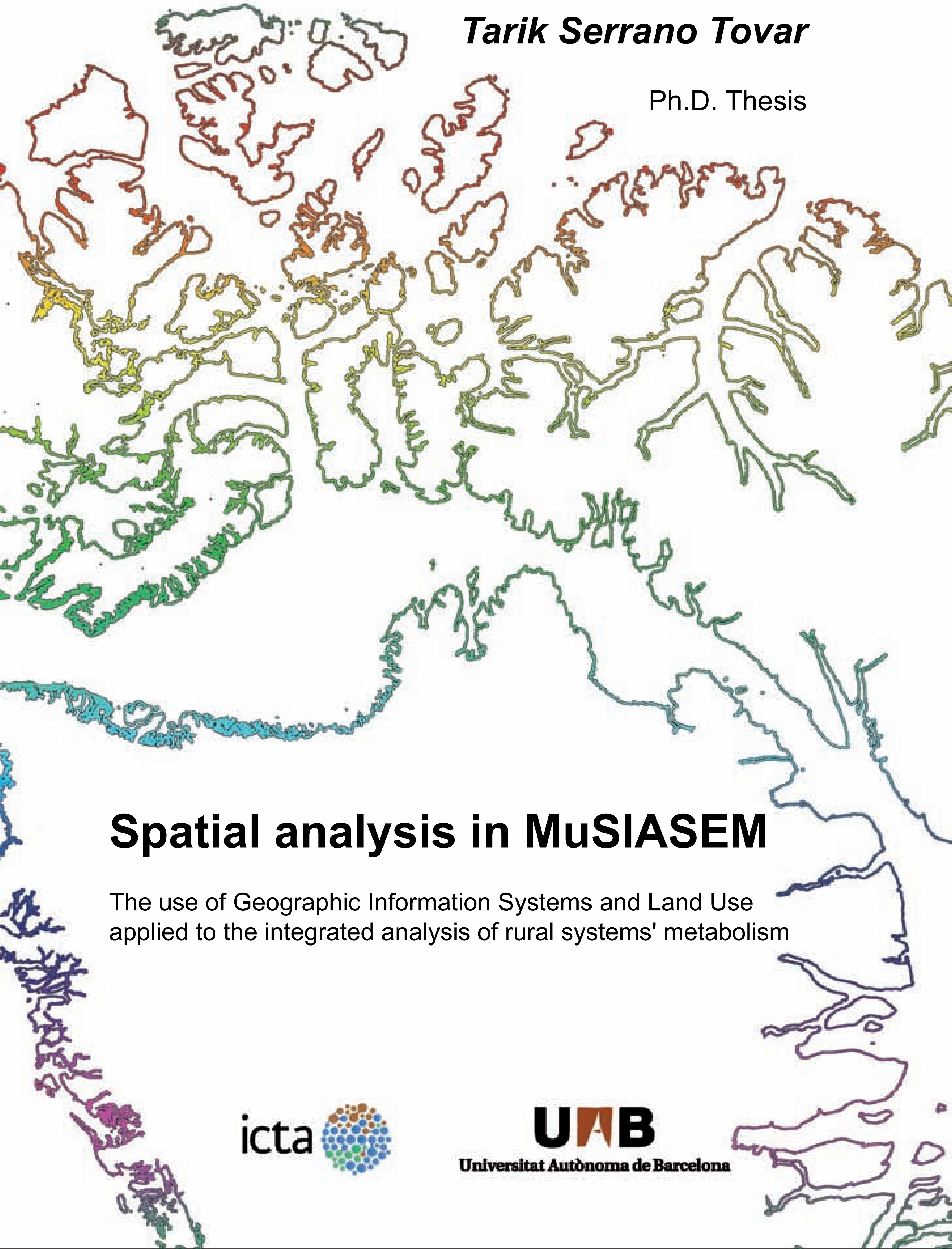

Tarik Serrano Tovar

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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Tarik Serrano Tovar

April, 2014

Institut de Ciència I Tecnologia Ambientals (ICTA)
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Cover: a look at the world (coastlines and main human settlements) from an alternative Reference Coordinate System (WGS 84 / SCAR IMW SU01 -05).

Design by Tarik Serrano Tovar

Preface

This doctoral dissertation can be considered as a compilation of some results of my personal heuristic process of learning in the academic world. The contents shown along the document reflect a formative trajectory in research which has a fuzzy starting point, since I have been–as far as I remember–always interested in multidisciplinary environmental studies. My doctoral candidature officially begun in fall 2008, when I registered in the PhD program, but in practice I spent the following year more focused working in two EU research projects and other academic tasks. It was in summer 2009 when I obtained a scholarship from the Spanish Ministry of Science funding my doctorate for 4 years, that I started to focus more on my personal research. Along these years I travelled to Guatemala and to the US and participated in some other investigation activities, which definitively gave me experience and maturity as a researcher. However, I would remark other two events that definitely represented a key change in my life pushing my career towards this academic trajectory: the first one was my trip to South India in 2007 for my Environmental Sciences degree final research project. That was my first real experience with research, and I can say that it was extremely intense in many aspects. I worked with committed scientists and learned on the go the first lessons of working in the academic world, I faced the fieldwork under very hard circumstances, but overall I shared with people some vital experiences that opened to me a clear path in which I wished to address my life. The other most remarkable event was discovering the scientific paradigm and ideas proposed by Mario Giampietro and colleagues, and later having the opportunity to participate in their research team. I just arrived from my project in India to Barcelona and I was willing to find people with interesting ideas. As usual, I have to admit that I did not understand a thing when I first met Mario in the fall of 2007 and he explained to me the last advances of his work in a 5 minutes speech, but this first shocking experience quickly transformed into a feeling of having discovered the most fascinating approach I could find. It was only after one year studying theory and undertaking the first practical case studies when I could finally say that I knew what this scientific approach was about, just to confirm that these ideas were much beyond what I could expect to research on at the beginning.

The final focus of this dissertation is on developing procedures for applying geographical analysis tools within integrated assessment approaches to societal metabolism. I have to say that I always felt personally interested in geography, cartography and had good skills with the spatial dimension, so this topic represented an opportunity to match my personal abilities to this very interesting scientific approach. The exploration of this research topic is merely enclosed in this dissertation to rural systems, where the land use and the ecosystem play a major role. It is relevant to mention that during my doctoral years I had the chance to promote a small group that established a working team on rural system analysis (www.ruralsystems.org), which later on became for me a very useful platform where to share research experiences with colleagues interested in the same topics and approaches.

Finally, I would like to say that the design of this dissertation has emerged at the end of the research process, when I decided to make it in this form and with these contents wishing to compile a story, which hopefully makes sense. I hope that in any case the outcomes of the work presented in this document will be interesting for people willing to apply similar studies on other cases and that some of the insights proposed in this thesis will result useful in their research.

Acknowledgements

I would like to say thanks to so many people who have been supporting me at many levels and inspiring in my research process, but I will have to limit myself to few sentences that cannot include all of them.

I really appreciate the public programme “Formación de Profesorado Universitario” (FPU) from the Spanish Ministry of Science that granted me with a 4 year scholarship. This economic support has offered me the opportunity to undertake many research activities, including travels, and the final elaboration of this doctoral dissertation. Without this crucial support I would have hardly accomplished any of the present research, and I hope that although the hard times for funding research from the public institutions of Spain, we manage to keep alive these initiatives which allow people like me to perform scientific activities that otherwise would have no chances of developing.

I would like to thank especially my two supervisors, Mario Giampietro and Jesús Ramos-Martín, who apart from being scientists literally much beyond their time and providing me with fascinating knowledge, they both are extremely caring persons who have been always there fully committed with their work and their students. I know from first hand that unfortunately it is exceptional to find supervisors so good at both professional and personal level, so I want to highlight this because I really appreciate this facet. Regarding Mario’s mind-blowing ideas, everything I could say about it is going to sound too adulatory to take it seriously!

I also greatly appreciate the uncountable inputs from the many colleagues met along these years in my research groups, and in ICTA, because apart from making me grow as a scientist, I really feel very lucky to have shared my life with them as they have always made a dreamed social environment where to live and work. These friends are too many to be named here (Zora, Alev, Hug, Meera, Laura, Elena, Pere... really too many!), but they all keep an important place in my heart, and I owe them many good things that have deeply influenced me and my work. In particular I imposed upon Zora Kovacic to make a free proofreading of this document.

For the case study of Laos I would like to gratefully acknowledge the financial support from the EU, contract no. 217213, project SMILE, Synergies in Multi-scale Inter-Linkages of Eco-social systems (http://www.smile-fp7.eu/), within the context of which this project was carried out. Mario Giampietro is the co-author of the scientific article in which this chapter is based, and the main contributor of the background theory exposed in this chapter. I would like to thank Dr. Clemens Grünbühel for his advice and for providing references and data for the Laotian case study, and Sandra Bukkens for editing the paper, which the chapter of this case study is based on.

I gratefully acknowledge the financial support for the case study in Guatemala from Fundació Autònoma Solidària that made possible the stay to participate in this project. I would like to thank specially Gonzalo Gamboa and Sara Mingorría, the main contributors of this study, for kindly allowing my inclusion in their difficult project and for supporting and participating during all the stages of this study. The whole studied communities welcomed me as a member of their families during my stay, but I would like to specially mention Gerardo Sub Sacul and Roque Sub

Sacul who are two exceptionally committed persons that contributed enormously to this study. Last but not least, all the members integrating the CONGECOOP were very warm hosting and supporting the project.

For the case study of Mauritius I gratefully acknowledge the Energy Team of the Climate, Energy and Tenure Division (NRC) of the UN Food and Agriculture Organisation (FAO) for the financial support for this project. Juan Cadillo Benalcazar, Cristina Madrid, Zora Kovacic, François Diaz-Maurin, Mario Giampietro, Richard J. Aspinall, Sandra G.F. Bukkens, Jesús Ramos-Martín, Pedro Lomas and Tiziano Gomiero are co-authors of the Mauritius case study, implementing the many parts of this large research case, although the chapter about this case study cannot reflect most of their contribution.

Finally, I want to mention those persons who have really made me the person I am now and then have ultimately contributed to the work presented here. All my family and my partner Zora have been inspiring me and supporting along this journey, they are my motivation to make this kind of work. But I would like to dedicate this thesis to my parents Eduardo and Yolanda, because they are ultimately the motivation of my personal and professional interests and the pillars of my rationale, and are the people that I am thinking about when I think of those things which are important in life. Os quiero!

Abstract

This doctoral dissertation is about exploring and developing procedures making it possible to incorporate spatial analytical tools, and more concretely Geographic Information Systems (GIS), into one of the most interesting approaches to study sustainability issues: the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM). In particular, this is a methodological exercise having the goal to develop, test and propose tools that can be used for the integrated assessment of the sustainability of socio-ecological systems, and more specifically rural systems.

Therefore, this thesis combines both theoretical discussions and practical case studies. The development of a robust methodology required dealing with the theory of complexity, whereas the test and calibration of the resulting methods required ground-based with empirical work. Thus, the dissertation goes through three main parts: an introductory part developing the theory, a second part with the three case studies and a third part with the conclusive reflections on the lessons learned about the methodology.

The first part is divided in three chapters where I firstly make a general introduction to the context motivating this thesis, a second chapter in which I explain the MuSIASEM approach, the background theories and I justify why I have chosen this approach rather than others, and a third chapter where I develop the general theory and methodology to analyse rural systems tested in the second part. The second part of this dissertation contains the core of the applied research; the three case studies. The first application is a case study of rural Laos, where I develop a system of accounting capable of handling the quantitative information about the metabolic performance of typologies of farming systems across levels and scales based in the land use and GIS information. This quantitative method can scale-up and scale-down the characterization of elements defined on different hierarchical levels of organization, which can only be perceived and represented on non-equivalent descriptive domains. The second case study was undertaken in Guatemala and it included empirical field work. There, I established a procedure to generate geographic information at local level to be used for the metabolic analysis of the system, in order to later simulate scenarios taking into account geographic constraints. The third case study is more complex, it is an analysis of Mauritius Island integrating many dimensions and scales (energy, food, water, money, land use, human activity) and handling data through the use of GIS and remote sensing to simulate possible scenarios of development.

The final part of the dissertation develops some reflections about the particular scope of this thesis (the use of GIS in MuSIASEM), and a last chapter of concluding theoretical remarks.

Resumen

Esta tesis doctoral trata sobre explorar y desarrollar procedimientos para poder incorporar herramientas de análisis espacial, y en concreto Sistemas de Información Geográfica (SIG o GIS en sus siglas en inglés), en una de las aproximaciones posiblemente más interesantes para estudiar temas de sostenibilidad: el Análisis Integrado Multi-Escala del Metabolismo de las Sociedades y Ecosistemas (MuSIASEM en sus siglas en inglés). En particular, estamos ante un ejercicio metodológico con el propósito de desarrollar, ensayar y proponer herramientas que puedan ser utilizadas para la evaluación integrada de la sostenibilidad de sistemas socio-ecológicos, y en concreto de sistemas rurales.

Así pues, esta tesis combina discusiones a nivel teórico con casos de estudio prácticos. El desarrollo de una metodología robusta ha supuesto tratar con teorías sobre complejidad, mientras que las pruebas y calibraciones de los métodos resultantes requerían trabajo empírico con casos prácticos reales. Así pues, esta tesis se desenvuelve a través de tres partes principales: una primera parte introductoria que desarrolla la teoría, una segunda parte con tres casos de estudio y una tercera parte con reflexiones sobre las lecciones aprendidas respecto a la metodología.

La primera parte está dividida en tres capítulos donde primero realizo una introducción general al contexto en que se basa y motiva esta tesis, un segundo capítulo en el cual explico la aproximación MuSIASEM, sus teorías de fondo y en donde justifico la elección del uso de esta aproximación frente a otras, y un tercer capítulo donde desarrollo la teoría y metodología general para analizar sistemas rurales probadas en la segunda parte. La segunda parte de la tesis contiene el núcleo de esta investigación aplicada; los tres casos de estudio. La primera aplicación se trata de un caso de estudio del Laos rural, donde desarrollo un sistema de contabilidad capaz de mover la información cuantitativa sobre el funcionamiento metabólico de ciertas tipologías de sistemas agrícolas a través de niveles y escalas, basándome en la información sobre uso del suelo y SIG. Este método cuantitativo puede escalar hacia arriba y hacia abajo la caracterización de elementos definidos a diferentes niveles jerárquicos de organización, los cuales pueden ser solo percibidos y representados en *dominios descriptivos no equivalentes*. El segundo caso de estudio fue realizado en Guatemala e incluyó trabajo de campo empírico. Allí, establecí un procedimiento para generar información geográfica a nivel local para ser utilizado en el análisis metabólico del sistema, para luego poder simular escenarios teniendo en cuenta los limitantes impuestos por la geografía de la zona. El tercer caso de estudio es más complejo, pues se trata de un análisis de la Isla de Mauricio, en el cual se integran muchas dimensiones y escalas (energía, alimentos, agua, dinero, uso del suelo, actividad humana), y se generan y analizan datos a través del uso de SIG y teledetección para simular posibles escenarios de desarrollo.

La parte final de la tesis desarrolla primero algunas reflexiones sobre el ámbito particular de esta tesis (el uso de SIG en MuSIASEM), y por último un capítulo concluyendo con algunas observaciones teóricas.

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Glossary

This section aims to offer to the reader a parallel resource with the definitions of some specific concepts used along the document for which I use a particular meaning within the context of the MuSIASEM approach. The readers can find the underlined words along the document that will lead to the definitions of the terms, in a kind of hypertext. The goal is to facilitate with an easy reading the non-experts in the approach by explaining dense concepts with plain words and simple examples.

Autopoietic systems: A class of systems capable of producing themselves as conceptualized by Maturana and Varela. Autopoiesis literally means "self-production" (from the Greek *auto* for "self" and *poiesis* for "production") (Maturana & Varela, 1980; 1987). The term autopoiesis describes a fundamental complementarity between structural types and functional types found in biological and social systems. All living systems are autopoietic systems, as their ultimate productive aim is their reproduction, differently from other mechanistic systems whose production is not aimed to make themselves. Non-autopoietic systems depend on other agents for their existence since they must be produced by other systems. For instance, a prokaryote cell is an autopoietic system because it can reproduce and it is autonomous, but ribosomes inside the cell are *allopoiesic* systems because they only produce part of the components to make ribosomes (Varela et al., 1974).

Colonized land (COL)/ Non-Colonized land (NCL): In short, the term "colonized land" is the land whose characteristics would be different without human intervention. That is, metabolic characteristics of colonized land (flows/hectare) are very different from those typical of natural ecosystems. In fact, both the pace and the density of biophysical processes in colonized land do not depend only on the natural regulations, but they are affected by human action (the heavy use of agricultural inputs produced using fossil energy). The distinction between colonized and non-colonized land depends on the context and the aims of the study. We can include in the category of Non-Colonized Land areas of land used by humans with such as a low intensity of activity per hectare that it does not change significantly the natural pace and density of the natural pattern of the ecosystem. For instance, a forest surrounding a rural community might provide some timber and hunting products, but if the natural metabolic profile of the forest is not significantly altered for the analytical aims of the analyst, then we can consider it as NCL.

Complexity / complex systems / complex adaptive systems: The first important clarification is that complex is not the same as complicated. From an analytical approach "a problem is complex when an explanation of its associated behaviour requires several disparate levels to be addressed simultaneously" (Ahl & Allen, 1996). Then "a system is complex when it cannot compress the information to describe it without losing fundamental information for the analysis" (Giampietro et al., 2011). Moreover, complex systems are also characterized by "emergent proprieties" found when aggregating and combining their parts. In these systems we can say, following Aristotle, that the whole is something other than the simple sum of the parts. These emergent phenomena can only be studied at a higher level of analysis than the basic pieces composing it, because the pattern of the complex system cannot be explained only by the isolated behaviour of its parts. Another typical characteristic of complex systems is the non-linearity in their behaviour, that is, the existence of positive and negative feedbacks determining lack of proportionality between the effects and the causes.

Desirability: see feasibility.

Descriptive domain: see domain.

Dissipative systems: They are self-organizing, open systems, operating away from thermodynamic equilibrium, dissipating energy and matter (increasing their entropy) in order to achieve their own internal required order (Prigogine & Stengers, 1983).All natural systems of interest for sustainability analysis (e.g. complex biogeochemical cycles on this planet, ecological systems and human systems when analysed at different levels of organization and scales above the molecular one) are "dissipative systems".

Domain / descriptive domain / non-equivalent descriptive domain: A descriptive domain is a selected formal representation referring to a perceived domain of reality that is based on a preanalytical choice on how to describe the system for the aims of the study (Giampietro, 2003). Non-equivalent descriptive domains are choices of representations of the same system that cannot be reduced to each other using a formal system of inference (Rosen, 1985). One domain would be expressed in the analysis through a limited set of descriptive methods that focus on one single aspect and scale of the observed system at the time. For instance, energy, human activity, monetary flow or land use are possible non-equivalent descriptions of a system that are accounting either from biophysical or socioeconomic perspectives, which are irreducible to a single measurement unit. In the MuSIASEM approach we use simultaneously non-equivalent descriptive domains in an integrated representation to deal with sustainability issues. This is especially useful when the analysis deals with hierarchical systems where the relevant patterns can be only detected at different scales, and to offer a contrast among different descriptions that might be considered relevant for the analysis (Mayumi & Giampietro, 2006). Rosen (1978, p. xvii) criticizes the reductionism of some scientists when using a single perspective to represent systems which are set at multiple scales in the analysis: “there exists no universal family of analytic units appropriate for the treatment of all interactions”.

Exosomatic / endosomatic energy: The exosomatic energy refers to energy flows transformed outside the body. This includes the energy used by society to power technical devices such as cars, computers or stoves. Endosomatic energy refers to energy flows transformed inside the human body obtained from food. While the endosomatic energy of one adult person is limited to about 11 MJ/day, the exosomatic energy consumed per capita to perform our daily activities in modern societies may reach to 840 MJ/day (Byrne et al., 2011). This distinction is very important in our approach for energy analysis of societies as it implies completely different meanings for the analysis of energy flows–exosomatic is about technical power and endosomatic is about reproducing humans–requiring different methods and materials for their study.

Feasibility / Viability / Desirability: In MuSIASEM analysis, these terms refer to specific conceptualizations distinguishing between different scales of analysis related to the internal/external points of view on human systems. We use the term *feasibility* in relation to *external* constraints imposed by the environment. These external constraints consist of biophysical factors outside human control determined by the boundary conditions established by the activity of the ecosystems where the society is embedded. We use the term *viability* in relation to the *internal* constraints determined by the processes taking place inside the black box (in our studies the black box usually comprises the human society). These internal constraints reflect the existence of social, economic and technical constraints limiting the viability domain of the studied society. We use the term *desirability*, as its own name indicates, in relation to what is desirable by the social actors relevant for the study. A definition of desirability depends on the multiple legitimate perceptions found in the society. Therefore, the desirability of proposed alternatives or policies could only be checked through participatory methods. However, a quick preliminary assessment of the desirability of proposed scenarios can be obtained by comparing benchmarks of societal performances associated with evaluations of desirability expressed in known typologies of societies.

Flow / Fund: In MuSIASEM this is a fundamental distinction between the types of accounted elements, which is essential in order to make a proper representation of metabolic systems. We follow here the work of Georgescu-Roegen (1971).

Flow elements are those that are produced or consumed during the analytical representation. They reflect the choice made by the analyst when deciding *what the system does* and how it interacts with its context. Flow elements can be described in terms of relevant monetary, energy and material flows (Giampietro et al., 2009).

Fund elements define *what* the analysed system *is made of*. They define and *size* the extent of the considered system, so they also act as an external reference. They can also be conceived as the ultimate production factors of the system, which metabolize the flow elements. Fund elements remain “the same” during the analytical representation and they express agency (consuming and generating flows). In the MuSIASEM approach the funds typically used to define social system are humans, land and technical capital, and they can be described in quantitative terms of Human Activity (in hours per year), Land use (in hectares per year) or Power Capacity (in watts per year).

Another important remark in relation to this distinction is that the MuSIASEM approach characterizes systems’ flows always in relation to funds. That is a given flow$_i$ = fund$_i$ x (flow/fund)$_i$. In this way any quantity of flow is always dependent on two assessments: (i) a quantitative assessment (the size of the fund associated with the flow); and (ii) a qualitative assessment (the flow/fund ration characterizing the pace or the density of the flow per unit of fund).

Fund: see Flow.

Functional / Structural: The functional part refers to the *role* of a particular component which is expected to be fulfilled within a given associative context to which the component belongs. Such a role emerges from the question of why this component is necessary or why it proved useful in the past, which translates into justifying why it is relevant to perceive and represent it in the first place!

The structural part describes the characteristics of the element regarding its form, composition and disposition with respect to the organized display of a particular system. The structural part of an element also tells us about the connections and relation with the other elements of the system.

For example, cars have a perceived useful function for humans, transporting people (they have a “why”), but they also have a particular organized structure to perform this function in the system (they have a “how”), they require four wheels, an engine, a chassis, etc. arranged in a certain way so the car can perform its function.

GIS / remote sensing: Geographic Information Systems (GIS) are integrated digital platforms to process geographical data. With these programs it is possible to capture, manipulate, analyse and make visualizations (maps) of georeferenced information. In this sense, using GIS all the data is linked at some point to spatial locations (georeferenced). Some insist on the importance of differentiating GIS from Remote Sensing, although they are often used in combination. Remote sensing specifically refers to systems that generate geographic data detecting the radiation reflected on the Earth’s surface through aerial and satellital sources (e.g. aerial photos or infrared detection). This information can be used as maps, and thus they can also be used in GIS programs.

Just for clarification, Land Use databases (e.g. the data provided by national statistics), does not necessarily relate to geographic entities. Land use data can simply account for the sum of amounts of certain types of lands in a system, and this information can be used without any spatial analytical tool (e.g. the total amount hectares of agricultural land in a system). On the other hand, GIS programs cannot handle Land Use data unless the information is georeferenced.

Grammar / multipurpose grammar: The concept of grammar refers to a logical relation between a given set of semantic categories and a given set of formal categories. A grammar makes it possible to implement a system of accounting for structuring the information about relevant elements of the system. In fact, it makes it possible to classify and organize in a formal way quantitative relations among fund and flow elements according to the role and the purpose of the analysis. For example, if we want to assess the economic profitability of a car factory, it is possible to establish the elements into play according to the class of productive factors required and generating expenses (e.g. machinery, labourers, materials), and the type of elements produced (e.g. luxury cars, vans, pick-ups) which generate the income obtained by their sales. This arrangement of the information allows the calculation of economic profitability and it is open and adaptable (e.g. by introducing new technology in the machinery or producing a new type of car).

The multi-purpose grammar is then a meta-system of categories, defining the relevant characteristics of the system by arranging the relations of their elements in a semantically open way, so it can be tailored and calibrated to specific situations and adjusted to include new relevant qualities in the analysis. The definition of a grammar requires a preanalytical choice of: (i) a lexicon –the categories of categories associated with the chosen narratives; (ii) a vocabulary –the list of semantic and formal categories used in the representation; (iii) a list of expected relations over the various categories; (iv) a set of production rules determining a given representation of these relations –how to calculate names (internal variables generated within the grammar) from the values of tokens (data inputs from external referents). The grammar has to be implemented through a set of semantic decisions about the choice and use of data.

Hierarchical: Complex systems are arranged in multiple levels where each level is composed of other sublevels in a hierarchical display. Tim Allen argued that “a system is defined as hierarchical if it can be described as composed or stable, observable subunits unified by a superordinate relation” (Ahl & Allen, 1996). The organization of the information in hierarchical structures is very useful for the analysis of societal and ecosystem metabolism because it allows abstraction (the elimination of redundant information referring to types describing equivalence classes) and closure on the accounting across the multiple levels and scales considered in the system (i.e. the sum of the size of the parts must be equal to the size of the higher level considered).

Holon: Holon is a term introduced by Arthur Koestler (1968; 1969; 1978) to stress the double (fuzzy) nature of “whole” and “part” of elements belonging to complex forms of organization. It can be also conceptualized as the “skin” of the object between the whole and the parts; it integrates both (for a discussion of the concept see also Allen & Starr, 1982, pp. 8-16):

- Holons must have an organizational structure (the parts interacting within the whole). When looking at this side of the coin we can perceive and represent *how* they work.
- Holons must express a functional role (the whole interacting successfully with its context). When looking at this other side of the coin we can perceive and represent *why* the studied subject makes sense in its context (why it is a relevant subject to study and why it is reproduced in the first place).

Identity: Identity is the selection of a set of relevant qualities that allows the observer to perceive the investigated system as an entity (or individuality) distinct from its background and from other systems with which it interacts (Giampietro, 2003). The perceived elements in the external world must be characterized by a particular identity known to the observer in order to be able to detect their existence and then to analyse their characteristics in relation to other observed systems (Mayumi and Giampietro2005). In MuSIASEM, the analysis of metabolism is related with the identity of the object, and this is quantified by the fund elements.

Impredicative: An impredicative element is defined by other elements, and these are at the same time defined by the former element in a cycle, as the chicken-egg predicament. In the MuSIASEM approach it is possible to establish relations between the whole and the parts, being the characteristics of the whole compatible with the characteristics of the parts and vice-versa, but since they are defined by each other, there are internal loops so that there are no linear causal relations (Giampietro et al. 2014).

Incommensurability: Social incommensurability puts on the table the existence of multiple legitimate values in society, this heterogeneity means that there is not one single legitimate point of view which is right for everybody. The technical incommensurability arises when there are complex systems that cannot be reduced to one single descriptive domain or scale as it has multiple identities (Munda, 2004; 2008; Giampietro et al., 2006c).

Integrated Assessment: It is a research approach based on the integration of multiple dimensions or scales of analysis into a common analytical platform. Integrated Assessments do not analyse separately the possible dimensions considered but its goal is to establish relations among them, in order to obtain a holistic representation considering simultaneously all of them and also the dependant relations of them affecting each other. It uses at the same time indicators from different disciplinary fields (Giampietro et al., 2006c).

Levels / Scales: The term level in our approach refers to the hierarchical stages of organization on a scale of analysis. For example, we could be studying a city at 3 hierarchical levels: household level, district level and the whole city level. This city could be studied from 3 dimensions, for example, economic, social and environmental. The term scale refers to the extent and resolution of the dimensions used for the analysis. For example, the economic dimension could be studied at two levels in this city: at households and district levels–defining one scale of analysis. But the environmental dimension in this city might be only analysed at the whole city level, defining another different scale of analysis; because in this case the resolution changes as it does not take into consideration differences at lower levels. This multi-dimensional analysis would be then considering 3 levels and 2 different scales of analysis.

Metabolic systems: They are systems that are able to use energy, materials and other natural resources to maintain, self-reproduce, adapt, and improve their own existing structures and functions, i.e. their identity (Giampietro et al., 2011). In our approach, by studying the metabolic patterns of human societies, we can quantify how these systems perform in stabilizing in time and space a network of useful energy and material flows under human control capable of reproducing the functional and structural organization, while expressing adaptability (Giampietro et al., 2011). Within this quantitative representation, the metabolic pattern of a socioeconomic system can be characterized as an expected set of benchmarks values defined over a network of material and energy flows controlled by a given set of fund elements.

Mosaic effect: The mosaic effect is the name given to the phenomenon where the flow/fund ratios can be used to move the chosen representation across levels and achieve closure in the accounting at the selected levels. For example, we can establish certain flow/fund ratios of the agricultural performance at cropland level (e.g. kg of rice/ha). Then in a higher level of analysis, e.g. village level, we can define the average productivity of land at the village level for growing rice, by weighting the different productivities of plots by the relative size of the different plots. Or vice-versa, knowing the rice production of a certain village and the productivity of different plots, we can calculate their relative size. With the mosaic effect, that is, using flow/fund ratios, it is possible to make double checks in the accounting, using quantitative bottom-up information (using technical coefficients to infer large scale characteristics) or top-down information (using statistical data to infer technical coefficients).

Narrative: A narrative about a given issue is based on the preanalytical choice made by a given story-teller about a given set of relevant perceptions of events (what the observed system is, what it does, what the causal relations to be analysed are, the boundaries and the time scale that should be used in the representation). This implies that a given issue may be framed using very different narratives. For example, the issue of Genetically Modified Organisms is often discussed using different narratives: biotechnologists adopt a narrative perceiving plenty of advantages compared to traditional agricultural varieties, whereas other scientists (e.g. ecologists or sociologists) adopt different narratives perceiving plenty of problems.

Representation: A representation is the formalization of the perception of the analyst according to some chosen attributes deemed relevant by the analyst within a given descriptive domain.

