were not suitable for any of the other crops (Figure 39). The outcome of this simulation, shown in Table 5, results again on a situation of external dependence on food imports, because the mix of crops used would be supplying only one third of the gross food requirement of the island. However, using GIS tools, it is possible to use this scenario to check the changes in the pattern of water consumption by agriculture, as shown in Figure 40 of the last part of Section 6.3.2.2, resulting in a very different pattern due to the lower demand of the new crop mix compared to sugarcane production. At this point just the feasibility of this scenario in relation to external ecosystem constraints has been checked.
However, looking at the resulting table (Table 5), we observe that this scenario clashes with an internal constraint: the availability of labour force (column HA). This makes an incongruence (the Sudoku cannot be solved) on the viability part as the shortage of human activity required for the agricultural sector (AG) in this scenario makes the realization of this alternative impossible. The resulting expansion of the new crop mix demands an increment of labour requirement in the agricultural sector that is incongruent with the existing profile of allocation of labour in society. A major readjustment of the labour profile of economic sectors would mean that the system will also be affected in economic terms, because the ELP of agriculture in Mauritius is 5.6 USD/hours, much lower than the other economic sectors. It is very unlikely that workers in Mauritius would change their jobs to an economic sector with lower wages and much harder working conditions. Moreover, in economic terms it is more convenient to keep producing the surplus of money in the PW* sectors with much higher ELP, and use the money to buy the food they require.

Scenario 2b: Replacing sugarcane with food crop using all the agricultural labour

In this last scenario a variation of the previous scenario 2a was implemented; the current allocation of labour in agriculture is maintained to test how much they could improve their food self-sufficiency using this limited work force (Table 6).

Mauritius Scenario 2b	FLOWS				FUNDS		
	FOOD (PJ)	**ENERGY (PJ-GER)**	**WATER (hm3)**	**MONEY (million US$)**	**HA (million hr)**	**LU (k ha)**	**PC (GW)**
HH	5.9	16	98	N/A	10000	28	4.5
PW*	0.8	37	44	8200	600		1.4
AG	2.5	0.11	260	410	72	39	0.02
EM	N/A	0.62	260	180	8	negl.	0.01
EXPORTS PW*	N/A	N/A	3	4900 (50% of GDP)	590	N/A	N/A
EXPORTS AG	negl.	negl.	0	0	0	negl.	negl.
WHOLE	9.2	54	670	?	11300	67	6
IMPORTS	7.8	52	N/A	?	N/A	N/A	N/A
DOMESTIC SUPPLY	1.4	1.4	670	?	11300	67	6
VIRTUAL IMPORTS	N/A	N/A	880	N/A	?	270	N/A

Table 6. Multi-level table of the scenario 2b in Mauritius.

In Table 6 we can see that if we use the present level of human activity allocated for agriculture (72 million hours per year in total) to grow food crops on the island rather than sugarcane, the alternative crop mix would just be expanded to half (39,000 ha) of the current agricultural lands of Mauritius. Then this scenario is not representing any substantial improvement in the self-sufficiency of food for this system. Maybe this situation could be different with an improvement of the rate of production per hour of work, possibly obtained by introducing higher mechanization in the agricultural sector, but then this would imply some other considerations such as superior investments on agriculture, and higher impacts on the ecosystems. This option is out of the scope of the present exercise, whose aim is limited to illustrate the toolkit through some varied simulation processes.

6.5 Conclusions

Mauritius represents a prefect pilot case to apply geographic analytical tools in MuSIASEM, since it is a kind of a reduced, yet modern socioeconomic system and a politically autonomous State. Its geographic particularities make it a physically delimited territory given its insular condition, and also highly dependent on imports to supply the current metabolic pattern. In addition to this, Mauritius requires an urgent policy decision on the sugarcane issue, since this sector is consuming much of the production factors of the island but generating low revenues, and moreover, the future demand of sugar is very uncertain. In this sense, looking at the multi-level table it becomes evident the enormous difference of the allocation of flows and funds for the agricultural sectors in the consumption and supply parts. The tables also showed the exchanges of the system with other systems providing information about the degrees of self-sufficiency or dependency on various dimensions (energy, food, water).

The scenarios permitted a quick check on the feasibility and viability of alternatives. The Sudoku effect made evident the incongruence of scenario 2a. However, this scenario served to test the power of the spatial analysis to create scenarios and provide much more detailed information for the results. The GIS tools used the Mosaic effect to simulate the behaviour of the system in the different dimensions when some variables were modified for the scenario simulations.

This case study is limited to the illustrative purposes of the approach; the diagnosis stage needs more reliable empirical data and the scenario building stage proved to require serious checks on the desirability of the alternatives. Therefore, in order to provide useful policy advice, a larger study is required with participatory approaches in close contact with the local agents to ensure the quality of the analytical process.

Independently from the results obtained, the scenario building of the Mauritius case poses a successful integration of the tools employed in the MuSIASEM approach, illustrating the usefulness of the undertaken methodology. The general conclusion is that the Mauritius case study served successfully for the ultimate aim of this exercise: testing the methodology and the incorporation of innovative spatial analytical tools.

Part III

Conclusions

Chapter 7

Implications of the use of GIS in MuSIASEM

7 Implications of the use of GIS[21] in MuSIASEM[22]

7.1 The use of geographic information in MuSIASEM is beyond land use quantification

As seen along this dissertation, in the MuSIASEM approach the land use is a key dimension for the analysis, representing the fund that sizes the ecosystem where the studied human society is. The use of land in our approach is so relevant because the land use acts as the bridge between the socioeconomic system and the natural environment. Through the use of Geographic Information Systems (GIS) we can include data from those dimensions into a common platform for data management and analysis, but the summary measure "total area" of a land use in a system is uninformative about the distribution of the land use across the study area. With GIS, the data is structured according to geographical locations. The fund land is measured as area (ha, km^2, etc.) and GIS can provide this information for geographic regions from spatial data. The key to measurement of area of the fund land, however, is the definition, specification and delimitation of the region of interest and creation of appropriate data in the GIS database, and this is not trivial. Additionally, the identification and mapping of the types of land use needed for MuSIASEM is highly dependent on the context within which MuSIASEM is being used. MuSIASEM needs land use data that describes appropriate categories of land, with sufficient spatial resolution, and that are from an appropriate date compatible with other data used in MuSIASEM.

