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DYNAMIC COUPLING OF MULTISCALE LAND CHANGE MODELS

Evaldinolia Gilbertoni Moreira

Doctorate Thesis at Graduate Course in Applied Computation, advised by Dr. Gilberto Câmara and Dra. Ana Paula Dutra de Aguiar, approved in _______, 2009.

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FOLHA DE APROVAÇÃO

“O cálculo e o rico corpo de análise matemática à qual ele deu origem tornaram a ciência moderna possível; mas foi o algoritmo que tornou o mundo moderno possível”.

DAVID BERLINSKI

“Todo animal deixa vestígios do que ele foi. Só o homem deixa vestígios do que ele criou [...] O homem não é uma figura na paisagem. Ele é um modelador da paisagem.”

JACOB BRONOWSK
The ascent of man 1973

A meus muito queridos filhos,
Lorena e Antônio.

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ABSTRACT

Land changes are the result of a complex web of interactions between human and biophysical factors, which act over a wide range of temporal and spatial scales. Understanding processes of change from local to global scale and their impacts on the coupled human-environmental system is a main scientific challenge. No single model or scale can fully capture suh interactions and processes of land change. This thesis presents a methodology for building multiscale, multi-locality land change models that include top-down and bottom-up relations. At first, we conceptualize two types of spatial relations among geographic objects at different scales. To handle the interaction of nested spatial objects at different scales, we propose hierarchical relations. To handle the interaction between networks and spatial objects, we propose action-at-a-distance relations. Then in a second step, we propose a modular software organization to build multiscale land change models. We consider the case when single-scale models, using different modeling approaches, are independently built and then dynamically coupled. We introduce the concepts of Model Couplers to define the bi-directional flow of information between the scales. We implement these concepts using the TerraME modeling environment. As a proof of concept, we present a hierarchical two-scale example for the Brazilian Amazon. The conclusion of this work points out that combining hierarchical and network-based spatial relations provides a comprehensive conceptual framework to include top-down and bottom-up interactions and feedbacks in multi-scale land-change models. The modular software organization and concept of Model Couplers are general enough to be used for other types of applications, and to

contribute to the creation of Integrated Environmental Models from local to global scales.

ACOPLAMENTO DINÂMICO DE MODELOS MULTIESCALA DE MUDANÇAS TERRESTRES

RESUMO

Mudanças terrestres são resultado de uma complexa rede de interações entre fatores humanos e biofísicos, que atuam em diferentes escalas temporais e espaciais. Entender estes processos de mudanças terrestres de escalas locais a globais e seus impactos no sistema acoplado homem-natureza é um enorme desafio científico. Modelos em uma única escala podem não ser capazes capturar tais interações e processos de mudança. Esta tese apresenta uma metodologia para a construção de modelos de mudanças terrestre multiescala e multilocalidade, incluindo interações *top-down* e *bottom-up*. Numa primeira etapa, conceituamos dois tipos de relações espaciais entre objetos geográficos em diferentes escalas. Relações hierárquicas são propostas para tratar das interações entre objetos espacialmente aninhados, e relações de "ação a distância" são propostas para tratar de interações entre redes e objetos espaciais. Então, numa segunda etapa, apresentamos uma proposta de organização modular do software dos modelos. Consideramos neste trabalho o caso onde modelos para cada escala são independentemente construídos, possivelmente com abordagens distintas, e então dinamicamente acoplados. Conceitos de acopladores de modelos são introduzidos para definir o fluxo de informação bidirecional entre escalas. Estes conceitos foram implementado no ambiente de modelagem TerraME. Como prova de conceito, apresentamos um exemplo com duas escalas hierárquicas para Amazônia Brasileira. A conclusão deste trabalho aponta que a

combinação de relações espaciais hierárquicas com relações baseadas em redes provê um arcabouço conceitual abrangente para lidar com interações top-down e bottom-up em modelos multiescala de mudanças terrestres. A organização modular e o conceito de acopladores propostos são bastante genéricos para serem usados com outros tipos de aplicação, e com isso contribuir para criação de Modelos Ambientais Integrados, considerando escalas locais a globais.

SUMMARY

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LIST OF ABBREVIATIONS

INPE	Brazilian National Institute of Space Research
LULCC	Land-use and Land-cover change
TerraME	Terra Modeling Environment
CLUE	Conversion of Land Use and its Effects
CLUE-S	Conversion of Land Use and its Effects at Small regional extent
GEOMOD	GIS-based model
CMA-CGM	Compagnie Maritime d'Affrètement - Compagnie Générale Maritime
IIRSA	South-American Regional Infra-structure Integration Initiative
GPM	Generalized Proximity Matrix
LUCC	Land Use and Land Cover Change

1 INTRODUCTION

1.1 Background

Land change, also known as land-use and land-cover change (LULCC) is a general term for the alteration and conversion of the Earth's terrestrial surface. Land cover has been defined by the attributes of the Earth's land surface and immediate subsurface, including biota, soil, topography, surface and groundwater, and human structures. Land use has been defined as the purpose for which humans exploit the land cover. Land use and cover change refers both to conversion between classes (e.g., deforestation or desertification processes), and to alterations (such as agricultural intensification, and forest degradation) (LAMBIN *et al.*, 2006).

Land change results from a complex and interactive system, where human action and environmental feedbacks are connected (TURNER *et al.*, 1995). The study of these interactions in land change has become a major topic of research, due to local and global impacts, which vary from extinction of plants and animals to changes in the Earth's climate. An important area for land change studies is the process of deforestation in the Brazilian Amazonia, as deforestation makes Brazil the world's 4th largest emitter of greenhouse gases. Local alteration of land use and land cover can have global consequences, requiring local and regional solutions to global problems and the cooperation of the world's policymakers, land managers, and other stakeholders in land management at local, regional and global scales.

The methods of land change science include remote sensing and geospatial analysis and modeling, together with the interdisciplinary assortment of natural and social scientific methods needed to investigate the causes and consequences of land change across a range of spatial and temporal scales.

Modelling land change involves the use of representations of interactions within the land use system to explore its dynamics and possible developments (VERBURG *et al.*, 2008). Models can also be used to project the impact of policy changes on the current land use trajectory (PIJANOWSKIA *et al.*, 2002). Land change is the result of a complex web of interaction between human and biophysical factors, which act over a wide range of temporal and spatial scales.

In this work, we will concentrate on the development of land change models which are spatially explicit. These models use a spatial partition of the landscape (usually a cellular space) and assign many attributes for each spatial location. These attributes may include the current land use and land cover, the potential for change, physical data such as topography and climatology, and socioeconomic data such as population and distance to markets. One of the advantages of spatially explicit models is that they allow the modeler to visualize their outcomes and thus better interpret the impacts of public polices.

There is a great variety of methods for land change modelling in literature, with different objectives, techniques, theoretical basis and modelling traditions. (BRIASSOULIS, 2000) presents an extensive review of land change theories and modelling approaches. In general, there are two main approaches for designing spatial land change models: top-down and bottom-up. Top-down models originate from landscape ecology and are based on remote sensing and census data. In this approach the process of land change is made in three main steps. In the first step, the demand for change (quantity) is calculated for the study area using a non-spatial economic model or a trend analysis. In the second step, the land change suitability maps areas calculated by statistical or mathematical model. In the last step, the demand is allocated through a spatially-explicit model based on the land change suitability map. On the other hand, Bottom-up models describe explicitly the actors of land change as heterogeneous entities in time and space. This approach uses agent-based modelling theory, which consists of autonomous entities (agents), an environment where the agents interact and rules that define the relations between agents and their environment (PARKER *et al.*, 2002).

1.2 Concepts in Land Change Science

1.2.1 Driving factors

Land change models need to capture the driving factors, which are the most important forces governing the future trajectory of the land system. Driving factors are generally subdivided into two groups: *proximate causes* and *underlying causes*. Proximate causes are the activities and actions that directly affect land use, e.g. wood extraction or road building. Underlying causes are the “fundamental forces” that underpin the proximate causes, including demographic, economic, technological, institutional and cultural factors (GEIST and LAMBIN, 2001). Examples include soil suitability, population density, rainfall and accessibility. Driving factors can also be subdivided into biophysical and socioeconomic drivers.

Since different systems affect the land system, developing land change models requires combining expertise from different disciplines, as shown in Figure 1.1. Integrating these different perspectives is a challenge, since the driving factors are scale dependent. For example, in a local scale, such factors may include local law enforcement and the presence of ecologically valuable areas. At a regional scale, they may include distance to markets and population density. The understanding of biophysical and human factors and their interactions is a major interest of global change researches, as described in (MORAN *et al.*, 2005): "*An improved understanding of how human actions affect natural processes of the terrestrial biosphere will help to assess the risks faced by societies and their environments, and the ways in which societies deal with these risks*".

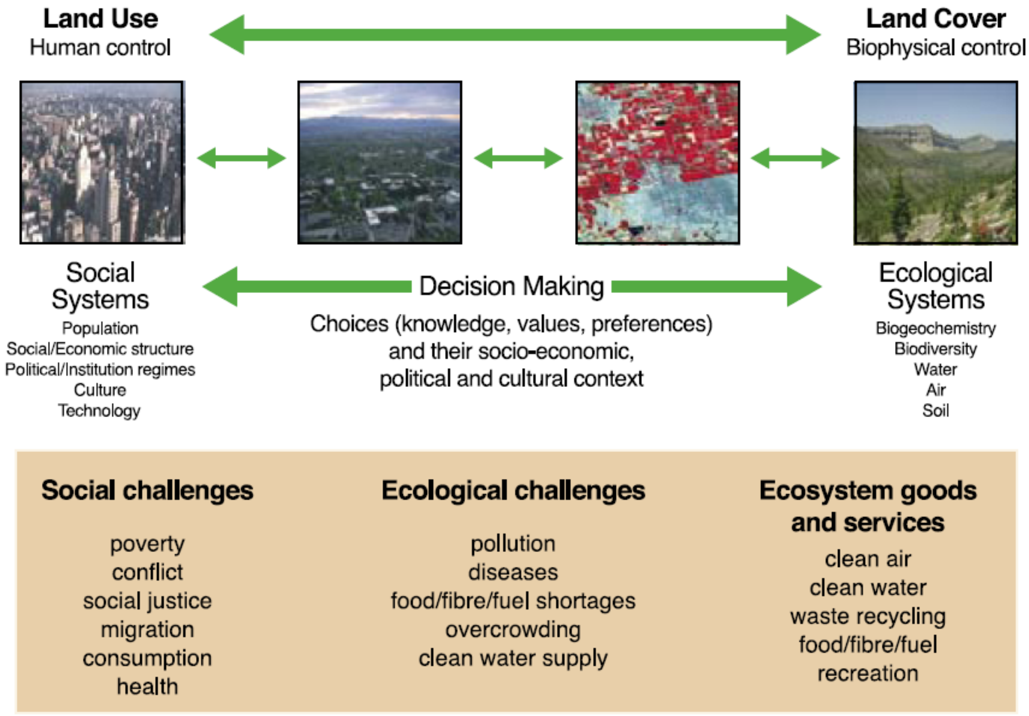

Figure 1.1 - The continuum of states resulting from the interactions between societal and natural dynamics.

Source: (MORAN *et al.*, 1995).

These interactions between social and ecological systems cause other important effects, denominated feedbacks, as discussed in the next section.

1.2.2 Feedbacks

Land use change is often non linear and complex feedbacks often play an important role. Feedbacks are seen as an important feature of complex systems such as land use systems and a key characteristic of the complexity of such systems (VERBURG *et al.*, 2004). Any land change model considers at least one feedback type, which is the dependence of land change at time *t* on land use at time *t+1* (VERBURG *et al.*, 2006). Such dependence on current and historic land change is essential to represent the land use pattern and is known as path-dependence. Land change also includes feedbacks between people and ecosystems, which may be induced by actual or perceived land system change, or through demographic and economic forces (MORAN *et al.*, 1995).

Several authors discuss the importance of feedback mechanisms in modeling land change and how modeling techniques must evolve to accommodate such mechanisms, such as (MORAN *et al.*, 1995), and Verburg (2006) who consider three different types of feedbacks:

- *Feedbacks between the driving factors and the effects of land use change,* most models assume one-directional process between driving factors and impacts. However, the impacts of land use change may affect future land use change as a consequence of feedbacks. Examples include soil degradation that affects future land use if soil suitability is a driving factor of land change.

- *Feedbacks between local and regional processes of land use change,* some land changes are directly determined by local processes such as the spontaneous regeneration of natural vegetation. However, feedbacks from the aggregated level (supply demand) can affect local decisions.

- *Feedbacks between agents of land use change and the spatial units of the environment,* decisions of the agents are influenced by spatial and social organization of these agents (PARKER *et al.*, 2003). For example, the decision of farm production increase can be influenced by the decision of other farmers who share the same social or organizational group.

1.2.3 Scale and Level

Scale and level of analysis are important concepts in land change. Gibson (2000) presents a survey about scale issues in different disciplines, where he makes a clear distinction between *scale* and *level.* Scale is a general concept applicable to spatial, temporal, or analytical dimensions used to measure and study any phenomenon. Level refers to the units of analysis that are located at the same position on a scale. All scales have extent and resolution, where *extent* refers to the magnitude of a dimension used for measuring a phenomenon and *resolution* refers to the partitioning or quantization used in such measurement. At different scales, different processes can have dominant influence on the land use system (GIBSON *et al.*, 2000).

Differences in scientific disciplines, tradition and research questions have resulted in differences in the scales and levels that are addressed by the different land-use models (VERBURG *et al.*, 2004). Social sciences researchers have a long tradition of studying the individual behavior at a micro-level. Geographers and ecologists have focused on land change at a macro-scale in order to identify social factors connected to macro-scale patterns. Recent models attempt to integrate different scales in order to better understand ecological and social systems (VERBURG *et al.*, 2008).

1.2.4 Multi-scale modeling

At different scales, different processes can have a predominant influence on the land use system (GIBSON *et al.*, 2000). Different factors have a dominant influence on the land use system at different scales of analysis: at a micro scale, land use patterns may be determined by household structure and local biophysical constraints. At a regional level the distances to markets and regional climate variations may determine land use pattern. Regional dynamics impact on and are influenced by local dynamics through top-down and bottom-up interactions (VERBURG *et al.*, 2004). Understanding processes of change from the local to the global scale and their impacts on the coupled human-environmental system is a major scientific challenge (MORAN *et al.*, 2005).