Rural system / agrosystem: For the specific aims of our research, rural systems are those social systems in which human activity is strongly linked to the natural metabolic performance of terrestrial ecosystems. They are found in natural areas or crop fields, and in those areas where extractive activities take place with some kind of natural resources exploitation, such as agriculture, hunting, gathering or mining. They are opposed to urban systems, which are identified by the predominance of human activities not dependent on the natural rhythms, such as manufacturing, services, administration, etc. I distinguish rural systems from agrosystems as the latter are particular systems inside the rural world identified by the agricultural activity. In this research, the rural areas might also refer to those parts of the system covered by natural areas not necessarily exploited by humans for agriculture, such as forests, shrubs, rocky areas, or protected natural areas.

Scales: see Levels.

Structural: see Functional**.**

Sudoku effect: The Sudoku effect is the name given to a set of integrated constraints determined by the MuSIASEM accounting method applied to a given dataset. The Sudoku effect makes it possible to check, in relation to different dimensions and different levels of analysis, the congruence of changes within the dataset. Within this accounting scheme different grammars impose non-equivalent sets of constraints to the values of the variables written in the cells of the grid. When a variable changes in a grid we must expect changes in the values of other variables (referring to different dimensions or processes taking place at different scales), that actually can be quantified. Therefore, the Sudoku effect makes it possible to study viability domains (when checking for possible incongruences/constraints) and trade-offs (when exploring the consequences of proposed alternative scenarios).

Territory: A territory is always a composition of two parts: the *environment* (e.g. the physical space, substrate, habitat, land, landscape) and the *population* inhabiting in it. Therefore, the term territory does not just refer to a physical space, at the same as it does not refer only to the inhabitants. The territory implies the *making* or *appropriation* of an environment by a territorial entity, which is in turn the element expressing the environment as its associated context (Serrano-Muñoz, 2006). These two components of a territory can be analysed separately but they are not autonomous and must be related at some point when approaching social systems. In fact, this thesis is somehow focused on developing an analytical representation around this term using simultaneously the two elements defining a territory; the human society and the physical environment are expressed in quantitative terms as the funds human activity and land use.

Type / Typologies: In our approach we often use types as units of analysis associated with the formalization of identities. Types consist of a defined set of attributes and possible relations of the elements of the system. Therefore, the typology employed must reflect the choice of the scientist for the aims of the analysis. For example, when analysing aquariums we could associate their identity with the fishes living in them. Then, instead of generating an analytical representation of the aquarium describing all the particular elements of it (e.g. fish 1 is red, fish 2 is green, fish 3 is red, fish 4 is green, etc.) a typology based in colours of fishes can be established and we could represent the aquarium as made of a mix of “red fish type” and “green fish type”. Using typologies in the analysis instead of concrete “realizations” has various important implications: firstly, it entails the selection of a finite set of observable characteristics, excluding all remaining possible qualities (Mayumi & Giampietro, 2006). Secondly, a type is not associated with a scale tag (Allen & Hoekstra, 1992), the set of relations of elements within a type might be applicable at multiple scales; “it is only when a particular typology is realized that the issue of scale enters into play” (Giampietro, 2003). Using typologies has also the advantage of making the analytical representation of the system still valid for the aim of the study even when there are changes in the particular values of the realizations. That is, continuing with the previous simple example, if we represent the aquarium as made of red and green fish types, this description of the system is still valid even if we increase the amount of red fishes of the aquarium, because the identity of the semantic categories remain unaltered and we just need to adjust the particular values of the data input.

Viability: see Feasibility.

Part I

Introduction

Chapter 1

Leitmotif of this research

1 Leitmotif of this research

1.1 The reason for a thesis about developing methods and tools.

In recent history, human society has developed across the world rising extraordinary problems that have become major challenges on sustainability issues at global and local scales, such as deforestation, soil degradation, climate change, biodiversity loss, or the societal dependency on fossil energy (McNeill, 2000). There are several emergent problems which are adding to the "traditional" ones (e.g. issues like social and economic problems such as racial discrimination or distribution of wealth in a population, as humans are now interacting with natural systems in unprecedented ways), demanding renovation and innovation of the approaches trying to deal with them. Making a long story short, the use of sources of cheap exosomatic energy (i.e. fossil fuels) allowed unstoppable industrial development, because the unrestrained improvements of machinery offered virtually unlimited power capacity to carry out whatever activity imagined by humans and boosted the productive capacity. This emancipation (Mayumi, 1991) from biological constraints (based on endosomatic energy) enhanced the variety and intensity of human activities, making the economy and the human population explode initially at exponential rates (De Long, 1998). Unfortunately, at the same time, we created new kinds of problems when we clashed with the natural limits of ecosystems, threatening the sustainability of this type of human development characterized by population growth and consumption of natural resources. Thus, the current wellbeing of humans is fully dependent on the use of fossil fuels and other limited natural resources such as phosphates, agricultural land, or some metals, whose rates of exploitation will be unavoidably declining due to the implications of a bell-shaped curve given their condition of non-renewable resources (Hubbert, 1956; Meadows et al., 1972; 2004; Daly, 1995; Turner, 2008). In Figure 1 it is possible to see how clearly the world is actually following these trends in a recent comparison (PBL, 2009) between the two scenarios made in 1972 in the famous book *The Limits to Growth* (Meadows et al., 1972) and the aggregated values observed during the last 40 years.

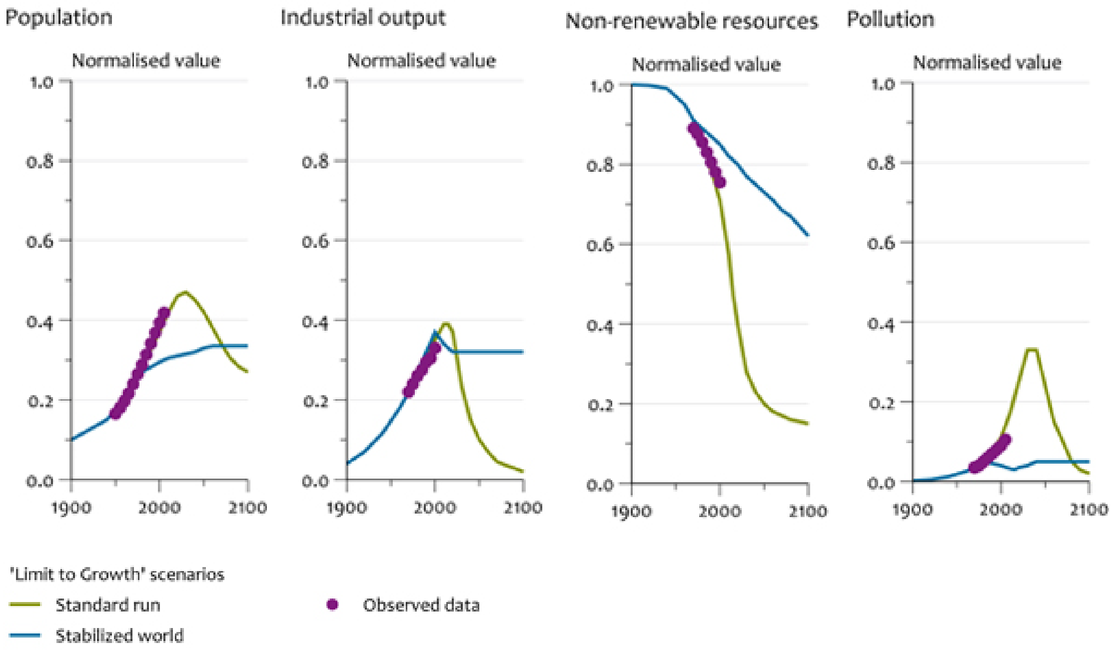

Figure 1. Comparing 'Limits to Growth' scenarios to observed global data. Source: courtesy of PBL Netherlands Environmental Assessment Agency (PBL, 2009).

Therefore, with challenges such as the impossibility of further economic growth due to the effects of Peak Oil (Hall & Klitgaard, 2006; Turiel, 2010; Brown et al., 2011), and many other current parallel social and environmental problems, an urgent answer at many political and cultural levels is required. In relation to what concerns us, Science is also in charge of addressing these problems by producing useful information and tools to facilitate informed discussions in society for dealing with this kind of complex issues (Funtowicz & Ravetz, 1991; Giampietro et al., 2006a; 2006c). In this sense, Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) is not just a promising research theoretical approach, but it has already demonstrated practical success regarding these research aims (Ramos et al., 2007; Sorman et al., 2009; Giampietro et al., 2011; 2014; Arizpe et al., 2012; Siciliano, 2012; Scheidel et al., 2013).

The research work exposed in this thesis is completely focused on the development of methods rather than on the search for solutions to specific problems. Therefore this dissertation is explicitly avoiding *substantive* research to focus completely on *procedural* research[1] (Simon, 1976), so the study here is paying attention to the methodological aspects of the process of scientific analysis. I chose this way of proceeding based on the belief that working on the development of tools can also be very useful to society, as an alternative way of applying specific approaches to one particular perceived problem to try to offer an explicit solution. In a metaphoric analogy, it could be said that Science could provide fish at some point for the hungry when applied to given problems, whereas theoretical Science can offer to the hungry the fishing apparel by developing research methods.

The feature of theoretical Science of suggesting explanations to perceived facts as a resource to provide useful information to society is always limited in some aspects. It cannot be assumed that just by producing some certain knowledge about a particular issue one solves those questions which are intended to be relevant for the society. Actually, any outcome in this way is just providing another point of view, another meaning for the issue (and not only speaking about the social and technical incommensurability). Unfortunately, the resulting representation of an analysed issue following a rigorous scientific method is not necessarily more valid or relevant for the interested actors than other possible legitimate viewpoints, such as traditional knowledge or a visionary prophet (this is assuming when Science is still trying to be useful for society and not just reduced to an economic activity for the self-reproduction of scientists) (Husserl, 1970; Funtowicz & Ravetz 1990; Jasanoff, 2004; Wynne, 1996). Moreover, given that in theoretical Science there are many possible perspectives based on different approaches and perceptions about the same issues (which actually can be opposed one to another) the scientific discussion is often reduced to try to defend one way of formalizing analytical representations of the perceived reality in front of others. Therefore, in this way, theoretical Science sometimes becomes in practice a process where scientists limit themselves to discuss within each other to try to impose their particular perspective as more valid than alternative ones. It is always necessary to bear in mind that Science is one more type of mechanism processing information that produces its characteristic stories attempting to provide relevant outcomes, and although it has some protocols to try to ensure certain quality on the process (i.e. the scientific method), the resulting *stories* are just that, simple stories not necessarily more valid or relevant for the interested actors than other types of non-science-based stories. Indeed, the choice of the appropriate story to try to understand a certain issue does not rely on how complex or rigorous is the explanation; for the society it simply depends on the credibility of the story-teller (e.g. Wynne, 1989). To make things even more complicated, no one (including the most aware researchers) is excluded, when formalizing the perceived reality into an analytical representation, of having to confront the duality as described in the modelling relation theory of Robert Rosen (1985) between "the internal, subjective world of the self" and "an external, objective world of phenomena", because "Science is [one more] way of importing the external world of phenomena into the internal, subjective world where knowledge is preserved" (Mayumi & Giampietro, 2005).

Please see section 2.2.3 for a sound explanation of these ideas within the background theory.

I choose to use theoretical Science as a process of quality control with the simple aim of developing research methods that can be offered as a set of tools *à la carte* to the affected actors asking for information. The interested receivers could in turn choose and adapt what they might consider as the relevant approach and then frame what kind of story will be produced from the analysis of their specific problem. This is the main reason why, although

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[1] Please see the next section 1.1.1 for a further explanation of these concepts.

using some case studies, the work featured along this thesis is fully focused on presenting a theoretical set of methods and tools, rather than attempting to provide specific solutions to particular problems of the case studies. I hope that the findings exposed along this work could contribute to amplify the available tools to deal with similar topics. Finally, I would like to underline that my unavoidable personal vision on the cases studied should not be taken into account as they are merely used for illustrating the methodologies introduced in this study.

1.1.1 Post-Normal Science, Science for Governance and Sustainability Science

Dealing with "science for governance" and sustainability issues requires a very cautious approach since the multiple scales and uncertainties entering into play for this type of complex problems demand the integration of various points of view, both from the socioeconomic systems and from the ecosystems (Mayumi & Giampietro, 2005; Giampietro et al., 2006c). Therefore, this dissertation follows the precepts of Post-Normal Science (Funtowicz & Ravetz, 1990; 1991), which is an epistemological framework proposing to "enhance the process of the social resolution of the problem, including participation and mutual learning among the stakeholders, rather than a definite solution or technological implementation. This is an important change in the relation between the problem identification and the prospects of science-based solutions" (Funtowicz et al., 1998). Post-Normal Science is especially addressed to how to deal with complex problems where there are multiple perspectives and uncertainties about the facts, contrasting values, and high stakes (Funtowicz & Ravetz, 1993). Using the framework of Post-Normal Science for sustainability issues means a focus on the process, where scientists learn how to perceive and make better representations, rather than intending to get a normative outcome to tell to the affected actors what is the proper thing to do. This means that along the work exposed I am implementing Simon's procedural rationality (based on the process) and not substantial rationality (based on the outcome) (Simon, 1976; 1978). This is caused by the fact that with sustainability issues it is never possible to know *the proper* way to analyse and express the characteristics of observed systems (Mayumi & Giampietro, 2005).

Finally, it is important to clarify that I frame the approach in "Sustainability Science". This term is referring to the epistemological paradigm addressing in a systemic way the theoretical considerations to study sustainability (e.g. Mayumi & Giampietro, 2006; Giampietro et al., 2006a). In this sense, this is a paradigm about the meta-analysis of sustainability issues rather than applied "sustainability studies". The term "sustainable" might seem ambiguous as the concept has different implications depending on who is the story-teller (e.g. Munda, 2004; Martinez-Allier, 2008). When the term Sustainability Science is used in this work, I am just placing the type of analytical approach in its theoretical framework. Therefore, along this work I explicitly avoid the designation of particular definitions of sustainability, according to the precepts suggested by Joseph Tainter and Timothy Allen (Allen et al., 2003) for addressing sustainability (sustainability of what?; sustainability for whom?; sustainability at which cost?). The definition of sustainability is case-dependent as it follows the particular narrative of the story-tellers for each study. As I just focus on the development of the methodology, not in particular implications of the specific cases (i.e. used with illustrative purposes), in this work definitions of sustainability are not applicable.

1.1.2 The spatial dimension

As it will be discussed later, the geographical space[2] evidently plays a fundamental role in the shaping of any physical system affecting its performance and possibilities of development. The morphology of the physical space cannot be considered a neutral container which is simply there supporting living systems without much interaction. There are relations in both directions which affect each other constantly and deeply, and the good news is that very powerful tools capable of analysing the geographical space have been developed. From ancient times Physical Geography has been very useful for the location and toponymy, evolving along the centuries and offering more and more analytical tools (e.g. for topography, navigation, hydrology) and explaining events in many research areas (e.g. biology,

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[2] The topological space might be also relevant and very interesting to research on (e.g. with network analysis), but in this research I am strictly focused on the geographical part.

geology, anthropology). The new information technologies have been the last revolutionary advance in Geography, offering extraordinarily powerful tools that were only dreamed of a few decades ago. It is then an almost obvious step for research advances the consideration of the physical space in the evolution of sustainability analysis, given the current mature degree of methodological development in Physical Geography. Given the very scarce existing attempts to incorporate the use of spatial analysis in integrated assessment approaches (see section 2.3), and more particularly, in the MuSIASEM approach[3] (Lobo Aleu & Baeza, 2009), I “take the baton” to explore this promising research areas.

1.2 Research questions and goals

As mentioned in the previous section, the ultimate goal of this thesis is to *develop a methodology that can contribute to quantitative analyses of sustainability issues*.

In particular, the partial goals articulating the work that is going to be exposed are:

A. Develop procedures to incorporate spatial and geographic analytical tools[4] into multi-scale integrated representations. For this task I will explore the utilization of Land Use[5] information and Geographic Information Systems (GIS).
B. Research and define the potential advantages and capacities of the previous tools, as well as the possible problems and constraints when integrating them into a broader analytical approach.
C. For the previous purpose, the aim is to *test* the approach using *empirical case studies* for the *calibration* of the methodology.

It is important to mention that the work presented develops these methods with a particular focus on rural systems and cases where agrosystems and the natural environment are the main research issue.

Therefore, the research questions are:

1) Is geographical analysis relevant for an integrated assessment of sustainability?
2) Are existing geographical analytical tools helpful in making multi-scale integrated representations?
3) *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?
4) Which are the possible limitations when applying these methods?
5) How are the outcomes of the incorporation of these tools?

1.3 The structure of the thesis

This dissertation is about methods for **quantitative** analysis framed in the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) approach (this concept will be properly described in the next Chapter 2), focusing on the *accounting* aspect of the geographical analysis and the land use. In a way, this thesis is ultimately aiming at the issue of “how to empower people to have a better understanding of their environment”. Since the study is focused on the land use and the geographic analysis, I am addressing those topics directly linked to the analysis of the territory. Particularly, there is a focus on rural areas, where market, technology and trade play a secondary role in shaping the pattern of production and consumption of goods and services, and the territorial

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[3] Although Land Use data has been long before incorporated into the MuSIASEM approach, a deep research on its possibilities (see Chapter 4), and overall, the geographical analysis, was not much attempted to develop methodologically.

[4] Spatial and geographic analytical tools are made to capture, manipulate, analyze and present geographic data and information related to the physical space. These tools could work with paper or digital maps, databases including physical locations, network representations, images, etc. These tools range from simple compasses, rules and papers to the most sophisticated software programmes calculating automatically millions of data entries from satellite imagery or generating very intricate maps for the simultaneous visualization of multiple aspects of a certain territory.

[5] Land Use data is about the amounts of certain types of surfaces in a system, and it is not necessarily linked to spatial data.

structure (i.e. the metabolic patterns in relation to land uses) becomes crucial to define the sustainability in relation to both socioeconomic and ecological constraints.

The following Chapter 2 will introduce some theoretical points to understand the selected analytical approach–MuSIASEM–and a brief revision to the theoretical framework in which MuSIASEM is based. These elementary theoretical notions will serve to understand the practical part of this research and also to introduce the particular contribution of the proposed methodology. In Chapter 3, I focus more specifically on the particular background and methods developed to analyse and express representations of rural systems.

Part II of this dissertation is also divided into three chapters. Chapter 4 presents the first case study undertaken in this research, which is based on an article published in the scientific journal Land Use Policy (Serrano-Tovar and Giampietro, 2014). In this chapter an integrated characterization is provided, in quantitative terms, of the metabolic patterns of rural Laos across different scales. For the purpose of this study I considered different hierarchical levels of organization–i.e. household, village, region, the whole country. The main contribution of this case study is the creation of one of the few practical applications of Hierarchy Theory (see section 2.2.3). Therefore, this study demonstrates how it is possible to make quantitative analysis of metabolic patterns across hierarchical levels.

The following two chapters are explaining more practical concepts about the methods implemented in two cases studies where I build scenarios incorporating the use of GIS tools, in order to provide information about possible geographical constraints and to visualize the final arrangement of the territory with the resulting simulated metabolic patterns.

Specifically, Chapter 5 is based on a paper prepared for the journal “Environment, Development and Sustainability”. It presents a case study undertaken in Guatemala where I develop an application to generate the primary information at local scale about some peasant communities. This chapter basically proves that within the proposed approach and methodology; our own data can be collected when needed so that it is possible to decide how to measure the systems under analysis.

In Chapter 6, I present a more elaborated case study based on the chapter “The Republic of Mauritius” prepared for the book “Resource Accounting for Sustainability Assessment: The Nexus between Energy, Food, Water and Land Use” of the Routledge series ‘Explorations in Sustainability and Governance’[6] (Giampietro et al., 2014). I was the main author for that chapter and the principal coordinator of the Mauritius case study in the research project. In this project, funded by the Food and Agriculture Organization of the United Nations (FAO), an analytical framework was developed integrating the nexus between water, energy and food security in relation to sustainability issues of three case studies: Mauritius, Punjab and South Africa[7]. In the case of Mauritius I present how to put together information from different areas, organized with MuSIASEM for addressing policy options of sustainable development. In particular, the case demonstrates how the analysis can be in practice applied to make scenarios.

Part III of the thesis is divided into two concluding chapters. In Chapter 7, I develop the theoretical and practical lessons learned regarding the implications of the use of spatial analysis within MuSIASEM, and I make some last remarks to be taken into account when using these tools. This chapter represents a necessary reflection to underline the findings obtained along the practical studies, while it links their contributions into the common aim of this thesis regarding the use of geographic analytical tools in MuSIASEM. This chapter shares some ideas also with the chapter “GIS protocols for use with MuSIASEM” prepared for the mentioned book “Resource Accounting for Sustainability Assessment: The Nexus between Energy, Food, Water and Land Use” (Giampietro et al., 2014).

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[6] www.routledge.com/books/details/9780415720595/

[7] www.fao.org/energy/81320/en/ , nexus-assessment.info/

Finally, Chapter 8 closes the document with few final reflections and remarks about the overall thesis, divided into theoretical lessons from the MuSIASEM approach, conclusions about what has been learned along the case studies, and finally highlighting the main implications of the use of GIS in the MuSIASEM approach.

Chapter 2

The chosen framework

2 The chosen framework

2.1 The MuSIASEM approach

The Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) is a recent and still evolving approach introduced by Giampietro and Mayumi (1997; 2000a; 2000b) created with the purpose of generating integrated analytical representations of socioeconomic systems for sustainability issues. The aim of the MuSIASEM approach is to analyse the feasibility and viability of development patterns of observed systems making a quantitative characterization of metabolic performance at multiple levels and scales. This approach establishes a relation among the socioeconomic activities (e.g. for households, economic sectors, or national economies) and possible biophysical constraints studying the metabolism of some types of energy and matter (e.g. water) of human societies interacting with natural ecosystems (Giampietro et al., 2009).

As I will develop in the following sections, the MuSIASEM approach builds on the theoretical concepts developed in the field of complex systems analysis and in particular on Hierarchy Theory, the branch of complexity theory explicitly dealing with the issue of scale (Simon, 1962; Grene, 1969; Pattee, 1973; Allen & Starr, 1982; Salthe, 1985; O'Neill et al., 1986; O'Neill, 1989; Allen and Hoekstra, 1992). In particular, the applications presented here are based on the concept of metabolic pattern–the existence of a set of expected benchmark values that can be used to characterize a network of flow elements controlled by a set of fund elements (Giampietro et al., 2011). This notion combines elements of the metabolic theory of ecology (e.g., Brown et al., 2004) with Georgescu-Roegen's fund-flow model (Georgescu-Roegen, 1971; 1975).

As we are studying sustainability of social systems whose identity is characterized by changing overtime, it is important that the tools we use to analyse them are semantically open[8]. The "multi-purpose grammar" in which MuSIASEM is based can be adapted to make representations of the changing identity of these systems. In fact, it is characterized by being capable of establishing relations between ''relevant semantic categories and pertinent formal categories across hierarchical levels and across different narratives" (Giampietro, 2003; Giampietro et al., 2009).

In conclusion, the MuSIASEM approach provides an integrated meta-system of accounting capable of establishing linkages across the representations of changes taking place over the various indicators. This way, it becomes possible to study the unavoidable presence of sustainability trade-offs. With MuSIASEM, when one indicator changes in one direction, one can expect that also other indicators will have to change. The approach does not try to establish a deterministic relation over changes, but it makes it possible to define viability domains (the combinations of changes which are consistent with each other) and, even more relevant, define non-viable domains (a set of values for the various indicators which would generate an impossible state). This last feature is extremely important for building more robust representations of possible scenarios of changes.

2.2 The pillars of the MuSIASEM approach

Some of the fundamental theoretical frameworks in which MuSIASEM is based are introduced in the next sections. They are keys to later understand the work developed along this thesis and its potential implications and contributions.

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[8] In MuSIASEM we provide analytical tools that are capable of adapting to the purpose of each particular study utilizing a semantic check on the process. That is, the formalization of the analytical model, the selection of the relevant data and the meaning of the outcomes depend on external references, being thus adjusted to what is required by the actors demanding the analysis. This approach represents an alternative to "semantically closed" models where there the meaning of the information processed is pre-established and formalized by the analyst, without possible check to external references and adaptation to the case.

2.2.1 Metabolic systems

Metabolic systems are self-organizing dissipative systems. They are able to use energy, materials and other natural resources to maintain, reproduce and improve their own existing structures and functions, i.e. their identity (Giampietro et al., 2011). The concept of metabolic system was extended to the analysis of social systems early in the last century (Ostwald, 1907; 1911; Zipf, 1941; White, 1949; Cottrell, 1955; Lotka, 1956; Georgescu-Roegen, 1975), thus paving the way for the perception of the metabolic pattern of society. The metabolic pattern of society is based on the expression of a set of stabilized energy and material flows capable of guaranteeing: (i) the expression of an expected (desirable) set of functions, (ii) feasibility with the boundary conditions (with the ecological processes embedding the society), as well as (iii) a certain internal adaptability (viability) to allow for evolution and resilience. Indeed, the idea of self-organization in dissipative systems is intricately linked to that of: (1) parallel levels of organization on different space-time scales and the consequent need of using multiple identities; and (2) evolution, meaning that the identity of the state space is changing in time.

Metabolic systems express predictable metabolic patterns that are directly related to their identity. This feature is particularly valuable and is at the basis of metabolic theory of ecology (e.g. Brown et al., 2004). For example, human beings have a predictable body temperature of 37 ºC, a blood pH of about 7, and a fixed relation between the weights of internal organs. Similarly, by looking at the trophic structure of ecosystems, one can distinguish a marine ecosystem from a terrestrial one and a tropical forest from tundra. This peculiar feature is also expressed by socio-economic systems and therefore it is possible to define expected metabolic patterns associated with the identity of given typologies of society (Giampietro et al., 2011).

2.2.2 The flow-fund model proposed by Georgescu-Roegen

The flow-fund conceptual model proposed by Georgescu-Roegen (1971; 1975) has shown to be extremely useful to characterize in quantitative and biophysical terms expected metabolic patterns of social systems (Giampietro et al., 2011). Following this model the researcher has to define first of all, in a preanalytical step, the fund elements used to represent the system. Fund elements are associated with the identity of the system; they define *what the system is* (e.g. human population, or territory). The analyst then has to associate relevant flow elements to these fund elements. In the representation these are the input and output flows expressing the functions getting in and out the fund elements. The flow elements define *what the system does* (e.g. use energy, or make economic transactions). They allow us to represent both: (i) the interaction of the parts within the chosen system (the whole); and (ii) the interaction of the whole with the context. Using this flow-fund model it becomes possible to integrate in a coherent analysis various pieces of quantitative information referring to different dimensions of analysis (e.g. biophysical, agronomic, economic, demographic and ecological). In particular, using two complementing but non-equivalent definitions of fund elements–one relevant for socio-economic analysis (human activity) and one relevant for ecological analysis (land uses)–the MuSIASEM approach can generate an integrated characterization of the metabolic pattern of rural systems by combining two non-equivalent systems of accounting (see Chapter 3).

2.2.3 Hierarchy Theory and Complex Systems Theory

Hierarchy Theory is the branch of Complex Systems Theory studying the epistemological implications of multiple scales. Ahl and Allen (1996, p. 29) suggest the following definition: “Hierarchy Theory is a theory of the observer’s role in any formal study of complex systems”. Indeed, in accordance with this definition, we find that the same system can express different identities depending on the chosen representation. It follows that when defining an identity for an observed system, we also have to define the associated descriptive domain. The descriptive domain defines what is included and what is excluded from the representation depending on the attributes used to perceive and represent the system under study. Hence a descriptive domain necessarily requires a definition of scale: the boundary (the extent in space and time) and the resolution (the grain in space and time) of the description associated with the observable attributes. The existence of multiple scales implies the unavoidable coexistence of non-equivalent descriptive domains. For instance, no matter how many pictures we take of a person through a microscope we will never be able to reproduce her/his face by aggregating this information. The personal identity associated with the face can only be detected at a much larger scale of observation.

Another useful building block derived from complex systems theory is the concept of *holon*. Arthur Koestler (1968, 1969, 1978) introduced this concept as an epistemic device providing useful insight to the analyst in the study of complex systems. Each component of a complex system organized in nested elements may be called a 'holon'. For instance, a farmer cultivating rice in Laos is a holon. Consider a certain Mr Kahmphoukeo who is an "incumbent" in the "role" of rice farmer (the "organized structure"). To justify the categorization of this organized structure as rice farmer, we must define the functional role of "rice farmer", which is determined by the social context within which the specific instance (Mr Kahmphoukeo) is operating. Hence two non-equivalent scales have to be used simultaneously to define the holon "farmer cultivating rice in Laos": a time extent of at maximum 80 years when considering the individual human being (the organized structure or incumbent in the role) and a time extent of several centuries when considering the function "rice farming" (functional type or role).

The existence of this dual nature (fuzzy identity) of elements of complex systems has been flagged under different names in complexity theory by different authors. Simon (1962) talks about "organized structure" and "relational function", Bailey (1990), dealing with human societies, talks about "incumbent" and "role", Salthe (1985) about "individuals" and "types", while Rosen (2000) suggests, within a more general theory of modelling relation, the terms "individual realizations" and "essences". Whatever the wording used, the theoretical concept of holon refers to the mechanism of human perception of the external world. Relevant components of a complex system are perceived as such because they have a "why" (they express a useful function), but at the same time they must also have a "how" (they can only express that function thanks to the existence of an organize structure). For example, the school of a village is perceived as such by the villagers because it is where the youth learn some knowledge, that is, by its educative function (which is autonomous) within the context of the community. But the school also has a particular organized structure; it is a particular building of the village with desks, blackboard, chairs, teacher, books, etc. which combined in certain way allow the expression of that perceived function. Then the school is a "whole" made of multiple parts, and at the same time it represents one particular piece of the multiple functions of a village (the place for the transmission of knowledge), and thus is perceived by the society: a part of the village made of parts with a specific function which makes it also a whole singular entity for them. Therefore, the epistemological challenge associated with the practical application of the concept of holon lies in the fact that the narratives and data required to study and represent the functions are different from those required to study and represent the structural organizations (Giampietro et al., 2006b). Clearly, the final usefulness of the concept of holon depends on the robustness of our mapping between a class of organized structures and the associated functions.

The issue of scales, and more specifically the process of up scaling across levels in our approach, will be analysed in Chapter 4 with a practical case study.

2.3 Alternative approaches to MuSIASEM

There is a variety of analytical frameworks alternative to the MuSIASEM approach dealing from different methodological perspectives with some of the topics of this dissertation (i.e. analysis of sustainability, for rural systems, including multiple dimensions and the geographic features). Along the next section I will present some of their characteristics to expose the different capacities and the convenience of using the MuSIASEM approach for my work.