Provided the information about relevant land use quantities, it is possible to use rates of the different flows over land uses (for the selected compartments, types, or sectors of the system), but these coefficients are not only linked with the quantitative amount of surface associated with that particular use. In MuSIASEM, data can be organized in a matrix, or in a map, because the information about metabolic patterns over the land uses can also be represented in their specific geographical locations through the use of GIS. Therefore, when using GIS we are not just dealing with the *extent* of the land uses; now we can map in detail (depending on the availability and quality of the geographical information) particular realizations within the system to answer to the questions of (i) *where* specific metabolic performances are taking place, and (ii) *what* lies where. As we will conclude along the first part of this chapter, this feature is not trivial for the possibilities of the analysis. A variety of characteristics of the spatial distribution of land uses–the architecture of land use in a landscape (Turner et al., 2007)–influence the performance of land and ecological systems. As we will see in detail along the following sections, these include area, shape, and fragmentation of parcels of individual land use types, and the configuration of land uses across a region, notably interspersion and juxtaposition. These spatial, architectural qualities of land use are most often described using methods from landscape ecology coupled with GIS (Turner, 2005).

In conclusion, GIS is able to measure areas of land according to the particular criteria of the analysis, obtaining the quantity of hectares corresponding to the elements under study. However, the main utility of GIS in relation to the measurement of the fund land is not the measurement of area itself, but the ability of GIS to identify the specific land use types and compartments of interest, and to provide area measurements for each.

Following, we will specify the power of these tools, but it is also relevant to highlight the lately widespread utilization of advanced spatial analysis for many applications, due to the fact that technologies such as powerful computers, GIS software and GPS devices have become very affordable and thus accessible to many researchers. Actually, considering than computers are anyway essential equipment for nowadays researchers, and discarding possible high

[21]This section does not provide a guide to all aspects of GIS. There are many sources of further reading on database design and construction, analysis, and other principles and issues associated with GIS (Arctur, 2004; Longley et al., 2010).

[22]This chapter is based on some reflections made on the chapter "GIS protocols for use with MuSIASEM" prepared for the book Giampietro, M., Aspinall, R.J., Ramos-Martin, J., Bukkens, S.G.F. (Eds) (2014) *Resource Accounting for Sustainability Assessment: The Nexus between Energy, Food, Water and Land Use*. Routledge, London. http://www.routledge.com/books/details/9780415720595/

costs of databases, working with digital maps has become cheaper than using multiple paper maps in a research project (not even considering the major versatility of GIS compared to paper cartography).

7.2 General abilities of GIS for the representation of metabolic systems

GIS provides a powerful suite of tools for management, analysis, representation and communication of geographically-referenced data and other information. The use of GIS allows, in addition to the obvious mapping capabilities, the spatial overlay function. This amplifies the capabilities of analytical approaches such as MuSIASEM due to its inherent ability to incorporate in a single system analytical representation:

- Data from very different types of information (e.g. non-equivalent dimensions), making the analysis much more robust.
- Various sources of data (e.g. statistical, maps, photographs, interviews).

This ability provides as well a common platform for formal representations, allowing the interaction of analysts coming from different disciplines to deal with common problems, such as pedologists with geologists' maps, or environmentalists with foresters' maps.

In addition, there are some other basic functions provided by GIS that might be relevant for the analysis and representation of the metabolic performances of territories. In general, it is possible to state that using maps always provides a source of supplementary data simply by providing another dimension (i.e. spatial) to the analysis, but along the next sections I will show some other features providing additional information that might be very useful:

7.2.1 Shape of particular polygons (the physical form of the analysed element)

The particular shape of one piece of land can affect its performance. For example, looking at Figure 41, we can see two schematic visualizations of the same type of land use. The land A has the same amount of surface as the land B, but the perimeter, height and width are different. If these shapes represented pieces of water bodies in a map (e.g. lakes), it is clear that it would be much easier to cross from the top to the bottom the lake A, and from the left to the right the lake B. This feature could affect the performance of the land uses if for example the surrounding areas required communication to implement their activities (e.g. the workers living in a residential land that to work in the lands at the other side). On the other side, given that the perimeter is greater in the lake A, there could be more economic activity as there would be more coast line to place hotels for tourists. In conclusion, knowing the disparity in the shape of lands A and B in a map could provide additional information for the analysis, or it could determine some constraints for proposed scenarios.

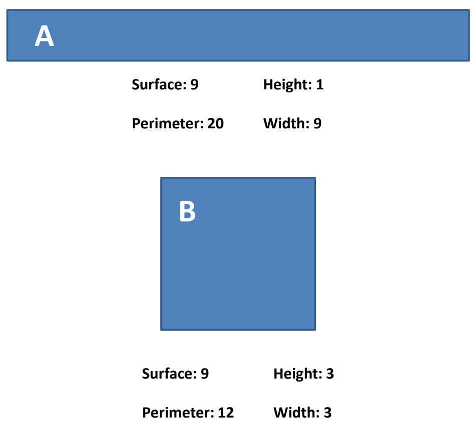


Figure 41. Example of different shapes for the same amount of land use.