Land change processes are also intimately linked to processes of globalization. Globalization is the growing and accelerated interconnectedness of the world in an economic, political, social and cultural sense. It has increasingly separated places of consumption from places of production, in such a way that land systems cannot be adequately understood without considering their linkages to decisions and structures made elsewhere. In this sense, understanding the role of networks is essential to the understanding of land-use structure (VERBURG *et al.*, 2004). Such networks can be physical, such as infrastructure networks, and logical ones, such as market chains, linking a certain location to distant consumption or influential sites.

According to Becker (2005): “it is impossible today, more than ever, to understand what happens in one place without considering the interests and conflicting actions at different geographical scales”.

Another important aspect is intraregional interactions and feedbacks. Land change processes may have different impacts on different localities of a given region. Restrictions and opportunities imposed by biophysical and socio-economic conditions, such as local policies and accessibility, may induce distinct land use trajectories. These local land use trajectories may, in turn, indirectly affect other localities, as local processes interact with higher-level processes. Such intraregional interactions result from processes that act on different hierarchical levels. At a global scale, the national and international commodities market (beef, grains and timber) imposes demands for land change. At a local scale, different actors operate in their specific socio-economic and biophysical contexts, creating different land-use trajectories.

Multi-scale land change models have been developed to address these issues. Some multi-scale modelling approaches combine different spatial models at different scales, mostly simulating top-down influences (VERBURG *et al.*, 2008). Bottom-up interactions and scaling issues started to be addressed by multi-agent systems (PARKER *et al.*, 2002), in which interactions among individuals can simulate the emergent properties of the systems. Most current land use change modelling embody the notion of space as a set of absolute locations in a Cartesian coordinate system, thus failing to incorporate spatial relations dependent on topological connections and network fluxes. Current land change models often deal with spatial interactions over large regions using (transport) network analysis to compute driving factors representing travel time and distance to ports, markets, etc. In spite of the progress in multi-scale modelling and spatial interaction analysis, there is still a need for approaches and techniques to deal adequately with scaling interaction issues (VERBURG *et al.*, 2006).

1.3 Thesis Objective

The above review indicates the need for multiscale, multi-locality models to help understand land change processes. These models need to allow interactions among and across scales, as well as to consider the effects of globalization on local land change processes. Given these scientific challenges, this thesis addresses the following question:

> "*How can we design multiscale models that handle interactions among nested spatial objects (e.g., states and municipalities) and also interactions between networks and spatial objects (e.g., wood market chains and municipalities in Central Amazonia)?"*

Interactions among nested spatial objects include, for example, how land tenure policies established by the federal government relate to land use practices by local agents in different municipalities. Interactions between networks and spatial objects include, for example, how international wood markets influence local deforestation agents.

To answer this question and provide a conceptual basis for the dynamic linking of multi-scale models, this thesis investigates two research lines:

- The conceptualization of two types of spatial relations among geographic objects at different scales. To handle the interaction of nested spatial objects at different scales, we propose hierarchical relations. To handle the interaction between networks and spatial objects, we propose action-at-a-distance relations.

- The proposal of a methodology for dynamic coupling of land change models at different spatial and temporal scales, introducing the concepts of Spatial, and Analytical Model Couplers.

We implement these concepts using the TerraME modeling environment. As proof of concept, we present a hierarchical two-scale example for the Brazilian Amazon. We analyze alternative patterns of deforestation in a given site under different regional scenarios, and then test bottom-up feedback mechanisms from local decisions to regional distribution of deforestation rates.

1.4 Thesis layout

- Chapter 2 discusses the conceptual definition of these multi-scale spatial relations, and discusses an implementation of these concepts.

- Chapter 3 presents the methodology for dynamic coupling multiscale models. We show the proposed software structure to build multiscale and multiapproach computational models.

- Chapter 4 presents an illustrative study case and results of the multiscale model application in the Brazilian Amazonia. We show a real world case study for modelling deforestation in the Brazilian Amazon, using two scales. At a regional scale, we have a deforestation model covering all Brazilian Amazonia at a 25 x 25 km^2 resolution. At a local scale, we have a deforestation model in

São Felix do Xingu, Pará State, a hot spot of deforestation in Central Amazonia. We show how the explicit definition of such hierarchical and action at a distance spatial relations allow the representation of top-down and bottom-up linkages' in multi-scale models.

- Chapter 5 presents the conclusions of this thesis, recommendations and suggestions for future work.

2 SPATIAL RELATIONS ACROSS SCALES IN LAND CHANGE MODELS[1]

In this section, we discuss the incorporation of hierarchical and network spatial relations in multi-scale land change models. Most land use change modelling embodies the notion of space as a set of absolute locations in a Cartesian coordinate system, thus failing to incorporate spatial relations dependent on topological connections and network fluxes. Current land change models often deal with spatial interactions over large regions using (transport) network analysis to compute driving factors representing travel time and distance to ports, markets, etc. In spite of the progress in multi-scale modelling and spatial interaction analysis, there is still a need for approaches and techniques to deal adequately with scaling interaction issues [Verburg, Kok, Pontius Jr et al. 2006]. Understanding the interactions among and across scales, and the effects of globalization on local land-change processes, will remain the research frontier of land use/land cover for the next decade.
Our goal is to conceptualize the spatial relations among pairs of spatial objects at different scales to allow a broad representation of top-down and bottom-up interactions in land change models.

We discuss two types of spatial relations: hierarchical and relative space relations. For simplicity, we refer to the representation of spatial objects as Entities. Examples of representation of such objects include: (a) area

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[1] Based on: MOREIRA, E. G.; AGUIAR, A. P.; COSTA, S. S.; CÂMARA, G. Spatial relations across scales in land change models. In: BRAZILIAN SYMPOSIUM IN GEOINFORMATICS - GEOINFO 2008, 10. Rio de Janeiro, RJ, Brasil. Proceedings... São José dos Campos: INPE, 2008a.

regions whose boundaries are closed polygons; (b) cellular automata organized as sets of cells, whose boundaries are the edges of each cell; (c) point locations in two-dimensional space (Figure 2.1)..

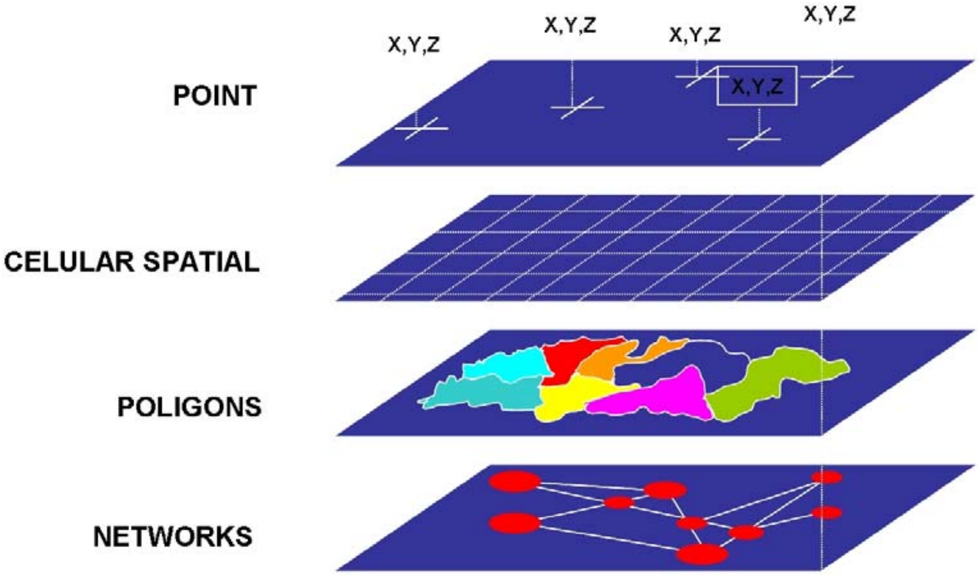
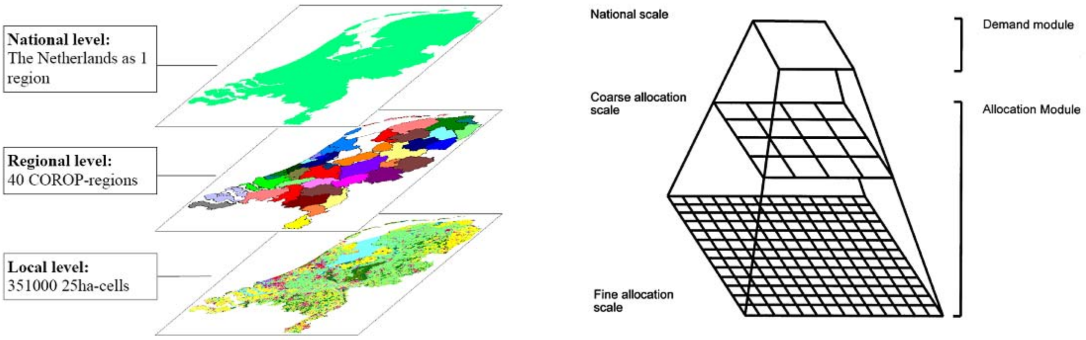


Figure 2.1 - Representation of spatial objects.

Several existing land change models are organized in top-down manner, in which a demand for change is spatially allocated according to cell suitability. This includes the CLUE and CLUE-S, Dinamica (SOARES-FILHO *et al.*, 2002) GEOMOD (PONTIUS *et al.*, 2001), and Environmental Modeler (ENGELEN *et al.*, 2003). Such models use *Hierarchical spatial relations*, in which nested scales are combined, as exemplified in Figure 2.2. The Environmental Modeler uses three different scales. Economic models at national and regional scales compute land requirements for different land uses, based on economic and demographic factors. These land requirements are then allocated in a regular grid using a cellular automata model at a local scale. The CLUE model framework consists of two components: a demand module, that projects the overall amount of change; and an allocation module, the spatial component that acts in two scales (a coarse and a fine resolution grid) to localize such changes, based on cell suitability.



(a) (b)

Figure 2.2 - Examples of hierarchical structures used in land change models: (a) Environmental Modeler (ENGELEN *et al.*, 2003); (b) CLUE model (VELDKAMP and FRESCO, 1996).

Entities in these cases are regular cells with different resolution at different scales, or polygons representing administrative units at different levels of organization. The spatial relations represent parenthood relations (father-son and son-father), see Figure 2.3.

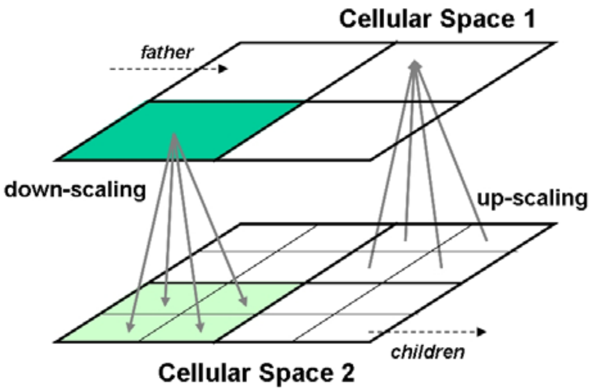


Figure 2.3 - Father-son relationship among cells at different scales.

Father-son hierarchical relations are necessary to inform lower-scale model of the context provided by higher-level models, and are the most common type of relation found in current land change models. Son-father relations allow local scale models to inform regional models (*bottom-up* interactions). Although bottom-up interactions have to some extent been included in hierarchical land change models (for example, (VERBURG *et al.*, 1999), the full integration of top-down and bottom-up scale interactions is still a research topic (VERBURG *et al.*, 2006).

Such hierarchical spatial relations embody the notion of space as a set of absolute locations in a Cartesian coordinate system. However, flows of resources, information, organizational interaction and people are essential components of space, and should be treated in land change models. Efficient representation of such flows in connection with representation of absolute space is essential to achieve a realistic perspective of spatial relations, and to inform land change models (HARVEY, 1989). These flows, which are normally represented as networks (AGUIAR *et al.*, 2003,VERBURG *et al.*, 2006,VERBURG *et al.*, 2004), link processes that act on different scales.

The global and continental market connections in Amazonia are an example of this, as Figure 2.4 illustrates. Different flows connect areas in the region to distant places of consumption, influencing the land use system in heterogeneous ways. Wood products from Brazil are mostly exported to Europe, as Figure 2.4a illustrates. However, internal market also plays an important role in the wood market. Becker (2001) estimates about 80% is sold to the Southeast of Brazil. Global markets play a determining role for other commodities too. Santarém, in Pará State, has international connections related to the international soybean markets, due to the presence of Cargill in the area. São Felix do Xingu, also in Pará, has different national and international connections related to meat market, due to the presence of global companies like Bertin. The IRSSA (South-American Regional Infrastructure Integration Initiative, (IIRSA)) integration axes (Figure 2.4b) will change the commercial connectivity of places like Roraima and Amapa, due to the Guiana-Venezuela-Suriname planned axe (Guiana Shield Hub).

Large container transport companies, such as CMA-CGM (French container transportation and shipping company), have already announced they will use the Madeira River corridor to export wood, cotton, and meat. The Madeira corridor is also part of the Brazilian Infrastructure Plans for the Amazonia, linking Porto Velho, Rondonia State, to Manaus, in Amazonas State. Incorporating such heterogeneous connections in land change models is essential to improve our understanding of their impacts on the land use system, and to envision the future scenarios for the region.

Combining such hierarchical and network-based relations is essential to provide the necessary conceptual support to multi-scale land change models. Sections 2.2 and 2.3 present a conceptualization of these two types of relations. Our implementation of such concepts is briefly described in Section 2.4.

