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# Landscape Change and Land-Use/Land-Cover Dynamics in Rondônia, Brazilian Amazon

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# LANDSCAPE CHANGE AND LAND-USE/LAND-COVER DYNAMICS IN RONDÔNIA, BRAZILIAN AMAZON.

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To Claudia and my family

# LANDSCAPE CHANGE AND LAND-USE/LAND-COVER DYNAMICS IN RONDÔNIA, BRAZILIAN AMAZON


## ABSTRACT

Deforestation and colonization processes within the Brazilian Amazon have attracted substantial attention since the early 1970s. The phenomenon has been associated with issues related to global change, alteration of biogeochemical cycles, land-use/land-cover (LULC) dynamics, and biodiversity losses. This dissertation focuses on an area of approximately 3,000 $km^2$ within the State of Rondônia in western Amazon. Two adjacent settlements of similar age, similar biophysical features, and similar assets among colonists were compared to assess the role of their different architectural and institutional designs in LULC dynamics and landscape change. Vale do Anari was planned as an orthogonal road network system. The majority of Rondônia was colonized following this scheme. Machadinho d'Oeste was designed with attention to topography in laying out the grid of farm properties and included communal reserves with right-of-use to local rubber tappers. Field research was undertaken in conjunction with the use of multi-temporal remotely sensed data (1988-1998), GIS integration, and landscape ecology methods. The results indicate that the communal reserves play an important role in maintaining lower levels of fragmentation in Machadinho, where 66% of forest cover remained in 1998 (after 15 years of colonization), in comparison with just 51% in Anari. Without the reserves, forest cover in Machadinho is also 51%. Although analyses at the property level showed that the area deforested per property per year is the same in both settlements for the entire time period of study, in Anari the rate of deforestation was lower before 1988 and higher between 1994 and 1998. Also, pasture conversion is more significant in the fishbone scheme of Anari. Analyses of landscape structure confirmed that Machadinho is less fragmented, more complex, and more interspersed. The combination of privately based decisions for the properties and community-based decisions for the reserves clearly indicates that this architectural and institutional design can produce positive social and environmental outcomes. By comparing different settlement designs, this dissertation contributes to the rethinking of colonization strategies in the Amazon.

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## PREFACE

When I was a kid I had a dream. I wanted to buy the entire Amazon, so I could preserve it. Time passed by and my dream did not come true. Neither was I able to buy the Amazon nor was it entirely preserved. On the contrary, I decided to pursue an academic career, and the money necessary to pay for that enormous region went to other hands. But I kept my interest in understanding the region and its paradoxes. As a researcher at the Brazilian Agricultural Research Corporation (EMBRAPA), I had numerous opportunities to visit and study the Amazon, delimiting the first Extractive Reserve decreed in the region (Alto Juruá, Acre), participating in the Land Zoning of the State of Tocantins, studying the ecological and spatial dynamics of grasshopper populations in Mato Grosso, and following the trajectory of production systems in northeastern Rondônia. More recently, at the Anthropological Center for Training and Research on Global Environmental Change, ACT-Indiana University, I had the opportunity to work with other Amazonian sites, particularly Tome Açu and Bragantina, both in Pará State.

This trajectory came along after a master thesis about the Fernando de Noronha Archipelago, a set of islands totaling 20 $km^2$ in northeastern Brazil. In that work, I used aerial photos, field surveys, GIS, and ecological cartography to characterize the area in terms of its biophysical aspects as well as alterations in ecological systems produced during its history of occupation. The Archipelago has since become a National Park, and the results of my work have been used to subsidize management plans within the islands.

During my thesis research, I was already working at EMBRAPA and involved with the projects mentioned above. From the small islands of Fernando de Noronha to the huge areas of Amazônia, my attention was always related to the spatial heterogeneity of landscapes, particularly when altered by human action. Moreover, I became very attracted to the importance of comparative studies and their application to policy making and development plans.