7.2.2 Degree of fragmentation.

The same amount of land use could be fragmented into pieces that can be only observable when looking at the map. The level of fragmentation could be determinant for the possibilities of the system, because the structure of the territory changes affecting the interaction of its functions by possibly disconnecting a previously integrated system (Nagendra et al., 2004). For example, in China, since the government allocated an equal amount of land to each farmer, it can be seen from a map how a certain amount of land is divided into several plots although they all have the same use (e.g. cultivating wheat). This in fact is preventing the use of heavy machinery in agriculture, resulting in a type of metabolic pattern very different from what it could be if the land use were not fragmented. In Ecology is well known that fragmentation of habitats influences species' distribution, abundance and population dynamics. That is, although keeping the same amount of natural areas, with fragmentation of habitats many species will be affected as they could not interact or move to crucial areas if patches composing the system are isolated one from another.

7.2.3 Coverage/spread of land uses over the system.

The total amount of a certain land use type in a system does not give us any information about how common it is to encounter that land use in a determined area of interest. Using maps it is possible to check how spread that specific land use is over the territory. For instance, it might be useful to know that there are many water bodies spread in an area where we want to use irrigation for agriculture, which would be very different if the same amount of water resources are concentrated in one single zone of the system, and they are not *covering* the rest of the territory that requires watering, affecting the possible performance of the land uses in that system.

7.2.4 Relative position of the features.

In a complex system there are many interactions among the elements. These relations depend on many factors, but the relative geographic location of the different activities might be determining the possibilities of the metabolic performance. A very clear example would be some lands close to a road which could have activities that require heavy transport, differently from the same type of lands which are not next to roads. Another example would be an island in the middle of a lake; it is a piece of land isolated from the rest of dry lands because it is surrounded by other type of cover (water) that prevents direct communications through land, so the capability of performing the same activities as the rest of the dry lands can be very constrained due to its relative geographical position, although pertaining to the same type of land use. GIS provides a range of tools for analysis of accessibility, proximity, and connections across landscapes, linking data describing transport infrastructure and networks with patterns of land use through network analysis and overlay operations.

In the following example a case with a mix of the previously described features (shape, fragmentation, coverage and relative position)is illustrated, to see how they can actually affect our analysis of metabolic systems:

In South Africa it is possible to see that the different land uses associated with the sectors of the human society are clearly not homogeneously distributed on the territory (Figure 42). The human population is mainly located in very specific areas (red areas), but various natural resources and their extractive activity are located in some other exclusive areas, at different densities depending on the type of land use and the geographic configuration of the mix of biophysical constraints located in each place. For example, there is a large area of arid land in South Africa, but since these arid areas mainly dominate the west of the country (this semi-desert region is named the Karoo), most of the human productive land uses are located in other parts of the map (Figure 42). As a consequence, associating an average population density of the country (total population/total land) would be clearly missing the fact that many areas are deserted. The same happens if we want to check densities of other dimensions per hectare to assess the metabolic performance of the system; we would be misleading a crucial property telling us that the average results for the whole country do not describe properly the actual metabolic patterns.

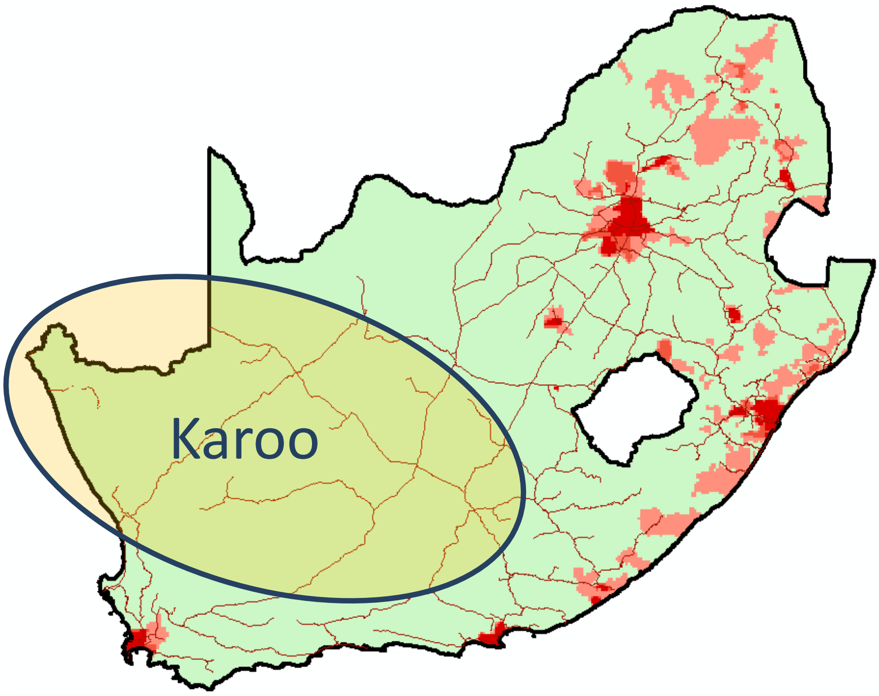


Figure 42. Map of South Africa showing the heterogeneity in the distribution of land uses.

Therefore, it is relevant to take into account the spatial structure of the territory (its heterogeneity) when analysing the societal metabolism of a system. In an additional and more detailed arrangement of the information through the use of GIS, the metabolic performances of the diverse parts of the system can be segregated and thus not affected by the average values for the system. Making a geographical representation of the case through GIS in turn allows us to take care of individual realisations of the system, instead of only considering types. Mapping the distribution and location of the different land uses and features allows the proper distinction and isolation of the different elements composing systems in order to assess appropriately their metabolic performance.

7.2.5 Distances

The previous Chapter 6 explained the use of grammars for the representation of the MuSIASEM approach. However, within the topological relation of elements found in the grammars, there is another property influenced by a variety of geographical relationships: the distance metrics. As we could see in practice in section 5.2.2.4 of Chapter 5 with the scenario of peasants working as labourers for the agro-industries, the relative spatial distances among the different elements of the analysis give crucial information about constrains to the performance of particular areas of the system, due to the significant increase in the costs of communication and transport of flows with distance. This feature (distance) can explain by itself many of the uses that are actually given or not to the physical territory, as there are always **thresholds** for transport costs (costs in different terms such as time, energy or money) which in turn define the suitability for the possible uses of land, and explain many configurations of the territory as well as patterns of metabolic performances (related to the efficiencies in the use of resources). Knowing these facts, the spatial analysis is a useful approach to incorporate to MuSIASEM and GIS provides a range of tools for analysis of distance, such as the proximity analysis.