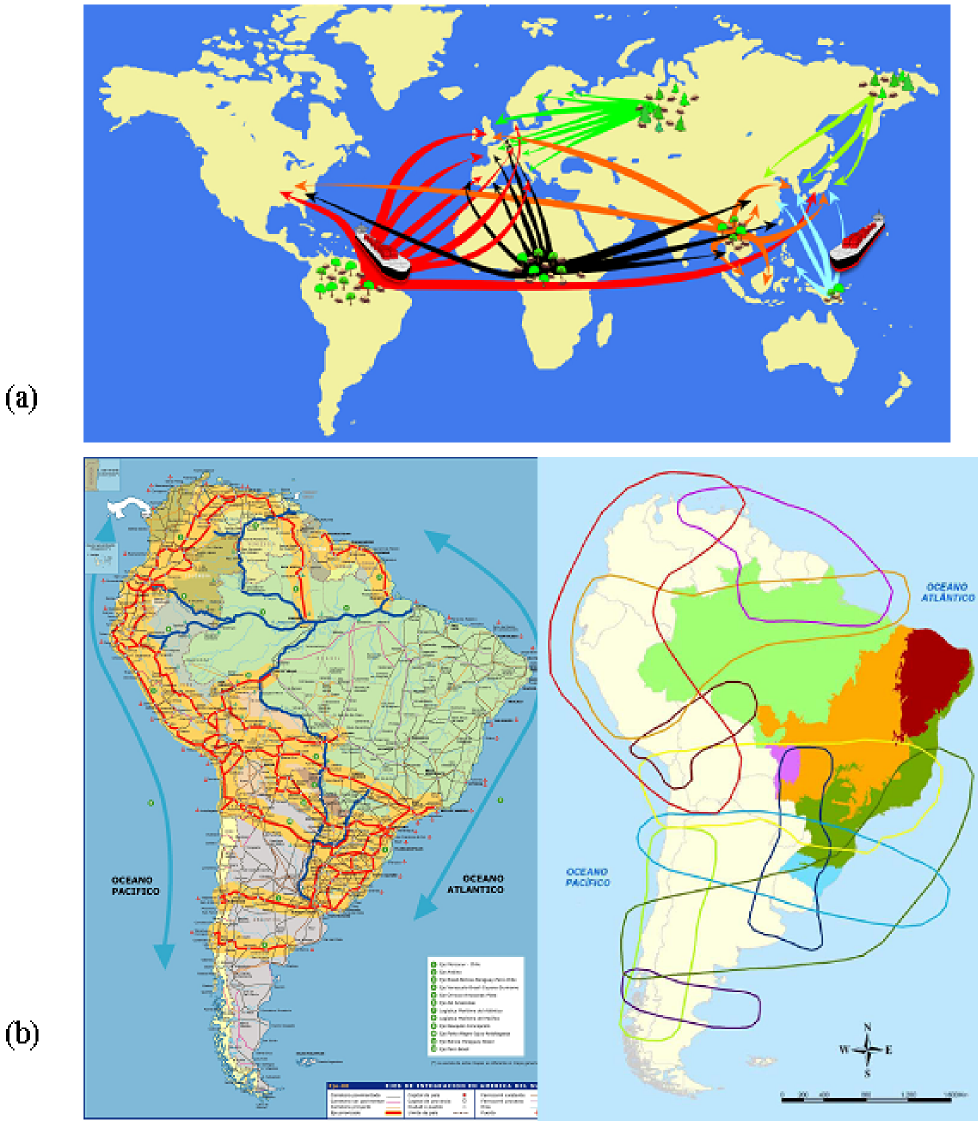


Figure 2.4 - Examples of links to global and continental markets: (a) International flow of wood from Amazonia;

source: Greenpeace, www.greenpeace.org

(b) IIRSA infra-structure integration axes in South America, facilitating the commercial flow from different areas.

2.1 Hierarchical relations

We propose to represent a hierarchical relation as a directed graph *G* composed of a set of nodes *N1* and *N2*, representing *Entities* at Scale1 and Scale2; and a set of arcs *A* linking nodes *N1* to *N2*.

The arcs *A* can have attributes or not, depending on the strategy used to construct them. When *Entities* at both scales have an area representation (polygons or regular cells), we propose three alternative strategies, illustrated in Figure 2.5. They are based on topological relations as described below.

- *Simple*: when spatial resolutions are perfectly matched, simple “within” or “coveredby” or “equals” spatial operator can define the parenthood relation among scales.

- *ChooseOne*: for area representations, when hierarchical spatial resolutions do not match, this strategy chooses the upper scale unit cells with larger percentage of intersection as the father and the “intersection” spatial operator can define the relation.

- *KeepInBoth*: also only for area representations, when hierarchical spatial resolutions do not match, this strategy keeps all intersected upper unit cells as fathers and the “intersection” spatial operator can define the relation. The percentage of each intersection is stored as an attribute of the Arc A.

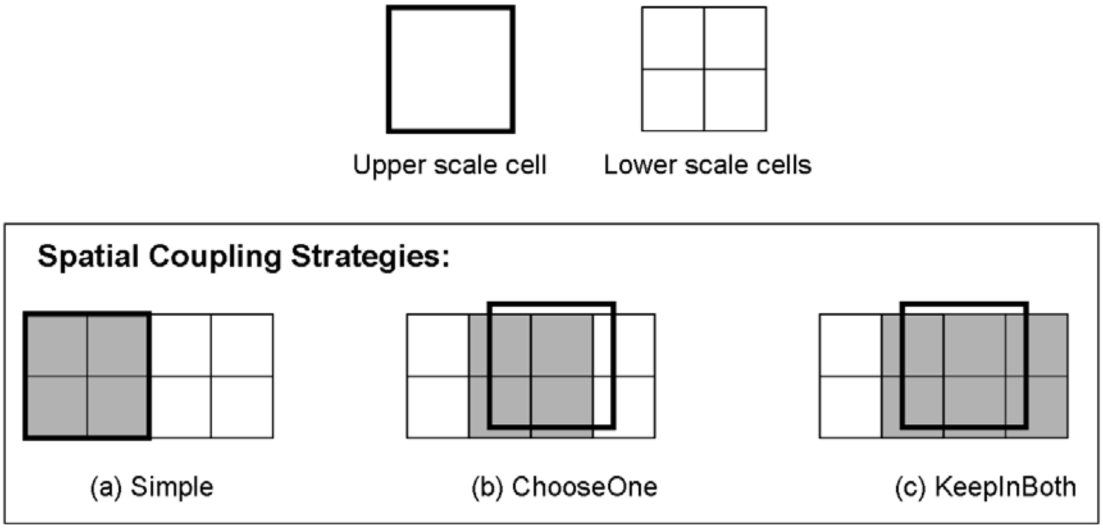


Figure 2.5 - Schematic representation of strategies for spatial coupling in the case of regular cells: (a) Simple; (b) ChooseOne; (c) KeepInBoth.

Hierarchical networks can represent spatial relations of point entities at different scales, such as urban centers (State capital at the macro scale; major cities at the meso scale; villages at the local scale) (see Figure 2.6).

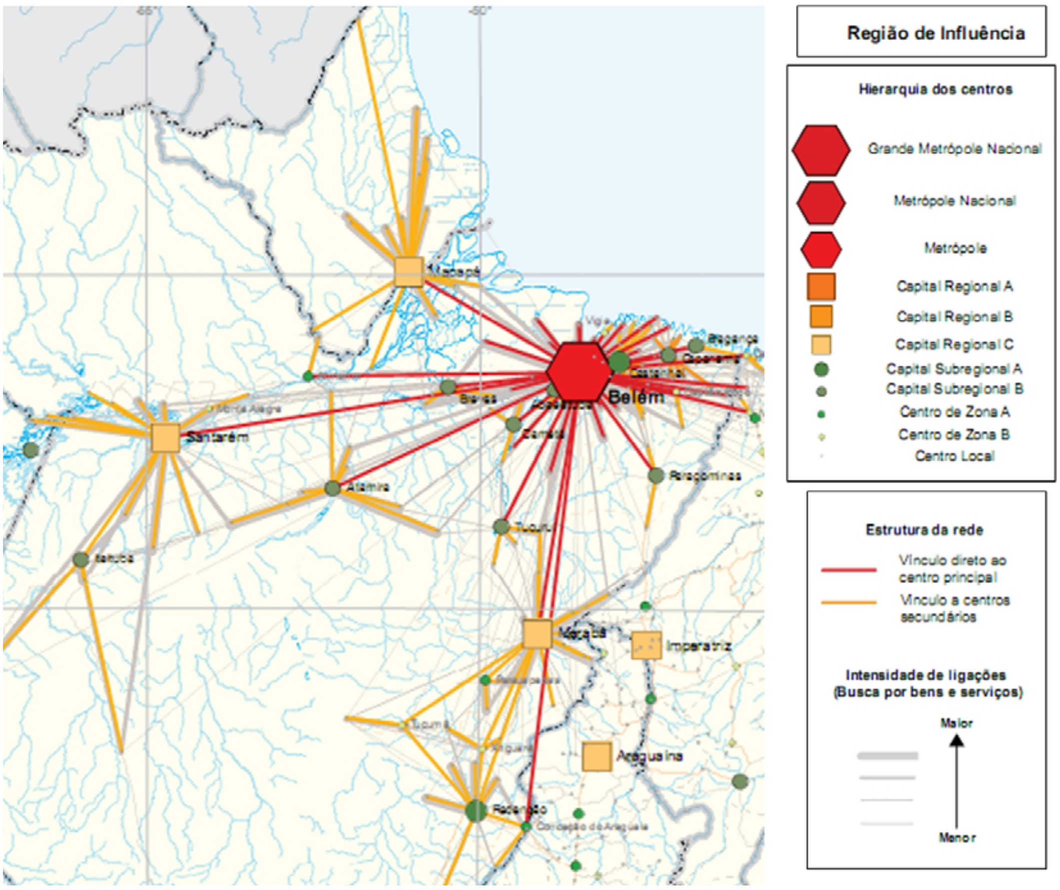


Figure 2.6 - Example of Hierarchical networks can represent spatial relations

To construct graph G in this case, manual or attribute based strategies could be envisioned (for example, administrative unit name to establish son-father relations). The attributes of the Arcs A could also be derived from geographical objects (such as percentage of population) (see Figure 2.7).

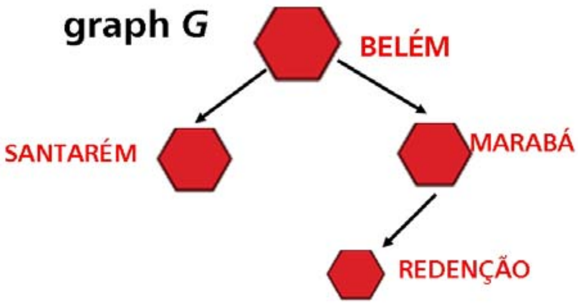


Figure 2.7 - Example of graph' Hierarchical networks can represent spatial relations.

2.2 Network-based relations

We also represent *network-based relations* as a directed graph *G* composed of a set of nodes *E1* and *E2*, representing *Entities* at Scale1 and Scale2, and a set of arcs *A* linking nodes *E1* to/from *E2*. The representation is the same for hierarchical relations. The difference resides in the strategies to construct *G*. A network *T* is required to represent physical (roads, rivers, energy) and logical (airline routes, market chains, migration fluxes) linkages between elements *E1* and *E2*. These linkages will be established using network analysis operators.

According to characteristics of the network, specific construction strategies will decide: (a) if two nodes in *E1* and *E2* are connected; (b) the strength of this connection. The construction strategies presented here are based on the concepts introduced by (AGUIAR *et al.*, 2003) regarding the construction of a Generalized Proximity Matrix (GPM). The GPM represents absolute and relative space neighborhood relations among objects of the same type, at the same scale. A GPM is used to support spatial analysis and cellular automata dynamic models. We modify the GPM construction strategies to consider objects of different types, at different scales to support the development of multiscale land-change models. Two strategies are then proposed:

- *Multi-scale Closed-networks linkages*: to connect entities at different scales using networks in which the entrances and exits are restricted to their nodes. They encompass *logical* (such as banking networks and productive chains) and some types of *physical networks* (railroads, telecommunication networks).

- *Multi-scale Open-networks linkages*: to connect entities at different scales using networks in which any location is an entrance or an exit point. These are always *physical networks*. Transportation networks such as roads and rivers are good examples. For open networks, it is necessary to make use of the actual line coordinates that correspond to each arc in order to be able to compute the closest entrance/exit points from any arbitrary position.

The strategies can be summarized as follows:

- For each object in *O1*, compute the nearest entry point *E1* in network *T*.
- For each object in *O2*, compute the nearest entry point *E2* in network *T*.
- The existence of a linkage from *E1* to/from *E2* is computed using network analysis.

Figure 2.8 illustrates the process of constructing graph *G* to represent relative space relations. A set of parameters bounds connectivity limits according to network and case study characteristics. For instance, one can define that objects at Scale1 are not linked to the network if they are more than a 100 km away from the closest entry point. Limits can also be imposed for minimum path in the network. For instance: only objects at Scale1 not more than 10 hours away from the markets (represented at Scale2) through the infrastructure network are considered connected. Minimum path computation depends on network attributes. Different case studies can use, for example, distance or travel time (infrastructure networks), flow of people (migration networks), dollars (banking networks), and added value (production chains).

Note that when *Entities* at both scales have an area representation (polygons or regular cells), the connection is performed using the area centroid.

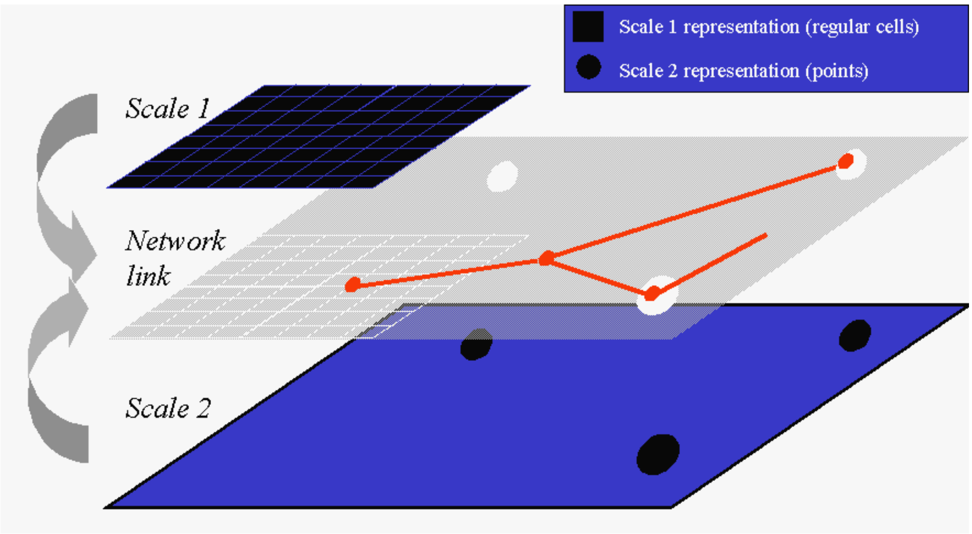


Figure 2.8 - Schematic representation of a network-based spatial relation between cell objects in Scale 1 and point objects in Scale 2.