Starting from the most simplistic approaches, it could be said that in general, most of analytical models used to tackle sustainability issues are commonly based on fixed "universal" indicators which intend to fit to the description of all possible cases without any semantic adaptation. For instance, the GDP or the Human Development Index (published by the United Nations Development Programme) are well known examples of indicators widely applied for attempting to characterize the overall "development" of a country. The GDP is one-dimensional (only accounts for monetary transactions and it cannot be used to reflect any other aspect such societal or environmental performance) and the HDI is trying to normalize different dimensions with dissimilar semantic and formal identities (i.e. education, monetary income and life expectancy) into one single composite indicator which is meant to be applicable to compare (so different in so many aspects) nations as Switzerland and Bhutan! One-dimensional indicators and composite indices–e.g. HANPP[9] (Vitousek et al., 1986), Emergy[10] (Odum, 1988; 1991) or Ecological Footprint (Wackernagel, 1999)–have crucial limitations such as important losses of information in the encoding process due to too much reductionism (the outcomes become completely meaningless without any external reference!), or arbitrary assignment of weights of the components among other constraints (Saisana et al., 2005). Leaving aside unidisciplinary approaches, there are some frameworks which try to make integrated representations, but unfortunately "multi-disciplinary" views still dominate over "trans-disciplinary" perspectives, since a true integration of the knowledge among disciplines is still recent in formative processes of academia.

2.3.1 Integrated Assessment Models

However, there are some interesting approaches that have attempted to make integrated representations at different scales from systemic points of view. The idea of MuSIASEM that systems analysis and modelling is a powerful approach to understand and assess complex relationships is certainly not new (e.g., Campbell & Sayer, 2003; Grimm et al., 2006; Holland, 2006). For instance, Integrated Assessment (IA) and Modelling (IAM) are approaches trying to make representations of complex systems considering biophysical, institutional, social and economic aspects (Harris, 2002). IA models are made combining existing one-dimensional models using data of the different considered dimensions, so at the end these models can just deal with one question at a time, because the resulting integrated model is only applicable within a range given by its model components–examples of these models are: DICE (Nordhaus, 1993) and RICE (Nordhaus and Yang, 1996) or RAINS (Amann et al., 1999), IMAGE (Bouwman et al., 2006). One of the main problems of IA models is the capacity of adaptation to different applications due to the conceptual and technical requirements manifested for the coupling among the available models (i.e. the technical incommensurability of the considered dimensions). MIT (Prinn et al., 1999), the "Trade-offs Analysis Model" (Stoorvogel et al., 2004), ATEAM (Schroter et al., 2005), or Eururalis (Westhoek et al., 2006; Verburg et al., 2008) are examples of IA's with weak connections among the models composing them.

Regarding IA models focused on agricultural issues, there are some attempts made at single scales of analysis, such as field/farm (Kokic et al., 2007), regional (Stoorvogelet al., 2004), continental (Ewert et al., 2005; Rounsevell et al., 2005) or global scale (Rosegrant et al., 2001; Parry et al., 2004; Fischer et al., 2005). However, few IA models are applicable across multiple scales (Ewert et al., 2009), and none of them have yet demonstrated the feasibility of applying Hierarchy Theory to the study of practical issues such as sustainable rural development (see Chapter 4).

One example of efforts in combining spatial analysis models with other dimensions for the assessment of yield gaps (i.e. the potential crop production of a region) and related agricultural issues is the research programme "Sustainable Land Management[11]", where the spatial analysis model PROMET (PROcess of radiation Mass and Energy Transfer) (Mauser & Bach, 2009) is combined with the market model "Common Agricultural Policy

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[9] HANPP stands for "Human Appropriation of Net Primary Productivity", is the nth attempt to reduce to a single value the whole impact of human society on the environment by trying to transform everything to the extraction ofkilograms of organic matter composed by photosynthesis in ecosystems.

[10] Emergy is the term used to express the "embodied energy" required to produce the goods and services of human societies, taking into account the products' life-cycle. It aims to reduce to one single type of energy dimension the cost of using devices for energy saving issues or greenhouse emissions.

[11] Website:http://nachhaltiges-landmanagement.de/en/

Regionalised Impact Analysis" (CAPRI)[12], and the economic model Dynamic Applied Regional Trade (DART) (Springer, 2002; Klepper et al., 2003; Kretschmer et al., 2008). In this example it is not even possible to speak about an Integrated Assessment Model, since the only interaction between the biophysical factors of the PROMET model and the economic models CAPRI and DART is the yield level of crops. Moreover, these economic models are driven and based exclusively on the monetary profitability of the agricultural sectors (!), and the rest of links among dimensions accounting for possible constraints and trade-offs (e.g. shortage of labour, competition among economic sectors, or depletion of limited resources such as water or soil) are simply avoided!

2.3.2 The Ewert's SEAMLESS-IF Model

One of the most notable efforts on multi-scale analysis for agriculture, and probably one of the most advanced IAM is called SEAMLESS-IF (Ewert et al., 2005, 2006; Van Ittersum et al., 2008). It claims integrating "relationships and processes across disciplines and scales and it combines quantitative analysis with qualitative judgments and experiences" (Ewert et al., 2009). This IAM takes into account the socioeconomic and natural environment and the possible multiple functions of agriculture. Similarly to the MuSIASEM approach, the SEAMLESS-IF considers some "preanalytical" steps since it deals with the problem and scenario definition and with the particular selection of indicators. It also acknowledges the importance of participatory processes at some stages of the study. The main advance of this model is that it claims certain flexibility and adaptive capacity "for a range of issues and functions and attempts to enable flexible coupling of models and tools", although they also affirm that the "scientific basis for linking models across disciplines and scales is still weak and requires specific attention in future research" (Ewert et al., 2009), that is, they are stuck with the issue of social and technical incommensurability. Regarding the problem of scaling of information, they attempt to make up-scaling by simply aggregating or sampling with extrapolation algorithms using descriptive response functions and technical coefficients, so there is no consideration of the possible semantic differences of the perceived system at different scales. In this sense, they acknowledge that "conceptual mismatches between models are often overlooked when linking models across scales". And furthermore, they consider that "more advanced methods are required when the underlying processes are non-linear as typical for many environmental indicators" (Ewert et al., 2009).

In conclusion, IAM are complicated models–and few of them consider scaling methods–which are difficult to operate and understand, and moreover, the combinations of models might even result meaningless for the desired purpose, as they themselves recognize. In any case this type of models requires high amounts of data and suffer from the accumulation of uncertainty due to the sum of multiple models (Ewert et al., 2011).

2.3.3 The Bollinger's Multi-Model Ecology

Another approach called "Multi-Model Ecology" has been very recently introduced by L.A. Bollinger (2013). It is a very interesting new modelling approach that claims to reinforce the issue of adaptation of the models to different contexts and problem definitions making possible the integration of multiple system levels, timescales and perspectives. It is intended to make a "systematic exploration of assumptions space" through a "fragmentation and gradual reconstitution of a problem's multiple components and dimensions in an evolving participatory context" (Bollinger, 2013). However, apart from recognizing to have found similar limitations to the mentioned problems of SEAMLESS-IF (i.e. semantic gap between component models and difficulties to compatibility to different contexts), this model is still on a very early development stage (at the moment there is one single published experimental pilot case in a conference proceedings that raised many further research questions). Thus, at the moment this approach could be considered just a promising meta-model that still has to demonstrate the feasibility of practical applications and successful achievements of the intended aims.

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[12] Website: http://www.capri-model.org/index.htm

2.3.4 Comparing MuSIASEM with the alternative approaches

In any case, both SEAMLESS-IF and "Multi-Model Ecology" are still computational models. The problem with this kind of models is that it is simply not possible to predict the future of complex autopoietic systems (such as human systems) independently of how complicated the model is (actually making models more complicated is not good to assess complexity) (Giampietro, 2003). These computational models require that everything else must remain the same (the *ceteris paribus* hypothesis), but it is not possible to know all relevant attributes to analyse complex systems (Giampietro et al. 2012) or establish linear causations among all the elements in a model (Giampietro et al. 2013). These models cannot make a formal representation addressing systems that are changing in time, because complex dissipative systems, especially living systems, are constantly adapting and coevolving with their environment (Prigogine, 1980). Therefore, predicative models (those whose element's definitions do not depend on the other elements of the system) cannot make good simulations of their evolution (Giampietro et al., 2011).

In this sense, MuSIASEM offers the concept of "multi-purpose grammars", instead of trying to make semantically closed models to deal with this type of systems. The representation provided by a grammar is firstly based on the definition of the semantic categories, and only then it sets the relations among semantic and formal categories. Therefore, grammars are "semantically open" because they can be adapted to specific situations and incorporate new relevant qualitative elements in the analysis. By using grammars it is possible to check what remains the same for the analyst (in terms of semantic relations among the elements) when the observed system evolves– independently of changing the formalization of the represented elements of the system (Giampietro et al., 2009; 2013). A real application of the use of multipurpose grammars is shown in Chapter 4.

Moreover, most of modelling approaches are clearly normative, although few of them are starting to incorporate some epistemological concerns–related to the topic of science for governance in sustainability issues–such as problem definition, multiple valid perspectives, or participatory processes, which are the theoretical pillars of the MuSIASEM approach from its origins.

Another important remark is that when the MuSIASEM approach includes the creation of scenarios to explore and represent potential constraints and trade-offs of selected future alternatives, these are intended to be descriptive rather than normative (Nijkamp & Blaas, 1994), and explorative rather than trying to make predictions (VanIttersum et al., 1998).

Finally, maybe the most relevant fact is that nowadays, none of the listed approaches for integrated multi-scale representations have ever incorporated spatial analysis in their models. There are available many studies about "integrated land use assessment" and "integrated assessment of land use changes", but there no one has ever publicly shown efforts in integrating true Integrated Assessment Models (as described in the Glossary) with spatial analysis. This is one more reason for the work presented in this thesis and the main innovative contribution of this methodological research.

Chapter 3

Introduction to the analysis of rural systems

3 Introduction to the analysis of rural systems

The methodological approach generated through this research work is particularly applied to sustainability issues of rural systems and agricultural activity, nowadays a hot topic due to its role in providing the most basic resources for humans (e.g. food, clothing, shelter) and the problems regarding its current and future limitations. There are huge challenges to ensure the food production for human population and to maintain the health of the systems supporting agriculture along the next decades (Smil, 2001; Tilman et al., 2002). Improving the yields without compromising the integrity of ecosystems becomes a major problem taking into account that the law of diminishing returns is applied particularly strictly to agriculture –and other extractive industries–because it depends on natural limited production factors (e.g. land, soil, fresh water, nutrients). Moreover, the reason why industrialized agricultural systems were increasing yields all around the world in the past, is exclusively due to the application of fossil fuel technologies to boost the natural pace of edible biomass production, causing a total dependence of the current level of agricultural production on cheap fossil energy (Odum, 1967; Pimentel & Pimentel 1979; Brown, 1981; Hall et al., 1986; 2000; Odum, 1989; Conforti & Giampietro 1997; Arizpe et al., 2011). Perspectives from different approaches, like studies on the carrying capacity for agricultural activities (Harris et al., 1996) or the level of depletion of natural resources by humans (Daily, 1995), highlight the relevance of the issues on demographic policies, consumption levels, and distributional equity in a world of constrained agricultural growth, and project that many world regions will unavoidably face many important problems along the next years due to the (un)sustainability of current agricultural systems (Bruinsma, 2003).

Please note that the following chapter does not provide an overview of theories about farming systems, agro-ecology or peasants studies, but it just focuses on the particular representations of the MuSIASEM approach on rural systems.

3.1 Applying MuSIASEM approach to rural system studies

As previously mentioned, this dissertation is based on the MuSIASEM approach for developing methods for the analysis of rural systems. In fact, MuSIASEM was originally developed to generate multi-scale indicators of sustainability for rural systems (Giampietro & Pastore, 1999; Pastore et al., 1999; Gomiero & Giampietro, 2001; 2005; Giampietro, 2003), but is now also applied to the analysis of developed economies (Ramos-Martín et al., 2007; Giampietro et al., 2011; 2012).

Quantitative analysis of sustainability in rural systems presents formidable epistemological challenges. From the metabolic analysis perspective, it is possible to say that rural systems are characterized by a particular reproductive relation of the society in the context of its natural environment. Agricultural activities are at the interface of socio-economic and ecological processes, each of which expresses specific patterns and controls that can only be observed and explained by adopting different dimensions and scales of analysis (Giampietro, 2003; Ewert et al., 2009; 2011). In rural areas the ecosystem constraints are as important to check possible development options as socioeconomic factors. The land in rural systems is associated with both natural areas (Non-Colonized Lands) and areas with extractive activities of natural resources such as agriculture.

In Figure 2 we can see an example of a dendrogram where it is possible to observe the display of the types of land uses across levels in our approach. In this case, the focus is on the share of land corresponding to the Colonized Land (COL), that is why it is named level n, being the level n+1 the total available land in the considered system which includes the Non-Colonized Lands (NCL). As shown, depending on the purpose of the study, we could analyse the lower levels composing the rural areas, in this case the subsectors of the urban areas are not considered. The land of the rural areas can be typically split into two main sectors for a metabolic analysis: the land for the households represents the consumption part of the society and the land of the Paid Work sectors is the productive part. The land in this last sector can be again divided into economic sectors, and if the focus is on agriculture, another sublevel with relevant types of agricultural lands can be created for our study (e.g. cereals, pastures and other vegetables). Note that according to this figure representing a hypothetical rural system, the land use would be notably urbanized, as the agricultural area plus the non-colonized land would only represent less than half of the surface of the system.

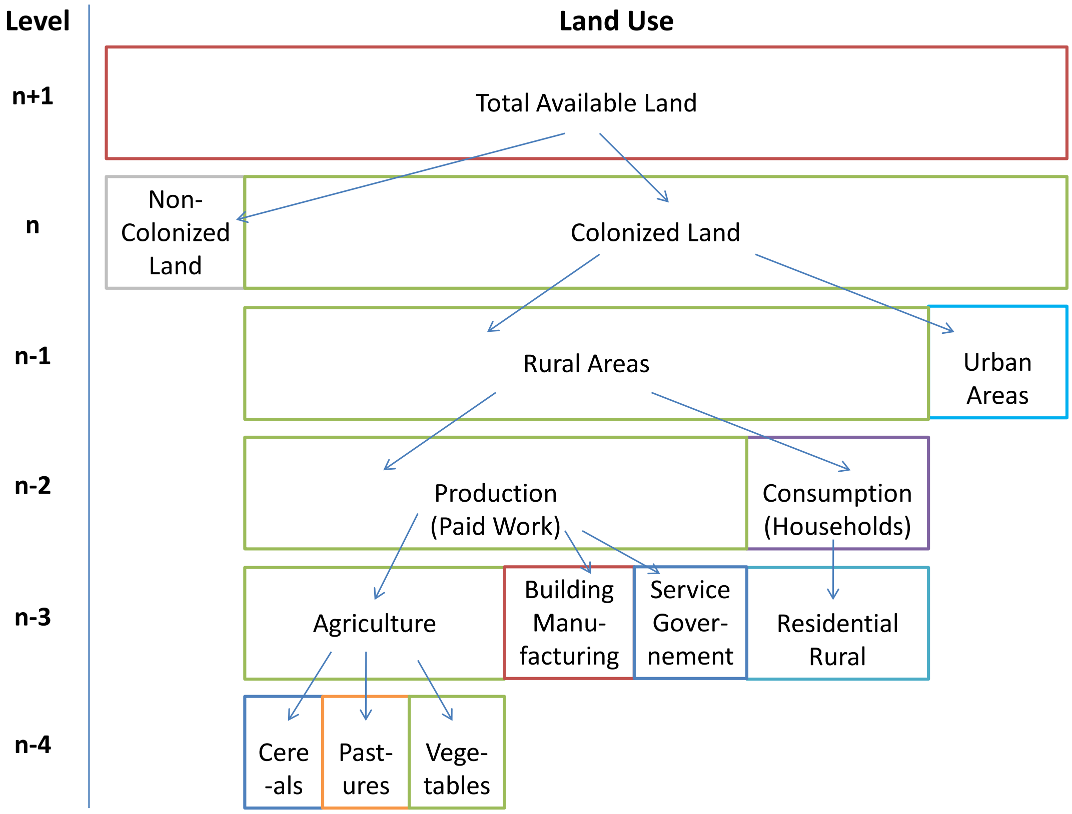

Figure 2. Example of dendrogram for Land Uses. In this case the area of the boxes corresponds to the surface of each type of land use.

As mentioned, there are many other types of activities that take place within rural areas like tourism, all kinds of services, or even some industry. Sustainable rural communities must be multi-functional in order to produce and maintain a complex structural and functional organization (McConnell & Dillon, 1997; Pretty, 2008). They must be capable not only of stabilizing the existing patterns of activity, but also of expressing adaptability and resilience in case of changes in boundary conditions and perturbations (Conrad, 1983; Pattee, 1995; Gunderson & Holling, 2002). For this reason, although farming is the most distinctive activity in rural areas, it is essential to provide a holistic vision of the complex set of activities expressed by rural communities and acknowledge that agricultural production is just one of the many functions to be performed (Bohman et al., 1999; Knickel & Renting, 2000; Giampietro, 2003; Wilson, 2010). Thus, rural systems are considered as the set of all the human activities taking place within rural areas, including the non-farming activities.

3.2 Expressing an integrated representation of rural systems

3.2.1 Farming implies a holonic relation between categories of human activity and categories of land use

Farming is, by definition, about land uses and therefore its study requires quantification based on land use analysis. However, farming is also about human activity, as it is the agency of humans that reproduces the expected features of given patterns of land uses. The direct relation between the human activities associated with agriculture (the various tasks performed on the farm during the year) and the land uses resulting from these agricultural practices, shape the metabolic pattern of rural areas. Thus, in this thesis a framework has been developed (Serrano-Tovar & Giampietro, 2014) to establish a relation between the categories (typologies) selected to describe human activity and those selected to describe land uses. The capability of a rural community to successfully reproduce itself in time depends on the appropriate combination and coupling–in qualitative and quantitative terms–of the various categories of human activities and land uses. Or, in our technical jargon, the emergent property of the whole (a reproducing farming system) depends on the characteristics and sizes of the functional and structural parts and their relative abundance in the system.

Then, the MuSIASEM approach is able to adopt two non-equivalent definitions of “size” for the fund elements (structural parts) in the metabolic pattern: (i) hours of human activity and (ii) hectares of colonized land. This fuzzy definition of size allows a high degree of flexibility in the scaling of the information gathered at different levels of organization. Note that the total size of the system, either in terms of hours of human activity or hectares of land-use, provides an external referent for the definition of the system boundaries (delimitation).

As regards the fund human activity, the size of the whole system defined over the duration of one year equals the total time (in hours) associated with the total human population in the system (population size x 365 days x 24 hours). This total amount of human activity (the size of the whole) is then divided over lower-level elements (the parts making up the whole), as we can see in Figure 3. In our representation this is done by defining categories (typologies) of human activity at lower hierarchical levels that represent useful functions of the society. In this way local fund elements (structural parts) are associated with the expression of specific functions (e.g., rice farming). The size of each of these parts is measured in hours of human activity per year dedicated to the corresponding function. The resulting “skeleton” of fund elements (defined over various hierarchical levels) indicates how much of the total endowment of human activity (the whole) is allocated to the various functions in the system. This characterization allows us to define a series of benchmarks in terms of flow rate per hour of human activity across compartments (e.g., kg of rice produced per hour of human activity in rice production). Thus, in a given system we have a set of expected values for technical coefficients (e.g., productivity of labour), which are defined as the flows of either input or output per hour of human activity allocated to different tasks.

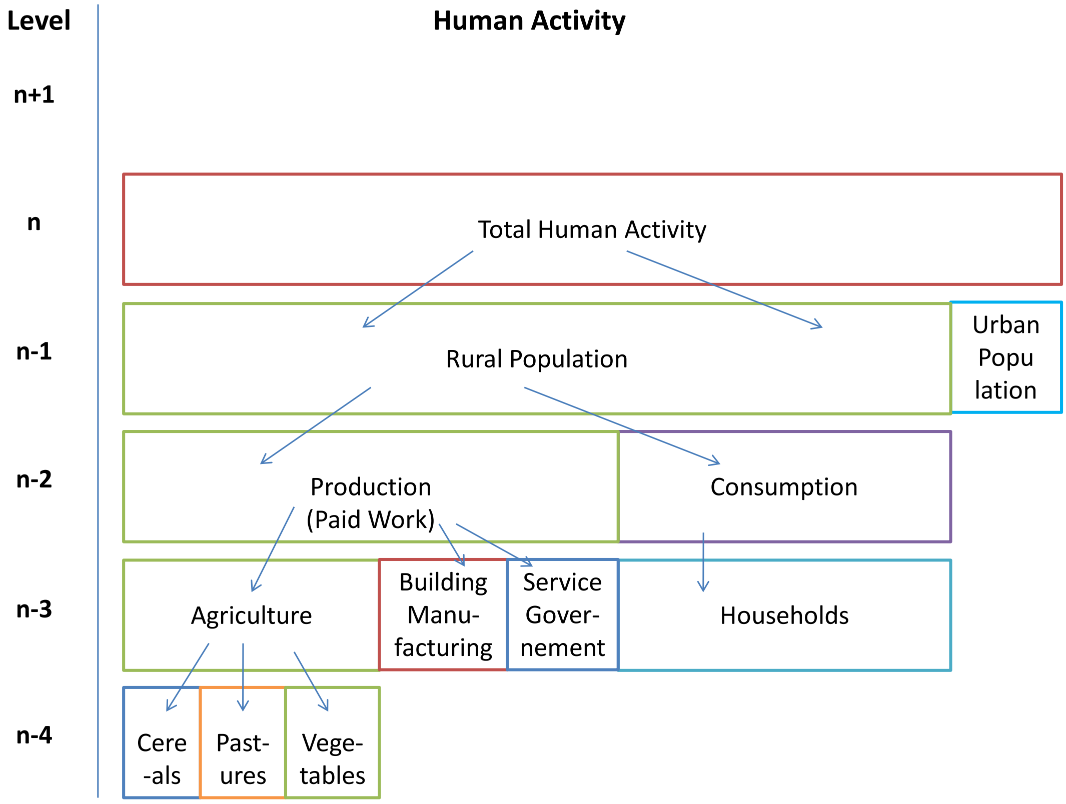

Figure 3. Dendrogram for Human Activity. In this case the area of the boxes corresponds to the amount of hours of each type of activity.

As regards the fund Land Use, the size of the whole system is defined as the total amount of land controlled by the population making up the system in a given year. Similarly to human activity, this total amount of colonized land (the size of the whole) is divided over lower-level elements (the parts making up the whole). This is done by defining relevant categories (typologies) of land uses at lower hierarchical levels, such as crops, pastures, and urban settlements. The resulting set of fund elements is then used to define another series of benchmarks of the type flow/fund ratio across compartments and levels, namely the *density* of flows per hectare (e.g., kg of rice produced per hectare of colonized land in rice production). Also in this case, with prior knowledge of farming techniques, one may expect, in a given year and for a given farming system type, certain values for these flow densities (within a reasonable approximation). For instance, we may expect a certain rice yield per hectare, a certain density of fertilizer application per hectare, or a certain load of grazing animals per hectare. In general, the continuous human alteration of natural processes associated with agricultural techniques implies the establishment of a pattern of biomass production that is different (both in quantity and quality) from that in the original ecosystem without human interference (Giampietro et al., 1992).

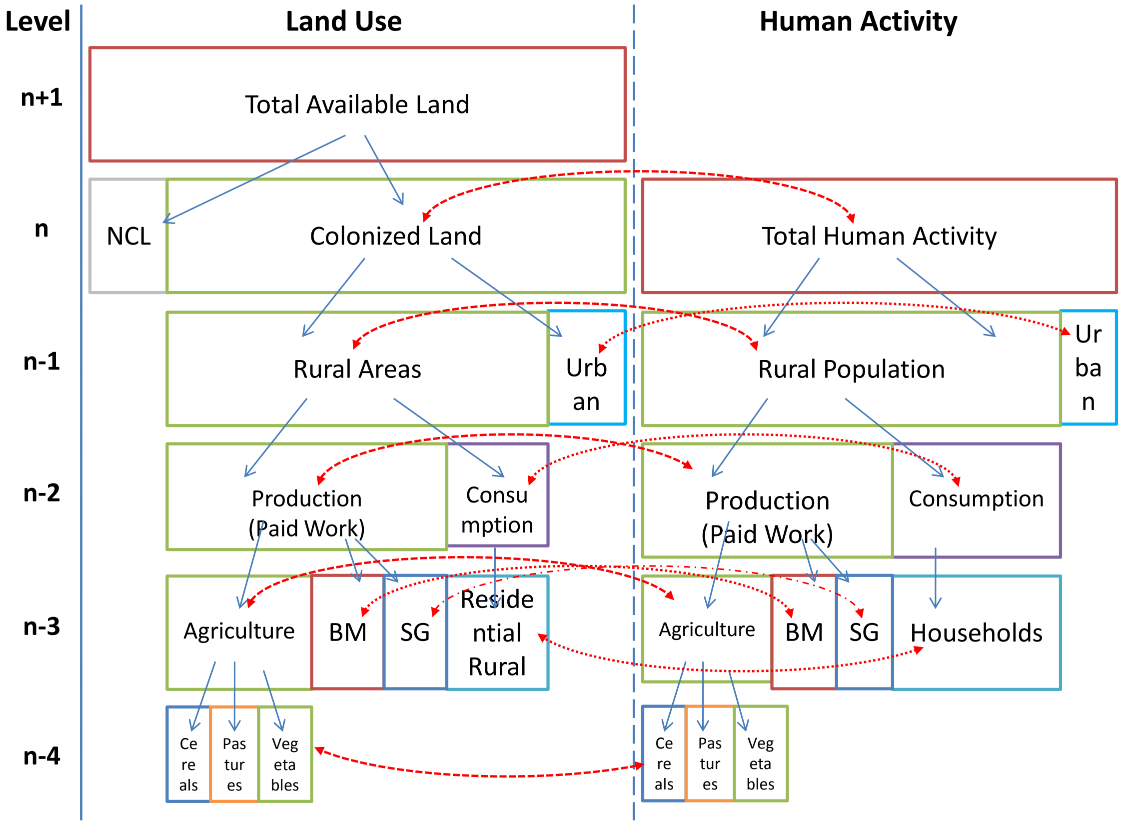

Figure 4. Bridging the two definitions of size for the fund elements (Land Use and Human Activity) representing the same system.

Looking at Figure 4, we can see that although our two definitions of size (human activity and land use) are non-equivalent, they do refer to the same observed system (a given farming system in a given year) in relation to the same set of observed flows. To use them simultaneously and coherently in the definition of the metabolic pattern, we make use of the "holonic" nature of a metabolic system. In fact, for any homologous pair of categories of human activity (e.g., cultivating rice) and land use (e.g., land in rice cultivation) we have that the same flow (e.g., output of rice in kg per year) is mapped against two different fund elements, giving us, respectively, yield per hour and yield per hectare (both expressed on the basis of one year or another a priori defined time interval). If we set the factors in our system that influence the yield (technology, inputs, climate, pests, soil erosion, etc.), for any given year, a given quantity of rice production can be related to the corresponding amount of both human activity (in hours) and land (in ha) needed for its production. Hence, one can establish a relation between the size of the two fund elements, human activity and land use, belonging to the same functional/structural category. This relation of coherence can be established across all the holons making up the rural system.

3.2.2 Self-reproducing rural systems must be able to express an integrated set of functions

A second mechanism or criterion providing coherence to the metabolic pattern is related to the self-organizing nature of dissipative systems. Any individual functional/structural element (described as a category, such as rice cultivation), even if very effective, is not sufficient in itself to reproduce a rural community. Many different functional/structural elements are needed simultaneously to express an emergent behaviour of a rural community that is sustainable in time. Indeed, for any rural community one can identify a set of integrated functional/structural elements that guarantees the reproduction and adaptability of the system (i.e. the autopoiesis). It follows that the representation of the metabolic pattern of a given rural system should be based on an integrated analysis of *all* the flow/fund ratios (assessed in hours of human activity and in hectares of land use) relevant for the reproduction of the system. Thus, the analysis has to be based on a set of categories that properly reflects the mix of functional/structural elements needed for expressing the emergent property of reproduction.

Having thus defined the semantics of the metabolic pattern, one can also establish for each flow (e.g., rice output, cash flow, firewood) a relation between the two fund elements, human activity (intensity of flow per hour) and land use (density of flow per hectare). For the overall metabolic pattern to be viable, the relative size of the two fund elements (that is, the ratio human activity per unit of colonized land or population density at the level of the whole system) become crucial. Given the duality of our original definition of "size" of a rural system (expressed both in hours of human activity and hectares of colonized land) the metabolic pattern of a given rural community can be described either:

1) From the human perspective (view from inside): as the required pattern of land uses (the profile of allocation of hectares to a given set of land uses) per unit of human activity; or
2) From the external perspective: as the pattern of human activities (the profile of human time allocation to a given set of tasks) that can be supported per unit of colonized land.

For example, we could be studying a hypothetic certain rural territory in Neverland, which has a population of 314,159 inhabitants using 986,960 hectares of land for their activities. Then, we could express, from the human perspective, that this human system requires 3.14 hectares of land per person, or alternatively, we can say that one hectare of land of this ecosystem can support 2,788 hours of human activity per year (i.e. the activity per year of 0.32 persons).

Note that these two non-equivalent ways of approaching the accounting (the views from the inside and from the outside) refer to the same set of flows (money, energy, food, water, other key materials) of the rural metabolic pattern.

3.3 The "Fund-flow diagram" of rural systems

In order to visualize schematically the metabolic performance of rural systems and the relations among the multiple dimensions considered (both funds and flows) in an integrated way, a graphic visualization that expresses in one single image the main considered features has been designed. In turn, at the same time I am making a visualization of the grammar used in MuSIASEM to analyse rural systems. The aim is to capture in a single illustration a holistic view of the performance of the system at a given level of analysis to be able to:

1) For **analytical** purposes: observe qualitatively a comprehensive visualization of all the elements into play at a given level of analysis to check (i) the extent of the black box, (ii) external (ecosystem) and internal (socioeconomic) constraints, (iii) established trade-offs among dimensions (iv), the relative size of the funds and flows, (v) benchmark values for each type at that level, and (vi) for incomplete information in the system's representation. Since this visualization of the system illustrates the inputs and outputs of the flows, it is possible to quickly check the net balance of the considered flows (and detect possible problems in the system or the data).
2) For **communication** of the results to the actors: describe in a compact illustration the main metabolic characteristics of their system. Once the elements visualized on the diagram are known, the results of the analysis and the implications of the key features characterizing the system become extremely clear. It also allows observing some indicators to compare different scenarios or types of system in an intuitive way.