When I first met Professor Emilio Moran in 1996, he was teaching a course on human ecology at the Brazilian Institute for Space Research (INPE). By that time, I already had a dissertation project in mind, focused on comparative analysis of landscapes in Amazônia. Early discussions with him brought to surface the importance of maintaining control over some variables during a comparative research while searching for significant differences among the cases being compared. The settlements of Machadinho d'Oeste and Vale do Anari in the State of Rondônia were then selected for the study. They are adjacent to each other and about the same age, and have similar biophysical features within their landscapes and similar assets among colonists. However, the role of their different architectural and institutional designs in producing distinct land-use/land-cover outcomes and changes in landscape structure were as yet unveiled.

By the beginning of 1997, I was granted with a scholarship by CAPES (Program for the Advancement of Education) and approved for the doctoral program at Indiana University. The coursework as well as the research experience at ACT allowed me to integrate GIS, remote sensing, and spatial and landscape structure analysis to address the questions proposed by this dissertation. Moreover, institutional analysis on the human dimensions of landscape change provided complementary understanding of the colonization processes within the study area. Of course, none of these tasks would have been possible without fieldwork, when gathering data was not just a part of the project, but an enlightening experience.

Even though I cannot realize my earlier dreams, I hope this dissertation contributes an impartial debate for the sake of the dreams of the Amazonian people.

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- ACT - Anthropological Center for Training and Research on Global Environmental Change, Indiana University, the place where I learned so many things in so little time
- CIPEC - Center for the Study of Institutions, Population, and Environmental Change, Indiana University, which funded fieldwork in Rondônia through the National Science Foundation grant SBR-9521918
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- A special thanks goes to my family in Brazil, which always makes me feel I am not alone and with whom I learned that 'the strength of a man is not measured, yet.'
- Last but not least, thanks to Claudia, my companion, soul mate, and friend, for her love, kindness, and character. Claudia has looked deeply into my being and has made me a better person. For the moments we have shared and the moments we will still enjoy together, I thank you.

## LIST OF ACRONYMS

ACT - Anthropological Center for Training and Research on Global Environmental Change, Indiana University

CAPES - Fundação Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (Federal Agency for Post-Graduate Education)

CEPLAC - Comissão Executiva do Plano da Lavoura Cacaueira (Executive Commission for Cacao Crop Implementation)

CIPEC - Center for the Study of Institutions, Populations, and Environmental Change, Indiana University

EMATER - Associação de Assistência Técnica e Extensão Rural do Estado de Rondônia (Rondônia State Agency for Technical Assistance and Rural Extension)

EMBRAPA - Empresa Brasileira de Pesquisa Agropecuária (Brazilian Agricultural Research Corporation)

IBAMA - Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis (Brazilian Institute of Environment and Renewable Natural Resources)

IDARON - Agência de Defesa Sanitária Agrossilvopastoril do Estado de Rondônia (Agency for Agrosylvopastoral Sanitary Defense of the State of Rondônia)

INCRA - Instituto Nacional de Colonização e Reforma Agrária (Brazilian Agency for Colonization and Agrarian Reform)

LULC – Land use/land cover

PLANAFLORO - Plano Agropecuário e Florestal de Rondônia (Rondônia Natural Resource Management Project)

POLONOROESTE - Plano Integrado de Desenvolvimento do Noroeste do Brasil (Northwestern Brazil Integration Development Program)

RO - Rondônia

SEDAM - Secretaria de Estado do Desenvolvimento Ambiental (State Office for Environmental Development)

SPEA - School of Public and Environmental Affairs, Indiana University

# CHAPTER 1

# MOTIVATIONS FOR THE STUDY OF LANDSCAPE CHANGE IN RONDÔNIA, BRAZILIAN AMAZON

*'O amanhecer em uma terra distante*
*pode ser o crepúsculo diante*
*de nossos olhos'*