2.3 Implementation

We implement the conceptual definitions presented in Sections 2.2 and 2.3 using the Terralib GIS library. For both types of relations, construction strategies are added to the library as an extension of the Generalized Proximity Matrix functionality (AGUIAR *et al.*, 2003). The new strategies deal with relations among objects in two different layers of information, representing the geographic objects at different scales. The relations can be constructed for polygon, points and cell representations of objects. For hierarchical relations only the absolute space Cartesian coordinates are considered to define the father-son and son-father relations. For network-based relations, a third layer is necessary representing a logical or physical network used to define the connectivity among the objects. The case study described below uses the Terralib implementation to construct the graphs G representing the relations. They are stored in a database, and can be exported as text files. Once constructed, tools for dynamic modelling can be applied using the relations. We use the TerraME modelling environment (CARNEIRO, 2006) to develop our land change models using the stored relations.

We exemplify the use of these concepts in Section 4 in a multiscale land change model for the Brazilian Amazonia developed by Aguiar [2006] and Moreira et al [2008], using the TerraME modelling environment [Carneiro 2006].

3 DYNAMICAL COUPLING OF MULTISCALE LAND CHANGE MODELS [2]

This section describes the proposed approach to build multiscale computational models. Section 3.1 contextualizes our proposal based on previous work, and Section 3.2 details the new approach .. Similarly expressed by Gibson (2000), this section uses the term *scale* in a broader sense than its traditional cartographic meaning, which is associated to spatial measurements. For us, a scale has *spatial*, *temporal*, and *analytical* dimensions. The spatial property of scale considers the geographical area under study and the spatial resolution used for data sampling. The temporal dimension of scale takes into account the time period considered in the analysis and the frequency when changes are recorded. The analytical dimension of scale refers to the rules (for example, agent behaviour) and to the indirect techniques (for example, statistical methods) that represent change.

3.1 Review of previous work

Multiscale modelling has long been in the research agenda of the land change community (Veldkamp and Lambin 2001; Turner et al. 1995; Veldkamp et al. 2001). One approach for multiscale land change modelling is to build a hierarchical spatial structure, which incorporates mostly top-down interactions. These models calculate the quantity of change (often referred as demand for change) using tools such as non-spatial economic model or trend analysis, usually at national or regional scales. This demand is then spatially assigned

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[2] Based on: MOREIRA, E. G.; COSTA, S. S.; AGUIAR, A. P. D. D.; CAMARA, G.; CARNEIRO, T., 2008b, Dynamic coupling of multiscale land change models, Landscape Ecology. Special Issue (Submitted).

based on suitability maps built using selected controlling factors such as soil quality and nearness to roads. The rationale for this approach is the demand-driven nature of land use change, specially related to commodities. Examples of this approach are: CLUE (Veldkamp and Fresco 1996; Verburg et al. 1999), CLUE-S (Verburg et al. 2002), Dinamica (Soares-Filho et al. 2002), GEOMOD (Pontius et al. 2001) and RIKS (White and Engelen 2000; White et al. 1997). For instance, the CLUE model (Veldkamp and Fresco 1996) has two spatial grids with different resolutions, representing a coarse and a fine scale. Results of changes in the coarser scale are passed on to the finer one for change allocation. Both scales use the same allocation procedure with different driving factors, and different linear regression models estimate cell suitability for change.

Some recent applications of these models involve combining different approaches at different scales. Castella (2007) applied two modelling approaches to the same study area in a district in Vietnam. He used an ABM (agent-based model) and a pattern-oriented statistical model (CLUE-S) to link the underlying causes of land change to their resulting spatial patterns. The CLUE-S model covered the whole district area, while the ABM model was applied to the villages within the district. But in this case, there was no direct coupling between the models. In a broader context, the EURURALIS project (Verburg et al. 2008) coupled a global economic model and an integrated assessment model to calculate changes in demand for agricultural areas at country level in Europe, and CLUE-S translated these changes at 1 km2 resolution. In this case, interaction was top-down only.

Bottom-up relations and scaling issues have also started to be addressed by agent-based models (ABM) (Parker et al. 2002), in which communication between individuals produces global patterns from local actions. The flexibility of ABM also allows both top-down and bottom-up relations (Brown et al. 2008). The research community views ABM as a promising approach to address multiscale modelling problems (Verburg et al. 2006).

Considering the current state of research, the goal of this section is to present a method to build multiscale land change models. We consider the case when single-scale models, using different modelling approaches, are independently built and then dynamically coupled. Our proposal makes it easy to introduce top-down and bottom-up relations. Such single-scale models may use an ABM or any other modelling technique. Allowing independent development of models at different scales is a convenient assumption, since many useful single-scale models exist, each using a spatial and temporal scale most convenient for their purposes. The challenge for coupling independent models is to support a bidirectional flow of information from one model to the other. To address this challenge, we introduce the ideas of Spatial and Analytical Model Couplers, as discussed in the following sections.

3.2 Proposed method for building multiscale models

The method we propose allows researchers to develop independent scale-specific models, and then combine them at run time. This method concerns model structure and software organization. We expect individual models to have different temporal and spatial scales (resolution and extent) and use varied modelling techniques. When coupled, a model may be influenced by the results of the upper or lower scale at each time step. In hierarchical models such as the one shown in Figure 3.1, the top-down linkages provide context information from higher levels; the bottom-up linkages provide feedbacks to the upper hierarchical model.

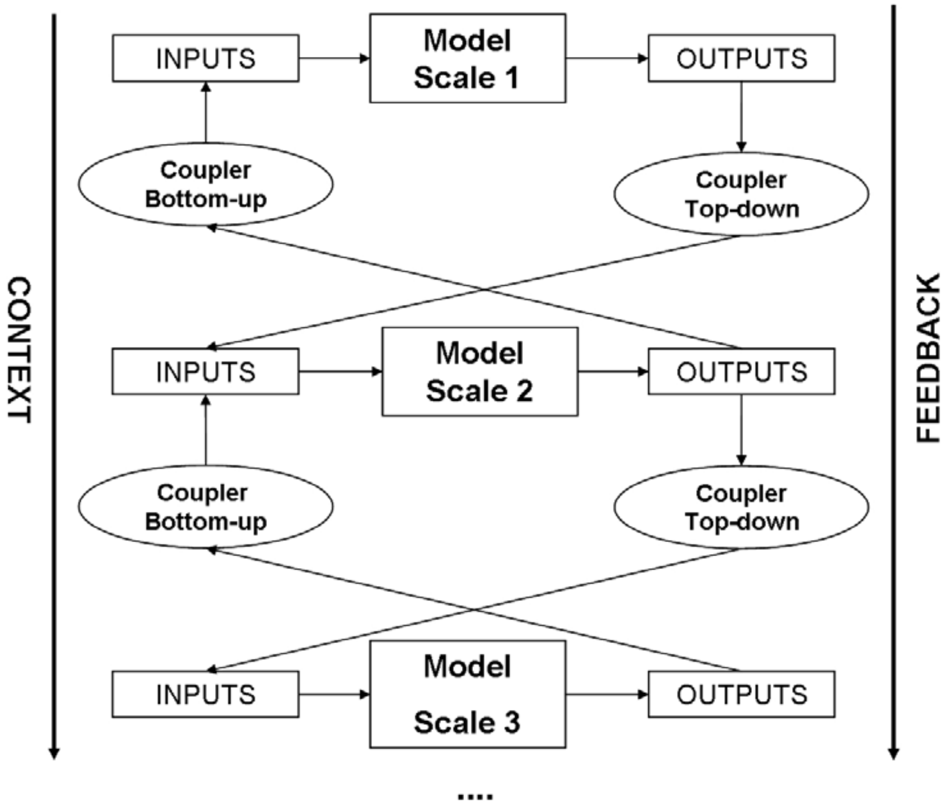

Figure 3.1 - Schematic representation of the multi-scale coupling mechanism.

Our proposal allows links among as many scales as necessary. Multi-agent models can be combined with other approaches, such as cellular automata and statistical models, and the software organization allows bidirectional feedbacks in multiscale models. By allowing mixings of different models, the proposed model organization differs from existing multiscale land change models, such as CLUE (VELDKAMP and FRESCO, 1996), which has two spatially explicit scales that use the same allocation procedure.

Our approach to build multiscale models uses a two-step approach. First, the researcher designs a separate model for each scale, and divides each model into *Spatial*, *Temporal* and *Analytical* submodels. The second step introduces the idea of *Model Couplers* to define links among scales. Three types of couplers are necessary: (a) *Spatial Couplers*, which define the spatial relations among scales (for example, father-son cell links); (b) *Analytical Couplers*, which define the top-down and bottom-up flow of information among models. These couplers represent the multiscale dependencies and feedbacks; and (c) *Temporal Couplers*, which set up the combined temporal execution of the models. The rest of this section details this software organization.

3.2.1 Modular Design

Decades of experience in software engineering suggest the hardest parts of software production are achieving a clear *architectural design* (BROOKS, 1982) and setting up a feasible strategy for modular development (PARNAS, 1972). Good design and modular organization are also important for land change models, since they allow easier maintenance and reuse. Thus, to be able to handle multiple scales in a flexible way, a land change model should be organized into distinct submodels, independent of one another (CARNEIRO, 2006). The *spatial submodel* describes the different extents and resolutions of the spatial scales used in the model. Each spatial scale can define its own proximity relations and its local properties or constraints. The *temporal submodel* describes the time period and the frequency of execution of rules and inference methods. The *analytical submodel* includes rules that describe the behaviour of agents. Alternatively, the analytical submodel uses pattern-oriented, empirical procedures to simulate change.

At first, it may seem difficult to design land change models that are modular. However, a modular organization brings about large gains, since it simplifies creating complex models with multiple approaches. The TerraME software used in this work (see Section 4.4 below) is one example of a modelling environment that provides the modularity needed for flexible multiscale integration.

3.2.2 Model Couplers: Spatial Couplers

A *Spatial Coupler* makes spatial relations explicit, linking geographic objects in different scales. At each spatial scale, the geographic objects may be represented differently. In Chapter 2, we describe spatial relations among geographic objects at different scales and consider hierarchical relations and action-at-a- distance´ relations. Hierarchical relations handle nested objects, such as the relation between states and municipalities. Action-at-a-distance relations handle interactions which are network-dependent, such as when a modeller uses the global wood market chain to define the relation of deforested areas in Amazonia to wood market consumers in Europe and USA. In this work, we focus on hierarchical multiscale models. In such models, the links represent father-children (for downscaling) and children-father relations (for upscaling). We propose three specific *Spatial Coupler* strategies to deal with hierarchical relations, when geographic objects at both scales use an area representation (polygons or regular cells), as shown in Chapter 2. Other coupling strategies are possible and the whole mechanism of coupling the models would be similar. In Section 4.4 describes how we implemented these strategies in the TerraME modelling environment.

3.2.3 Model Couplers: Analytical Couplers

An Analytical Coupler sets up the flow of information among scales. In hierarchical multiscale models, it defines how the output of a model (at a certain time step) serves as the input to another. The modeller may use top-down analytical couplers, bottom-up analytical couplers, or a strategy with both top-down and bottom-up couplers. The content of each of these couplers depends on the models being coupled, and on the multiscale application goal. Analytical couplers use spatial couplers to assess geographic object-to-object relations, in cases where the flow of information occurs among specific objects at different scales (for example, father to son). In the example we discuss in the next section, the top-down analytical coupler is a function that sums the deforested area at a coarser scale using cells that have children at a local scale. The coupler then sends the result to a finer scale model as the demand for change. The local model uses this demand as a non-mandatory input for an agent-based model. In other applications, other linkages could also be implemented for the same stand-alone models.

3.2.4 Model Couplers: Temporal Couplers

A Temporal Coupler is a scheduler that controls execution of different models. Consider a model that samples forest clearing and land abandonment on a monthly basis. Suppose we couple it to a hydrological model at a finer temporal resolution (weekly) and to a climate change model at a coarser temporal scale (yearly). Each model needs a different execution scheduler, defined in its temporal submodel. This scheduler coordinates the execution of each *Analytical Submodel* and related *Analytical Couplers*. This *Temporal Coupler* (scheduler) defines when the results from one model are sent to another. For the nested forest clearing and hydrological model mentioned above, the

Temporal Coupler would ensure that the hydrological model (which has a finer temporal resolution) sends its results to the forest-clearing model at the right moment.

As *proof of concept of methodology*, we present a hierarchical two-scale example for the Brazilian Amazon in the next section. We show how top-down and bottom-up feedbacks can be incorporated into a real world hierarchical model, covering different area extents.

4 ILLUSTRATIVE EXAMPLE: AMAZÔNIA AND SÃO FELIX DO XINGU[3]

The problem we deal with is understanding deforestation in the Brazilian Amazon, and building scenarios to support decision-making in the region. The Brazilian Amazon rain forest covers an area of 4 million km^2. It is a heterogeneous region in which sub-regions with different rates of change, resulting from the diversity of ecological, socio-economic and political conditions and accessibility coexist (AGUIAR *et al.*, 2007). Due to the intense levels of human occupation in the last 2 decades, about 17% of the original forest has been cleared. Most of the deforested area is concentrated in the south-eastern part of the Amazon, in the area known as the "Deforestation Arch". Central Amazonia is currently another vulnerable area where the new occupation frontiers are located (BECKER, 2005).