The adopted illustration is a combination of (i) a flow diagram representing the flow elements entering, exiting and circulating through the considered black-box of the system, and (ii) two pie charts expressing the characteristics of fund elements defining the metabolic system. The topological extent of the system is also delimited in the diagram, so that it is possible to map the exchanges of the considered system with other systems; both for systems at the same level of analysis and for systems at higher hierarchical levels in which the considered system is embedded (e.g. natural ecosystem, country, or international markets). Therefore, with this visualization is very easy to check the **degree of openness/closeness** of the studied system in relation with its surrounding environment. In this sense, it is important to bear in mind that this diagram is meant to represent one single hierarchical level of analysis at a time, although diagrams of lower and higher hierarchical levels can be used to complement the representation of the rest of the system considered in the study.

The following Figure 5 is going to be used for illustrating and explaining the prototypical rural fund-flow diagram used for my studies. The subsequent explanations of this figure are referring to the example categories shown in this template, but please take into consideration that the categories could be readjusted for the specific purposes of each case study. Along the following chapters of this thesis dissertation I will show examples of variations of this diagram adapted to the particular aims and contexts of the case studies.

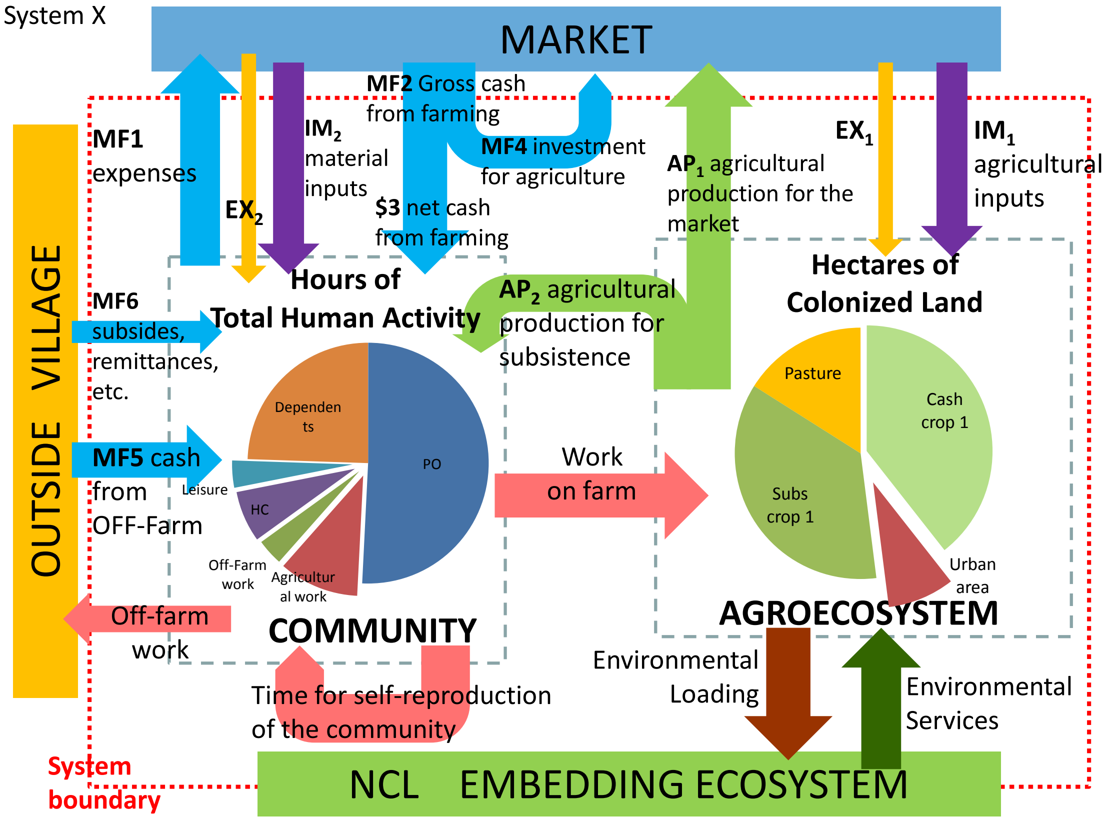

Figure 5. Template of a rural fund-flow diagram. Note that the categories do not correspond to any particular case and might be changed to adapt to specific studies.

Pie chart of the pattern of human activities

The left pie chart of Figure 5, labelled Total Human Activity (THA), illustrates the pattern of human activities, classified into relevant sectors similarly to the dendrogram of Human activity shown in Figure 3. It shows the profile of allocation of the total human time over the relevant categories of time use for the farming system in question. The total area of the pie is proportional to the total amount of human activity (THA in hours per year) in the system, which is directly proportional to the total population size through the relation: THA = population x 8,760 hours/year

(365 days x 24 h/day). Thus THA defines the size of the metabolic system, considered as a whole and defined as 'level n', in terms of human activity.

For instance, in the template shown in Figure 5, I distinguish six categories of Human Activity (HA_i), which allow us to divide the overall number of hours of THA (at level n) over six lower-level 'compartments' (level n-1):

- Physiological Overhead (HA_{PO}): this category includes sleeping, eating and personal care.
- Dependents (HA_D): this includes all the activity (time) of the dependent population (children, disabled and elderly), including the education time of children.
- Leisure (HA_L): this category includes all the hours of human activity allocated to socialize, cultural and religious activities and leisure.
- Household Chores (HA_{HC}): this category includes the hours of work allocated to those household chores, such as cooking and gathering firewood, that do not involve agricultural work (as defined below) and that do not generate monetary flows.
- Agricultural Work (HA_{AG}): this category includes the hours of work allocated to agricultural activities involving land use, such as planting, weeding, and harvesting. It could be further subdivided in cash crop (HA_{CC}) and subsistence farming (HA_{SC}) or any relevant sub-category.
- Off-farm Paid Work (HA_{PW}): this category includes the hours of work that are paid with wages, but do not involve exploiting lands of the system.

The rules of MuSIASEM for creating a multi-level matrix dictate that the following identity must hold, as the accounting must achieve **closure** across levels:

$$THA = HA_{PO} + HA_{DR} + HA_L + HA_{HC} + HA_{AG} + HA_{PW}$$

Pie chart of the pattern of land uses

The right pie chart in Figure 5, labelled Colonized Land (COL), illustrates the pattern of land uses. It shows the allocation of the total amount of colonized land by humans over the relevant categories of land use for the farming system in question. The total area of the pie is proportional to the total hectares of colonized land in the system (on a year basis). Thus COL defines the size of the metabolic system, considered as a whole and defined as 'level n', in terms of land use (see Figure 2).

In this template I distinguish four examples of categories of Land Uses (LU_i), allowing us to divide the overall value of COL (at level n) over four lower-level compartments (level n-1): cash crop (LU_{CC}), subsistence crops (LU_{SC}), pastures (LU_P) and the urbanized area comprising buildings and diverse infrastructure (LU_{UA}). The rules of MuSIASEM dictate that the following identity must hold:

$$COL = LU_{CC} + LU_{SC} + LU_P + LU_{UA}$$

The relation between human activity and land use determines either the population density (persons/hectare) or land requirement (hectares/person) for each type of farming system.

Flow diagram representing the interaction of the farming system with the context

The flow diagram of Figure 5 represents the interaction of the rural system with its context. Given the concept of metabolism, a rural system is defined as an open system interacting with its context by exchanging different types of flows. In this particular illustrative template I include monetary flows, crop flows, agronomic inputs, and energy inputs. The intensity of this flow exchange defines the degree of openness of the metabolic pattern.

In this template I distinguish three different kinds of contexts:

i. The market transactions related to agricultural production with which the farming system exchanges flows according to price-based transactions of exports/imports (top of diagram). The outputs and inputs moving across this border can stabilize or destabilize the existing metabolic pattern. This part of the flow diagram reflects the effect of market transactions on the metabolic pattern.
ii. The socioeconomic context within which the rural community exchanges human activity, goods and monetary flows (left side of diagram). This interaction refers only to human activity and money flows that are *not* related to the work on colonized land represented by the right pie chart. This part of the flow diagram measures the degree of independence from land of the metabolic pattern;
iii. The ecological context with which the farming system exchanges biophysical flows of inputs and outputs (direct input of production and indirect environmental services) (bottom part of flow diagram). The ecological context is the ecosystem embedding the rural community and may be defined by the amount (ha) of non-colonized land (NCL). This part of the flow diagram measures the dependence of the metabolic pattern on the natural processes taking place in the landscape.

In this illustrative diagram for a rural system I distinguish four types of flows (note that for instance in this template water is not included):

i. In blue, MF stands for the monetary flow (e.g. in equivalent US dollars)
ii. In green, AP is the agricultural production (e.g. in kilograms)
iii. In purple, IM could account for material inputs
iv. In yellow, EX would be the commercial exosomatic energy (e.g. in Joules)

It is possible to use the relative values of these flows and the net balances to define and identify typologies of rural metabolic patterns. For example, starting from the output of agricultural production, a certain share of the produced crop mix will go to the market and will be exchanged for money (AP_1) while the remaining part will be consumed directly inside the village as subsistence agricultural production (AP_2). These relative shares depend on the type of farming system considered. Specialized commercial farming systems (high external input agriculture) typically sell the entire crop output to the market, while subsistence farmers (low external input agriculture) use almost the entire crop production for internal consumption.

From the sales of agricultural production in the market (MF2) one part goes to the people in the farming community as disposable cash (flow MF3) and one part must be reinvested in agricultural production (flow MF4) by purchasing material inputs (IM_1–Imported Inputs, including fertilizers, seeds, pesticides, and machinery), energy to run the machinery (EX_1–commercial energy such as oil for tractors and electricity for pumping), or in taxes related to the agricultural activity. The relative importance of these flows indicates to what extent market transactions influence the integrated performance of a rural system. For instance, in typical subsistence farming systems, the flow of commercial exosomatic energy invested in agricultural production would be negligible as there is no significant use of technical devices such as tractors or motor-ploughs. Indeed, in these systems the monetary flow used to buy inputs (MF4) would be a negligible fraction of the money obtained from selling crops (MF2).

Monetary flow MF5 (Figure 5) accounts for all the earnings obtained in the village from off-farm work, and MF6 would reflect some other possible monetary incomes not produced with the labour of this system (e.g. subsidies, remittances, interest revenues). The combined input of monetary flows MF3, MF5 and MF6 allows the community to buy goods and services (MF1), corresponding to the biophysical flows IM_2 and EX_2 from the market. In good years, a surplus of money may be saved, while in bad years debts may arise. However, I have not reflected this aspect in this particular example of template, as anyway in many rural areas the savings and debts accumulated along the years tend to level each other out.

Depending on the goal of the analysis, other flows may be added to (or excluded from) the template to better represent the specific interactions of the farming system with its different types of context. For instance, material flows such as water consumption or nitrogen and phosphorous leakage in the water table may capture the critical impact of the farming system on the environment. These flows should be represented on the bottom interface. In general, the relations between human activity and land use on the one hand and a set of material flows on the other hand can provide many useful indicators of performance. These indicators can refer to both ecological criteria (considering the density of key material flows per hectare that are either taken away from the ecosystem or dumped into it) and socio-economic criteria (considering material flows per hour of human activity, such as food security and income level). Deciding on the appropriate information for inclusion in the template (which criteria and indicators of performance are relevant?) requires tailoring the analytical tool on the specificity of the system under study.

Part II

Case studies

Chapter 4

Using spatial analysis for up scaling rural metabolic patterns across hierarchical levels. A case study of Lao PDR.

4 Using spatial analysis for up scaling rural metabolic patterns across hierarchical levels. A case study of Lao PDR.[13]

4.1 Introduction

In this chapter I explore the applicability of the concept of metabolic pattern to rural systems in order to develop integrated packages of multi-scale indicators useful to characterize the performance of rural and poorly-monetized socioeconomic systems. A methodology is shown for up-scaling quantitative information across hierarchical levels based on spatial analysis and the information provided by the fund land use. As introduced in Chapter 3, quantitative analysis of farming systems requires adopting several dimensions and scales since there are both socioeconomic and ecological processes into play, and rural systems must be multi-functional to be able to self-reproduce the structural and functional elements of these complex systems. In line with this thinking, Bouman et al. (1999) have pointed out that, for policy makers to adequately address the issue of sustainable rural development, it is necessary to rely on quantitative tools of analysis integrating biophysical, social and economic variables (i.e. different dimensions) preferably organized in Geographic Information System (GIS) data bases.

One additional implication to this rationale already introduced in Chapter 3, and the particular focus of this chapter, is that, in order to produce useful information for governance, it is necessary to tackle the technical conundrum associated with the issue of *scaling*. For instance, when studying the effect of land-use changes on the atmospheric CO_2 concentration we have to deal with a variety of processes taking place across different scales, including soil bacterial activity, crop field cultivation, watershed management, regional planning, and national policies. Indeed, quantitative analysis of sustainability requires us to effectively handle the transfer of information between different hierarchical levels of organization and scales, not only within each dimension but also between dimensions (Ewert et al., 2011). Adding to this challenge is that decisions and policies regarding rural development are generally made at different hierarchical levels. As a consequence, goals defined at different levels may be conflicting and decisions taken at any one scale will invariably affect those taken at the other scales (Laborte et al., 2007). Yet, despite the vast literature stressing the need for appropriate up-scaling and integration (e.g., Wolf & Allen, 1995; Bellamy and Lowes, 1999; Bouman et al., 1999; Overmars & Verburg, 2006; Groot et al., 2007; Laborte et al., 2007; Ewert et al., 2009; van Delden et al., 2011; Volk & Ewert, 2011), the scientific basis for linking models across disciplines and scales is still weak (Ewert et al., 2009; 2011).

In conclusion, this is one of the few applications that has yet demonstrated the feasibility of applying Hierarchy Theory to the study of practical issues such as sustainable rural development. This case study is a concrete step in that direction.

The choice of Laos as a case study to test the usefulness of the concept of metabolic pattern for rural economies was motivated by the unique characteristics of the Laotian economy (see section 4.3.1) and by the fact that field work had already been carried out there based on tools (land-time budget analysis) related to the MuSIASEM approach (Grünbühel & Schandl, 2005). Bear in mind, however, that the work presented in this case study has the sole goal of illustrating the potential of the concept of metabolic pattern of rural communities for multi-scale analysis. It does not pretend to provide indications about how to solve the specific sustainability problems of Laos.

This chapter also continues the explanation of methods for quantitative characterization of rural systems featured in Chapter 3. I start making a theoretical introduction of how to use types of farming systems for the arrangement of the information across scales (section 4.2). Then I implement our approach to generate a multi-scale integrated

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[13] This chapter is based on the following publication: Serrano-Tovar, T., Giampietro, M. (2014). *Multi-scale integrated analysis of rural Laos: Studying metabolic patterns of land uses across different levels and scales.* Land Use Policy, Volume 36, Pages 155-170.

characterization of the rural economy of Laos, thus illustrating the potential of the concept of metabolic pattern of rural systems (section 4.3). Following, I show the numerical results of our analysis and how the resulting series of non-equivalent characterizations of the performance of rural Laos can be integrated across different scales (section 4.4). In the last section 4.5 I comment on the significance of the results and the potential and limitations of our approach.

4.2 Looking for typologies in the rural metabolism representations

In section 3.2.1 I exposed how to make representations of farming systems adopting simultaneously two non-equivalent definitions of "size" for the fund elements (structural parts) in the metabolic pattern: (i) hours of human activity and (ii) hectares of colonized land. Next I explained how to express the functional parts of the system making ratios of flows/funds for both the human activity (intensity of flow per hour) and land use (density of flow per hectare). In this section, I introduce how to make typologies in order to arrange the information describing the metabolic patterns of the system across hierarchical levels of analysis. Then, after having generated that integrated representation across dimensions, it would become possible to generate different typologies of quantitative indicators, so that it is possible to ultimately characterize the performance of the metabolic pattern of Laos in relation to:

(i) different hierarchical levels of organization: at the level of households, rural village, whole farming system typologies, different geographic regions of rural Laos, the whole country

(ii) different dimensions of analysis (when considering the economic performance, social impact, technological performance, or ecological impact).

4.2.1 Individuating typologies of farming systems

To define a metabolic pattern useful for characterizing a farming system typology (according to its performance), several conditions must be met:

- At the local scale (with a resolution of hours and an extent of one year) we must be able to define the structural/functional elements (the parts of the whole) in such a way so as to account for both the hours of human activity and the hectares of land use (e.g., rice production, livestock production, firewood supply, post-harvest activities). This condition implies the existence of benchmarks for specific categories of human activities (flow rate per hour) and specific categories of land uses (flow density per hectare). In other words, it must be possible to estimate an expected series of technical coefficients characterizing the flows per hour and per hectare, such as crop yield per hour and per hectare, the human activity and space needed for household chores, and the human activity and land area needed for fuel wood provision.
- At the scale of the whole rural community, we must be able to define the relevant parts of the whole system and how they interact to express the emergent property of the system. This condition requires us to identify an integrated set of fund and flow elements that fully covers the expression of all the functions involved in the reproduction of the system. Thus, given the totality of human activity and colonized land of the rural community, we must allocate this overall endowment to a set of relevant, lower-level functional/structural elements. The scale associated with this exercise has a resolution of one year and an extent of several decades or even centuries, depending on the time horizon chosen to define the sustainability of the community.

The rules of accounting of the MuSIASEM approach further dictate that:

- The categories (typologies) of fund elements (structural/functional compartments of the rural community) respect the holonic nature of the system and hence are relevant (valid) for a definition both in terms of human activity and land use. This being the case, the metabolic characteristics of all lower-level elements can be expressed in terms of flow rate per hour and flow density per hectare;
- The aggregate size of the structural/functional compartments (the parts) must match the size of the whole

system both in hours and hectares. That is to say, the accounting must achieve closure across levels (see Giampietro et al., 2011).

If all these conditions are met, then the metabolic pattern can be used to characterize a series of predictable attributes of performance of the farming system as a whole, that reflect the characteristics of the structural/functional elements defined at lower hierarchical levels (local scale). From this type of analysis we can derive an incredibly rich set of indicators, such as the share of crop land for subsistence per person, the demographic structure of the population, the crop mix in agricultural production, the average income of farmers, the work load for farmers, the power requirement and crop yields on specific land uses, the specific use of inputs on specific categories of land uses, economic cost per hectare, the net revenue per hectare and gross revenue per hectare, etc. That is, defining a typology of farming system on the basis of its metabolic pattern makes it possible to establish bridges across information gathered at different scales and in relation to different dimensions of analysis. In this way, we can not only move between quantitative assessments rooted in different disciplines (e.g., economic, agronomic, social, and ecological analyses) but also between quantitative assessments carried out at different hierarchical levels (e.g., households, village).

4.3 The analysis of rural metabolism of Laos

4.3.1 Why Laos?

The economy in Laos(officially the Lao People's Democratic Republic) shows a low diversity of tasks in the production and consumption of goods and services and therefore lacks the functional complexity of modern economies. This allows us to adopt a representation based on a limited number of typologies of farming systems without losing much accuracy, especially when studying the economic performance based on monetary flows. The country’s socioeconomic structure is still largely based on agriculture, and subsistence agriculture continues to play an important role. According to data from the Lao PDR National Statistical Centre (NSC), about 73% of the population lives in rural areas (NSC, 2005). The scant foreign trade is based on natural resource extraction, basically wood products and electricity from hydropower, but the revenues of these economic activities remain in the capital city (practically the only important city of the country) with little effect on the countryside. Subsistence agriculture, dominated by rice, accounts for about 40% of GDP and occupies 80% of total jobs (CIA, 2008). This assessment probably still underestimates the value of the food and other services consumed by the local population in subsistence (which are produced and consumed outside the market).

The Lao Expenditure and Consumption Survey 2002/03 from the NSC reveals that an estimated 99% of rural households are engaged in at least some form of agriculture (including livestock raising and fishing). Two thirds of the Lao households are basically in subsistence mode, complemented by some market production. In fact, 43% of the agricultural land is entirely allocated to subsistence production, with no market production at all (Grünbühel & Schandl, 2005). Finally, out of the total gross economic output, only 37% of the production values go to the market. For most agricultural products less than one third of the production is sold at the market (NSC, 2003). From these data we can deduce that Lao PDR is a society where rural communities are still largely isolated from trade and communications. The lack of infrastructures for transportation and communication also makes the spatial analysis a relevant issue in relation to future discussions over development policies.

4.3.2 Data sources

This case study is based on processing of secondary data gathered from two sources: 1) a three year EU INCODEF project in the 5th Framework Programme, entitled Southeast Asia in Transition (SEAtrans), and (2) statistical data from the Lao Statistics Bureau (formerly called Laos National Statistics Centre).

The EU project SEAtrans collected primary data in local studies within Southeast Asia (Thailand, Philippines, Vietnam, and Laos) with the aim of analysing local management of natural resources and consumption patterns. Data were gathered in Laos during various periods between April 2001 and February 2002. Most of the data obtained in these local studies have been previously published for other purposes (Grünbühel 2004; Grünbühel & Schandl, 2005). A detailed description of the methods of data collection has been provided by Grünbühel & Schandl (2005) and is also available in the deliverables of the EU SMILE project within the context of which this work was carried out (http://www.smile-fp7.eu/?id=deliverables).

Practically all statistical data used in this work are from the National Statistical Centre (NSC) of Laos (http://www.nsc.gov.la/), most notably from the *Lao Expenditure and Consumption Survey 2002/03* (LECS 3) results, which are compiled by the Committee for Planning and Cooperation (NSC, 2005). It represents the largest and most important survey that the National Statistical Centre undertakes every five years. It covers a wide range of subject matter areas related to the household living situation. The most recent survey available at the time of this analysis was undertaken from March 2002 to February 2003.

The results in the LECS3 report are based on data collected from sample villages and then extrapolated to the national level. The LECS3 sample was made up of 8,100 households from 540 villages, 15 households from each, enumerated over 12 months, from March 2002 to February 2003. More details about the sample design and selection, the survey operations, and data reliability can be found in the original document (NSC, 2005).

4.3.3 The three types of farming systems used in this study

The quantitative analysis developed in this study is based on the following three types of farming systems, which are used to characterize rural Laos:

- Farming System 1 is characterized by the presence of slash-and-burn practices. It is generally situated in the uplands. Farmers typically practice intercropping of rice with vegetables, and a large part of the production is for self-subsistence. They also have some livestock. They show significant dependence on hunting and gathering non-timber forest products (NTFP) for food and income.
- Farming System 2 is based on intensive paddy rice cultivation. It is generally found in the lowlands. Farmers typically raise livestock and also practice some fishing and hunting for self-consumption. Use of fertilizers, pesticides, and motor ploughs is not uncommon.
- Farming System 3 is more focused on the cultivation of commercial crops like coffee, tea, fruits and vegetables. In this typology of farming system farmers show greater dependence on the market for the production and consumption of goods. This type of farming system is located mainly in the southern region of Laos.

These three farming system types have been previously identified by other authors as covering the vast majority of the rural activities taking place in Laos (Grünbühel, 2004; Thongmanivong, 2004). Therefore, by representing the colonized land of Laos as composed of these three farming systems we can achieve an acceptable accuracy in the operation of scaling. In the technical jargon of MuSIASEM we say that these three typologies provide closure of the system of accounting: the sum of all the hours of human activity and the sum of all the hectares of land uses belonging to these three categories of farming systems equal, respectively, the total human activity of the population and the total area of colonized land of rural Laos.

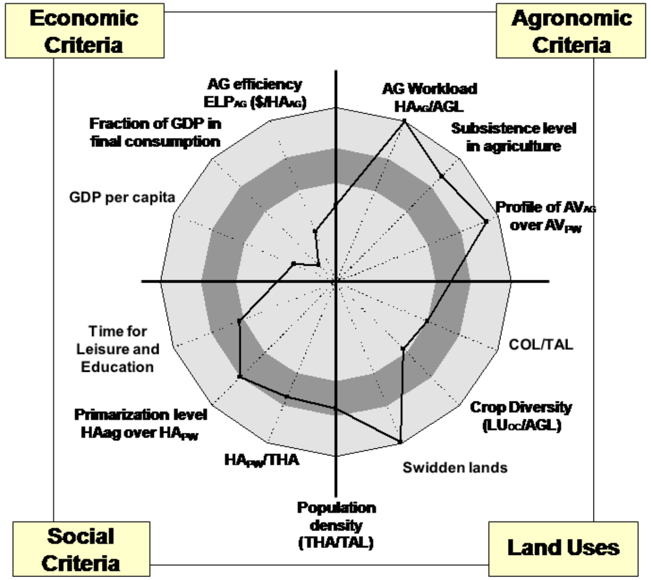
For each one of these three types of farming systems we further define a taxonomy of categories for the metabolic pattern, thus making it possible to: (a) characterize the metabolic pattern in intensive terms (pace per hour); and (b) define their distribution in space in the various regions of Laos (density per hectare), i.e. the relative sizes to be used in the scaling in relation to land use.

The profile of distribution of the three farming system typologies in the three regions of Laos (chosen in this study) has been estimated according to proxy indicators selected from official statistical datasets. This information, based on crossing proxy indicators of presence of selected categories, is not very robust. In order to obtain more reliable estimates of the distribution of instances of farming types over rural Laos, primary data from remote sensing would be preferable.

4.3.4 Templates for representing the metabolic pattern at the local level

The templates for representing the metabolic pattern of these three farming system types are illustrated in Figures 6 to 8, and include the following information:

Farming System 1



Farming System 1: Slash and Burn

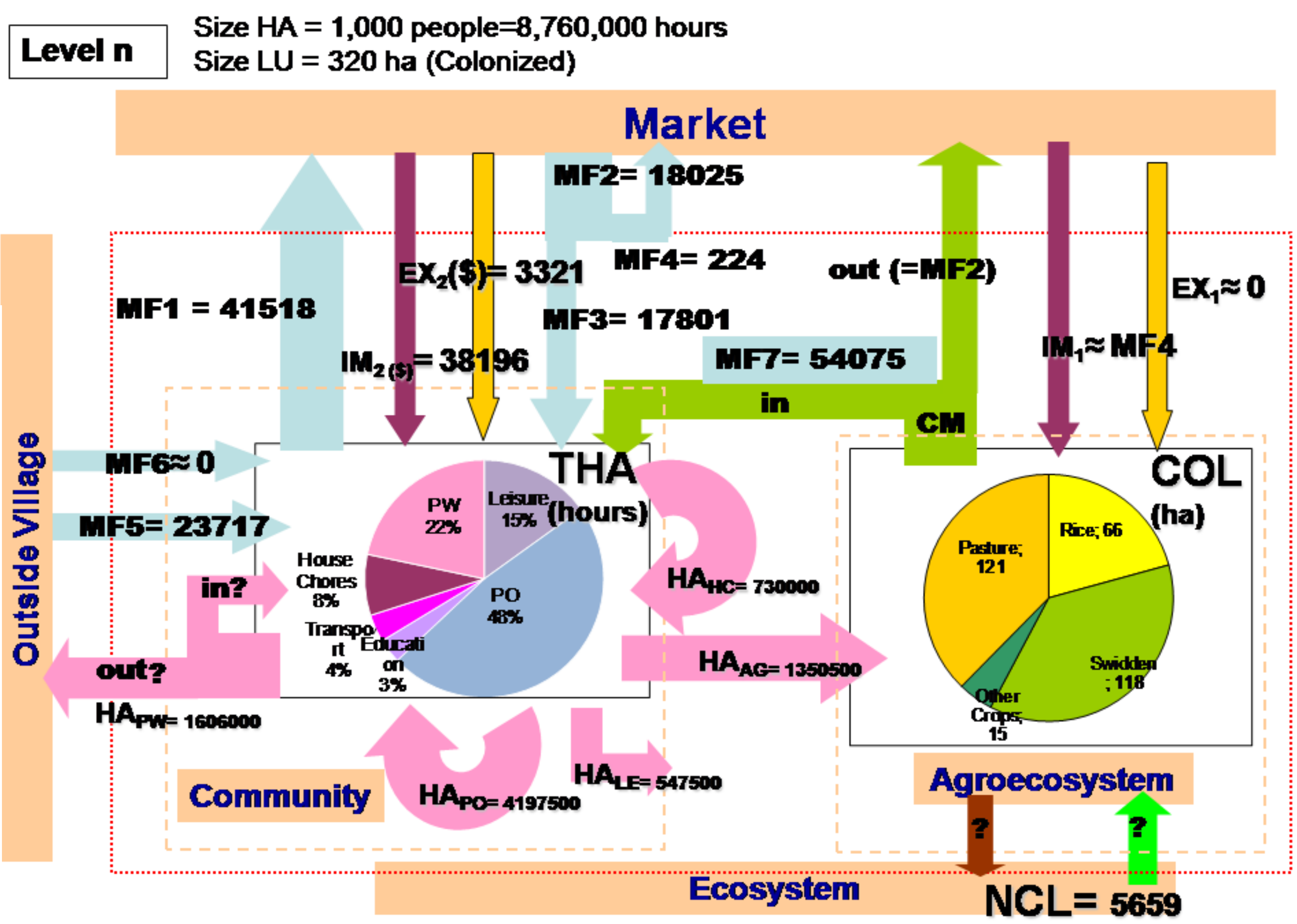
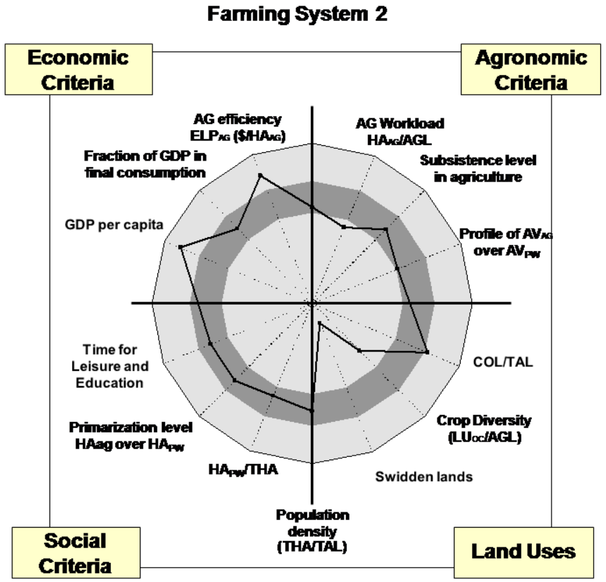


Figure 6. Metabolic pattern of Farming System Type 1 (Slash and Burn).