## 1.1 - INTRODUCTION

Sometimes the easiest way to say what a dissertation is about is to emphasize what it is not about. This dissertation is not about vegetation ecology, remote sensing, land use/land cover (LULC), landscape metrics, or human dimensions of landscape change. Although these topics are present throughout the research, they are used as lenses focusing on different aspects of the Amazonian colonization rather than as ultimate objects of study. The investigation of trajectories and consequences of occupation in a region known mostly by its agroecological failures than by its successes is appealing. In recent years, this challenge became even more fascinating, as the human dimensions of environmental change started to be recognized not just as a new field of research, but as a way of understanding ecological causes, consequences, and outcomes. These latter three terms portray a dynamic character and lead to responses of both people and the environment.

The analyses described in this dissertation represent an effort to better understand how colonization processes within the Brazilian Amazon affect landscape change and LULC dynamics. More specifically, it focuses on one area of the well-known State of Rondônia, a land of change and challenge that deserves an impartial approach. Throughout the pages of this work, Rondônia is not considered just a 'frontier', as the Amazon is not just a 'jungle.' Anacondas, myths, and catastrophic views we leave for the poets. Explicit boundaries were defined to control the research questions and the search for answers. The rationale behind this initiative was to understand that a remote region is not just an object of study, but also a home for millions of people coping with a heterogeneous and diverse environment on a daily basis.

Landscape transformation and its implications to problems such as global change, biogeochemical cycles, LULC dynamics, deforestation, and biodiversity have become central issues in environmental science (Turner et al. 1994, B. Turner et al. 1995, Kaimowitz and Angelsen 1998, National Research Council 1998). As a consequence, new ecological theories (Wilson 1998), modern methods to study spatial dynamics (Costanza et al. 1993, M. Turner et al. 1995) and many applications to natural resources planning and monitoring have taken place (Goodland et al. 1993). To address the process of landscape change by using a spatial-temporal integrative methodology is highly important to regions such as the Brazilian Amazon, where deforestation has attracted international attention (Moran 1993a, Skole and Tucker 1993). The integration of remote sensing data, GIS techniques, and landscape ecology methods have emerged as a promising area to help us understand deforestation dynamics and land use, and their ecological and social impacts (Mausel et al. 1993, Lambin 1997, Liverman et al. 1998).

Within the Amazon Basin, some particular areas offer great potential for such studies. One of these areas is located in the State of Rondônia, where deforestation rates have been the highest in the Amazon during the last twenty years (Dale and Pearson 1997, Alves 1999). A number of studies about colonization projects in the Brazilian Amazon have taken place (Moran 1981, Smith 1982, Uhl and Vieira 1989, Schmink and Wood 1992, Browder and Godfrey 1997, Miranda et al. 1997). The processes of deforestation associated with human occupation in the region have also been studied. Research has focused on the amount and rate of deforestation (Malingreau and Tucker 1988, Skole and Tucker 1993, INPE 2000) and on social, economic, and ecological processes related to the phenomenon (B. Turner et al. 1993, Brondizio et al. 1994, Moran 1994, Walker et al. 2000). Understanding LULC changes to achieve a sustainable strategy is a matter of growing interest to communities in the Amazon, to regional and national policy makers, and to all those concerned with the consequences of deforestation (Goodland et al. 1993, McCracken et al. 1999). However, no comparative research has been made about the role of different settlement designs on landscape change and fragmentation.