Deforestation rates increased from 2001 to 2004 from 18,165 km^2 to 27,970 km^2. In 2005, the estimated rate dropped to 18,900 km^2 and in 2007 to 11,224km^2 (INPE, 2008). The lower rates observed since 2005 are partly associated with control actions conducted by the Brazilian government, including law enforcement actions and the creation of protected areas, and partly associated with lower commodity prices in the international market. However, rates may start to rise again in the period 2008-2010, due to a rise in commodity prices and to the expansion of biofuels. Recent evidence (INPE, 2008) points out that localized deforestation control policies applied to one municipality, such

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[3] MOREIRA, E. G.; COSTA, S. S.; AGUIAR, A. P. D. D.; CAMARA, G.; CARNEIRO, T., 2008b, Dynamic coupling of multiscale land change models, Landscape Ecology. Special Issue (Submitted).

as the creation of protected areas or localized law enforcement actions, might stimulate the occupation of other areas in the medium and long run. The productive system may reorganize and induce occupation of other areas to support a growing demand for agricultural products. Such intraregional interactions result from processes that act on different hierarchical levels. At a global scale, the national and international commodities market (beef, grains and timber) imposes demand for land change. At a local scale, different actors operate in their specific socio-economic and biophysical contexts, creating different land-use trajectories. This calls for multiscale, multilocality studies to understand the land change process.

4.1 Study area and scales

To clarify our proposal, we have built a case study for modelling deforestation in the Brazilian Amazon, using two scales. At a regional scale, we have a deforestation model (see Appendix A), covering all Brazilian Amazonia at 25 x 25 km^2 resolution. At a local scale, we have a deforestation model (see Appendix B) in São Felix do Xingu, Pará State, a hot spot of deforestation in Central Amazonia (BECKER, 2005); (ESCADA *et al.*, 2005). The local model covers an area of roughly 50,000 km^2, using 1 x 1 km^2 cells. Figure 4.1 shows both study areas. The two models at different scales provide complementary information about human occupation in the region.

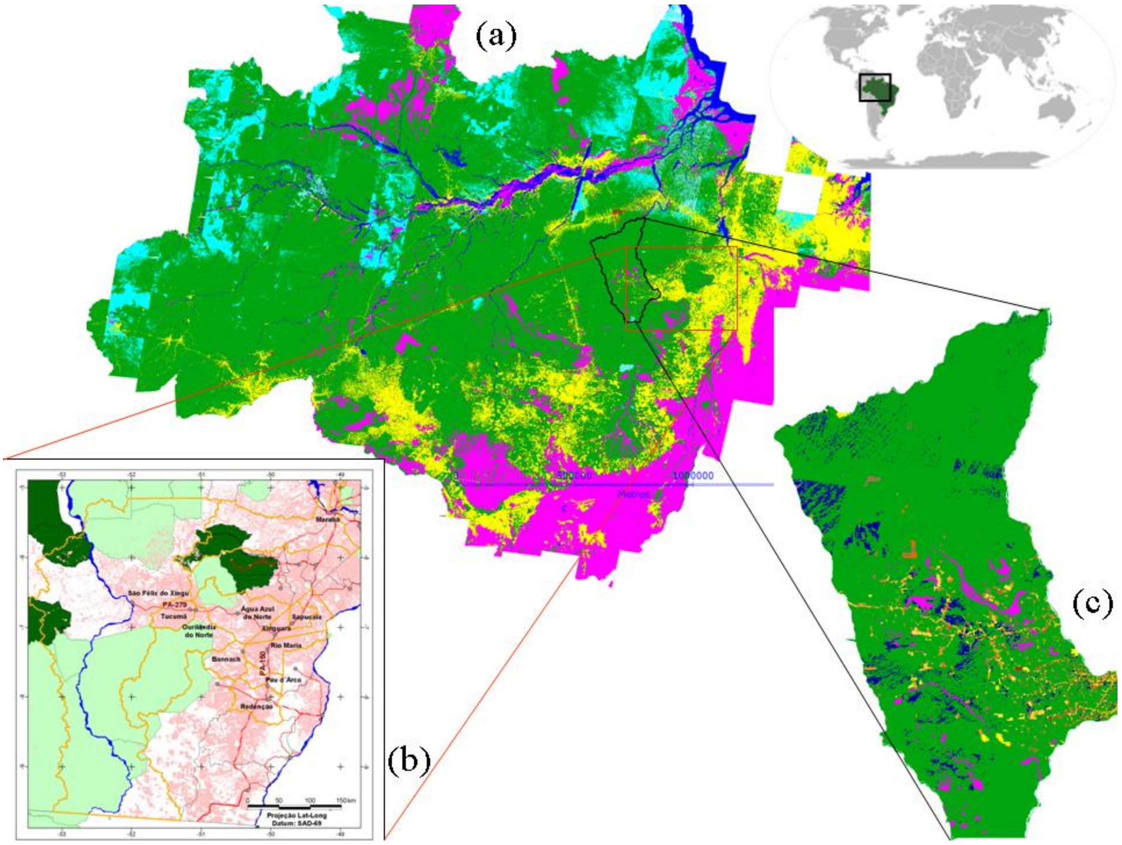


Figure 4.1 - Study area: (a) Macro model: Brazilian Amazonia; (b) PA 279 area, which is the connection to the local study area (Iriri/Terra do Meio), including the municipalities of São Felix do Xingu, Tucumã, Ourilândia and the southeast of Pará State; (c) Local model: Iriri/Terra do Meio.

Source: (INPE, 2008).

At a macro scale (Amazonia) we have used a statistical allocation procedure based on regression models, adapted from the CLUE model (VELDKAMP and FRESCO, 1996) by Aguiar (2006). The statistical analysis uses a database combining remote sensing and census based information. As independent variables, we have taken 40 environmental, demographical, agrarian structure, technological, and market connectivity indicators. The dependent variables are the land-use patterns (pasture, temporary and permanent crops, non-used agricultural land). We have projected the percentage of deforestation in each cell from 1997 until 2025 under different scenarios of market pressure for land and conservation policies. Starting from 1997, the model captured new deforestation frontiers according to 2003/2004 deforestation maps (INPE 2008), including São Felix do Xingu. For details of model parameterization and validation, see Aguiar (2006) and Aguiar (2007). In the multiscale model we have built this work to explain our method, the macro scale model represents the agricultural frontier expansion over the whole Amazonia. It answers questions such as: *Given a certain pressure for expansion of agricultural land, which areas in the Amazonia would be occupied first?*

At a local scale, we have built an agent-based deforestation model for a hot spot of deforestation in São Felix do Xingu, with two sets of agents: small and large farmers. Small settlers favour closeness to roads and urban centers. Large farmers prefer large pieces of inexpensive land, not necessarily close to roads. Each actor has its set of controlling factors and decision rules. These factors include nearness to roads, land availability and cost, and law enforcement. Currently, a Brazilian law (known as the Forest Code) dictates that 80% of forest inside private properties must be preserved. However, landowners often disrespect this law. To account for this practice, the model scenarios consider cases where the law is enforced or is not enforced. The amount of change in the area is an exogenous variable. However, it may not be allocated fully, depending on the behaviour of local agents. Thus, this model answers questions such as: *Given a certain pressure for expansion of agricultural land in São Felix do Xingu, how would local deforestation patterns evolve under different scenarios?*

These case studies show our method in practice. First, we illustrate the usefulness of coupling the models using a pure top-down interaction. We combine two macro scenarios (high and low demand for new land) to a local scenario with no law enforcement. This provides alternative contexts of pressure for new agricultural land to a local scenario with no law enforcement. In a second step we illustrate a complete loop of top-down and bottom-up interactions. We compare two local scenarios (without/with law enforcement) to one macro scenario (high pressure for new land). The local model interacts with the regional model modifying the regional distribution of deforestation results according to alternative local actions to enforce the law. In the next step, the macro models, in their turn, send a modified pressure to the local model.

4.2 Hierarchical and network-based spatial relations

In this section, we exemplify the use of hierarchical and network spatial relations presented in Section 2 to build this multi-scale land change model for the Brazilian Amazonia. In this model, spatial relations are established across three scales: (a) at a national level, the main markets for Amazonia products (Northeast and São Paulo) and road infrastructure network; (b) at a regional level, a regular grid of 25 x 25 km^2 resolution cells for the whole Brazilian Amazonia, covering an area of approximately 4 million km^2; and (c) at a local level, a nested regular grid of 1 x 1 km^2 resolution cells for a deforestation hot-spot in Central Amazonia, the Iriri region, in São Felix do Xingu, Pará State. This local grid covers an area of approximately 50,000 km^2. Figure 4.2 illustrates the three scales and their geographic object representation.

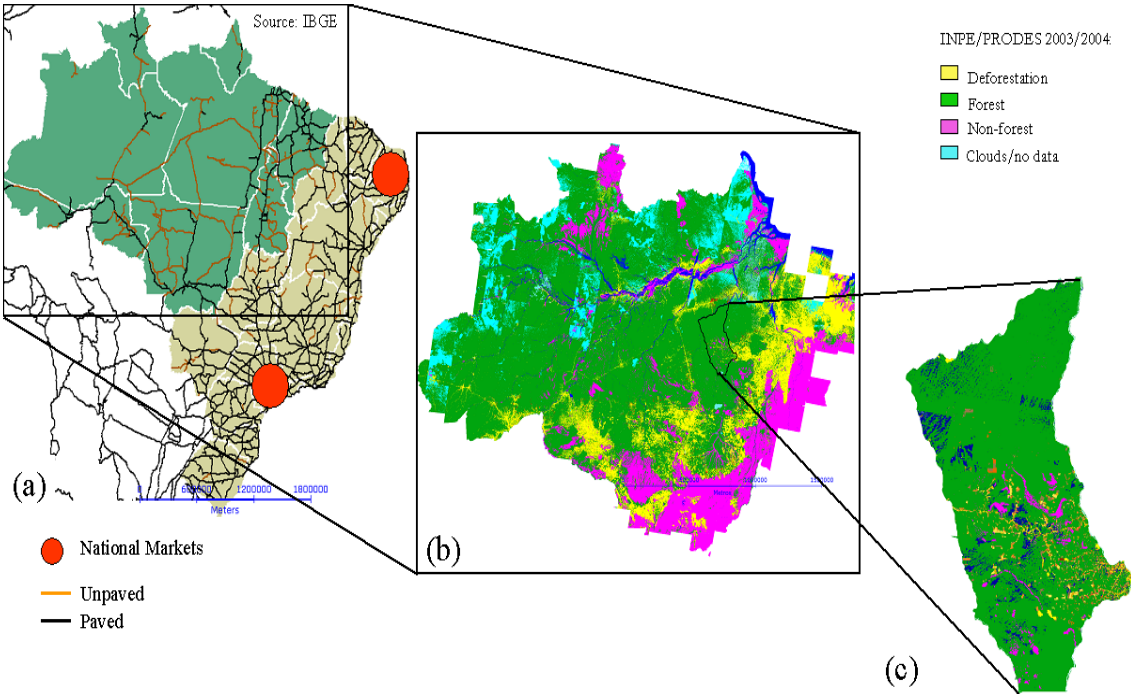


Figure 4.2 - Study area: (a) Brazil: roads network and main markets (São Paulo and Northeast); (b) Brazilian Amazonia: deforested areas map; (c) Iriri/Terra do Meio in São Felix do Xingu, Pará State: deforested area map.

As discussed in the previous section, the goal of the multi-scale model is to explore *complementary information about the occupation process* in the region (MOREIRA *et al.*, 2008b). The model includes the following interacting model components and spatial relations:

- The regional scale model projects the percentage of deforestation for each 25 x 25 km^2 cells. We use a statistical allocation procedure based on regression models adapted from the CLUE model (VELDKAMP and FRESCO, 1996) by Aguiar (2006). It represents the process of agricultural frontier expansion over the whole Brazilian Amazonia. The macro model seeks to answer questions such as: given a certain pressure for expansion of agricultural land, which areas in the Amazonia would be occupied first? One of the goals is to explore the hypothesis that connection to national markets through road infrastructure is a key factor to explain the distribution of deforestation in the region. *This requires the establishment of a network-based relation to link the cells in Amazonia to places outside the region.* This relation is used to define the suitability of the 25 x 25 km^2 cells for change according to their level of connectivity.

- The nested local model seeks to answer questions such as: given that a certain amount of pressure is projected for the Iriri by the regional model, how would local patterns of occupation evolve? The top-down interaction consists of the regional model signalling an expected demand for change at the Iriri. *This requires a father-son relation to select the 25 x 25 km^2 cells corresponding to the Iriri 1 x 1 km^2 cells.* The model uses this relation to add the large-scale projected change at 25 x 25 km^2 cells and to send the resulting demand for change to the local model.

- The Iriri model is an agent-based deforestation model. Two sets of agents were identified: small and large farmers. Small settlers favour proximity to roads and urban centres. Large farmer prefer large pieces of inexpensive land, not necessarily close to roads. Therefore, each type of actor is associated to a set of determining factors and decision rules. Local policy decisions, expressed at local scale, may prevent the full extent of projected change from occurring. A *bottom-up feedback mechanism* sends this information back to the larger scale thus modifying the macro scale model corresponding cells. *This requires a son-father relationship to link 1 x 1 km^2 cells to the upper-scale 25 x 25 km^2*

cells. The model uses this relation to correct the projected change at the 25 x 25 km^2 cells.

To support the implementation of such scale interactions in this land-change model, we define and compute the following hierarchical and network-based relations.

4.2.1 Hierarchical relation between the nested grids

We use a hierarchical relation to provide the spatial support to dynamically link the two nested grids at 25 x 25 km^2 and 1 x 1 km^2 resolutions. The strategy we use to construct the relation is the *KeepInBoth*, as the cellular spaces are not coincident.

Each coarse scale cell is linked to approximately 625 finer scale cells (father-son relation). Most finer scale cells are linked to only one coarser scale cell (son-father relation), but depending on their relative position (on the borders of the coarse scale cells) they can be linked to two, three or even four parent cells (see Figure 2.5.c). The father-son and son-father hierarchical relations allow the incorporation of *top-down* and *bottom-up* interactions between regional and local models, as discussed in Section 2.2.