Farming System 2: Lowland Paddy Rice

Level n

Size HA = 1,000 people=8,760,000 hours
Size LU = 479 ha (Colonized)

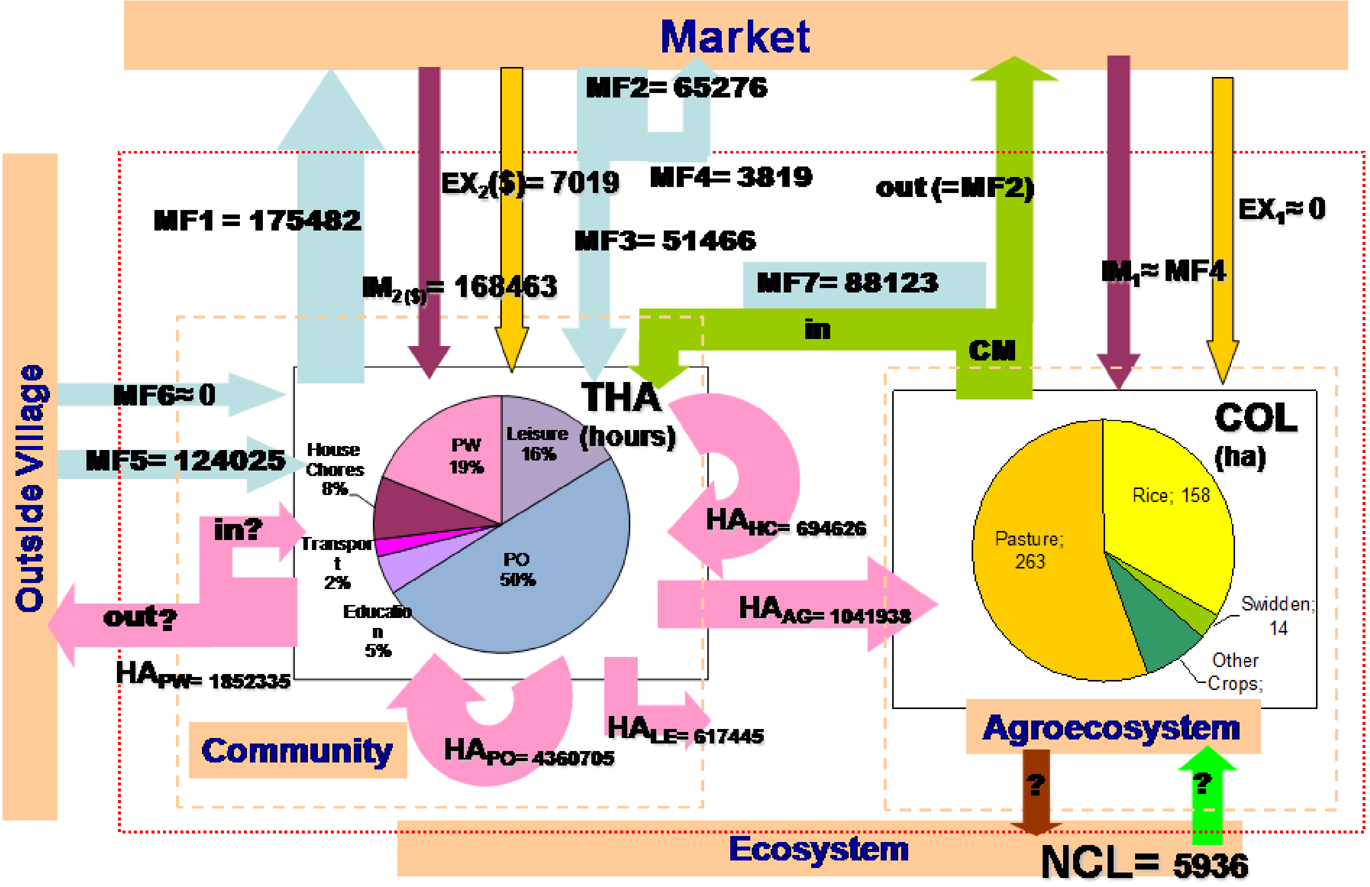
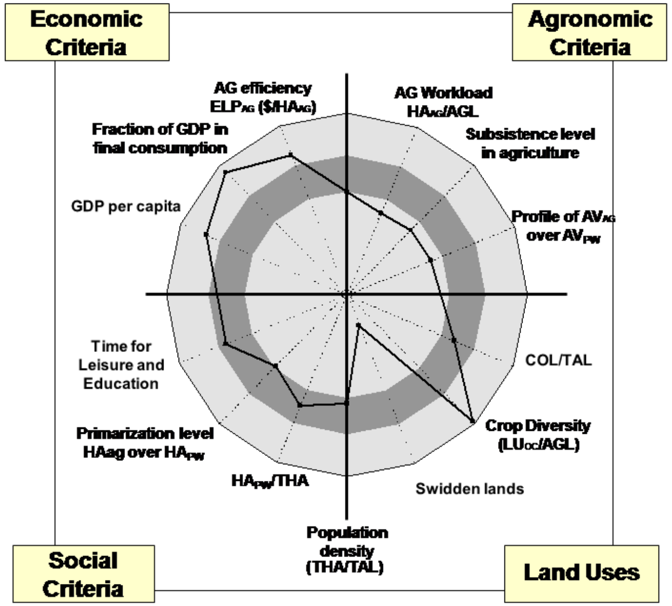


Figure 7. Metabolic pattern of Farming System Type 2 (Lowland Paddy Rice).

Farming System 3: Commercial Crops



Farming System 3

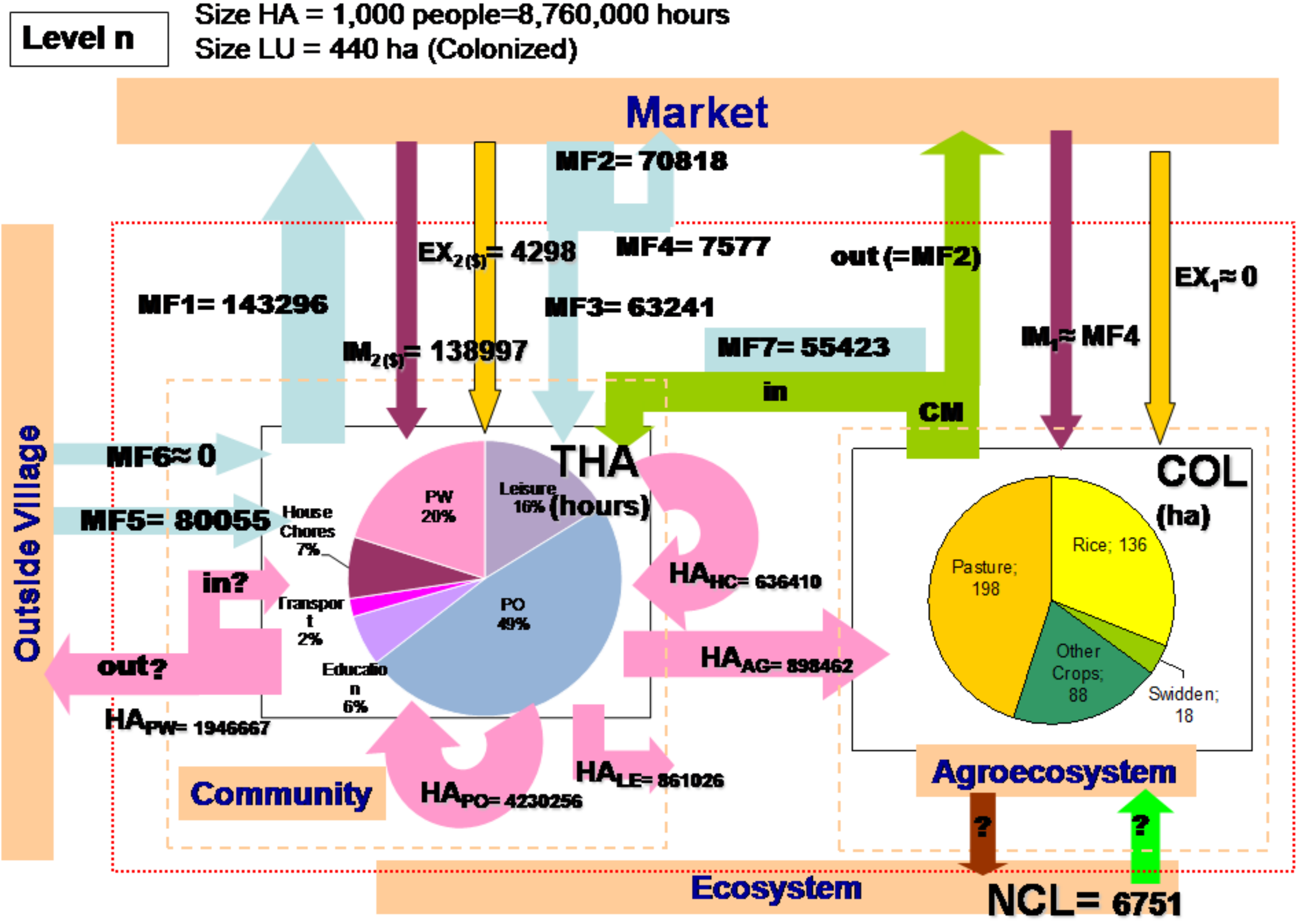


Figure 8. Metabolic pattern of Farming System Type 3 (Commercial Crops).

4.3.4.1 Map of the pattern of land uses and land covers

In the upper left corner of Figures 6 to 8, we have a map representing the pattern of land covers. With the use of Geographic Information Systems (GIS), this information is digitalized and the relevant categories of land uses accurately quantified in hectares. As regards to the land-use quantification, statistical data was insufficient to feed numbers into the metabolic categories at the lowest levels of analysis (those differentiating among types of crops). Therefore, for these cases, spatial analysis tools can be used to quantify the land in every type of farming system with Remote Sensing and GIS (see example in Figure 9). These tools allow the identification of the different patches of agricultural lands at village level, so that it is possible to obtain a sample of some farming systems and then identify the land use of every farming system. However, it is not recommended to completely rely on these tools to identify land covers, because at this scale the recognition of land covers is not practicable for every kind of crop. It is recommended that land cover patches are verified using information gathered from field work in the village (*ground truthing*).

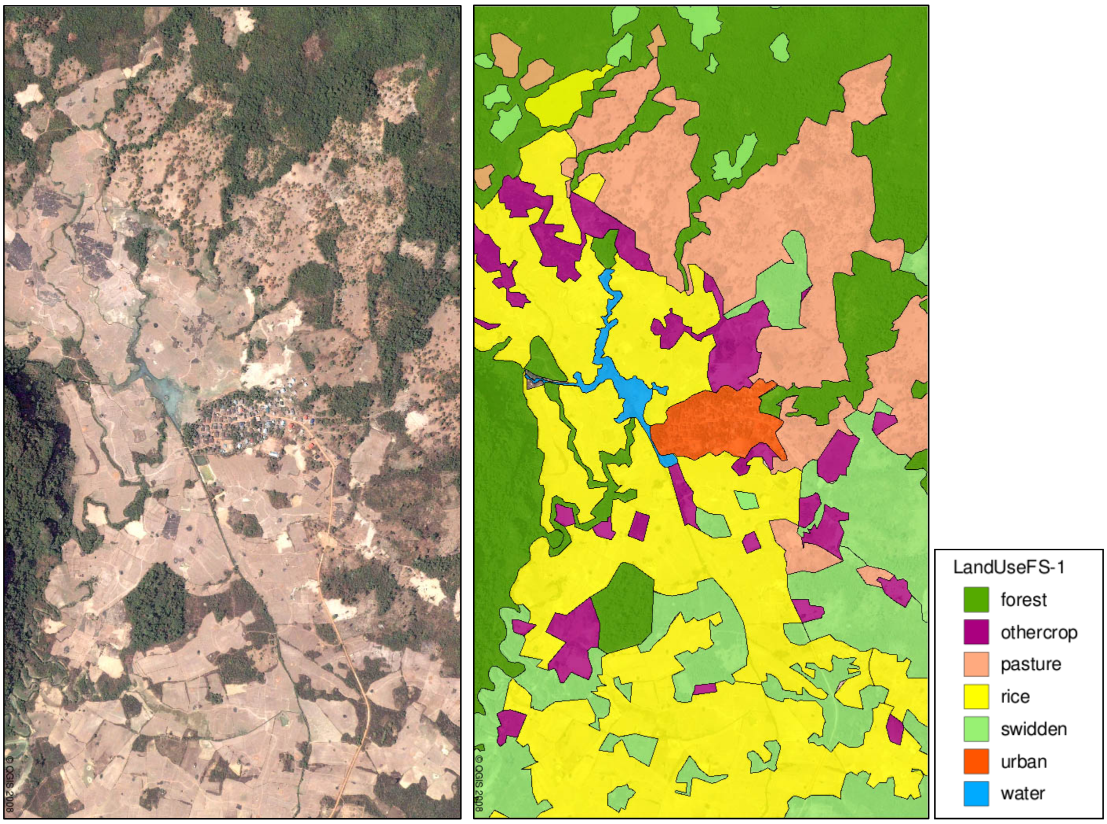


Figure 9. Example of map of Land Uses of Farming System 1 obtained from Remote Sensing imagery.

4.3.4.2 Multicriteria space of performance

In the lower left corner of Figure 6 to 8, the performance of the farming systems is represented in a multi-criteria space by an integrated set of indicators referring to different dimensions of analysis. Our particular template includes economic, social, agronomic, and land-use criteria (Figures 6 to 8). The quantitative value for each indicator has been normalized over the average values found for rural Laos. The thick grey line in the graphs represents the average value (100%), and we thus see how the performance of each farming system type, for each of the criteria/indicators considered, compares against the average performance of rural Laos.

This radar diagram is an example of a multi-objective integrated characterization of performance. More details on the application of this method to characterize farming systems are available in Gomiero and Giampietro (2005). The

MuSIASEM approach allows us to select "à la carte" packages of integrated indicators reflecting those criteria of performance that are judged relevant by the stakeholders (e.g., in participatory integrated assessments).

4.3.4.3 The fund-flow diagram

With this case study, we show a particular application of the fund-flow diagram adapted to the aims of the study and the available information of Laos (see section 3.3 in Chapter 3 for the detailed theoretical explanation of this kind of representation). These versions of the fund-flow diagrams are an example of how we can adapt this representation to the specific aims of each particular case study. Note that despite subsistence production is not sold, we may still assign a virtual cash flow to it, equalling the monetary price that would have been paid for it in the market (MF7 in Figures 6 to 8), in order to be able to compare in the same dimensions the share of agricultural production remaining for self-consumption and the production exiting the system to the markets. The monetary flow is transformed to current US Dollars of 2003 (the year of the rest of the data).

4.3.5 Characterization of farming system types at the local scale

Using the template described above we can characterize and compare the metabolic pattern of our three types of farming systems in Laos at the local scale (village level). The intention with this exercise is limited to create prototypical farming systems of Laos to illustrate our methodology. For more precise results, more data on the rural areas of Laos should be gathered.

Slash and Burn System (Farming System Type 1)

Comparing the metabolic pattern of slash and burn agriculture with the average pattern of rural Laos (Figure 6 and Figure 13), we find a relatively large share of time allocated to agricultural work (71% of the total working activity) and a relatively large share of crop land dedicated to swidden rice (37% of colonized land). Looking at the performance in the multi-criteria space, this system has tough working conditions and heavily relies on self-subsistence production. The money flow reinvested into agricultural production is very small. For this reason, the level of technical capitalization of slash and burn agriculture is extremely low. We are dealing with a traditional, pre-industrial type of agriculture: low external input agriculture with a high labour demand. The colonized land is 0.32 ha per capita.

Lowland Paddy Rice (Farming System Type 2).

Comparing the metabolic pattern of the lowland paddy rice system (Figure 7) with the average pattern of rural Laos (Figure 13) we observe a relatively large share of land allocated to raising livestock and intensive rice cultivation. The crop output per hectare is higher than the rural Laos average due to the better conditions in the lowlands, where it is possible to have more than one harvest per year. They use 0.48 ha of colonized land per capita due to the large pasture lands they have.

Cash Crop System (Farming System Type 3).

Comparing the metabolic pattern of the cash crop system with the average pattern of rural Laos (Figure 8 and Figure 13) we find a specialization in commercial crops. This type of farming system obviously depends on the availability of infrastructures (e.g., reliable roads) for transportation and communication to reach the market for the produced crops. In this farming system, reliance on subsistence agriculture is less pronounced and we have more investments in inputs for agricultural production. The requirement of colonized land per capita is 0.44 ha.

Table 1 summarizes some key differences among the three farming systems using the indicators presented earlier in the radar graphs. These indicators, grouped in four areas, are just examples of the numerical results that can be obtained by adopting this method. When adopting participatory methods, the MuSIASEM approach allows stakeholders to select 'à la carte' the indicators of performance that best accommodate their specific needs.

Domain	*Indicator*	*Calculation*	*Units*	*FS1*	*FS2*	*FS3*
Agronomic Criteria	Ag. Workload Density	HAag/LUag	hr/year/ha	4,223	2,177	2,044
	Level of subsistence in Ag.	Subsis. ag. /total ag.	% of $	0.75	0.57	0.44
	Income from Ag.	GVAag/GVApw	% of $	0.76	0.47	0.41
Land Uses	Colonized Land	COL/TAL	% of ha	0.05	0.07	0.06
	Crop Diversity	LUoc/AGL	% of ha	0.11	0.08	0.20
	Swidden lands	LU swidden/AGL	% of ha	0.37	0.03	0.04
	Population density	THA/TAL	cap/ha	0.17	0.16	0.14
Social Criteria	Working time	HApw/THA	% of hr	0.22	0.19	0.20
	Agricultural labour level	HAag/HApw	% of hr	0.71	0.63	0.51
	Time for Leisure & Education	HA_{LE}/THA	% of hr	0.18	0.21	0.22
Economic Criteria	GVA per capita	GVA/THA	$/cap	41.5	175	143
	Income reinvestment in Ag.	GVA ag reinvested	% of $	1	6	11
	Ag. Economic Labour Productivity	$/HAag	$/hr	0.05	0.15	0.14

Table 1. Example of selected indicators showing key differences in metabolic pattern among the three farming systems (GVA=Gross Value Added, GVAag=Agricultural Gross Value Added, GVApw=Gross Value Added in off-farm paid work, TAL=Total Available Land, LUag=Agricultural Land Use)

4.4 Results from the integrated multi-level analysis of farming systems in Laos

4.4.1 From the household level to the village level

Observing a single farming system type at both the household and village level, we find that we deal with more or less the same set of categories of human activity and land use to characterize relevant flows. Therefore, between these two hierarchical levels it is fairly easy to scale-up or down the characteristics of the metabolic pattern. All the same, when moving from the household to the village level, we have to add several new categories of land uses and human activities that represent functions/structures typically found only at the village level, such as transportation/roads, education/schools, religious functions/temples (Gomiero & Giampietro, 2005). After integrating these specific village-level elements into the accounting (adding new categories of land uses), we can assess the characteristics of a village (made up of households) by extrapolating the characteristics of the lower-level elements (the hours of human activity and land uses associated with different household types in the village) to a larger scale. The resulting set of values for the indicators of performance for this farming system (at the village level) can then be used to characterize the performance of individual households belonging to that specific farming system by analysing whether they score better or worse than the average.

In this situation, we can generate quantitative information about the metabolic pattern in two ways:

1) Top-down: using official statistics, i.e., aggregate values that refer to the whole village such as total population, total area, etc.
2) Bottom-up: using empirical data gathered at the household level and extrapolating technical coefficients observed at the local scale (residential density of different household types averaged at the village level over the profile of distribution of instances of households over the set of types).

This multi-level analysis between the household and village level has been illustrated in previous studies of rural areas (see Giampietro & Pastore, 1999; Pastore et al., 1999; Gomiero & Giampietro, 2001; Giampietro, 2003) but it is not viable when enlarging the analysis to the whole country.

In fact, this mechanism of scaling only works well if the elements observed at the different scales (villages and households) express the same type of metabolic pattern and can be described with the same set of structural and functional categories (for the fund elements human activity and land uses). When we further enlarge the spatial scale of the analysis to the regional or national level, we almost certainly will find heterogeneity in farming system types related to existing geographic and cultural differences. In that case it becomes impossible to use just one single type of metabolic pattern to perform scaling across levels. For example, in our case study of Laos, intensive rice cultivation on lowlands cannot be studied using the same set of categories of human activity and land use that are useful to characterize extensive livestock husbandry on marginal areas. Therefore for large-scale studies it is necessary to adopt several different definitions of “what farmers’ villages are” and “what farmers’ villages do” so as to capture the characteristics of the different relevant farming system types. It is to this purpose that in our Laos case study we have defined three farming system types covering the majority of colonized land in the rural areas.

4.4.2 How to scale-up in relation to a geographic criterion: from the local to the meso level

We have seen in section 3.2.1 that the concept of metabolic pattern allows us to establish a correspondence between the two non-equivalent criteria defining system size: (i) fund elements described in terms of human activity, and (ii) fund elements described in terms of land use. This correspondence provides us with an impredicative definition of “expected values” for typologies of farming systems (of the type “if/then”), but cannot provide a clear-cut definition of size for the chosen typology of farming systems. Types are by definition out of scale (Allen & Starr, 1982; Giampietro et al., 2006b). A quantitative characterization of types can only be obtained *per unit of size* (using intensive variables), such as hectares of colonized land per person or number of persons expressing the pattern of activities per hectare. For this reason we need an *external referent* for the process of scaling up, a distinct criterion that provides additional information on the size of the system. This external referent may be the specific geographic location and/or the specific history that shaped either the land size to which the population has had to adapt or the population size to which the land uses correspond.

In this case study the integrated characterization of the metabolic pattern of rural Laos was organized on the basis of the three main political subdivisions: North, Centre, and South (Figure 10 and Figure 11), that is, we adopted an administrative criterion (providing geographic/administrative boundaries) as external referent to define the size of a new class of elements: the regions at the meso-scale. Obviously, this criterion has little to do with the expression of a coherent metabolic pattern. In fact, the definition of the boundaries of these three administrative regions has been imposed on local metabolic patterns from the “outside” as a result of historical, geophysical, political and administrative processes. It follows that the definition of size, in terms of hectares of land covered by the region and number of people living in the region, is “special”; an individual instance determined by stochastic events. It no longer represents a typology!

It is thus necessary to find a method to link these characteristics based on extensive variables (the sizes of the administrative units) to the benchmark values based on intensive variables that were assessed at the local level when characterizing farming system typologies. When performing a quantitative analysis at the meso-level (based on a geographical size imposed by administrative units) it is possible to use the constraint of congruence on the fund element land: the sum of the areas of the three rural regions (level n+1) must equal the total area of rural Laos (level n+2). So it is required to find a method to scale-up the areas of the farming system types to the areas of the three administrative regions.

For instance, for the Northern Region the total colonized land (COL_{NR})is expressed as the sum of the colonized land areas of the three types of farming systems:

$$COL_{NR} = COL_{FS1} + COL_{FS2} + COL_{FS3}$$

Following, as it was established a population density ratio for the three farming systems (Figures 6 to 8), based on the population data of every farming system in the region[14] it is possible to associate the fractions (X_i) of total colonized land of the Northern Region occupied by each one of the three farming systems:

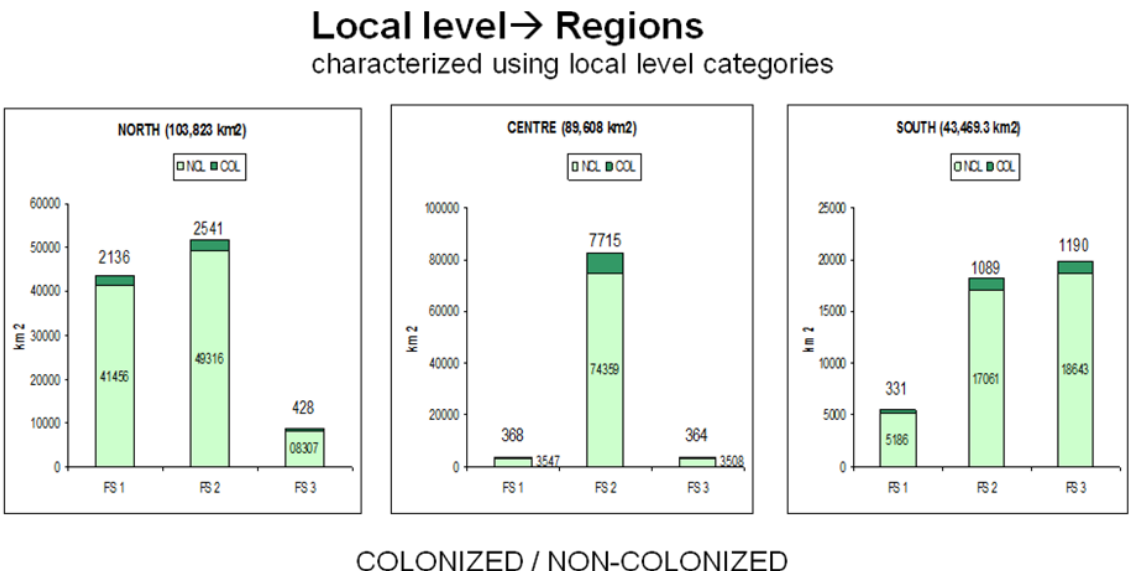
Farming System 1: $X_1 = COL_{FS1}/COL_{NR}$

Farming System 2: $X_2 = COL_{FS2}/COL_{NR}$

Farming System 3: $X_3 = COL_{FS3}/COL_{NR}$

As a result, these fractions can then be used to calculate the weighted average and weighted total of the flow elements over the three farming system types for the total colonized land of the Northern Region. The same is done for the Central Region and the Southern Region.

At this point we still have to scale-up from the total colonized land area (COL) within each region to the total area of each region (COL+NCL). To this purpose I use the farming system-specific ratios of colonized land/non-colonized land. This last step provides us with important pieces of information on 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. At this level of analysis it is possible to study the interface of societal and ecosystem metabolism. The combined use of a top-down approach (e.g. statistical data of land uses, or remote sensing with GIS providing data on colonized/non colonized land covers) and a bottom-up approach (analysis of land use corresponding to human activities of production and consumption within the metabolic pattern) provides a tool to obtain the ratio colonized land/non-colonized land for each type of farming system and to study the issue of sustainability from this perspective.



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[14] The data about the distribution of population in every region for each selected type of farming system is made through a broad estimation based on proxies indicators (obviously statistics were not classifying the population according to the same terms). Please be aware that this issue becomes a major data limitation that makes the results of this study non-reliable for real policy applications.

Figure 10. Distribution of colonized land and non-colonized land for the three farming systems in Lao administrative regions

The calculation of the ratios colonized land/non-colonized land (COL/NCL) for each of the three regions of Laos is shown in Figure 10. It starts from the bottom up approach of the distribution of each of the three farming system types among each region of Laos. Then we use the ratio of colonized land/non colonized land of the geographical region obtained from information from above gathered with either top-down statistical sources (as employed in this present case) or with non-colonized land covers information based on remote sensing data. When combining these two sources of information we can double-check and look for congruence among the data from both sides (bottom-up and top-down), and we might correct the differences found, due for example, to non-colonized areas that do not correspond to any of the farming system types considered (e.g. protected areas like national parks, or deserted areas).

After completing this step, we have a quantitative characterization of these regions that includes the characteristics of the three different farming system types. The average characteristics of the metabolic pattern of each region have been determined by the weighted contribution of the three farming system types present in that region (pace of flows per hour and density of flows per hectare). This scaling-up process is illustrated in Figure 11.

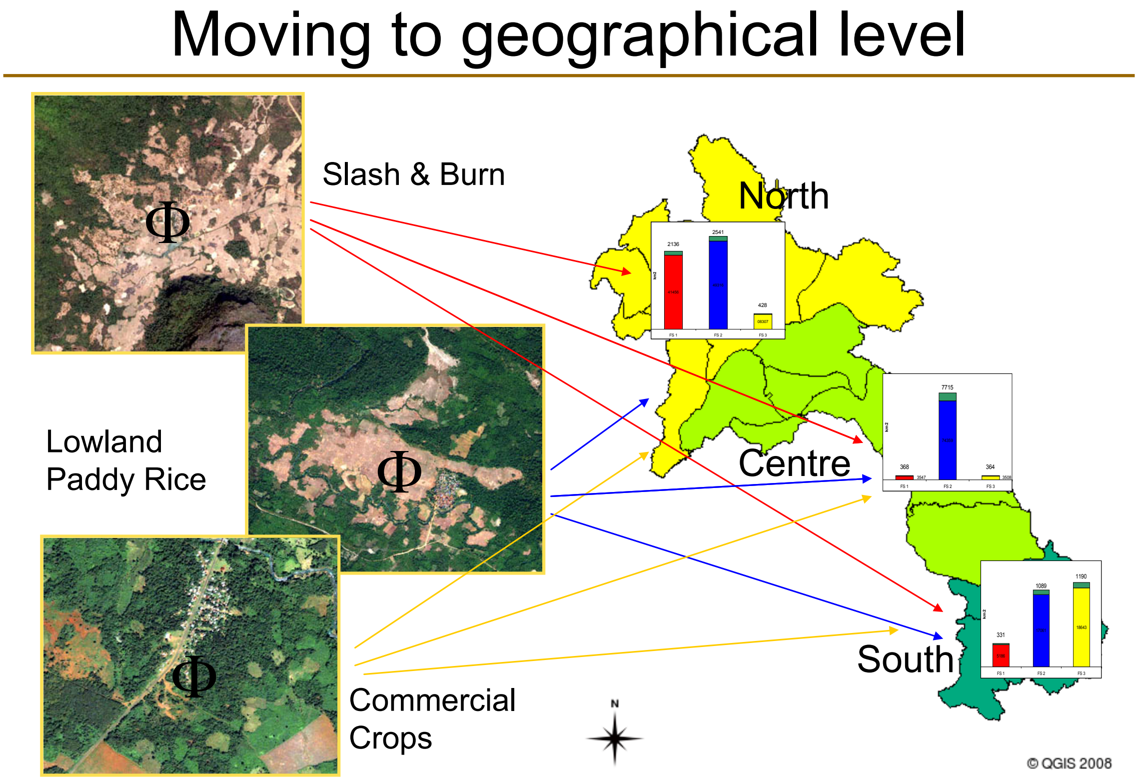


Figure 11. Distribution of the chosen three farming systems types over the three geographic regions (North, Centre, South).

4.4.3 Moving up another step: characterization of rural Laos

The next step is the scaling up of the analysis from the regional level to the whole of rural Laos. Note that in the case of Laos we consider the whole territory as rural, because urban areas are almost negligible. Indeed, the capital city

Vientiane, the largest city of Laos, covers 3.8% of the population and 0.01% of the total land area of Laos. The process of scaling from the characteristics of the three regions to the characteristics of the whole of (rural) Laos is illustrated in Figure 12. As regards the areas, I simply sum for each farming system the corresponding total areas over the three regions into the overall area of the farming system type for the whole of (rural) Laos.