For example, for electricity or water distribution systems, distances between the production and the consumption areas are always major constraints, very difficult to overcome, requiring enormous infrastructure and operating costs. Electricity grids are very expensive infrastructures which require several devices to ensure a proper supply (voltage, intensity, power, etc.) along large distances. Moreover, there are always considerable losses of energy dissipation on the cables. This is the reason why when there are long distances to cover, normally it is preferable to produce locally the electricity, by transporting to close power plants other energy vectors such as coal or fuels that are themselves close to the consumption points. Regarding water transportation, in Spain there was a very famous case known as "Trasvase del Ebro", in which the Government was willing to divert water from some river basins in the Northeast areas to irrigate some drier agricultural lands in the South of the country. It consisted in a megaproject requiring enormous infrastructure along 800 kilometres, and it would have deeply affected many ecosystems. It seemed so costly in many terms (not only economically) that finally the strong social contestation stopped the project. However, in Spain there are plenty of other small projects diverting water from some basins to others, when distances do not suppose huge costs for the infrastructure.

In conclusion, we have seen that in general distance is always a key feature that determines the feasibility of certain functions, such as using some kind of electricity sources, or producing certain crops in specific areas. The only way to account for this factor is dealing with the spatial dimension, and GIS tools inherently provide this sort of information.

7.2.6 Particular additional features provided by coupling GIS with MuSIASEM

We have seen along the previous sections an introduction to how the geographic information provides the MuSIASEM approach the opportunity to obtain additional information about the metabolic performances of systems that otherwise would not be available. Specifically, along the case studies presented in this thesis, it has been possible to learn some important lessons about the potential of GIS when coupled to the MuSIASEM approach:

In Chapter 5 and Chapter 6, we learned that the feasibility of certain metabolic patterns could only be checked with GIS, due to the fact that geographic analysis is capable of accounting for the interaction with the boundary conditions of the ecosystem determining the compatibility of the socioeconomic systems with its natural environment. Through GIS we can provide a characterization of the flows entering the black box of the system over the data about possible constraints provided by the spatial configuration of the ecosystem.

In Chapter 5 and Chapter 6 we also learned how to build scenarios using GIS and its capabilities to employ the Mosaic effect to calculate the total flow at upper levels of the system under analysis. For example, the rate of flow per hectare (the density) for each land use, combined with the distribution and extent of each land use in the study region, allows to calculate the total amount of flow at different levels of geographical aggregation in the study region. Moreover, we could check how this also resulted in a detailed display visualizing how different patterns are distributed across specific locations in the system through a resulting map representing the spatial heterogeneity of the metabolic performance. This last feature can be very useful to the affected actors as they could check the particular implications on different zones of the system that they might be especially interested in.

Furthermore, the ability of GIS to extrapolate profiles of performance to other geographic areas is being also used by other approaches in Geographic Modelling to successfully predict and analyse outcomes across varied territories– e.g. through Gradient Analysis (Ter Braak & Prentice, 1988). Once, models could only be addressed at one single location, but now they can be run to multiple locations using Gradient Analysis (Hall et al., 2000). Therefore, the structure and geographical distribution of types of land uses with known metabolic profiles can be extrapolated with GIS, making it possible to make estimations in MuSIASEM about the performance of territories where no more data is available apart from information about the land use typologies.

Finally, in the first case study presented in Chapter 4 we saw how we can deal with multiple scales of analysis through the use of GIS and land use information. Differently from paper maps, which can only describe the elements of the territory at one established scale of analysis at a time, GIS is intrinsically capable of handling the hierarchical nature of geographic objects. The use of GIS to move between studies of the whole (region, system, etc.) and the parts (sub-regions, land uses, other functional and structural compartments) is central to the use of MuSIASEM in analysing sustainability. Moreover, we used data that could only be provided by spatial analysis to generate the information needed for the up-scaling across hierarchical levels of analysis.

7.3 Some practical issues when handling GIS

As this thesis is about developing methods, in this section I provide the reader with a series of difficulties and limitations regarding the utilization of GIS and land use quantification with MuSIASEM, in order to allow the potential researchers considering to employ this approach for similar studies to be aware and take care of some issues when using these tools.

7.3.1 Land use/land cover differences.

Although the distinction between these two concepts is crucial for our type of analysis, they are often confused, and it is very common to find maps that label wrongly or mix these two types of information. *Land cover* is the physical material at the surface of the Earth. Data comes from surveys or analysis of remotely sensed imagery. *Land use* is a description of how people *utilize* the land according to selected socio-economic activities. Therefore, a land use map is subjected to whatever classification we are interested in, in that moment, because the categories expressed in the map completely depend on the specific purpose of the study. The categories of land covers can only describe selected physical differences on land surfaces, whereas in a land use map it is possible to express whatever we want to associate with that piece of land, it is completely subjective and adaptable to the criteria of the analyst. Of course, it is possible to make a land use map based on a previous classification of physical covers (i.e. based on a land cover map), but again this would be a posterior stage where there is an intentional aim to describe the land uses of the system similarly to the classification of physical covers. This is the reason why some land use maps are sometimes very similar to land cover maps, but this is due to a fortuitous chance. Evidently, in MuSIASEM what we require ultimately are land use maps describing the different utilization of land by humans.

7.3.2 Problems for obtaining the proper data for land use.

This is a derived problem from the previous explanation. Often the available categories found in existing land use maps do not fit exactly the categories one is interested in for the study. As stated, since existing land use maps made their classification based on whatever criteria for the particular purpose of that description, we cannot expect to find a map of our analysed case categorizing the land uses in exactly the same way as we would require. Normally we will have to make our own land use map based on a mix of information obtained from varied sources.