4.2.2 Network-based relation: connection to markets

We use a *Multi-scale Open-network* strategy to connect the regional scale 25 x 25 km^2 cells to the main places of consumption at a national scale (São Paulo and Northeast). Graph G representing the relation between these objects is computed using the following parameters:

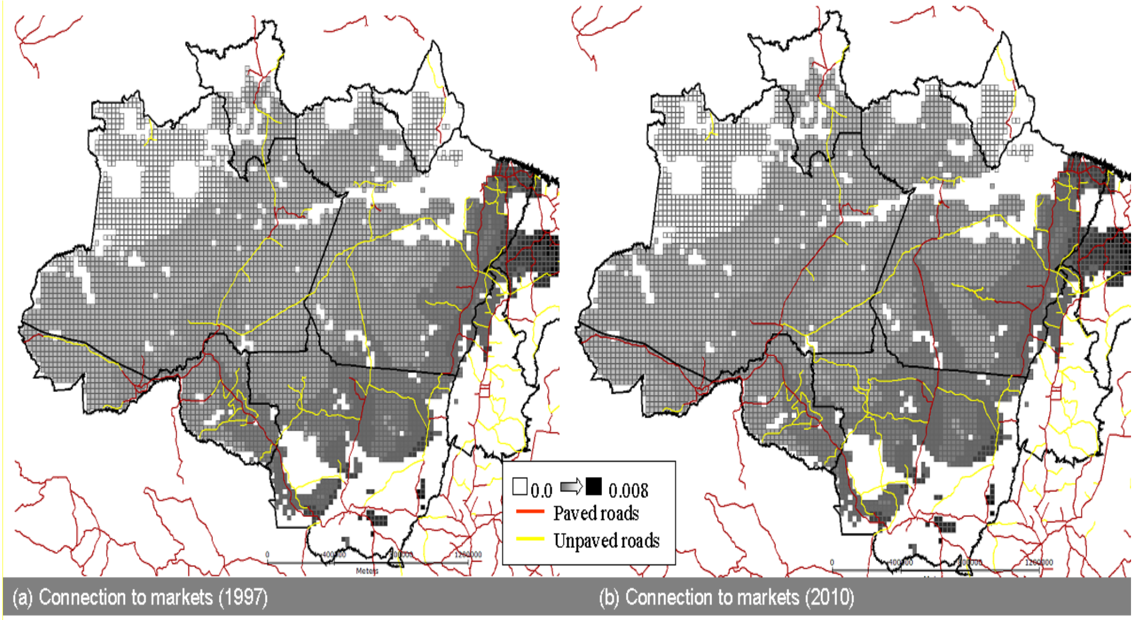
- Maximum distance from cells to the road network: unbound (all cells are included).

- Maximum distance from entrance points *E* through the network: unbound.

- Weight computation: inversely proportional to the minimum path distance from the cell to each national market, using the road network. We distinguish paved from non-paved roads (non-paved roads are supposed to double distances).

Graph *G* includes the *2:n* relationship from the two markets to every cell, and a *n:2* relationship from every cell to the two markets. Both directions could be used in land change models. For example, the *2:n* (from market to cells) could be used to establish a remote influence between São Paulo and their most connected cells. We could include a rule in the model to bound change in Amazonia cells as a result of a behavioral or policy change in São Paulo. This change in the market conditions can be an incentive (demand increase) or a restriction (need of certification).

In this work, the land change model uses the *n:2* relationship (from cell to market). We derive a new cell attribute based on graph *G* to represent the level of connectivity of each cell to any of the markets. If road conditions change, the variable is recomputed. Each cell receives as attribute *conn_markets* the minimum weight value stored in *G* according to the road network at that time. Figure 4.3 illustrate the connection to markets and variable in 2000 and the projected 2010 level of connectivity, supposing some roads are to be paved.



(a) Connection to markets (1997)

(b) Connection to markets (2010)

Figure 4.3 - Connection to markets variable constructed using a network-based multiscale spatial relation: (a) in 1997; (b) in 2010 (paving some roads).

This network-based relation is used to construct one of the main variables in the model. Using the connection to national markets, the model has been able to reproduce the different stages of occupation of the new frontiers of the XXI century, using 1997 as the base year, including São Felix do Xingu (AGUIAR, 2006) comparing to 2003 deforestation maps (INPE, 2008). The model captures the process in which cattle ranchers decided to migrate to the São Felix area due to its biophysical, accessibility and market conditions. The connection to markets variable represents a process that acts in a higher hierarchical level, and could not be captured in a single scale study.

4.3 Scale interactions

This section describes how we have coupled the two models, creating feedback loops. The top-down relation provides context to the local model. The regional model captures the process in which cattle ranchers decided to migrate to the São Felix area due to its biophysical, accessibility and market conditions. It signals an expected demand for new land (forest conversion to pasture) at a local scale. Local policy decisions, expressed at a local scale, may prevent all expected change from occurring. *Bottom-up feedback mechanisms* send this information back to the larger scale , thus changing the macro scale model.

To build a multiscale model from the individual parts, we specify Spatial, Analytical and Temporal coupler. For the top-down *Spatial Coupler*, we used the *KeepInBoth* strategy to set up the father-son relations, as the cellular spaces were not coincident. For the top-down *Analytical Coupler*, we define a function which sums up the allocated area for all agricultural uses in the 25 x 25 km^2 area that matches to the 1x1 km^2 cells of the local scale. This value is the demand for change at a local scale at simulation time t. As bottom-up *Analytical Couplers* we define two functions:

a) *At time t, update land use of each 25 x 25 km^2 cell.* This updates the result of the macro model at time t, making the percentage of agricultural land use at a regional scale compatible with the results of the local scale. A difference in total allocated area at a macro scale may arise, if local policy decisions prevent all the expected change (sent by the top-down coupler) from occurring. In this case, we change the macro demand value defined for the next year, adding this difference.

b) *At time t +1, update suitability of each 25 x 25 km^2 cell.* This changes the suitability of the 25 x 25 km^2 cells based on the previous results at the local scale. If local actions prevent full allocation of the projected demand, the upper scale cells will decrease the original suitability estimate.

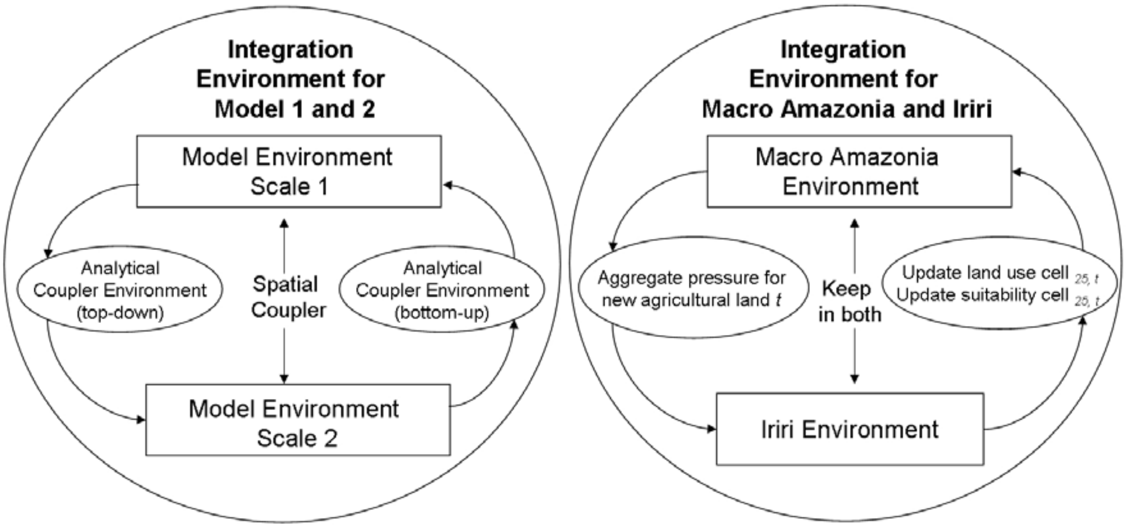
In this example, the *Temporal Coupler* is sequential, as both temporal scales are the same. Both models run from 1997 to 2025, on a yearly basis. At each time step, we first run the macro scale analytical submodel (Amazonia), followed by the top-down *Analytical Coupler (pressure for new land)*. Afterwards, we run the local analytical submodel (São Felix) and then the bottom-up *Analytical Couplers*.

4.4 Implementation using TerraME

We have used the TerraME software (CARNEIRO, 2006) to test our proposal and build case studies. This software matches our needs for modular multiscale model development, providing a high-level modelling language and direct access to a geographic database, and supporting the broader definition of scale proposed by Gibson (2000) and adopted by the authors. TerraME provides the Environment data type, which encapsulates the analytical, spatial and temporal dimensions of a scale, which are modelled separately. *Environments* can be nested, creating a multiscale model from individual parts. To build our proposed software organization in TerraME, we use the *Environment* data type as a container for each model. The software also provides a scheduler that controls the flow of execution for each Environment, which matches our idea of a *Temporal Coupler*. We have used TerraME functions to build our *Analytical Couplers*.

We have added the *Spatial Coupler* data type to TerraME, as an extension to the basic Neighborhood functions provided by the software, which uses a Generalized Proximity Matrix (GPM) (AGUIAR *et al.*, 2003). A GPM is a generic way of expressing spatial relations between geographic objects such as cells and agents. The original implementation of the GPM captured absolute and relative space neighborhood relations among objects of the same type at the same scale. The *Spatial Coupler* is an extended GPM that links objects of different geometries (points, lines, cells, polygons) at different scales. Moreira (2008a) details how to parameterize Spatial Couplers.

We now describe the steps to create a multiscale model using TerraME. First, the single-scale models are developed in a modular way describing their spatial, temporal and analytical dimensions. Then, we enclose each model in a *Model Environment*. For each pair of *Model Environments* to be coupled, at least one *Analytical Coupler* function (top-down or bottom-up) has to be implemented, and a specific *Coupling Environment* created to encapsulate them. Then, we choose the suitable *Spatial Coupler*. We create an *Integration Environment* nesting the two *Model Environments*, the necessary *Coupling Environments* (bottom-up and top-down) and the *Spatial Coupler*. Figure 4.4 shows the TerraME approach conceptually and in our case study.



(a) Schematic

(b) Case Study

Figure 4.4 - Implementation approach in TerraME: (a) schematic representation; (b) case study.

4.5 Scenario Exploration

In this work, we use four combinations of macro and local scenarios top-down and bottom-up interactions. For the top-down interaction, Local Scenario A (no law enforcement) was combined with Macro Scenarios A (high demand for new land) and B (low demand for new land). This provides alternative contexts of pressure for new agricultural land to a local scenario with no law enforcement. To analyse the bottom-up interaction, Macro Scenario A (high pressure for new land) was combined with Local Scenarios A (without law enforcement) and B (with law enforcement). This provides feedbacks according to alternative local actions to enforce the law.

4.6 Case study results and discussion

4.6.1 Top-down influences: comparison of local model results under two alternative macro scenarios

In this section we show how local patterns of occupation evolve out of two alternative macro scenarios related to the overall distribution of deforestation over the whole Amazon. The demand curves of deforestation for the whole region in both scenarios are presented in Figure 4.5. These demand curves are used to generate projected spatial patterns of deforestation. The macro model uses the amount of change (deforestation demand) for the whole region from 1997 to 2025 as an exogenous variable. Macro Scenario A (*high deforestation pressure*) assumes that deforestation rates after 2008 will be similar to the average of the last decade (around 19,400 km^2/year). Macro Scenario B (*low deforestation pressure*) represents a constant decrease of rates until they reach a low rate of 1000 km^2/year, assuming combined market and policy mechanisms will work to achieve a low residual rate. The projected percentage of deforested areas in Amazonia would rise from the current 17% (in 2007) to 27% (in 2025) in the Macro Scenario A, and to 20% (in 2025) in Macro Scenario B.

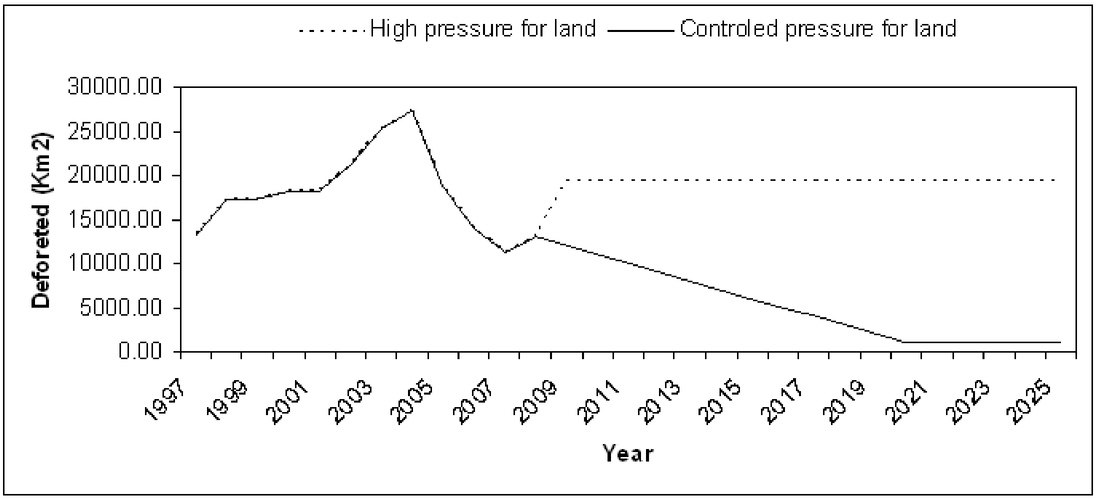


Figure 4.5 - Deforestation demand curves: Macro Scenarios A and B.

At a local scale, we use a scenario with no law enforcement. The projected deforestation in the Iriri area for each of these macro scenarios is shown in Figure 4.6.