In Rondônia, the demand to settle migrants induced the establishment of rural development projects. Often these projects include an orthogonal road network known as 'fishbone' and have been implemented without considering the environmental constraints and landscape characteristics of each region. The settlement called Vale do Anari (Anari) is a typical example. During the early 1980s, the Brazilian Agency for Colonization and Agrarian Reform (INCRA) tried a new model of settlement, in which the road network and the property grid follow the watershed topography and communal forest reserves were allocated for local populations. This settlement is called Machadinho d'Oeste (Machadinho). The study area totals approximately 3,000 $km^2$ and is located approximately 400 km from Porto Velho, the capital of the State, encompassing both Anari and Machadinho. A period of ten years (1988-1998) was defined for the satellite image-based analysis, so the trajectory of land occupation could be followed. To carry out the comparative study between the two designs of colonization (i.e., fishbone and topography-oriented designs), the environmental setting is an ideal laboratory to test hypotheses about the role of settlement architecture and institutions on LULC dynamics and landscape structure change.

In this sense, this dissertation contributes to two gaps in research about the Brazilian Amazon. First, it attempts to address LULC change at an intermediate scale, between the farm and the region, making the necessary link between local and regional processes. Second, it is concerned with colonization settlements in Rondônia, in an area at a transitional stage of occupation; that is, they are not along Highway BR-364, where older farms dominate the landscape, nor in marginal zones of the State, which are still without access and infrastructure. In addition, the research uses an innovative, comparative approach. Two adjacent settlements of similar age, with similar biophysical features in their landscapes and similar assets among colonists, were compared to assess the role of their different architectural and institutional designs in LULC dynamics and landscape change. Thus, this dissertation is about the study of trajectories of change within Amazonian landscapes under distinct yet concurrent regimes of colonization.

## 1.2 - HYPOTHESES AND RESEARCH QUESTIONS

Preliminary studies in Rondônia suggest that settlement design may affect human land-use preferences and influence ecological dynamics such as rates of deforestation and secondary succession (Miranda et al. 1997, Batistella et al. 2000, Batistella and Castro 2001). Based on these indications, three hypotheses were formulated for this study.

**Hypothesis 1:** The fishbone settlement design of Anari leads to faster deforestation than Machadinho's architecture based on topographic features and including communal forest reserves.

**Hypothesis 2:** Landscape fragmentation is higher in the fishbone settlement of Anari.

**Hypothesis 3:** Institutional arrangements accounting for different social actors and allowing governance over natural resources to local actors in Machadinho produce positive environmental and social outcomes.

The study of LULC dynamics and landscape change in Machadinho and Anari represents a rare opportunity for a controlled comparison between types of settlement architectural and institutional designs in areas of relatively recent colonization in the Brazilian Amazon. Because Machadinho and Anari are adjacent to each other, the study area provides a quasi-experimental approach. As shown in the following chapters, the assessment of the colonization impact within these two distinct settlements produced accurate information about landscape structure and LULC change. If the hypotheses presented above are confirmed, the study will create the challenge for rethinking settlement implementation strategies in the Amazon. Producing the elements for such debate is the main goal of this dissertation.

Differences between occupation design and strategies in Machadinho and Anari suggest that institutional arrangements, human land-use preferences, and ecological dynamics are also distinct. This dissertation seeks to use methods for the quantification of landscape heterogeneity and change for the two settlements, searching for answers to the following questions:

1. How can the study of vegetation structure inform LULC classifications based on satellite imagery and field data? (Chapter 3)
2. What are the colonization trajectories and their impacts through time in terms of LULC dynamics? (Chapter 4)
3. What are the rates of deforestation, secondary succession, and farmland conversion? (Chapter 4)
4. How does landscape structure vary in each settlement across time? (Chapter 5)
5. How are the human dimensions of landscape transformation depicted across the spatial and temporal scales of analysis? (Chapter 6)

In order to answer these questions, satellite imagery and bibliographic, cartographic, and field data were integrated. Multi-temporal Landsat TM images were used for characterization and analysis of landscape change and LULC dynamics. The integrated methodological strategy combined image processing, vegetation structure data analysis, interviews with local people, GIS techniques, landscape metrics computation, and institutional analysis. The topics encompassed by each chapter are briefly described below.