7.3.3 Problems for characterizing the land uses based on previous sources.

In line with the previous problems, it is possible that the mix of sources of geographical information used to make the map we are interested in present some additional difficulties. We might find relevant information in formats that are not necessarily compatible with our GIS platform, for example, paper maps. Then we have to digitalize and geo-reference these paper maps to be able to use them in our GIS platform. Additionally, if we want to transform into vector[23] format some scanned maps that are in raster[24] format (see example on Figure 43), this task could be

[23] A vector graphic is a format that represents images on a GIS map based on points, lines, curves and polygons referenced geographically. The resolution on vector maps is only limited the locational accuracy of the source data, referenced to the Earth's surface, the geodetic control on data capture, and, for digitized maps, aspects of both the digitalising process and source map.

extremely time consuming when doing it manually and there is not option to do it with automated GIS processes due to the nature of the image. Even when we are able to get digitalized geo-referenced layers, other common found problems to be able to use them are the Coordinates Referenced Systems of (CRS[25]) which could differ, then it would be required to find out the reference system of each layer and transform them properly to get the same projection on the GIS map, a task that can be sometimes complicated.

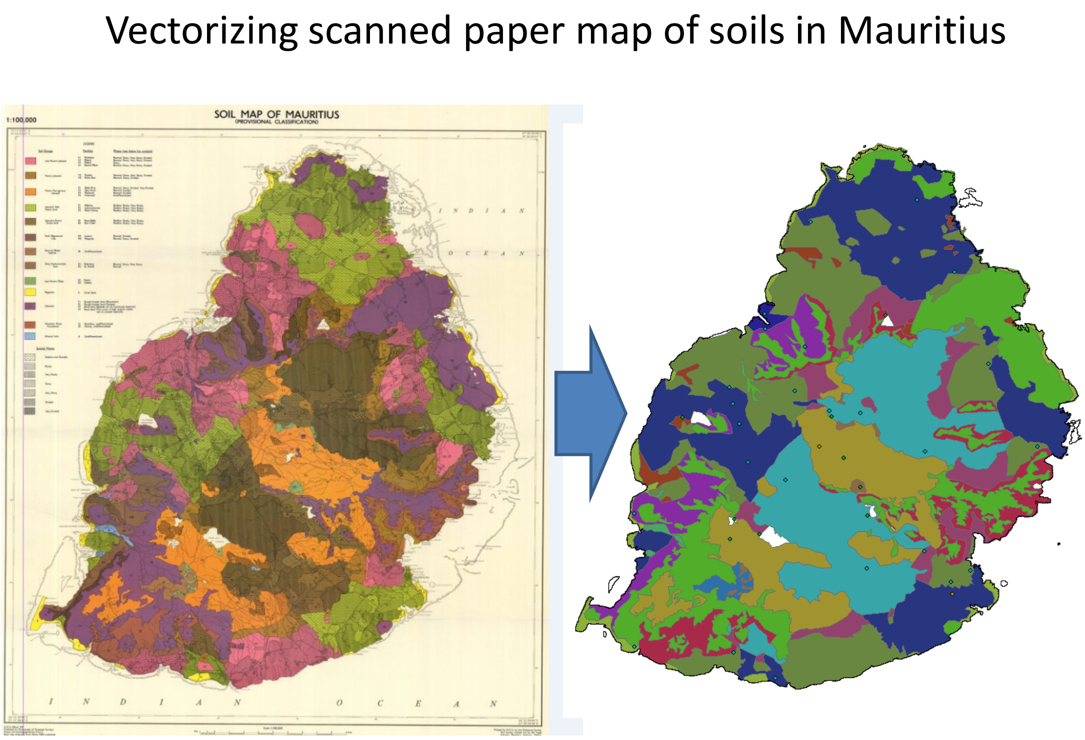


Figure 43. Digitalization of a scanned paper map of soils to a digital format to use in GIS.

7.3.4 Difficulties to disaggregate the land uses of different sectors in urbanized areas.

MuSIASEM often uses a division among functional compartments into Households (HH), Service and Government (SG), Building and Manufacturing (BM), and sometimes Transportation (TR). The problem for dealing with the land uses of these sectors is that many of these societal activities are taking place in urban areas, and land use maps are not disaggregating the urban areas into these categories for various reasons. The first one is that usually urban areas correspond to a very small area of maps when they are representing large regions, so everything appears as one single category. The second reason is that in many cases the activities for HH, SG and BM are overlapping in space, as they take place in the same buildings or on multiple floors of buildings, then it is very difficult to decide how to split them in a bidimensional map. Another reason would be that making detailed maps of urban areas requires some types of data sources and amount of resources very different from those maps made for larger scales, so they are not so commonly available. However, it is possible to overcome this problem (apart from being just lucky and getting the appropriate disaggregated categories we are interested in a map of urban areas): there are previous experiences

[24] A raster image is a format where the picture is composed by a matrix of values (the pixels), commonly known as a bitmap. This format is used for example in digital photography, which are images made of matrix of pixels with a colour value. The resolution of raster maps, like in a digital photo, depends on the density of pixels.

[25] A CRS defines a map projection, which is the selected system to transform latitudes and longitudes of the spherical surface of the Earth into a bidimensional plane. Maps always require the use of a map projection, and all of them distort the surface some way or another, depending on the purpose of the map.

with MuSIASEM (Lobo & Baeza, 2009) where it was possible to create a very interesting map of the Metropolitan Area of Barcelona with the location of the different human activities depending on the time of the day. Otherwise, there is no more solution than categorizing the HH, SG and BM as one single type of land use and bear in mind this fact for the analysis with the rest of dimensions in the study (as we could observe in Chapter 6).