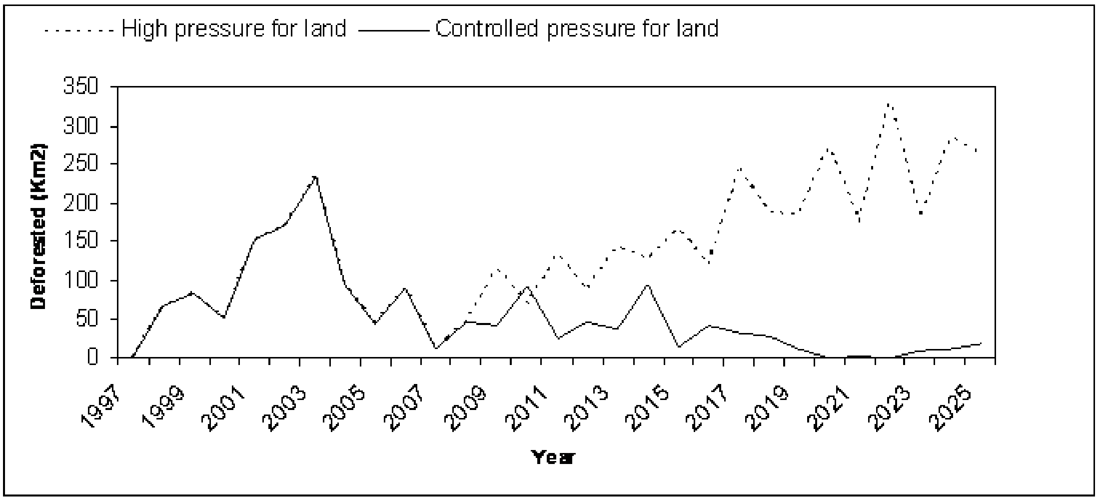


Figure 4.6 - Deforestation demand curves: Projected change in the Iriri region in relation to Macro Scenarios A and B.

Figure 4.7 and Figure 4.8 show the spatial patterns of deforestation projected for 2025 for both macro scenarios. Figure 4.9a and Figure

4.9b show the real deforestation patterns in the São Felix region (INPE, 2008) and the simulated one in 2005, using 1997 as the starting date. The simulated pattern matches the real deforestation. The projected deforestation for 2025 at the local scale for both macro scenarios is shown in Figure 4.10a and Figure 4.10b.

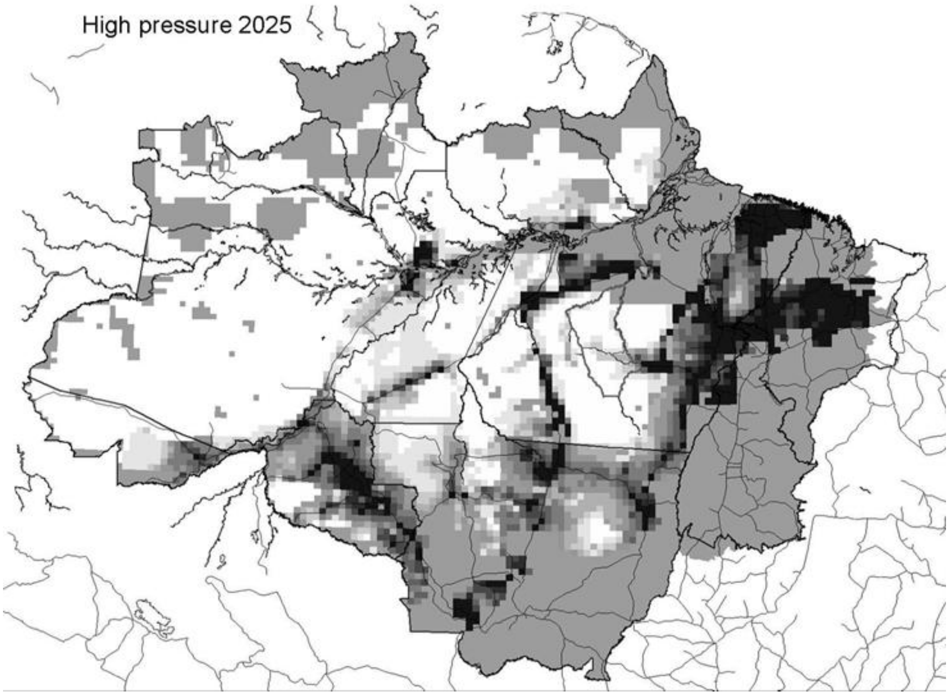


Figure 4.7 - Percentage of deforestation in each cell projected to 2025 in Macro Scenario A.

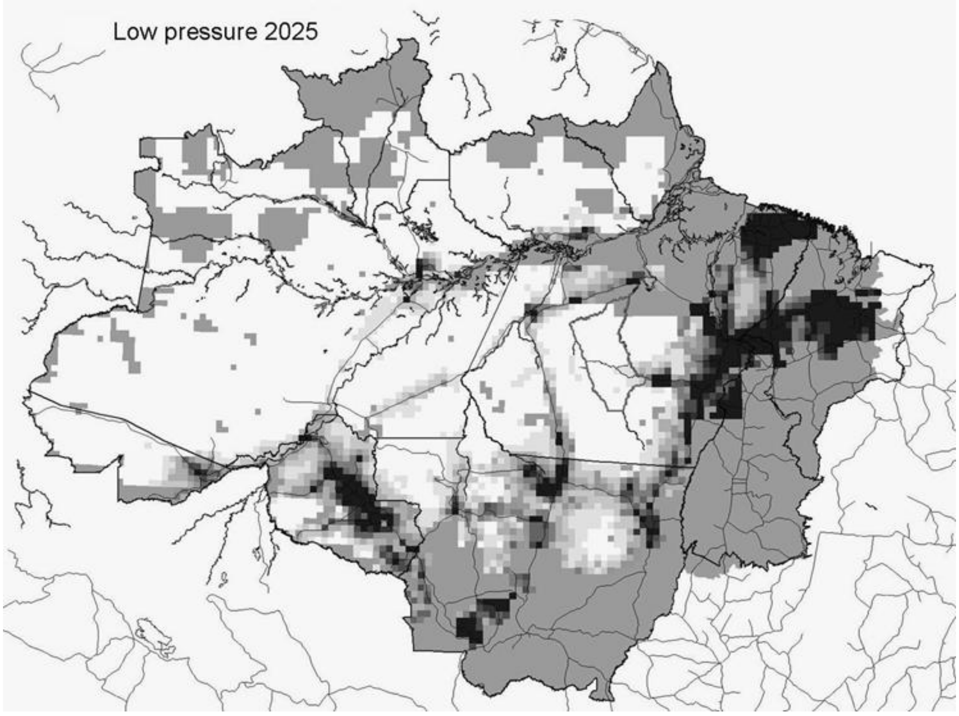


Figure 4.8 - Percentage of deforestation in each cell projected to 2025 in Macro Scenario A.

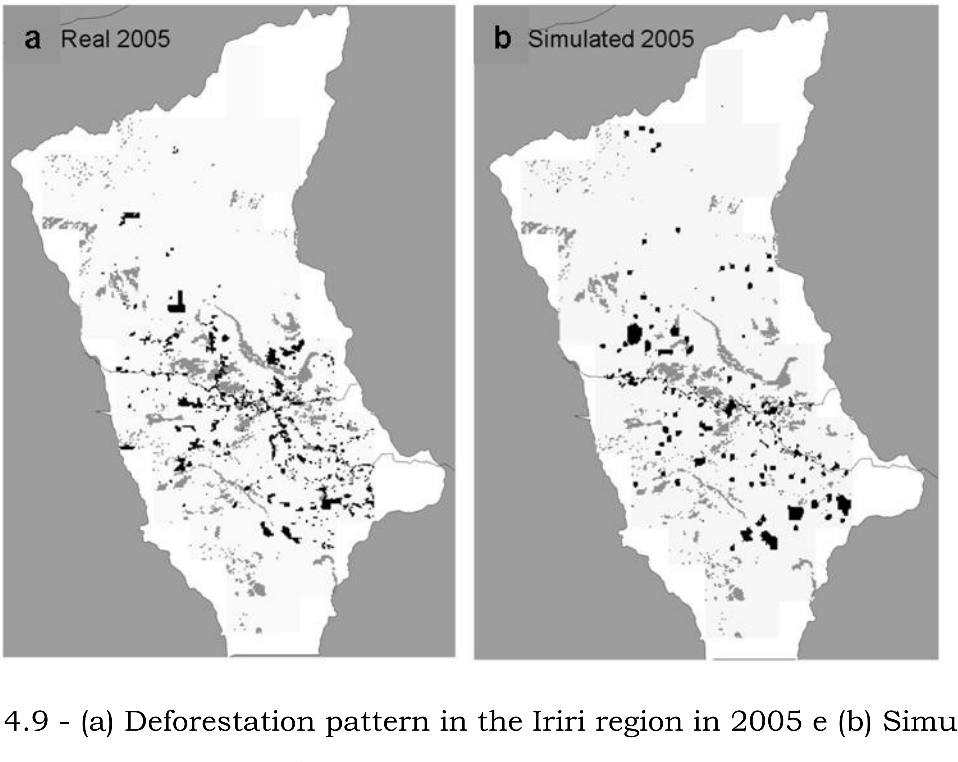


Figure 4.9 - (a) Deforestation pattern in the Iriri region in 2005 e (b) Simulated pattern in 2005.

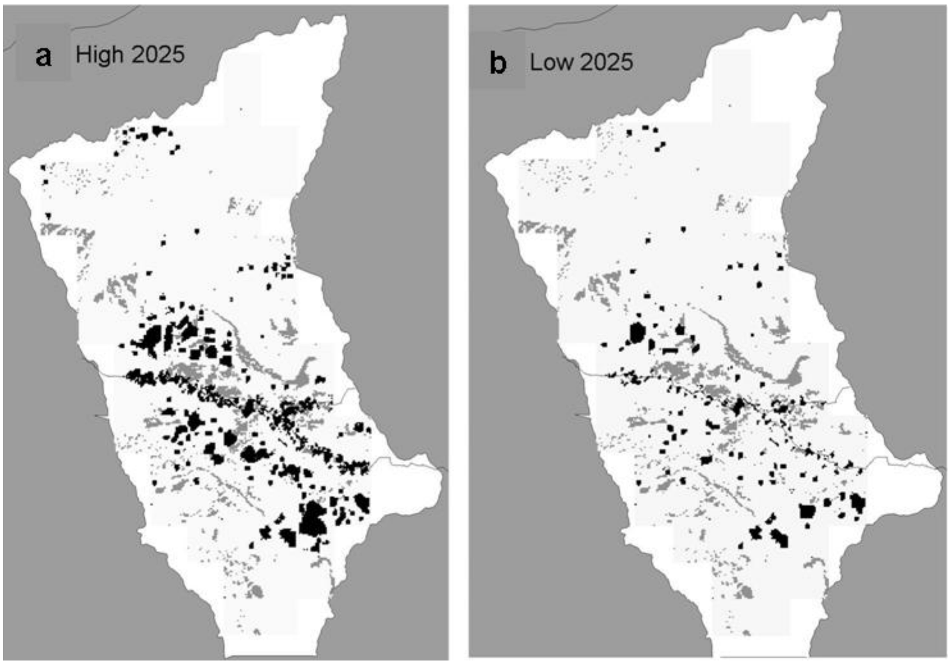


Figure 4.10 - (a) Simulated pattern in 2025 nested in Macro Scenario A e (b) Simulated pattern in 2025 nested in Macro Scenario B.

The results show that change in the macro scenarios is not homogenous over Amazonia, as socio-economic and biophysical conditions vary. Some areas are more suitable for agricultural expansion than others. Connectivity to markets has a strong influence on spatial patterns, as shown in Aguiar (2006). If we compare the increase in deforested areas in the whole Amazonia to a deforestation hot spot such as São Felix, relative increases are different. For the whole Amazonia from 2007 to 2025, the model projects an increase of 55% in the deforested area in Macro Scenario A and of 15% in Macro Scenario B. The change in São Felix is higher for the same period, even in a low-pressure demand scenario. In Macro Scenario A, the projected deforested area São Felix would increase by 263% and by 143% in Macro Scenario B.

This shows that pressure for change at different sites in a large region such as Amazonia depends not only on local conditions, but also on processes that act at higher hierarchical levels. The higher pressure for change in São Felix compared to other places reflects its higher suitability for cattle expansion when compared to other areas in Amazonia, due to climatic, soil and market conditions. Other areas may be more suitable for mechanized agriculture with plain relief and easier access to export facilities. This shows the potential of multiscale models to reveal local and regional land change processes, taking into account limits and opportunities associated to diverse biophysical and socioeconomic contexts.

4.6.2 Combining top-down and bottom-up influences: comparison of macro Amazonian results with feedback from the two alternative local scenarios

In this section we show the effects of combining top-down and bottom-up linkages. We use Macro Scenario A which assumes a growth of deforestation rates after 2008 to the levels of the last decade (see Figure 4.12, Figure 4.13 and Figure 4.14). Two spatial projections for deforestation in 2025 for the regional scale are shown in Figure 4.11, given alternative scenarios at a local scale. Local Scenario A assumes no law enforcement in obedience to the *Forest Code*. The whole area could be deforested given enough pressure. Local Scenario B assumes law enforcement in obedience to the *Forest Code*. Only 20% of farm areas will be deforested, independent of the external pressure for land.

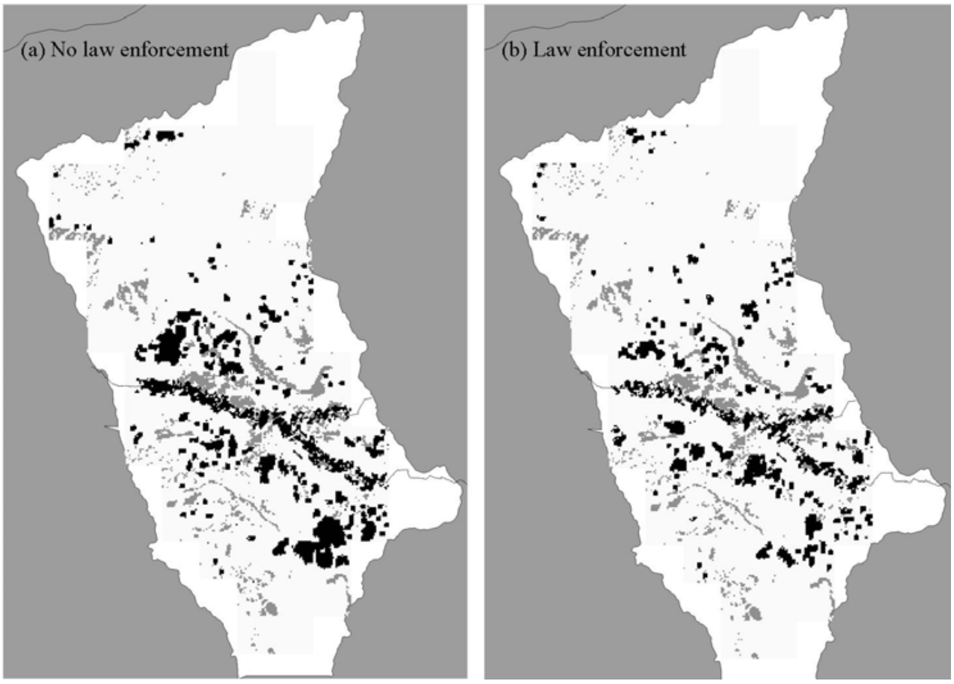


Figure 4.11 - (a) Local A: projected deforestation pattern in 2025 e (b) Local B: projected deforestation pattern in 2025.