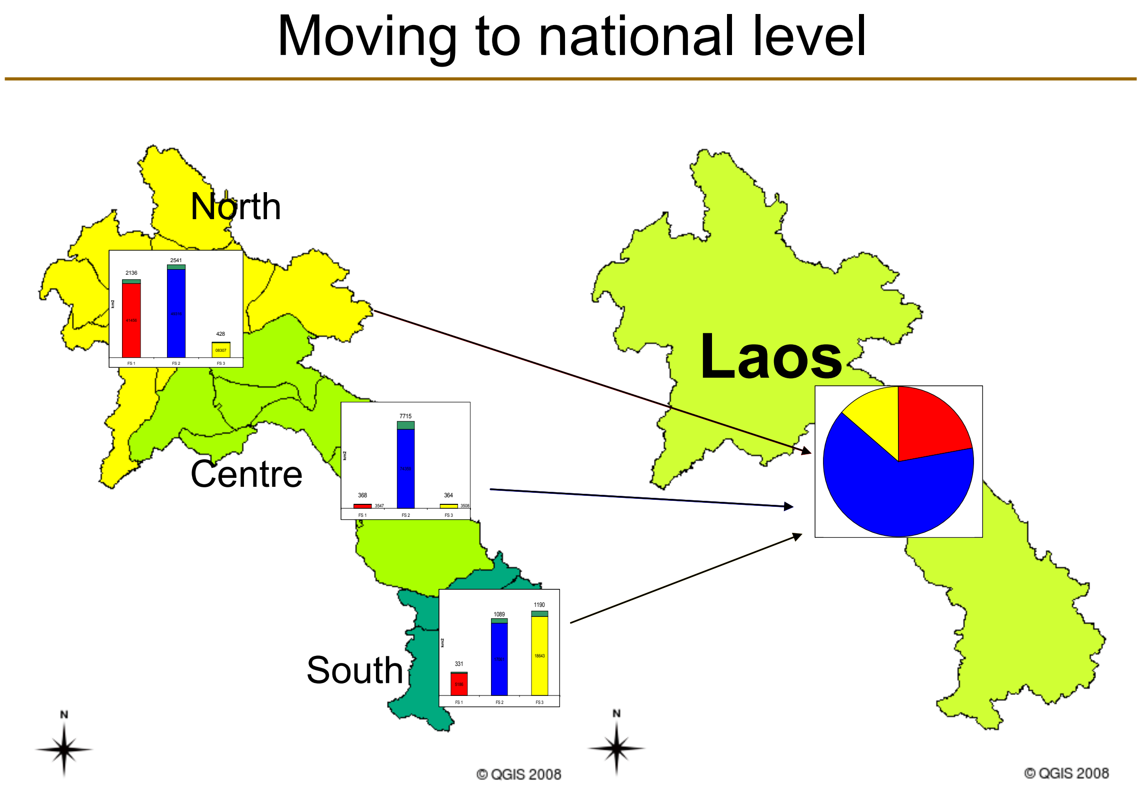


Figure 12. Moving from rural regional information to rural Laos's information.

Having applied this procedure of scaling it is possible to represent the metabolic pattern of rural Laos (at the national level) using the fund-flow diagram illustrated in Figures 6 to 8. This metabolic pattern, illustrated in Figure 13, represents that of a *virtual* average Laotian rural village of 1,000 persons, operating with average values of productivity (intensity and density of flows) found in rural Laos. Looking at this metabolic pattern, we see that the largest share of human activity is invested in agricultural activities (63% of the productive time), but the largest share of monetary income (66%) for the rural population comes from activities classified as building, manufacturing and services. To understand this apparent anomaly we must take into consideration the virtual flow of monetary value associated with subsistence agriculture. If we take into account this hidden economic value, agriculture is the predominant form of income generation for the population. This observation also underlines the importance of adopting an integrated analysis based on the combination of different dimensions.

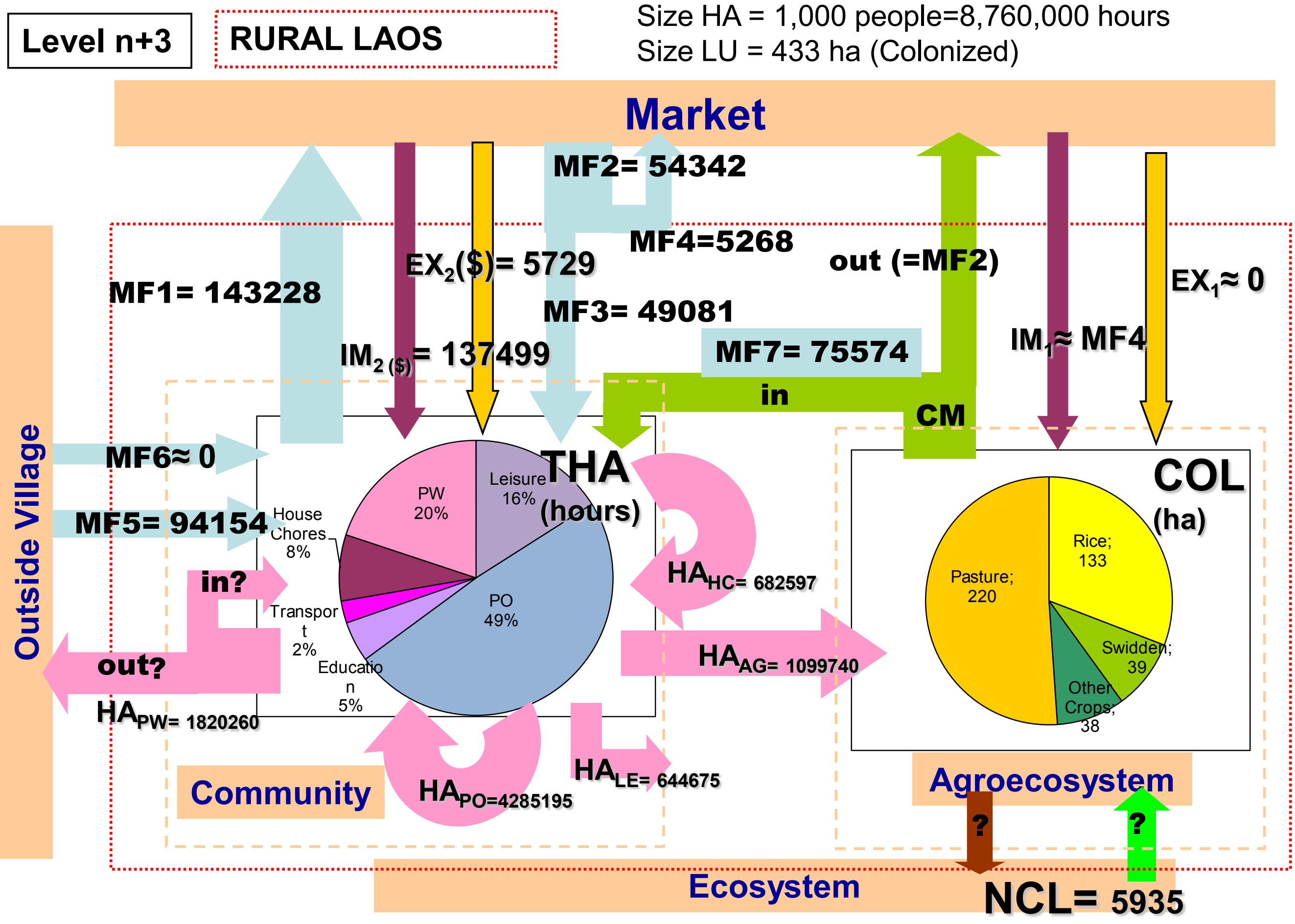


Figure 13. The metabolic pattern of a "virtual" rural village expressing the average characteristics of rural Laos.

Of course, the metabolic pattern illustrated in Figure 13 is not associated with any real external referent. In fact, the numbers reported in this graph are the final result of a process of scaling, based on the aggregation of different metabolic patterns across levels. They cannot be used in isolation (without the information given in Figures 6 to 12) to carry out an informed discussion about what is desirable and feasible at the local scale at which farmers are operating. However, it should be noted, that when using average assessments, many general statements about the performance of "the agricultural sector of Laos" are referring to this "virtual image" of a non-existent rural village (determined by a representation obtained at the level of the whole country), that does not have anything in common with any real village at the local scale (where actual instances of the three farming system types are observable!).

At this level of aggregation, we can perform a double check on the quality of the assessment by using simultaneously two different data sources:

1) Bottom-up approach: starting from the characteristics of the metabolic pattern of the three farming system types, measured at the local level, it is possible to calculate the expected overall performance of the agricultural sector in relation to the flows under human control associated with farming system activities.
2) Top-down approach: using national statistics and land use assessments we obtain data on the performance of the agricultural sector.

These two assessments obviously should be consistent.

4.4.4 Scaling-up to the level of the national economy: rural versus urban metabolism

There is an incompatibility in the definition of the identity (scale and lexicon used to describe parts and whole) of the metabolic pattern of rural and urban communities (Giampietro et al., 2011). The density per hectare and the intensity per hour of material, energy and monetary flows in urban areas are orders of magnitude higher than in rural areas. Indeed, even if urban and rural communities are operating in the same country, they express markedly distinct metabolic patterns. In our present fossil-fuel dominated societies, economic activities dependent on land and its natural materials and energy flows (e.g. agriculture and forestry) are no longer profitable as they generate little added value per unit of human activity and per unit of technical capital (Giampietro, 2003; Giampietro et al., 2011). As a consequence, if we use indicators that focus only on economic growth, it is almost sure that changes in land uses and land covers and the related ecological processes will be simply overlooked.

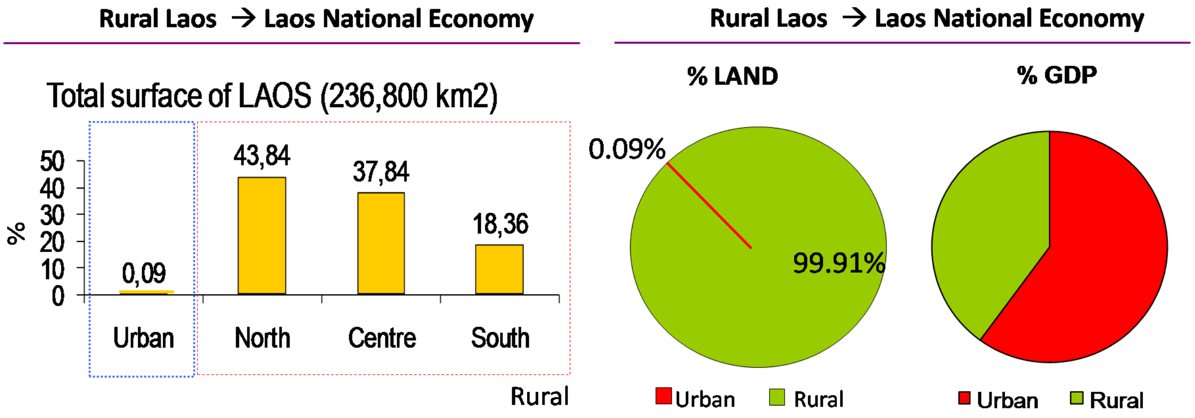


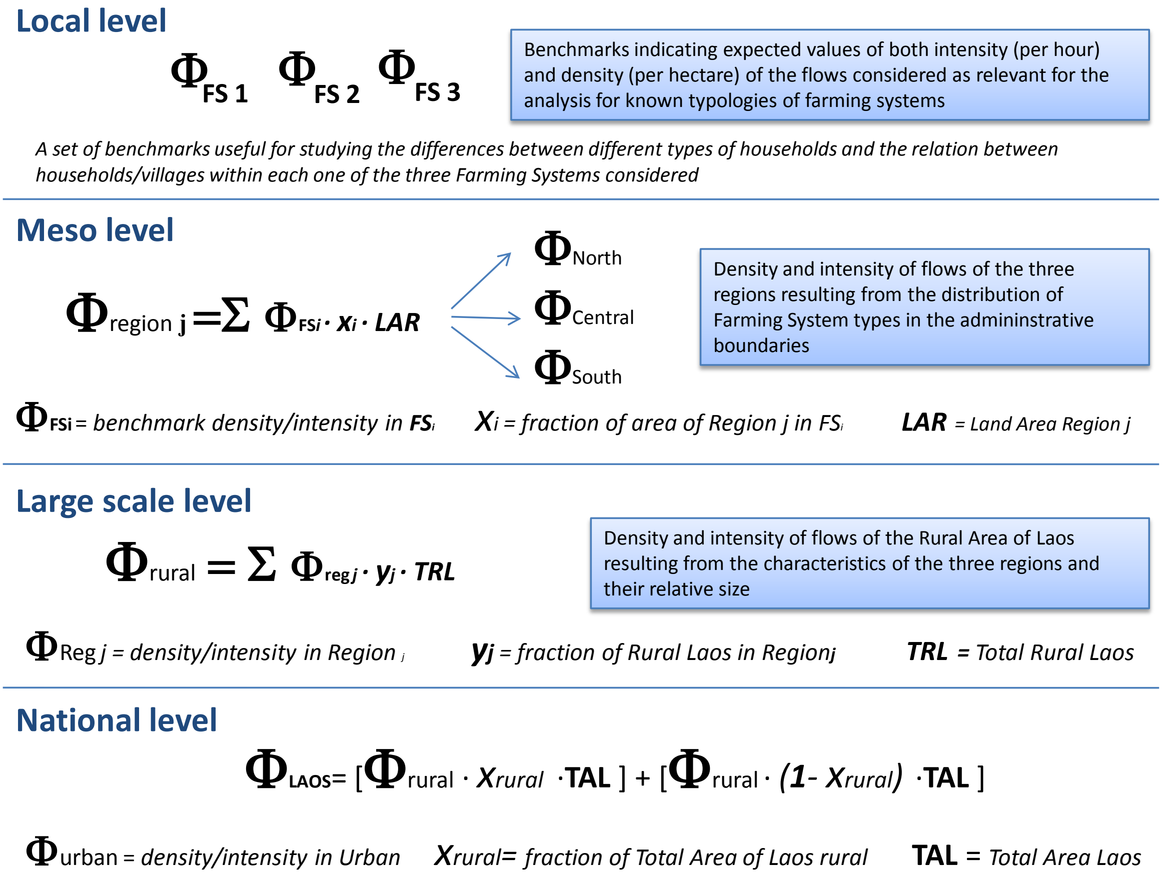
Figure 14. The non-linear relation in the profile of land use and monetary flows between urban versus rural pattern in Laos.

The terms of this problem are clearly illustrated by our case study of Laos. As shown in Figure 14, only 0.09% of the total land area of Laos is urbanized, the remainder being rural. Nevertheless, without taking into account the value of crops consumed in subsistence mode, more than 60% of the GDP of Laos is generated in these urban areas! And note that the capital city, Vientiane, with a population of only about 200,000 people (2003 estimated), is everything but a large metropolitan area. This striking difference between the urban and rural metabolism of Laos is highly relevant for development policies. If one is striving for rapid economic growth of the country, the focus will be limited to the less than 1% of the land area occupied by urban population. As a consequence, not only would we completely overlook the ecological view, but also the social view as a large share of the Lao population is still living outside of the market economy.

4.5 Conclusions

This work had the goal of illustrating with the case study of Laos the methodological procedure for analysing different levels and scales of societal metabolic patterns. We have shown a procedure that can be used to scale up. This case study shows that it is possible to move across different hierarchical levels, scales and dimensions, to arrive at an integrated representation of the metabolic pattern of farming systems. The representation is based on a quantitative assessment of relevant flows in relation to both socio-economic (intensity of flows per hour of human activity) and ecological aspects (density of flows per hectare of land use). While crossing hierarchical levels, the integrated assessment maintains coherence in the analysis of “entities” defined at different scales.

At this point it is convenient to visualize a summary of the proposed mechanism for up scaling the information across hierarchical levels of organization of the system, so the reader gets a snapshot of the whole process. The chain of different criteria of aggregation used in the case study of Laos is shown in Figure 15.



Local level

$\Phi_{FS\,1}$ $\Phi_{FS\,2}$ $\Phi_{FS\,3}$

Benchmarks indicating expected values of both intensity (per hour) and density (per hectare) of the flows considered as relevant for the analysis for known typologies of farming systems

A set of benchmarks useful for studying the differences between different types of households and the relation between households/villages within each one of the three Farming Systems considered

Meso level

$\Phi_{\text{region } j} = \Sigma\, \Phi_{FSi} \cdot X_i \cdot LAR$ → Φ_{North}, $\Phi_{Central}$, Φ_{South}

Density and intensity of flows of the three regions resulting from the distribution of Farming System types in the admininstrative boundaries

Φ_{FSi} = *benchmark density/intensity in* FS_i

X_i = *fraction of area of Region j in* FS_i

LAR = *Land Area Region j*

Large scale level

$\Phi_{rural} = \Sigma\, \Phi_{reg\,j} \cdot y_j \cdot TRL$

Density and intensity of flows of the Rural Area of Laos resulting from the characteristics of the three regions and their relative size

$\Phi_{Reg\,j}$ = *density/intensity in Region* $_j$

y_j = *fraction of Rural Laos in Region*j

TRL = *Total Rural Laos*

National level

$\Phi_{LAOS} = [\Phi_{rural} \cdot X_{rural} \cdot TAL] + [\Phi_{rural} \cdot (1 - X_{rural}) \cdot TAL]$

Φ_{urban} = *density/intensity in Urban*

X_{rural} = *fraction of Total Area of Laos rural*

TAL = *Total Area Laos*

Figure 15. The criteria used for up scaling the density and intensity of flows across different hierarchical levels in the analysis of Lao farming systems.

The up scaling was then possible using the funds as reference for the extent of each hierarchical level of the system. In this case the Land Use data played a crucial role as it allowed to shift the information about the metabolic profiles of the selected subsystems (the 3 types of farming systems). As shown, the proposed mechanism of up scaling is simple and at the same time very robust:

- Simple because i) the information about land uses can be obtained through different sources, allowing combinations of methods to gather the data (i.e. statistical, land covers from remote sensing, local studies), and ii) using typologies of farming systems related to a certain amount of land use, we get a flexible and adaptable conceptual pieces of the system to obtain the required representations with yet rigorous quantitative results.

- It is also very robust because i) through this accounting method–using land use information–is possible to perform double checks from top-down and bottom-up sources the congruence across scales and levels, and ii) offering also a process with clear quantitative closure among all the analytical levels.

Specifically, as the land use information was the key dimension of the proposed methodology, the spatial analysis tools such as remote sensing or GIS are particularly relevant in this case study. The pattern of land uses at local level for each type of farming systems can be obtained as shown through the land covers offered by imagery from satellital or aerial sources. Another example is that at meso and large scale levels, it could be possible to establish the amounts of Colonized Land (COL) and Non-Colonized Land (NCL) at a certain geographic region–required for the up scaling process–by selecting with GIS or Remote Sensing software those lands pertaining to each category. However, the use of spatial analysis has always important considerations: i) the data availability is always a major constraint, which although every time it is more easily accessed, in certain regions is still hard to obtain, and ii) when classifying the land use information according to our relevant categories, it is required good GIS skills because the conversions from the existing data (e.g. previous maps of land uses, maps of land covers, or satellital imagery) can be tough.

Another delicate issue is that since the scaling up at the meso-level requires specific data (e.g. the distribution of selected farming systems types along geographical areas) that require good sources for a certain degree of reliability and quality of information. The up-scaling at the meso-level in this case study was not very reliable due to lack of data resources (I could not analyse in detail information on land use obtained from remote sensing to double check the information gathered from national statistics). As mentioned, these problems can be tackled with the presented tools (e.g. GIS, remote sensing, triangulating between statistics referring to different levels, or using larger samples) depending on the goals and resources of the study.

Chapter 5

Generating a geographical representation of organized data for building integrated scenarios of rural metabolic patterns at local scale. A case study in Guatemala.

5 Generating a geographical representation of organized data for building integrated scenarios of rural metabolic patterns at local scale. A case study in Guatemala.[15]

5.1 Introduction

As scientists, apart from offering tools to analyse the current situations, we can also provide another set of tools to simulate possible future scenarios based on the previous information, in order to properly assess the potential constraints and estimate the possible trade-offs of for each particular case. As mentioned in Chapter 3, these analytical tools for sustainability issues in rural systems must be capable of dealing with multiple dimensions in an integrated way, handling the multiple levels and scales of these complex systems, and becoming adaptable to the different context and nature of every case. On the other hand, an extra set of tools is required for an informed debate about the proposed solutions; one way to do this is to simulate scenarios for a discussion with the stakeholders about the trade-offs of the alternatives and check whether they are possible or there are unavoidable constraints. This is an alternative to simply trying to forecast the future behaviour or offering an “optimal” solution. All the previous statements have to necessarily be generated through participatory methods with local social actors in order to (i) check what the problem definition is, (ii) obtain reliable data, and (iii) make an analysis coherent with the stakeholders’ view. Furthermore, the discussion about the final decisions should be undertaken by those who are affected in each case (i.e. not by the scientists providing the information, whose role should be limited to make representations of the manifested problems). This chapter aims to illustrate the practical use of some methods which can help to achieve some stages of the previous statements.

The purpose of this chapter is to prove that geographic information can be collected and produced when required by coupling the metabolic integrated representations of the MuSIASEM approach with Geographical Information System (GIS) at local scale. By generating our primary data it is possible to decide how to measure and account for the relevant elements considered in the analysis, for this purpose I illustrate the whole process through a practical case study. Along this chapter, an example of an application is presented using (i) previously obtained secondary data describing the metabolic profile of the systems, (ii) tools to gather primary geographical data at local scale, (iii) methods to analyse and represent the systems at local scale and (iv) a procedure to create virtual scenarios with some GIS techniques where it is possible to check the possible constraints and trade-offs. This case will be used to illustrate some insights about the relevance of the geographical analytical tools to make scenarios. The inclusion of GIS tools to build the scenarios is motivated by the fact that the spatial configuration of the environment and geographical distribution of key resources are crucial features to consider in this type of systems, since rural systems are defined and characterized by the use of land. Moreover, due to the capacity of these tools to build more detailed and specific representations of the resulting scenarios, the involved stakeholders could check how each area will be differently affected. Due to the ability of GIS to handle spatial features, it is possible to take care of particular realizations within the system, in order to focus on particular locations on the map if necessary.

This study has been implemented at one single scale at local level, with primary and secondary data gathered on the field. Since we are not looking at a lower scale (i.e. households or individual persons), it is not possible to check possible inequalities among the components of the village, which could explain some observed behaviours. Decisions taken in the community could also be affected by those possible social inequalities and power imbalances. These lower level analyses and implications can be found in Mingorría and Gamboa (2010) and Mingorría et al. (2013).

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[15] This chapter is based on a paper prepared for the journal “Environment, Development and Sustainability”.

5.1.1 Study area and the aims of the case study

This study is based on the data from two peasant indigenous communities located in the highlands of the Department of Alta Verapaz in Guatemala. The analysis carried out in this chapter is based in part on secondary data describing the biophysical metabolic relations and the production and consumption patterns of two communities. It is important to clarify that the present analysis does not consider the dramatic political context, whose constraints might be more determinant in real cases for possible development options, since the goals of this study are just limited to the methodological exercise. Considering this disclaimer, I underline once more that the quantitative results obtained by this application are merely illustrative and should not be taken as valid for policy recommendations.

The two case studies are rural settlements in an area close to large plantations of sugarcane, African oil palms and rubber trees. In this region there is a mix of settlements of communities with different livelihood systems, from those living almost exclusively as labourers of intensive agro-industrial plantations, to communities practicing subsistence farming together with some commercial crops. For this specific study, I focused on two communities henceforth referred as “community E” and “community F”[16]. The population in these communities are Q’eqchi’ indigenous peasants (of the Mayan ethnic groups), whose economy relies mainly on agricultural work, a large portion of which is for self-subsistence production. The two settlements are one beside the other, and they are both located at in a marginal steep area between the plain valley (where the agro-industrial plantations are) and the border of a natural protected area. Finally, the climatic environment of the case study is characterized as tropical, with stable warm to hot temperatures and high precipitation periods along the year, including sporadic hurricane hazards.

The exercise presented can be divided into four main stages:

1. Up-scaling the information of the metabolic pattern of households to village level. This task is based on secondary data and encompasses the up-scaling of variables and technical coefficients to describe the metabolic performance of the villages focusing on the agricultural production (e.g. production per hour and per hectare, production factors and supply sources for different dimensions, or time for transportation). It considers the farming activities of growing maize, beans, cardamom, and other relevant activities.
2. Simulation of two scenarios where I simulate changes in the farming production in two different ways:
    a. Expanding the cardamom cultivation to the maximum capacity of their territory.
    b. Making the peasants work for cash outside their village as daily labourers in the agro-industrial plantations of the companies of the valley.

    Although building these two scenarios has the only purpose of illustrating the tools, and their results cannot be taken as valid for policy recommendations (i.e. we should check at least their desirability by the affected people, and the secondary data used is not reliable enough for this purpose), I preferred to avoid simulating completely unrealistic or illogical scenarios. Thus, I selected these two alternatives about cardamom expansion and labourers for agro-industries based on the current context of these villages, and on previous studies in the area (Mingorría & Gamboa, 2010; Mingorría et al., 2013), which are, among other things, analysing proposed alternatives of rural development from official institutions (World Bank, 2007;, FAO, 2010; Deininger et al., 2011). Particularly, the cardamom is already being introduced by the villagers due to its good growing conditions and yield, so we simulate a radical shift to the specialization on this crop in our systems. In the case of the second scenario, the oil palm plantations are expanding in the area, so I simulate what would change for them if they became waged labourers.

3. To build the scenarios, I perform the following tasks:

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[16] I keep the confidentiality of the two communities because I have been asked to do so, due to the current struggles they have there. The rest of the project in which I was working had other communities named “A”, “B”, “C” and “D”.

   a. Check the geographical constraints of the territory (e.g. distances, incompatible land uses, slope, elevation, soil, topography, water, sunlight).
   b. Check the demand for work force and transportation time for the selected farming activities. I assume that access to funding for the transition to the new scenarios is not a limitation and I ignore other possible transition costs towards the new scenarios, as I just focus on the final trade-offs of the changes in the system.
   c. Estimate the resulting metabolic performance with an integrated representation interfacing the land use, human activity, agricultural production and monetary flow.
4. I make a comparison between the results of the two virtual scenarios and the current situation, to illustrate the resulting trade-offs for the two analysed communities in terms of monetary income, degree of self-sufficiency, labour demand, and use of their territory.

5.2 Material and methods

This case study is based on a combination of some secondary data (i.e. metabolic pattern at household level)–section 5.2.1–, and primary data collected following some gathering methods of geographical information–section 5.2.2. It is important to mention that the secondary data used based on the publication Mingorría and Gamboa (2010) has been later reviewed and updated for other publications.

5.2.1 The broader project hosting this study

The project named "Development of a framework for participative-analytical assessment of the socio-environmental dynamics and quality of life of the peasant communities in Polochic Valley, Guatemala"[17], was a collaboration among the Institute of Environmental Science and Technology (ICTA) of the "Universitat Autònoma de Barcelona" (UAB) and the Institute of Agrarian and Rural Studies of the "Coordinación de ONG y Cooperativas" (CONGCOOP) of Guatemala. The project aimed to identify and understand the indigenous-peasant economies of this study area, from household to community level, how these communities are structured, and face their challenges and conflicts. The metabolic performance of the two communities studied was assessed in this project applying the principles of the MuSIASEM approach. The project gathered primary data between 2009 and 2011 in three non-consecutive fieldwork periods. Here we use the information about demography, human activity, monetary flows and agricultural production presented in Mingorría and Gamboa (2010) to represent the performance of the communities. There, it is possible to find in detail the description of all the processes selection of the cases, the characteristics of the peasant communities, and the methodological steps and tools employed in these stages the analysis and data gathering.

Although the aim of the host project is different from the purpose of this study, it has represented a fantastic platform to implement the methodological advances presented in this exercise to an empirical case study.

5.2.2 The methodology of the geographical analysis

The application of the tools about geographic analysis of this study can be considered a pilot case, as the time and resource limitations prevented the full implementation of these methods to all the extent of the host project. The geographical data was collected from January to March 2010. I made a combination of varied sources and techniques to make the maps at local level which included (i) participatory mapping, (ii) GPS mapping and (iii) collection of existing digital and paper maps.

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[17] This is a direct translation of the original Catalan title of the Project: "Desenvolupament de un marc de avaluació analític-participatiu de les dinàmiques socio-ambientals i de la qualitat de vida de les comunitats camperoles de la vall del riu Polochic, Guatemala".

5.2.2.1 Participative mapping

After spending some time meeting the members of the communities, participatory sketch mapping was implemented following the methods recommended by IFAD (2009). Sketch mapping consists in freehand drawings on blank pieces of paper from the memory of the participants. They reflect in a map visualization their perception about the territorial features that they are asked about. This type of mapping technique does not involve exact measurements, although it can be combined with existing scale maps to represent more accurately the features. In any case, these maps are useful to visualize the relational size and position of the features perceived by the population of their own territory.

In this study, I divided the participants in different focus groups by sex, for two main reasons: women and men have very different perceptions of their territory since in this case they carry out very different activities, so each group will provide very different visualizations, from which it is possible to get interesting qualitative observations. The other reason is that in this area there is a strong predominance of the men that will prevent women from raising their voice and offering possible relevant information that otherwise they would freely say. As expected, the sketch maps made by women and men were very different. Men are in charge of managing their plots and they have a more extensive and accurate knowledge about the surroundings, since they also have more opportunities to move and explore their territory. Although women also work sometimes on the plots, in general they had a surprisingly poor knowledge about the geography of their territory, mistaking some features, confusing the orientations in the space, or misleading the relative size and location of spatial features. A possible explanation for this difference of knowledge of their territory and lack of spatial sense is that in these cases women are not in charge of the *management* of the lands, they are limited to do what they are told in the plots, so they seem not to need to know this kind of information to carry out their tasks.

The list and the location of all the houses and plots pertaining to every household of the two communities was obtained with the participatory mapping. The same was achieved for the relative location of the main land uses (cardamom, maize, pastures, forest, etc.) and key features, and the courses of the rivers, streams, and main communication paths. I also wrote down the surface of every plot to double check with the information obtained in the surveys. In Figure 16 we can observe the example of one of the resulting maps for community E, and in Figure 17 it is possible to see the detail of the information about the houses and some plots for community F.