7.3.5 Incongruence between remote sensing and statistical information.

The data from statistical services about the amount of hectares for different uses of the land are estimations based on surveys, and these surveys are based normally on limited samples, or in varied sources declaring the data. As in every estimation process, these techniques have certain error margins and biases, causing the information to rarely coincide with the data obtained from aerial or satellital observation. The remote sensing techniques do not make *estimations* from samples but they are based on direct *observations*. Although the quantification of the different categories of land through remote sensing techniques has also its own error margins and biases, since they are based on observations and not on estimations from samples, or on declarations from people, the data obtained is generally much more reliable. The problem for us is that this improved accuracy differs from statistical sources. Remote sensing is actually used by many organizations to check some declared geographic features through other means of data gathering, since this method offers much more reliable and detailed information about what is happening on the lands. Since MuSIASEM deals with multiple dimensions, and the rest of the data usually come from statistical sources, it is common to find inconsistencies among the data. Then, it would be necessary to make an explicit decision about whether to rely for the analysis on the data from one of the type of sources (statistical or remote sensing), or to try and make adjustments on the statistical data to make them more congruent with the observed information through remote sensing.

7.3.6 General GIS limitations

Finally, I would like to briefly mention some general limitations which are important to consider prior to the use of GIS in research projects. Firstly, GIS programs are very particular (idiosyncratic) and they require considerable training to be able to handle the software for the aims of the study. Moreover, there are available several GIS programs and sometimes one single programme is not capable of dealing with all the tasks we require in each study. Since the user interfaces are always different, users will have to invest some time adapting to the particular software used in each study. As mentioned in the previous section, geographic data availability is always an issue. For example, to start a project we at least require suitable data defining boundaries of the geographic region and regions of interest. Sometimes, data simply do not exist, although every year more and more GIS databases are available in the world. However, when the information comes from private sources, it is usually very expensive (satellital and aerial images are obviously very expensive to produce, and good maps require many workers making them). When demanding cartographic data from public institutions, information is often “politically sensitive” and for some strange reason the process of finally obtaining the data is always very slow. This means that the stage of gathering the GIS data normally takes most of time available in a research project. On the economic side, it is estimated that 60-85% of the costs of a pure GIS project are associated with data capture (Longley et al., 2010). For example, this thesis in particular is limited to show the potential of GIS, but the illustration with the examples of cases studies has been often constrained by the previous facts. As a matter of fact, the supposedly “hard part” of the research process shown along the case studies was even harder due to the data availability and quality. Probably I could have gone further in providing more useful examples of results if there would have been good availability of geographic data.

A final remarkable limitation of GIS is that it cannot make very well dynamic representations of how the data changes along time, like in some others visualizations where it is possible to see dynamic displays of evolving systems. However, this is not a big problem in our case, because anyway in general the representation of systems through the MuSIASEM approach is done with “snapshots” describing the system at one single point of the time.

7.4 Delicate issues about land use quantification in MuSIASEM

7.4.1 Colonized land vs. non-colonized land.

The distinction of colonized land (COL) and non-colonized land (NCL) is basic for the representation of the land use according to MuSIASEM because it tells us about the part of the ecosystem that is being used for human activities, and the natural part of the ecosystem that is left. The ratio NCL/COL could be used as an indicator of the population pressure on the environment, such as the demand of colonized land area per person (which depends on land quality, climate, inputs and production techniques), the land area still available for human expansion (i.e. severity of external constraints), and the land areas dedicated to the preservation of habitat and biodiversity and the stabilization of ecosystem services (i.e. the resilience of ecosystems). However, the criteria for establishing the boundaries between these two categories of land might need to adapt to the case and the purpose of the study, so it is important to bear in mind that there is no one single definition of what colonized and non-colonized lands are. For instance, the territory of a rural village might be composed of 5% of residential area, 30% of agricultural plots, and the rest (65%) is covered by forests. Although the forests are not under intensive human exploitation like the agricultural area, to a certain degrees the forests might provide still some natural resources to the community such as timber, hunting, or they may be recharging the aquifers used for irrigation. As a consequence, the choice of considering forests as colonized land or non-colonized land will dramatically change the results of the density of flows/hectare for that system.

7.4.2 The estimation of the virtual land.

Finally, in the list of considerations to be taken into account in the quantification of land for the MuSIASEM approach, the issue of how to account for the virtual lands is quite sensible for the final results, in case we want to incorporate this kind of information to the representation of the system (as seen in the case study of Chapter 6). Virtual land is land that supports the provision of food, water and energy used by society, but that is hidden because it is located in a different region, or otherwise embedded in the food, water and energy as commodities traded from one place to another. Virtual land is of growing relevance in a globalised economy (Scheidel & Sorman, 2012), and is relevant to both imports and exports. It is important to consider virtual land in studies that quantify land use within MuSIASEM, since this provides a metric of the land fund needed for use of goods and services from outside the immediate geographical limits of the study region.

As explained in Chapter 6, it is possible to estimate the amount of virtually exported land if we consider the land resources that were necessary to produce the exported good inside the system. For instance, food exports are associated with the amount of agricultural land required to grow those specific crops. We use the yield (tonnes of harvested crop/hectare) performed in our studied system for each crop to estimate the embodied land exported. Similarly, it is possible to estimate the virtually imported land knowing the yield of the imported products. However, depending on the choice of the yield rate used in the calculations, which depends on the reference system (i.e. the domestic production, or the country the imports come from), it is possible to make different assessments on whether we are estimating (i) the land that would be required inside the studied system to produce the goods that they are currently importing, or (ii) the land currently consumed in the external systems from where the goods are imported (i.e. this would give an idea of the impacts of the internal consumption abroad). For the last option, in practice there are few ways of making the estimation that may alter the results. Ideally, virtual land could be calculated knowing for every imported good all the quantities corresponding to every different origin and related yields composing the total imported quantity. However, usually this represents an enormous task when analysing big systems such as whole countries, and it requires very good sources of information. Alternatively, for sake of simplicity, an average yield of all the importers could be used in the case that the amounts of the imported good are equally distributed among the origins. Otherwise, it is possible to consider just the yield of the main importer and extrapolate it to the rest of the imported goods. Evidently the last two methods would lead to make bigger assumptions in the estimations.