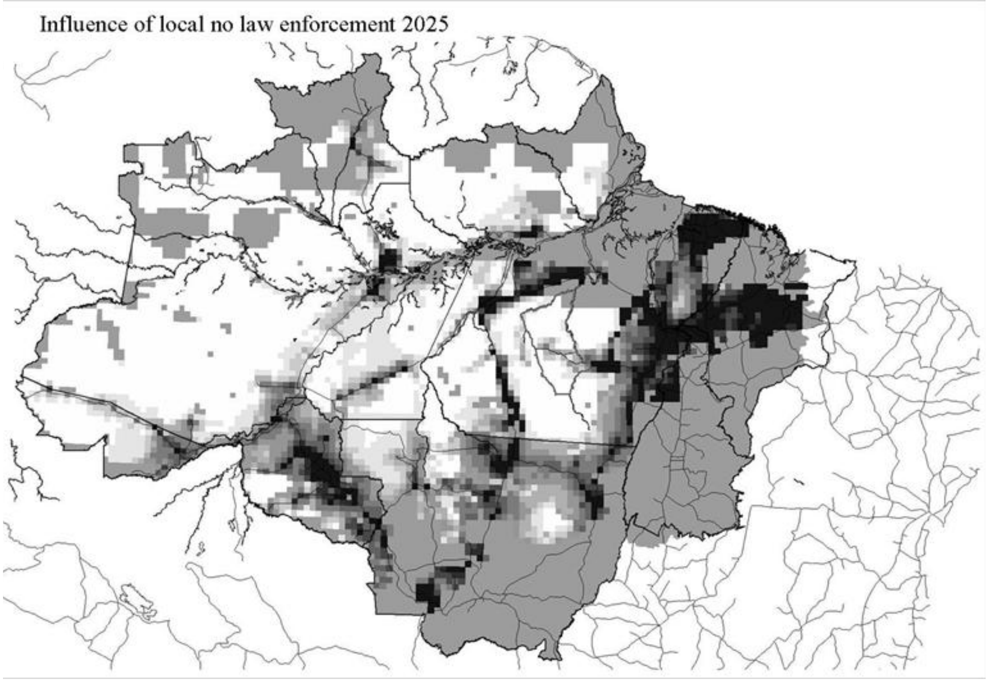


Figure 4.12 - Macro A: percentage of deforestation in each cell projected to 2025 with bottom-up feedback from Local A.

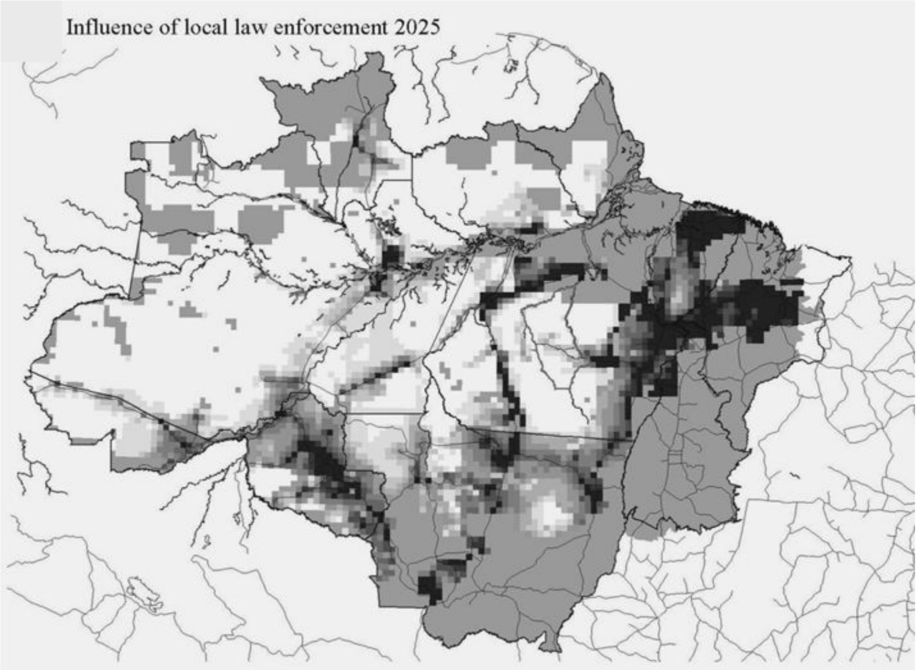


Figure 4.13 - Macro A: percentage of deforestation in each cell projected to 2025 with bottom-up feedback from Local B.

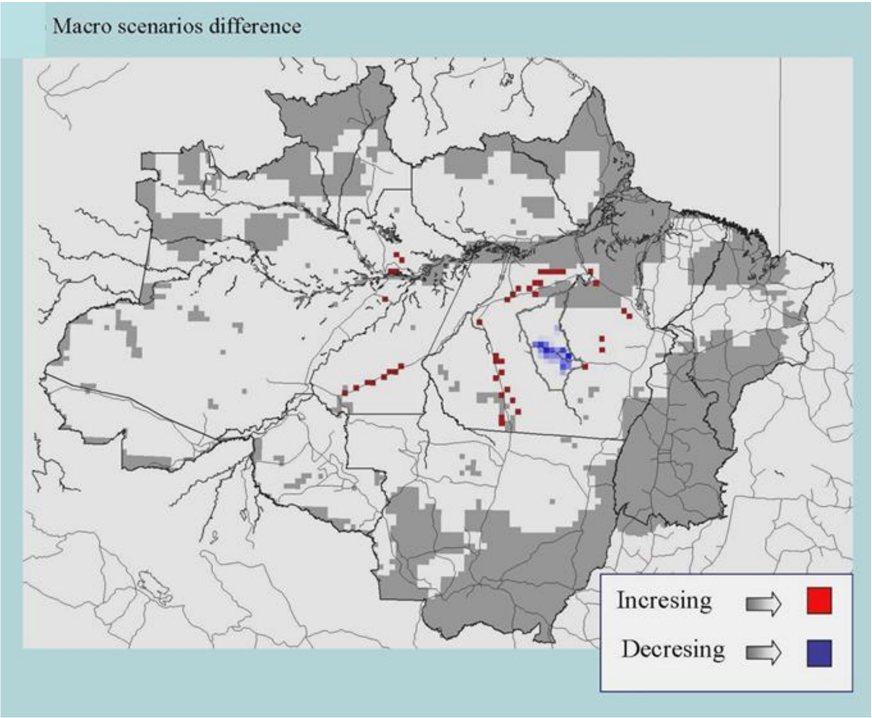


Figure 4.14 - Difference between 4.11 and 4.12.

As the São Felix region is one of the deforestation hot spots in Amazonia, the effect of having local law enforcement in the area is felt regionally at a macro scale model, due to the feedback mechanisms. Deforestation resulting from simulation depends on the local scenario conditions and the agents´ behavioural rules. When the finer scale model rejects the demand projected by the macro model, the bottom-up feedback corrects the projected areas at a macro scale and changes the suitability of the upper scale cells. The macro scale model assumes the demand for deforestation is an exogenous variable, dependent on external market forces. Demand increase and decrease are proxies of market constraints, representing higher or lower pressure for forest conversion. When the finer scale model rejects the demand projected for a given area, the difference will be redistributed as pressure to other locations. This simulates the intraregional "leakages" using the Kyoto protocol terminology. This shows an effect not previously considered in other modelling exercises in the Amazon (SOARES-FILHO *et al.*, 2006); (LAURANCE *et al.*, 2001). The productive system may reorganize when certain policies impose localized constraints (AGUIAR, 2006). Therefore, models incorporating top-down and bottom-up interactions project effects not easily detectable by single scale models.

5 CONCLUSIONS

This work discusses and conceptualizes the use of multi-scale spatial relations in land change models, and presents a conceptual approach for building multiscale, multilocality land change models that include top-down and bottom-up interactions.

Two types of relations are presented: hierarchical and network-based. Multi-scale land change models are often based on hierarchical relations, using nested objects at different scales. We argue that combining hierarchical relations with network-based relations provides a comprehensive conceptual framework to include top-down and bottom-up interactions and feedbacks in multi-scale land-change models. Network-based relations can represent remote influences on the land use system. This has a growing importance in a globalized economy, in which places of consumption and production have been increasingly separated. Land systems cannot be adequately understood without considering the linkages of different areas for decisions and structures made elsewhere. We exemplify the use of such relations in a multi-scale land change model for the Brazilian Amazonia.

A two-scale spatial application has been developed as proof-of-concept. We show how top-down and bottom-up feedbacks can be incorporated into a real world hierarchical model, covering different area extents. No single model or scale can fully capture the causes of land change. This work presents a methodology for building multiscale, multilocality land change models that include top-down and bottom-up relations. We have developed a two-scale model to show how to build top-down and bottom-up feedbacks in a real world hierarchical model that covers different spatial extents. This method works when single-scale models are independently built and then dynamically coupled. One hindrance to the proposed approach is the need to adopt a modular design, where each individual model needs to distinguish its analytical, spatial and temporal dimensions. At first, it may seem difficult to design modular land change models. However, a modular organization brings about large gains, since it simplifies creating complex models with multiple approaches. Another challenge is shared by coupled models in general. We need good techniques to validate coupled models, especially when they include multiple feedbacks.

This work is a first step towards more detailed studies on the balance between regional and local interactions. Our aim is to continue to improve such models and use them to better support policy making in Amazonia. Multiscale models provide insights of broader scope and complementary perspectives. They may help us to answer questions such as: *Which local measures could prevent the projected macro scenario of aggressive forest conversion to pasture? Are local actions enough? How would other regions – with heterogeneous socio-economic and biophysical conditions - be affected?* The software organization we propose contributes to the efforts to answer such complex questions. We consider that similar approaches could be applied to many other situations and parts of the world. We also believe this methodology is general enough also to be used for other types of applications, and contributes to create dynamic coupled Integrated Environmental Models from local to global scales.

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APPENDIX A - MODEL FOR MACRO AMAZONIA

The macro model is organized into distinct submodels: spatial model, temporal model and analytical model.

A.1 Spatial model

Brazilian Amazonia (4 million km^2) cells of 25×25 km^2, attributes related to land use, biophysical and socio-economic determining factors.

Land use attributes: pasture, temporary agriculture, permanent agriculture, non-used agricultural areas, planted forest and forest.

Biophysical and socio-economic factors: connection to national markets, distance to roads, percentage of protected areas, percentage of small farms, number of settled families, distance to urban centers, distance to mineral deposits, distance to large rivers, average humidity in the three drier subsequent months of the year, distance to wood extraction poles connection to main ports, distance to unpaved roads. For a complete list of variables and selection process see Aguiar (2006)

A.2 Temporal model

From 1997 to 2025, yearly.

A.3 Analytical model

The analytical model is based on the the CLUE (Conversion of Land Use and its Effects) modeling framework basic concepts (refs Vedkamp e Freco (1996); Verbug et al., (1999), and was implemented in TerraME (ref). The CLUE model consists of two components: a demand module, that projects the overall amount of change; and an allocation module, the spatial component that localizes such changes, based on cell suitability. Cell suitability is estimated based on statistical analysis of census and deforestation data. The model was applied to the Amazonia, using the same linear regression models developed by Aguiar [2006]. In this model, the demand for change is an exogenous variable, according to different scenarios, taken as a proxy of market pressure for new land. It defines the total area demanded for each land use type at each simulation year

APPENDIX B - MODEL LOCAL FOR SÃO FELIX/IRIRI

The Model based on representative agents São Felix do Xingu (see, Figure B.1).

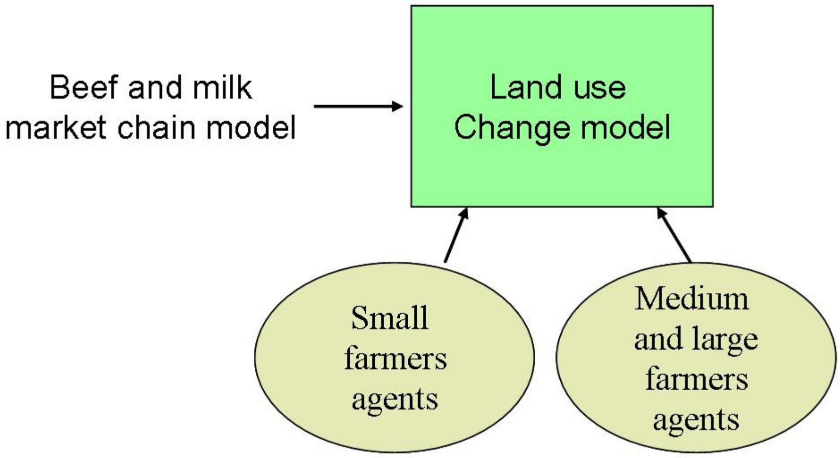

Figure B.1- Model for São Felix/Iriri.

B.1 Spatial model

Iriri region (50.000 km^2) with 1 km^2 cells, attributes related to deforestation, biophysical, special areas and accessibility factors.

Land cover attributes: *forest, deforest.*

Biophysical and socio-economic factors: distance to roads, connection to local industries, settlements and protected areas, existence of large areas, pressure for change (regional market pressure), local control policies (local scenario control).

B.2 Temporal model

From 1997 to 2025, yearly.

B.3 Analytical model

It is an agent based deforestation model. The representative agents act in the same space. Rules based on expert knowledge for two types of actors (small and large famers). Small settlers favour proximity to roads and urban centers. Large farmers prefer large pieces of inexpensive land, not necessarily close to roads.

In this model, the demand is an exogenous variable for the model, which was calculated separately as a proxy of market pressure for new land. That demand defines the total area demanded for each land use (deforest) at each simulation year.