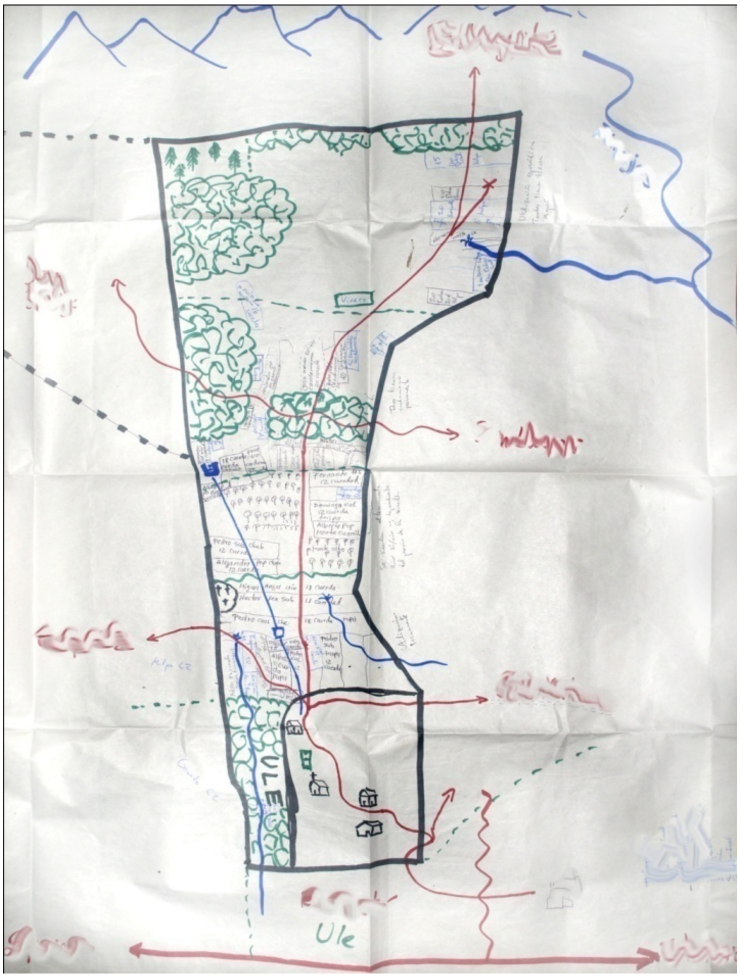

Figure 16. Resulting participative map of community E. Names are distorted to keep the confidentiality.

Figure 17. Detail of the participative map of community F. Names are distorted to keep the confidentiality.

5.2.2.2 GPS mapping

Global Positioning Systems (GPS) was used to get an exact location of some key features in order to later represent these locations on accurate GIS maps. I captured the coordinates of all the houses, walked through the main paths to capture the tracks, and located some boundaries, plots and key spatial features such as upwellings for the water provision of the communities (Figure 18). This tool allowed complementing the previous method about participatory mapping, resulting in an extremely accurate map of their resources. It is relevant to mention that the use of GPS is a relatively lower technology compared to other sources of information such as remote sensing, it is increasingly affordable, and the GPS receivers are quite easy to operate after a brief initial training. All these advantages make this tool very interesting for these rural communities, because it opens a window of opportunities to control their territory, resources and spatial features.

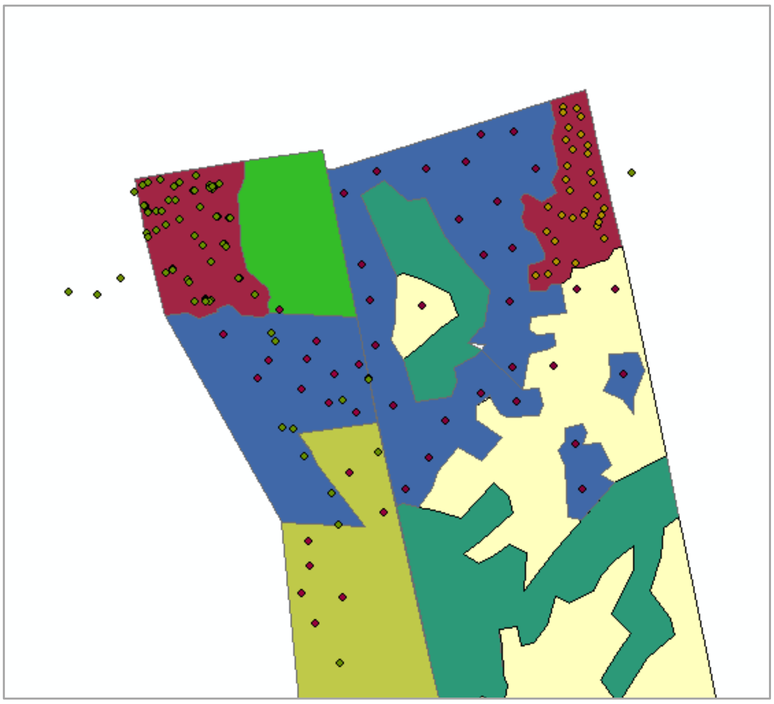

Figure 18. Example of the some GPS "waypoints" georeferencing some relevant elements on the territory.

5.2.2.3 Using existing maps of the area

In this case I could also get the scale maps made by engineers measuring the boundaries of their owned lands, so I could easily export the coordinates of their territory to a GIS platform.

Additionally, some available digital format maps were used to complete the information of the studied area. I was able to get high resolution digital orthophotomaps (aerial photos geo-referenced as maps) from the Guatemalan Ministry of Agriculture (MAGA), that although a bit old (2003), they were still very useful to identify the physical covers and elements on the land, such as streams, pathways, plots or buildings. From MAGA, I also got digital GIS layers with basic information including main populated areas, administrative boundaries, roads and rivers, water bodies, geology, and soils. The Digital Elevation Map (DEM) that is later used for the estimation of scenarios was obtained from Shuttle Radar Topographic Mapping Mission (2000). Data are downloadable from the NASA Earth Explorer (http://earthexplorer.usgs.gov/).

Joining together into GIS layers all the previous information of primary data from participative and GPS mapping, and secondary data from existing maps, made possible to build very complete GIS maps of the local area (Figure 19 and Figure 20) for the subsequent analysis.

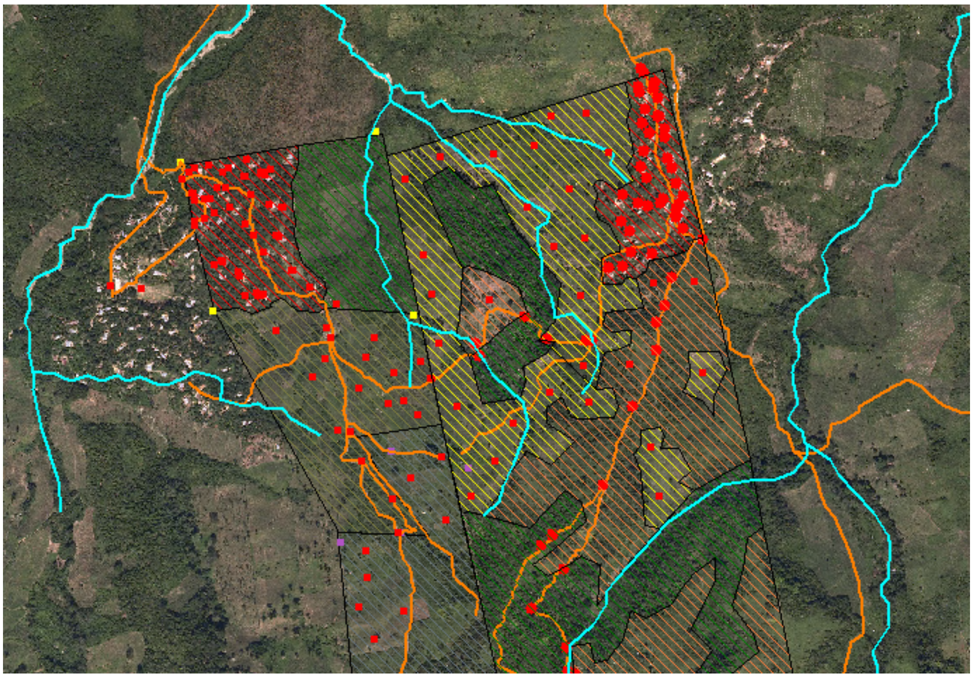

Figure 19. Detail of the resulting map visualizing the physical land cover, land uses, plots, houses, streams and pathways of the considered communities.

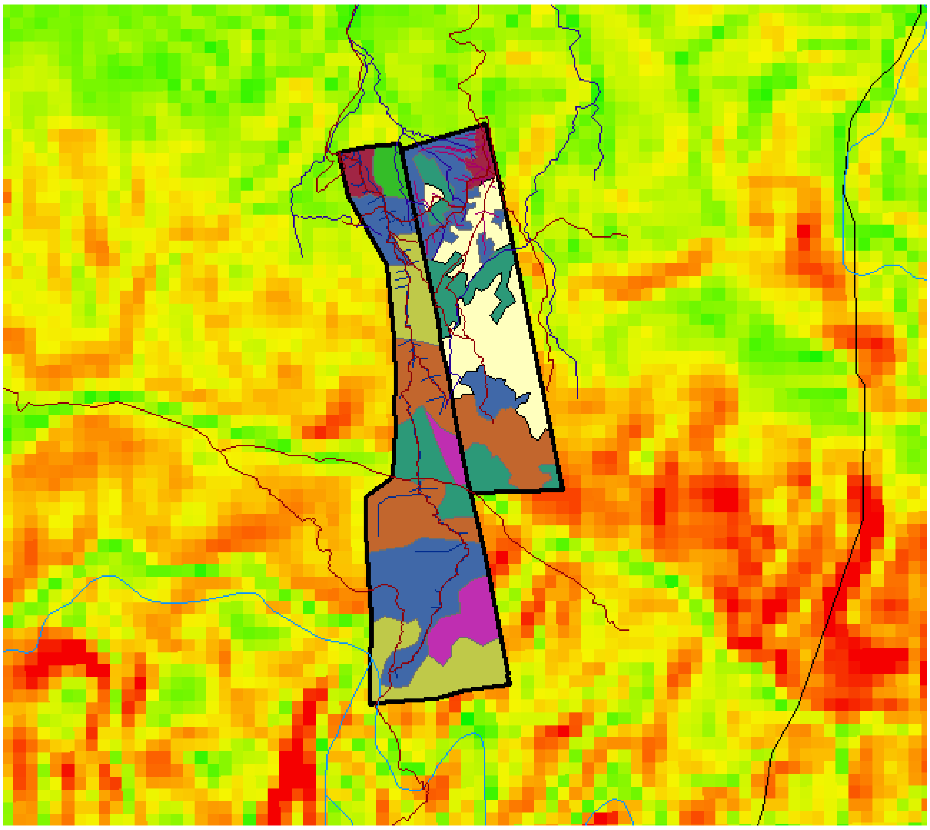

Figure 20. Resulting map considering the slope, land uses, and main rivers and paths of the area under study.

5.2.2.4 Calculation of distances and time for transportation

The gathered geographic information was useful to calculate the simulations made in the scenarios for the two communities. The software I used for the GIS analysis is Forestry GIS (fGIS) from ForestPal, a free GIS software being already used by the host organization.

As mentioned in the previous section, with the information from the participatory and GPS mapping and the orthophotomaps, it was possible to allocate accurately in the map the location of every plot pertaining to every household. This eventually allowed calculating quite accurately the distances from each house to their pertaining plots, and the differences in the time for transportation when working at the different types of crops in each plot. In Figure 21 and Figure 22 we can see that there are big differences in the distances from the houses (at the top of the map) to the nearest and furthest plots. In community E (the community at the left), the closest plots range from less than one kilometre to more than four kilometres in the case of some maize plots, so the time for commuting differs enormously. It is also possible to observe in Figure 21 and Figure 22 the use of a buffer (in olive green) to check the areas within 50 meters from the main pathways (in orange).

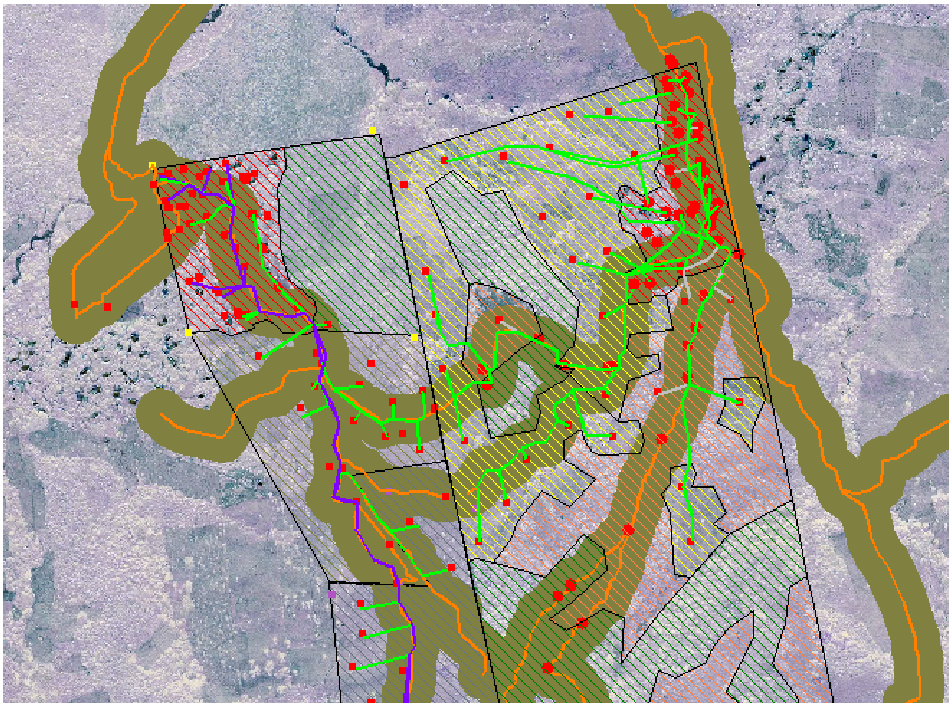

Figure 21. Detail of the map for the calculation of distances focused on a closer zone to the urban area. Note: the colour of the orthophotomap is inverted to better see the rest of features.

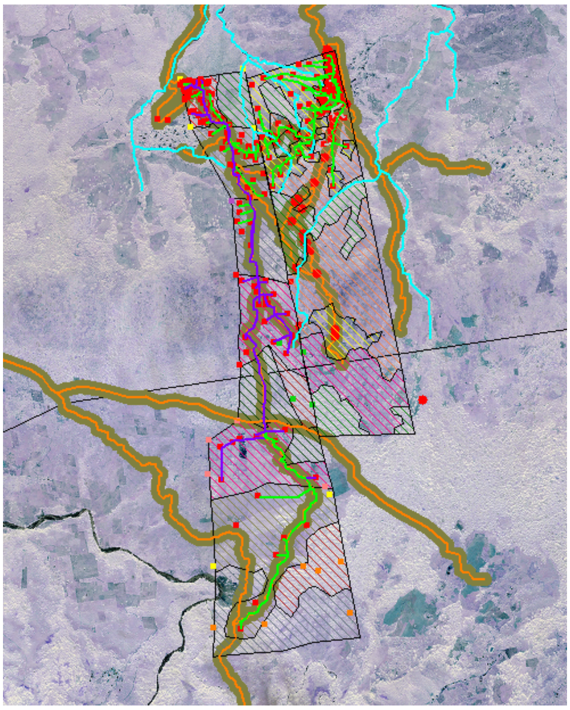

Figure 22. General map of the territory of the considered communities for the calculation of distances. Note: the colour of the orthophotomap is inverted to better see the rest of features.

Figure 23 is an example of the profile of one part of the track measured with GPS. This is part of the way from the houses of community E to some cardamom plots. It is possible see very clearly the extremely steep terrain of these communities, where measuring with the GPS through the way to the plots (which are actually narrow paths in very abrupt terrain and dense vegetation, but at least the pathways are naturally avoiding the steepest parts), we could measure and increment of 400 meters in altitude in a course of just 2.4 Kilometres, resulting in an average of more than 16% of slope in this pathway. We could also arrive to the conclusion with some other samples that the walking speed in the area is around 2 Km/h uphill, and 3 Km/h downhill. This datum is important in order to later estimate the allocation of time for commuting depending on the distances to the working places, since it is evident that in this type of rural systems this factor is not trivial.

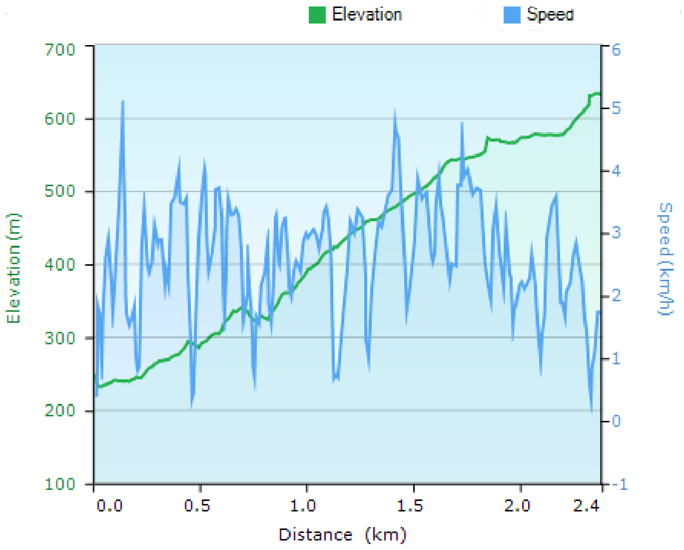

Figure 23. Elevation profile obtained with GPS of one example of pathway in the studied terrain with walking speed measurements.

5.3 Results and discussion

5.3.1 The chosen scenarios

The two selected virtual scenarios show two development options clearly aimed at increasing the specialization in one single activity to increase the cash income, by decreasing the available time for subsistence agriculture or other activities, and thus affecting the self-sufficiency for food and the independence from external markets for the income. The path that these scenarios put forward might not be desirable for the villagers, who may prefer developing in other ways.

Therefore, the sole purpose of this exercise is to illustrate the functioning of the tool with some examples using empirical data. Moreover, as we can observe, the implemented scenarios are not intended to be balanced, they are some kind of extreme examples to check what happens when we change radically some parameters using our approach.

One assumption I used is the following, when I obtained some working time left in the scenarios, I allocated the remains of the working time to the subsistence agriculture of maize and beans, since this is the manifested preference of this population due to the cultural importance for their identity (Gamboa & Mingorría, 2011), apart from ensuring some degree of food self-sufficiency.

Some important issues to be considered in the scenario of daily labourers working in the agro-industries are that those companies only hire male workers below 30 years old (Mingorría et al., 2014). For the sake of simplicity, this scenario is assuming a homogeneous distribution of the work force and tasks performed over the population structure. For example, we assumed that the remaining population working inside the communities (women and those men above 30 years) could maintain the same allocation of time of their current tasks. Note that this assumption is omitting the fact that changing the demographic structure (sex and age) of the available work force for the local tasks will also affect the possibilities and the profile of time required to perform many local activities. Unfortunately, the available quantitative and qualitative data was not enough to make a reliable simulation including the effect of demographic issues in the resulting activities.

5.3.2 Results from the spatial analysis

5.3.2.1 Calculation of the suitable lands for the cardamom expansion

GIS allows calculating the maximum suitable amount of land to grow cardamom in the territory of the studied communities knowing the requirements of this crop, and filtering these requirements with the GIS software, as shown in the following section. For example, the depth of the roots of cardamom is just up to 30 centimetres, so they do not require deep soils. The type of soils they require are rich in organic matter or compost, always wet soils, but well drained, so it grows better in slopes between 5-20%. The climate must be warm, very wet, ideally tropical areas with available shady areas. Cardamom only grows in medium altitudes ranging from 600 to 1500 meters.

Villagers' houses are scattered inside a small part of their territory, which is considered the urban area. It is located in the closest corner of their land to the main road, and it occupies 8.4 ha in community E and 6.5 ha in the case of community F of their total lands. It was assumed that all the other current land uses apart from the urban area was selectable for the cardamom expansion. I filtered the area inside the altitudes with the DEM map (Figure 24), and calculated a slope layer from the DEM layer, from where we selected the slopes between 5% and 20% (Figure 25).

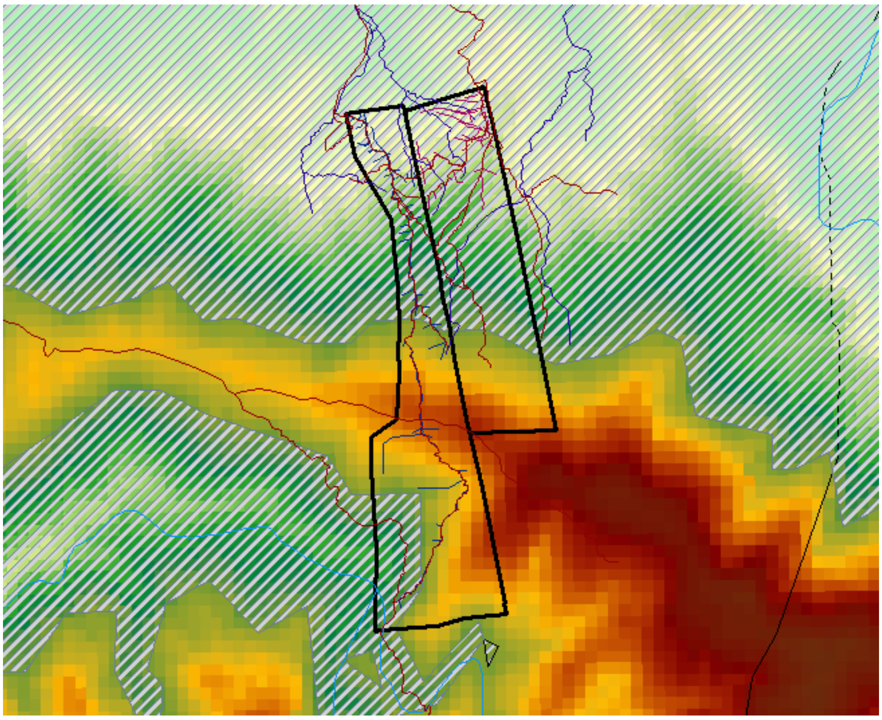

Figure 24. Map of the suitable lands regarding the required elevation for cardamom cultivation.

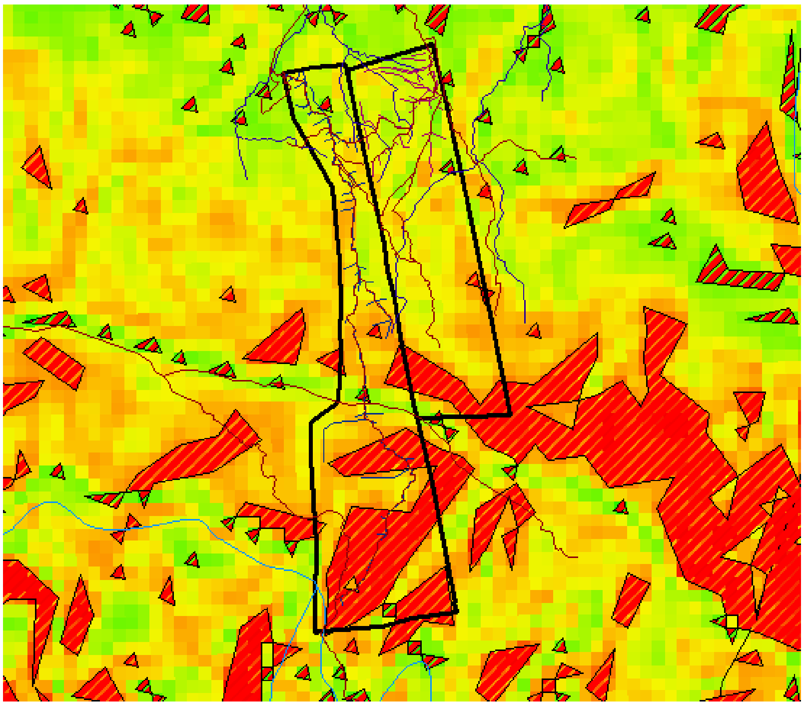

Figure 25. Map of the suitable lands regarding the required slope for cardamom cultivation

Checking the soil map allowed to find out that the type of soil is not a limiting factor for the cardamom expansion in this area, as I could check that both communities are located completely inside a soil area called Chacalté, which has a limestone base, and although it has a high percentage of clay, it is characterized by good drainage, that together with steep terrain helps to avoid ponding. This soil is around 50 centimetres deep, so it is enough for cardamom cultivation. It is relevant to mention that this type of soil is highly prone to erosion, and this is already one of the greatest concerns for cultivation in the area, as reported by the peasants themselves. Proximity to water sources is not a problem in our cases because cardamom does not require irrigation in our area due to the high annual precipitation of 3600 mm. If this was not the case, a buffer could be made with GIS (as shown previously in Figure 21 and Figure 22) with the courses of water in the area obtained in the maps, in order to check which zones are within a determined distance from the water resources. Finally, using the DEM layer it is possible to obtain the relief with the hillshade function, and the slope orientation towards the cardinal points, to estimate the areas of solar radiation. In the case of the cardamom this was not required because it grows in shady areas under other trees, so solar radiation was not a problem.

As a result of the previous calculations, I obtained that the resulting area suitable for cultivating cardamom in community E is 85.4 ha, and in community F it is 34.5 ha (Figure 26). Note that the level of accuracy depends on the spatial resolution of the layer maps used in GIS for the calculation. In this case the DEM and the slope map used had a resolution of 90 meters per pixel, so at this local scale the calculation of hectares is just an approximation good enough to estimate a possible scenario.

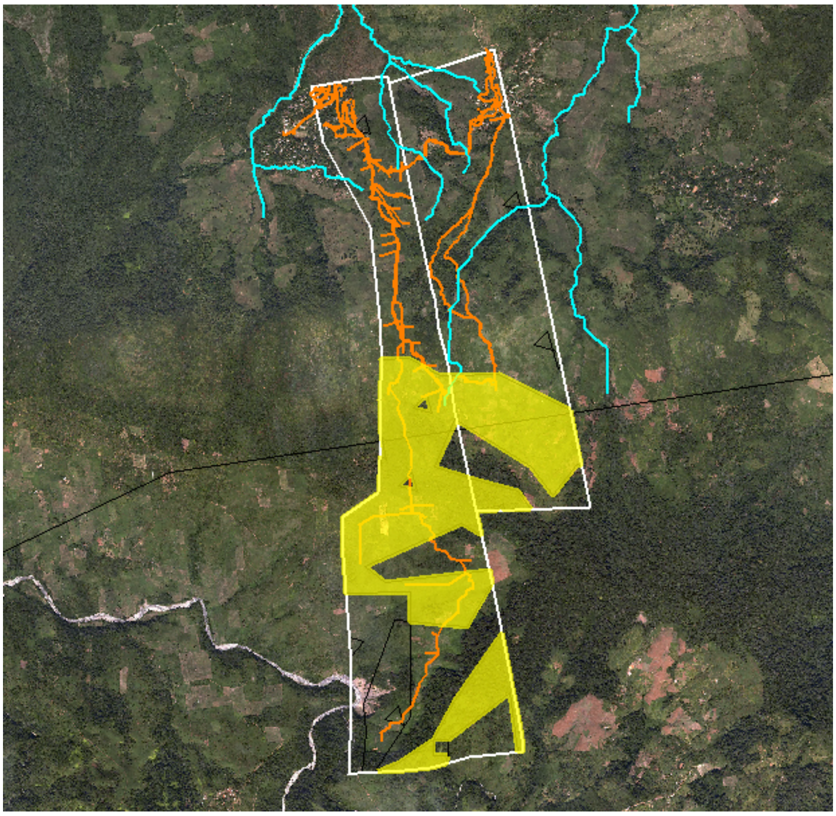

Figure 26. Map reflecting the suitable area for the cardamom expansion.

As expected, the distance from the houses to the location of the suitable area for the cardamom expansion obtained in our calculations is logically similar to the distances of the current cardamom plots (i.e. their current plots are within the limits of this area). As a result, in this case there are not significant differences for the commuting time to these lands in the new scenario.

5.3.2.2 Calculation of distances for working as daily labourers in the agro-industries

Data for simulating this scenario is taken from the information gathered in another village (community B) of the area. The detailed information about the material and methods to collect this information can be seen at Mingorría et al. (2014). In that case, the community members were mainly working as daily labourers in the oil-palm agro-industries of the valley, and their village was located next to the main road. When simulating this scenario in community E and F, we must take into account that these communities are quite far from the road, so we have to measure with maps the length of the paths from the households to the main road in order to calculate the extra time for transportation that the workers from community E and F have to invest in this scenario. The time is calculated using the average speed described in section 5.2.2.4. Once on the road, the companies pick up the workers and take them to the different industrial plantations. For this stage of the transport we took the average time found in Mingorría et al. (2014) of some other communities located in the valley.

When estimating the time that the daily labourers have to walk every day to the point on the main road where they are supposed to be picked up, we took into account the time for going and return every day, and the average amount of working days per year. As a result, the measured distance of 2,750 meters from community E to the pick-up stop means that the labourers have to add 140 minutes for transportation each day of work (around 2 hours and 20 minutes per day). In the case of community F this distance is 3,500 meters, meaning 175 minutes walking (almost 3 extra hours per day). These results demonstrate that distance is not a trivial feature and that with this kind of spatial analysis tools we can quickly check for changes in the time allocation profile of the system due to investments in transport time when commuting distances change.

5.3.3 Comparison of the metabolic performances

5.3.3.1 Estimation of technical coefficients for the scenarios.

The information about the human activity (HA), land use (LU), agricultural production and monetary flows from Mingorría and Gamboa (2010) was initially arranged in a table as the one shown in Table 2. The table can be adapted and tailored to whatever category or element of the system we want to calculate. The relevance of this arrangement is that it establishes links among the different dimensions of all the selected subcompartments of the system under analysis, and it shows the total amounts.

Community E	Production (kg)	Money (Q)	HA (h)	LU (ha)
Maize for cash	1625	1267	1687	1.1
Maize subsistence	29375	N/A	30488	19.9
Beans for cash	0	0	0	0
Beans subsistence	1575	N/A	2075	5
Cardamom	25250	132983	30000	23
Exports	26875	134250	31750	24.1
Self-consumption	30950	0	34750	24.9
Food Imports	Negligible	Negligible	N/A	N/A

Total agriculture	57825	134250	66500	49
Off-farm paid work	N/A	63750	18100	N/A
Community and HH chores	N/A	N/A	155350	N/A
Imports of other non-agricultural products	N/A	198000	N/A	N/A
TOTAL	57825	198000	84600	49

Table 2. Data about different dimensions of the current situation in Community E. Source: elaborated from Mingorría and Gamboa (2010).

This kind of table allows assessing the technical coefficients and ratios of the compartments of the system, useful to simulate scenarios. For instance, from Table 2 it is possible to obtain for community E that the cardamom has a production yield of 1,100 kg/ha, it was sold at an average price of 5.27 Q/Kg (Guatemalan quetzal), it required 1,300 hours of work per hectare of cardamom, and the resulting ELP (Economic Labour Productivity) of this crop is 4.4 Q/h of work. Now we can use the coefficients observed in this community to estimate the new value of the rest of the table when changing some parameters in the virtual scenarios.

Unfortunately, there was not much information about the amounts that have to be invested in each type of crop, so it is important to bear in mind that the calculations for the scenarios are just broad estimations to illustrate the method. Data were not available either in the specific area on the price at which the villagers would eventually have to buy food in case they were not producing their food. Then, for some products (maize and beans) I used the average price shown for the studied dates in the food basket of Guatemalan Statistical Service (INE Guatemala, 2010). This datum is important so I could estimate the extra monetary expenses in scenarios where our communities would be decreasing their degree of food self-sufficiency.