In particular, there is a very important aspect to take into account when estimating the virtual land associated with the production of meat, due to the existence of autocatalytic loops in the production of this type of product. For a vegetable crop, we simply need to know the specific yield of the crop. However, meat has extra land consumption to be considered, because meat comes from livestock (there are few exceptions from hunting), and the livestock generally use the land not only associated with cattle rising, but also the pastures and the land associated with the grain production for the fodder they consume[26]. Since we have to account for the feed when estimating the land for the meat, the final amount of embodied land can increase enormously in certain cases such as industrial cattle or pigs. For instance, it is possible to see the big differences estimated for the case study of Mauritius, when we calculated that 13 kg of grain are required for each kg of beef, compared to the 2 kg of grain needed to produce 1 kg of industrial chicken.

[26]In fact, it is estimated that one third of the world's land suitable for growing crops is used to produce feed for farmed animals. In total, taking into account pastures, 70% of all agricultural land is used for livestock rearing (FAO 2006).

Chapter 8

Final remarks and reflections

8 Final remarks and reflections

The aim of this research is to obtain a useful methodology offering a toolkit that enables more effective discussions for governance in sustainability issues related to rural systems, by introducing the spatial dimension to the analysis of the biophysical metabolism of socioeconomic systems in rural areas. In general, through the use of GIS it is possible to handle a robust accounting of the environmental part of a territory.

Along this brief concluding chapter I make some general reflections of the significances of the outcomes. They are classified into three sections: the first one is about the theoretical lessons given by developing the research within the MuSIASEM approach, the second is about particular remarks of the case studies undertaken, and the last section focuses on underlining the insights from the use of GIS within MuSIASEM. The last paragraphs of this chapter mention some ideas regarding possible future steps that could be explored through the window opened by this thesis dissertation.

8.1 About the theoretical lessons of the used approach

8.1.1 Multi-dimensional analyses are useful for governance

For a sound development of scenarios and policies we must have adequate tools to explore and study the non-equivalent definitions of goals and constraints found in a socioeconomic system. Indeed, targets and benchmarks for national policies can result quite different from targets and benchmarks appropriate for specific regional or municipal areas. Different goals and constraints can only be detected by observing the socio-economic system simultaneously at different levels and scales. These exercises will necessarily produce a mosaic of information. As a result, multi-scale analyses, such as our MuSIASEM approach, cannot (and should not attempt to) identify “optimal choices” or “best development policies” in normative terms. This is in line with the first five stages of Peter Checkland's Soft System Methodology (Checkland, 1990), where he proposes a way to collect and process data considering systems as epistemological rather than ontological entities. However, MuSIASEM does not address Checkland's last two stages about “defining changes that are desirable and feasible for taking actions to improve the real world situation”. Rather, what the MuSIASEM approach can do is feed an informed discussion and fair deliberation over possible development choices. An additional advantage of the MuSIASEM approach is the possibility of providing representations that can be tailored “à la carte” for specific social actors.

8.1.2 Integration of socioeconomic with land use analysis

The co-existence of markedly different metabolic patterns in rural and urban areas of modern societies underscores the problem of scaling when performing quantitative analysis for governance. When considering systems operating with clearly different metabolic patterns (e.g., urban versus rural), depending on the set of indicators chosen to quantify performance, it is likely that one of the two metabolic patterns loses visibility. For instance, with the current dominance of classic economic indicators, attention is invariably focused on the urban metabolism. But the reverse will be true if the indicators reflect deforestation or water use. For this reason it is important to use a method of flow accounting, such as MuSIASEM, that can conveniently couple the socioeconomic view to an accounting of the corresponding land uses, both in production and consumption when considering different typologies of metabolic pattern. In the MuSIASEM approach, the land use information is able to integrate the part of the natural ecosystem within the overall studied system.

8.1.3 The use of multi-purpose grammars for analysing complex systems

One of the greatest advantages of the MuSIASEM approach is its flexibility in adapting to different geographic and socioeconomic contexts by adjusting the taxonomy of categories included in the accounting system (i.e. a toolkit that is semantically open). For instance, depending on their relevance within the context, certain flows (e.g., water, energy or food) may be included in or excluded from the accounting. The concept of *grammar* allows us to adjust the definition of the relation between semantic and formal categories to different contexts. For example, the semantic concept "cash crop" can be easily formalized in different ways, depending on the system analysed. In China, cash crops may be vegetables produced for near-by cities, while in the USA it may be corn produced for ethanol-producing plants. Thus, the grammars employed in the case studies presented can be adapted to the specific characteristics of other rural systems.

8.1.4 Dealing with sustainability requires a methodology capable of establishing links across hierarchical levels

One of the major challenges in the analysis of complex systems is the unavoidable existence of non-equivalent perceptions of performance resulting from the chosen scales and dimensions of analysis. For instance, ecological impact at the regional level and economic performance at the national level are not directly reducible to each other in an analytical representation based on a single scale. With regard to this aspect, the MuSIASEM approach truly makes a difference by providing an integrated meta-system of accounting that establishes links across the representations of changes taking place at different levels. As we saw along the cases studies, within this integrated system of accounting, changes in the value of one indicator are linked to opposite changes in the value of another indicator. For example, allocating less hours of human labour to rice cultivation (at a given level of labour productivity) translates into reduced rice production, but it may increase the number of hours that can be allocated to other economic activities. At the same time, agricultural land (previously used for rice production) will be freed for other uses. In turn this change can affect the requirement of water, fertilizer, etc. The MuSIASEM approach does not establish a deterministic relation over changes, but defines *viability domains*, that is, it can analyse combinations of changes that are consistent with each other, and *non-viability domains*, that is a set of values for the various indicators that would be impossible according to the expected relations over production factors (internal constraints) and boundary conditions (external constraints).

8.2 About the case studies

I have merely used the three case studies for calibration of the analytical approach and testing the usefulness and outcomes of the tools introduced. Therefore, these case studies have successfully served to answer the research questions posed in Chapter 1: "How can data be gathered, incorporated and used in practice for spatial analysis tools (i.e. GIS and remote sensing) in multi-scale integrated representations?" and "How are the resulting outcomes of the incorporation of these tools?"

In the Laos case the analysis was made at three geographical levels: (i) local, (ii) meso and (iii) macro level. This case represents a practical application of the Hierarchy Theory used in MuSIASEM, by using the land use data and spatial analysis. This chapter introduces in practice some theoretical concepts about the background approach applied to rural systems, and at the same time it proves that it is possible to make quantitative analysis across hierarchical levels using the information provided by the land use.

In the Guatemala case study developed an application where primary geographic data is generated to build some scenarios. This study demonstrates that (i) it is possible to collect our own data when required and thus (ii) we can also decide how to measure the system under analysis. In particular I showed how to establish possible geographical constraints at local scale to build scenarios.

The Mauritius case study was about integrating all the previous lessons into a more elaborated case (considering 4 types of flows and 3 types of funds), and demonstrate that the type of information researched in the previous chapters is useful in more concrete practical applications such as the project demanded by FAO. I showed examples of how the GIS can provide some essential information for multiple dimensions (not only for land uses, but also for water and food) for both the diagnostic step and the simulation step that otherwise could not have been ever considered.

I would like to flag once more that the only purpose of the three case studies was to illustrate the potential of the theoretical approach and the particular methodology introduced. These applications represent just a mere explorative exercise and the results cannot be considered at all for policy recommendations. A proper application to try to address specific problems demands the involvement of local actors and experts, because they are essential in the preanalytical steps where the problem is defined, thus choosing the narrative in which the analysis will be formalized. The participation of local stakeholders is required for: (i) problem structuring–i.e., tailoring of the chosen grammars to the specific situations faced in the case study at a given point in space and time; (ii) pertinent modelling–i.e., quality check on the plausibility of the assumptions; and (iii) data quality–i.e., double checking the robustness and reliability of data by triangulating across different data sources (Giampietro et al. 2014).

Therefore, by no means do I claim that our approach represents the solution to the particular problems found in the case studies. What I believe, though, is that it represents a genuine step forward in the field of multi-scale integrated assessment of rural sustainability. We hope that in the near future it will be possible to test the approach with better data sources so as to generate practical results that can be tested for their usefulness in an actual process of governance.

8.3 About the use of GIS in MuSIASEM

Chapter 7 made possible to observe relevant implications for the MuSIASEM approach through the use of geographic information and land uses using GIS tools. GIS allows examining the specific characteristics and the heterogeneities of the territories of interest, complementing the insights from the analysis and results from others tools within the MuSIASEM approach, as shown along the case studies.

Since with GIS we can take care of *particular features* and *individual realizations* and the place-based geographies of the elements composing the system, then we can discuss how to analyse them as specific instances of the *types* that will be later used for the rest of the analysis.

I also showed how the spatial structure (i.e. the architecture) of the territory and its heterogeneity makes possible to segregate the metabolic performance of the diverse parts of the system with geographical analysis and thus not be simply accounted as average values for the whole system. Moreover, knowing the distribution and location of the different land uses, activities and features (i.e. mapping), we can distinguish and isolate the different subparts of the system in order to properly assess their metabolic performance. This in turn allows an additional and more informative understanding of the results of MuSIASEM. Furthermore, the results can be visualized in a detailed map, useful for both the diagnostic and the simulation stage. Using the Mosaic effect, with GIS tools it is possible to calculate (i) the average and (ii) total values for the whole system, (iii) the particular metabolic performance for the lower levels, parts, sectors, or organs composing the system, (iii) the particular metabolic performance for the types, and (iv) finally and as the intrinsic property of maps, we can also represent the outcome for the particular realizations of the system: the resulting performance depending on the different geographical locations in the analysed territory.

Therefore, along Chapter 7 I focused on developing the specific lessons learned along the case studies to address the research questions posed in Chapter 1 by: “Are existing geographical analytical tools helpful in making multi-scale integrated representations?” and “Which are the possible limitations when applying these methods?”, to be able to demonstrate the usefulness of the proposed methodology posed as “Is geographical analysis relevant for an integrated assessment of sustainability?”

8.4 Further steps

One big challenge that usually remains unsolved when dealing with this kind of analytical approaches is the stage of communicating the results to the interested actors. In particular, the MuSIASEM approach is dealing with multiple incompatible interpretations of the world, and Kahneman (2011) suggests that human minds have limited capacity to understand uncertainty. There have been few attempts to provide the MuSIASEM results in an understandable and user-friendly way, and I hope that map visualizations are a further step in that direction. However, in practice, representations of MuSIASEM results in maps have never been presented to those interested agents or decisions makers, thus I have not had the opportunity to test this potential ability yet for real.

It might be relevant to mention that during my doctoral research period I have also been involved in case studies about energy analysis of fifty states in the US. The information about the production, consumption and exchanges of energy carriers among the states is prompted to be represented through network analysis. This method has the potential of complementing and taking some further steps beyond the mere physical geographic analysis presented in this dissertation. This however implies the deliberation of many other considerations making it too different to the scope of the present research.

Regarding this personal interest for the network analysis approach, I would like to explore in the next future other possible tools for governance and capacity for self-organization of societies. I believe that network analysis offers interesting analytical capabilities in relation to these topics given that governance has an intrinsic net structure that constraints the functional possibilities and option space of the elements, because from a systemic point of view the power issues has also a structural part that can be mapped and depend on (i) the degree (quantity and quality) of connections among elements in the network and (ii) on the capacity of the elements to alter those links (e.g. make new ones, stop others' ones).

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