5.3.3.2 The fund-flow diagrams characterizing the rural metabolic performance

The results of the simulation of the scenarios are shown at village level (local scale) for each community, following the type of diagram explained in section 3.3. The information for the current situation of the considered systems is obtained from previous diagrams made at household level (Mingorría & Gamboa 2010) and up-scaled at village level.

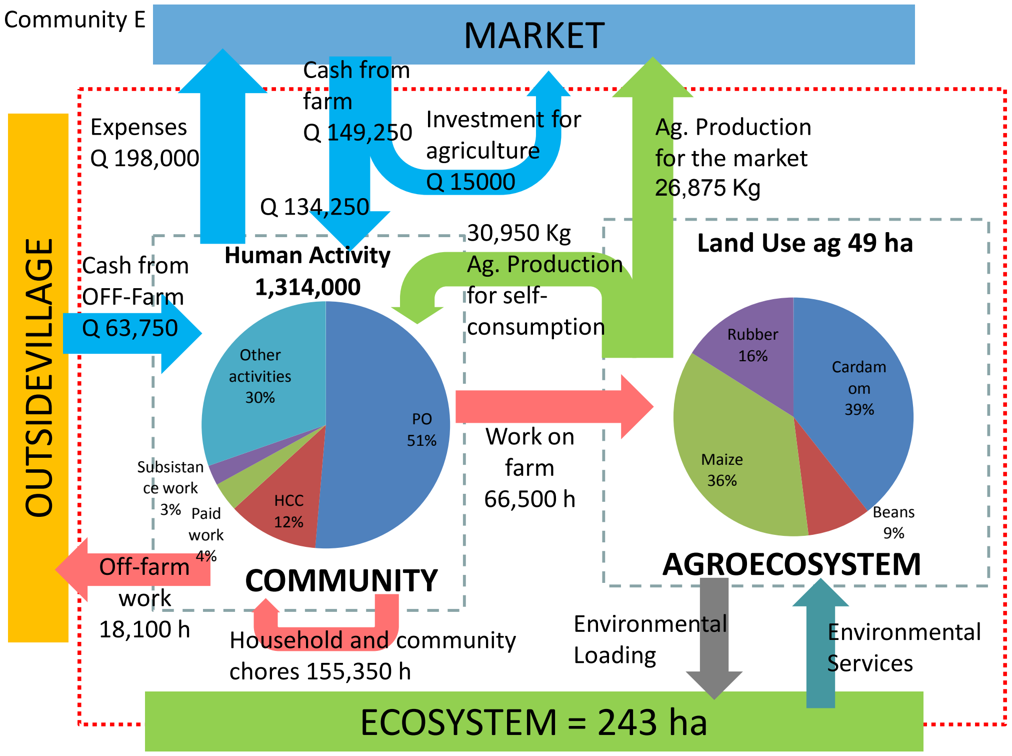

Figure 27. Current metabolic profile of community E. Elaborated from Mingorría and Gamboa (2010).

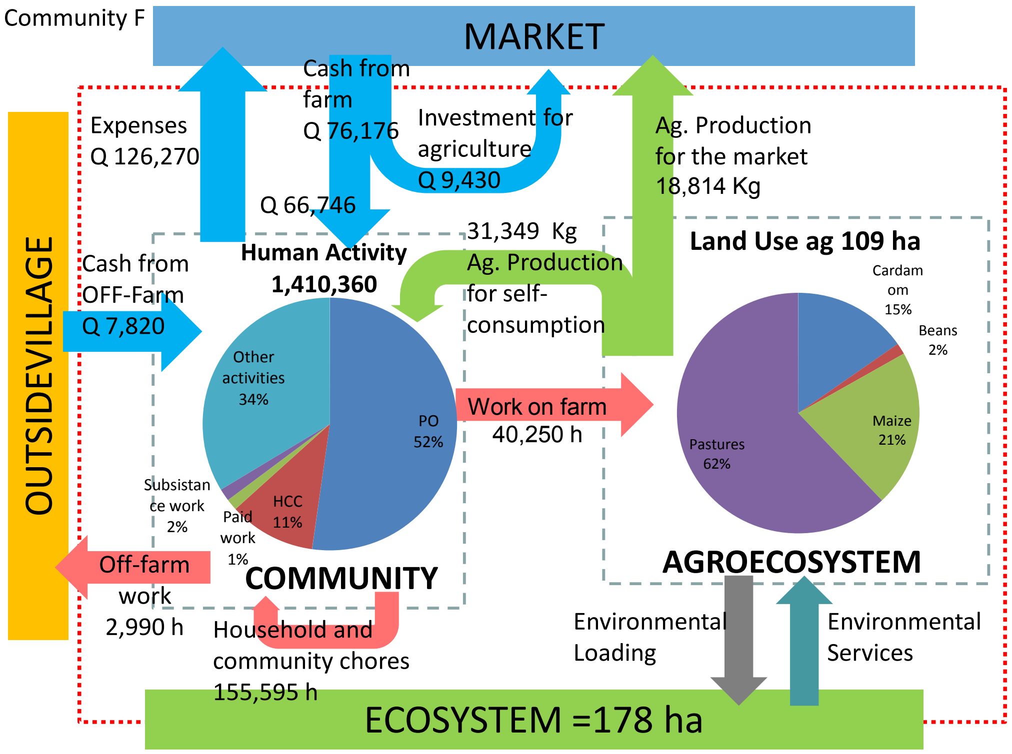

Figure 28. Current metabolic profile of community F. Elaborated from Mingorría and Gamboa (2010).

In Figure 27 and Figure 28 we can see on the left pie chart that the total amount of human activity is 1,314,000 hours in community E and 1,410,360 hours in community F, corresponding to the time per year of 150 persons and 161 persons respectively. I aggregated the human activity into categories relevant to the aims of this study. HCC is the time employed in house chores and common village works that the community requires for its reproduction. We divide the productive work into paid work or subsistence work depending on the kind of income (cash or food), and we leave "other activities" for the rest of the time, which include many important things such as the active time of the dependent members of the community (children and elderly), time for religious activities, education, assemblies or collecting firewood. The units employed to quantify the monetary flow are the Guatemalan currency Quetzals, as it is more accurate than trying to introduce conversion factors to other more recognizable currencies like US dollars, given the fluctuation of the exchange rates in the study period[18].

At this point we must mention that the data used is based on a limited sample of the households in the villages (13 out of 25 interviewed households in community E, and 13 of 26 interviewed households in community F), so the error margin might be quite wide, and the values shown are just illustrative.

5.3.3.3 The resulting changes in the systems

As we can see in Figure 27 and Figure 28, both communities E and F are currently characterized by investing a large part of their resources in subsistence agriculture, and they could be considered to be self-sufficient in terms of maize and beans, the products that constitute their basic diet. As mentioned before, these communities are quite isolated on the mountainous area, they explicitly chose to avoid working outside for the agro-industry companies of the valley, but they do carry out some other agricultural production to sell outside their community in order to get some cash income to complement their livelihoods (Mingorría & Gamboa, 2010, p. 71). Community E is presently dedicated to rubber trees and cardamom, and they acquired a cardamom drier that allows them to better sell their production. Community F is also growing cardamom, to a lower extent, and they are also starting to implement some cattle rearing.

Cardamom scenario

The scenario of the cardamom expansion assumes that the villagers would be able to sell all the increase in cardamom production, and at the same price as before. It is also assumed that their cardamom drier has the capacity to process all the new production.

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[18] Although I try to avoid focusing on the particular numeric results of this practical application, in case the reader is still willing to have an idea of the monetary value illustrated, it can be taken as reference that one US dollar was 7.7 quetzals, and one euro was around 10 quetzals in 2009, the year of the gathering of data.

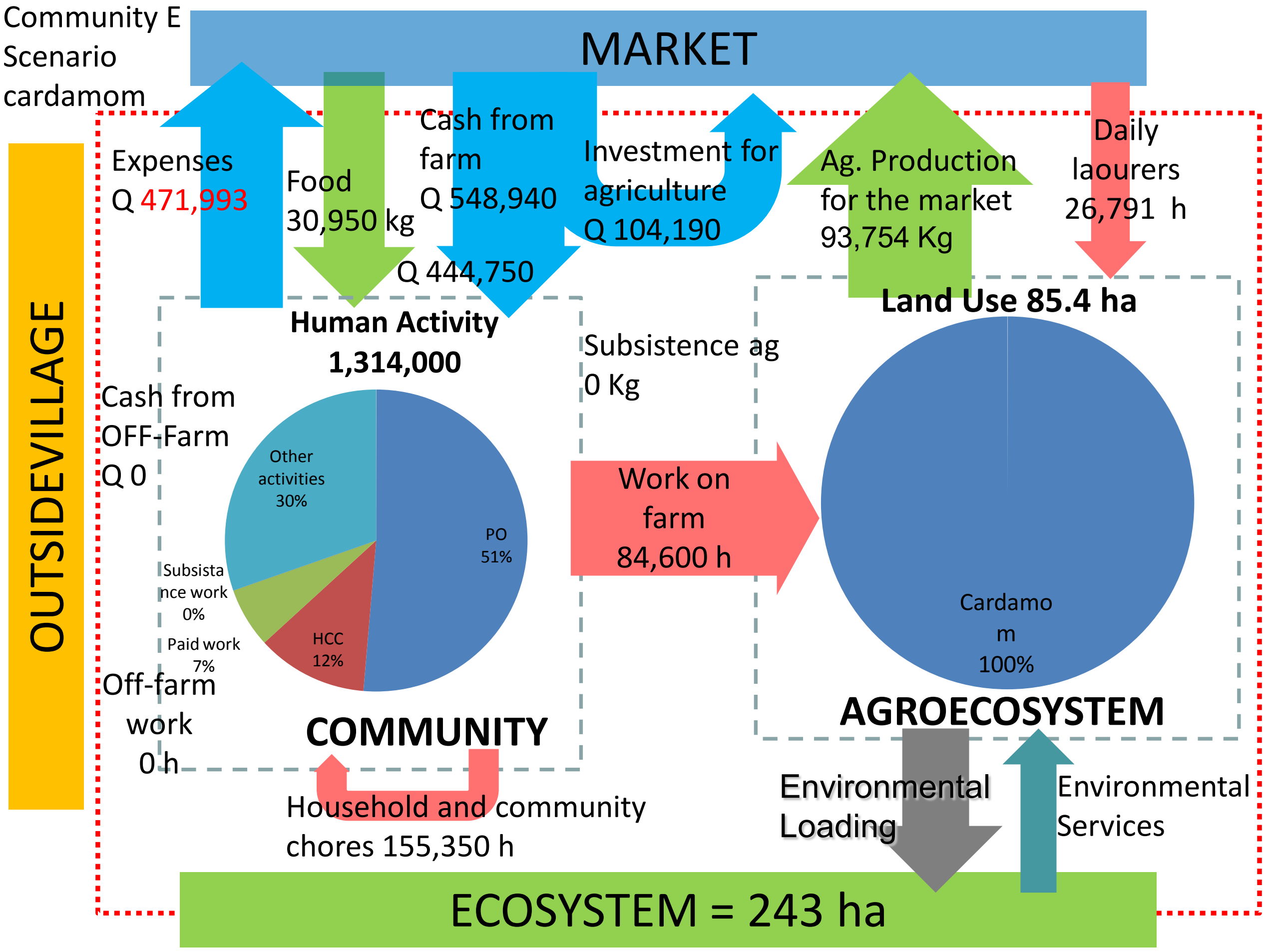

Figure 29. Metabolic profile of community E in the cardamom scenario.

The results show in Figure 29 that community E has enough land suitable for the cardamom expansion until the point where it surpasses the total available time for working in the system (84,600 h), so human activity acts as the limiting factor for the cardamom expansion in community E. When comparing Figure 27 and Figure 29 of community E, one can see that the total land use for agriculture increases 74%. This scenario implies for community E a radical shift in their working time, if they wanted to use all the suitable land for cardamom, they would have to spend 111,391 hours only for this crop, so they would have to stop cultivating all their other crops, including the commercial ones such as the rubber trees, and the subsistence crops that were ensuring their food intake independently from the markets. However, assuming in this “extreme” scenario that the population would go for the total possible expansion of cardamom in their lands (85.4 ha),they would have to “import” working time into the system, hiring daily labourers to work in their cardamom lands. The investment of money in agriculture also increases a lot due to the hiring of workers, but the community would still get some more surplus from the agricultural production than before. It must be taken into account that, in economic terms, this scenario induces community E into a specialized agricultural production unit completely dependent on one single crop for their livelihood. In this sense, it can be observed that the community would have to buy from outside 100% of the agricultural production that they had before when they were self-sufficient. The community members would increase 3.5 times their agricultural output, thus increasing largely their cash from farm (although the expenses also raise a lot). This goes in parallel with a total monetary input increase of 2.5 times. However, when applying the Guatemalan average price to the food they would need to buy, namely the maize and beans that they have stopped producing in this scenario (30,950 kg), it turns out that they would have to spend all the increased income from cardamom to buy the required food at that price. Moreover, they would not be able to get enough cash income to purchase everything they had before, so this scenario shows a clear constraint for this as an alternative in community E. Finally, the landscape changes radically, as the cardamom becomes the only crop in their lands. Although the total human colonized land increases in this scenario, all the plots would be located in a very specific area of their territory, with the remaining of the territory (65%) without any agricultural use and quickly covered by the tropical rainforest.

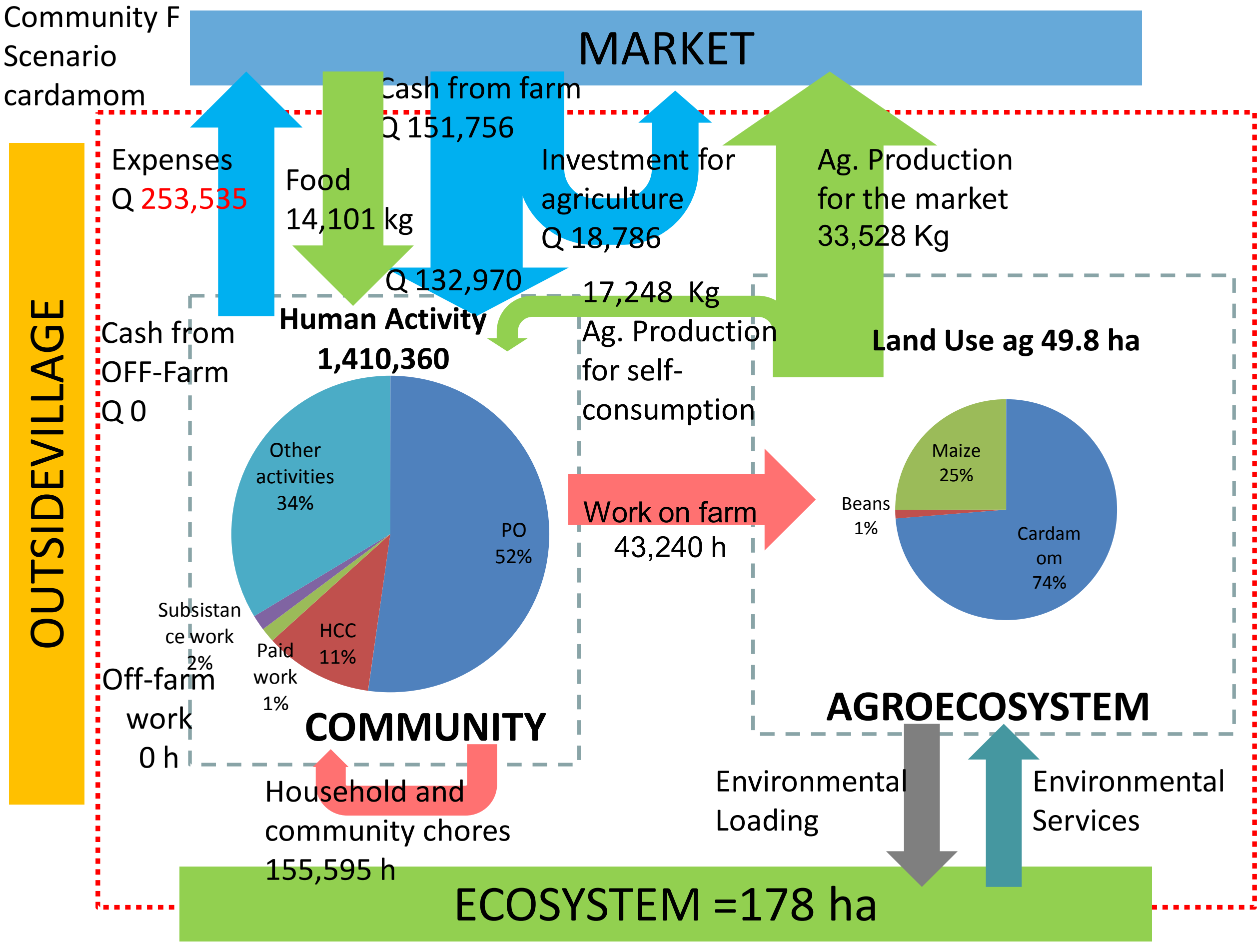

Figure 30. Metabolic profile of community F in the cardamom scenario.

For community F, although the changes induced by the cardamom scenario in their land use and human activity are not so radical, it shows in a similar final outcome of lack of income for their expenditure needs. When using all the suitable land for growing cardamom, they still have some available working time left. Then, it is assumed they would keep some of their subsistence maize and beans, although they would stop any other economic activity for cash income, such as the cattle rearing and working outside the village, since cardamom has the highest Economic Labour Productivity (ELP), i.e. the highest rate of income per hour of work, thus being the most profitable economic activity. We can see when comparing Figure 28 and Figure 30 of community F that the type of human activity allocation remains unaltered. Without the pastures for cattle rearing, the colonized land for agriculture would decrease 54%, although the total cropped land would increase a bit. The agricultural production for selling in the markets almost doubles, but the production for subsistence also decreases in a similar proportion. Comparing this situation with the same scenario in community E, community F would have to buy only half of their food that they were producing on their own before. However, the results show again that they would not gain enough cash to pay for all the food they stop producing by themselves. So, it could be said that even though the land use constrained more the expansion of the cardamom than in community E and they continued growing some crops for subsistence, the final outcome clashes with the constrain to purchase the food they stopped cultivating.

It must be remembered that the previous estimations cannot be used for advising policy given the level of reliability of the data in which they are based. However, it is possible to observe using this approach how the interactions of the different dimensions show the different trade-offs due to particular geographical arrangements of the systems, even though the results clash with the same type of constraint (i.e. lack of income to purchase the food). When exploring the option to stop undertaking some activities (i.e. subsistence agriculture), we might be confronting a constraint that cannot be simply bypassed, possibly making not viable the application of this alternative. However, this is also an important lesson that I would like to bring out from this case study: using this approach it becomes very evident whether the scenarios might be clashing with external (biophysical) or internal (socioeconomic or cultural) constraints of the system.

Daily labourers in the agro-industries

The results of this second simulation show that the extra time spent for commuting when working as labourers in the companies of the valley due to the longer walking distance was not trivial. The labourers from communities E and F spend respectively 28% and 36% more time along the year in total with this kind of job than the control community B (Mingorría et al., 2014) located in the valley used for comparison, but of course there would be no differences in wage. That means the final ELP for this activity (considering the working time plus the extra commuting time) is just about ¾ of the same activity for the current labourers of these companies, due to the spatial differences calculated in this scenario.

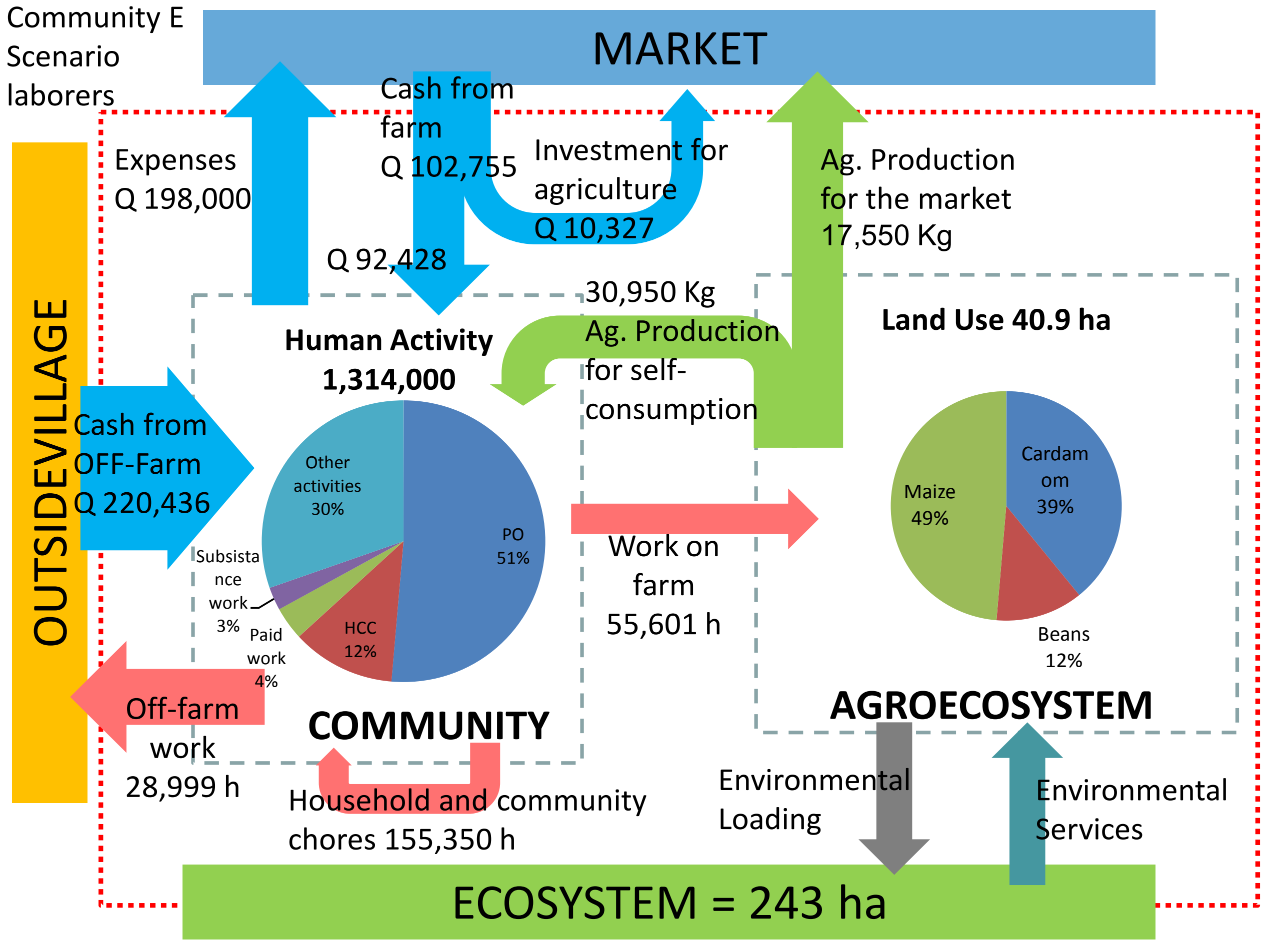

Figure 31. Metabolic profile of community E in the daily labourers' scenario.

As seen in Figure 31 of community E, when all the males below 30 years are working as daily labourers, using the last assumption mentioned in section 5.3.1, apparently there is still enough time in the remaining working force to maintain the same level of subsistence agriculture, so they do not require buying food from the market. There would even be some time left for keeping some cash crops. In this case it was assumed that they would use the remains of the time previously allocated to agricultural work to maintain some production of cardamom since it is the crop with the highest ELP. As the wage of daily labourers is very high compared to all the rest of the economic activities previously considered, and the remainder of the community still sells some agricultural products, in total they would apparently increase their gross monetary input compared to the current situation. We can see that the total use of agricultural land shrinks a bit because rubber is no longer cultivated and there is less time available to cultivate cardamom. However, notwithstanding the big increase in work outside the community, we see in Figure 31 that the paid work time does not change significantly in comparison with the overall distribution of human activity, because it is compensated in part by the reduction in time dedicated to cash crops. The reason why the scenario does not seem to change dramatically the current metabolic performance could be attributed to the few members per household (0.91 of 6 members) that could work as daily labourers. But as mentioned before, these particular results must not be taken into account as they require including more qualitative information such as preferences for the time allocation to try to better estimate the consequences of scenarios (Mingorría et al., 2014).

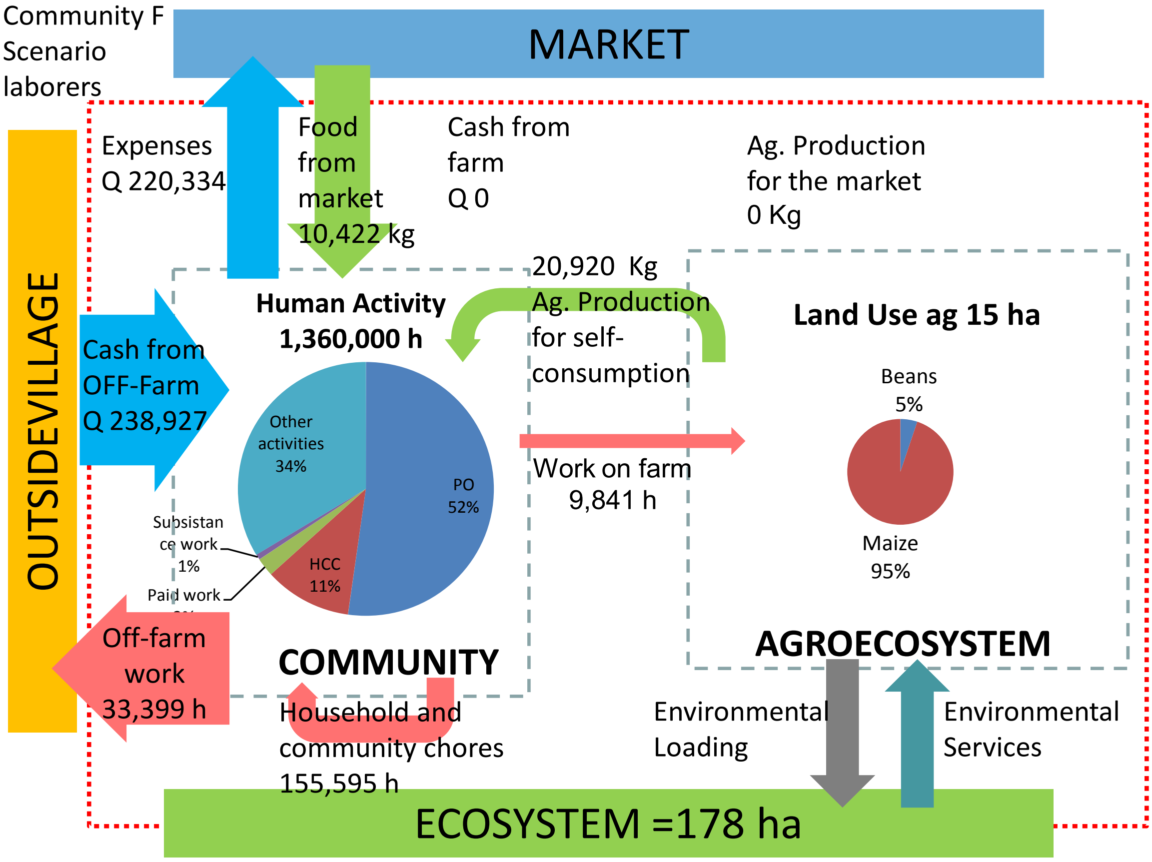

Figure 32. Metabolic profile of community F in the daily labourers' scenario.

In Figure 32 we can see how the results of the scenario for community F are quite different because when all the young males are working outside, there is no time left for any other paid work activity. The little time left for agriculture is assumed to be allocated to some subsistence agriculture. This however does not prevent them from buying some food from the market, but the big increment of cash income from the daily labourers would supposedly compensate this. What we can clearly see in Figure 32 is that the total land use for agriculture shrinks dramatically, as the community would stop the cattle rearing, the cardamom, and a significant part (37%) of the maize and beans cultivation.

There are some possible constraints not considered in these scenarios that in practice might make them difficult to be carried out, such as not enough demand of workers by the companies in the region, or other obstacles observed in practice related to cultural and political factors that might prevent people from the selected communities from working as daily labourers in the companies. However, my claim is that these scenarios are just virtual simulations whose goal is to illustrate with an empirical example how the MuSIASEM approach together with some GIS tools is capable of offering a robust method to quickly identify and check the main trade-offs and possible constraints for alternative paths for development in rural systems.

5.4 Conclusions

The main message of this chapter was to demonstrate the usefulness of the methodology presented to carry out similar studies in other rural systems, and to show some practical tools to generate our own primary geographic data at local scales. We saw examples of case studies at the village level where I applied the MuSIASEM approach to simulate scenarios with the support of GIS tools. The first scenario was about trying to use the local production factors (human activity and land use) within the limits of the system to illustrate an agricultural alternative taking into account geographical constraints and features. The second scenario was about exporting the labour force outside the boundaries of our local scale systems to check the internal consequences. It is possible to observe that also in this case the geographical features were not trivial as they affect the performance of the ELP and thus the overall results.

From this chapter it is possible to acknowledge that any kind of extreme scenarios, such as the ones employed, will change dramatically the identity of the systems, therefore, any proposed alternative should be checked seriously by the affected actors because the effects on other dimensions might not be desirable for them. By applying this methodology with the tools described along the text, one could quantify the possible changes in the identity of systems looking at the possible effects on the funds–because funds tell us *what the system is*–, apart from providing an integrated point of view of the trade-offs of possible scenarios for discussing the proposed development paths.

The presented scenarios are only reliable if there is a serious estimation on some qualitative factors not considered here such as the market demand and possible constrains for selling the products and getting the supposed benefits. This case study just illustrates how these tools work when taking into account a limited amount of dimensions, focusing in this case only on biophysical and economic factors. In fact, in this particular context the political background is by far the main problem that blocks possible alternatives. Furthermore, to build accountable scenarios (these ones were merely experimental ones), we must go through participative processes with other set of tools to gather the opinion the affected stakeholders, who in fact are the ultimate motivation for any study.

A potential further step would be to complement the analysis with a different starting point. As seen along the chapter, this study is ultimately addressing just the *supply* side, due to the focus on the production alternatives for the system (i.e. new forms of activities for the production of the livelihood for the communities). Looking at the other part of the system, i.e. the demand side, and trying to assess alternatives for the consumption part, would necessarily require adding some other elements to the study that we have not mentioned along this chapter. If we intend to go further in this analysis and complement it with alternatives on the consumption patterns (i.e. the other way around, from demand to supply), then we could start for instance by adding a study of the food flow, where we would go in detail through the nutritional mix requirement of the population diet, and then assess the processes to arrive to possible alternatives of crop mix and activities that would respond to these population demands. This further stage is explored in the next case study along Chapter 6.