## 1.3 - WHAT TO EXPECT

The itinerary followed by this dissertation reflects the multi-disciplinary character of the research. Each chapter is devoted to a topic supporting the comparative analysis between the two settlements in Rondônia. Every chapter contains a brief literature review on the topic, the methodological approach, results, and a discussion about the findings. Chapter 2 describes the environmental and cultural setting for the study. Machadinho and Anari are put in the context of the Amazon region colonization, and its heterogeneity and complexity. The reasons for the choice of these two settlements as an opportunity for a comparative study are also discussed. An extensive description of the study area and both settlements is included, using background data to describe the geographic locations, administrative boundaries, settlement architectures, climate, geology, geomorphology, hydrology, soils, vegetation, and fauna. Main rural production systems and calendars are also described to indicate people's activities, time allocation, and labor.

Chapter 3 addresses the vegetation structure of forest and secondary succession stands present in the area. Data collected in the field supported the creation of a database including vegetation variables such as number of individuals, height, diameter at breast height, density, basal area, and biomass. Trees, saplings, and herbaceous vegetation are described in terms of their importance in defining stages of regrowth, which are fundamental for the understanding of LULC dynamics within the landscapes. Moreover, spectral data referring to the same sites where vegetation data were collected were also integrated into the database. Statistical analysis indicated the potentials and limitations of using Landsat TM data to identify secondary succession stages. A discussion about the role of vegetation structure and spectral analysis for the study of LULC dynamics in colonization areas of Amazônia is carried out. Recent trends regarding this research topic are also listed.

Chapters 4 and 5 include the core quantitative analysis of LULC dynamics and landscape change carried out in this dissertation. In Chapter 4, remote sensing and GIS techniques are used to evaluate the impact of colonization within the settlements on a multi-level and multi-temporal basis. After describing the general spatial trends in LULC, other specific questions are addressed. Transition matrices between the LULC classifications produced results about distinct agroecological processes, such as deforestation, production, and secondary succession. In Machadinho, analyses including and excluding the communal reserves are carried out to evaluate their importance within the landscape. The investigation of LULC processes within buffers along roads in both settlements provides other elements for discussion regarding the spatial patterns of colonization. Property-based analysis completes the investigation about LULC in

Machadinho and Anari. A discussion about the colonization impact includes methodological and operational issues, main findings and their meanings, and the trajectories of LULC within the study area.

Chapter 5 takes advantage of the LULC classifications produced in Chapter 4 to analyze the study area from another perspective. Landscape structure rather than LULC is the focus of this chapter. Selected metrics measuring structure of landscapes, classes, and patches are used for this purpose. Each settlement is considered as one 'landscape.' Classes were recoded from the LULC categories and include forest, secondary succession, and production lands. Patches are individual areas (polygons) composing the landscape. Metrics concerning area, patch density, size and variability, edge, shape, core area, diversity, interspersion, and juxtaposition were calculated and discussed. Besides focusing on the meaning of results for each settlement, the chapter also addresses unresolved problems in landscape spatial data analysis.

In Chapter 6, an institutional-based approach is taken to analyze the human dimensions of landscape change in Rondônia. A historic ecological perspective is used to discuss the structure of rules and incentives affecting land-use decision making in Machadinho and Anari. The underlying processes of landscape change are also analyzed for the settlements' implementation and consolidation phases.

In the last chapter, concluding remarks are addressed. Questions and hypotheses are discussed based on the main findings of the dissertation. Further studies are also suggested in search of better interactions among actors and the environment in the Amazon.

# CHAPTER 2

# ENVIRONMENTAL AND CULTURAL SETTING: THE OPPORTUNITY FOR A COMPARATIVE STUDY

*'Aqui vêm os iludido e vão os arrependido'*

## 2.1 - AMAZÔNIA: A LAND IN SEARCH OF ITS DESTINY

The Amazon River and its affluents form the greatest river system on Earth. The Amazon Basin is bordered by the Andes and the massifs of the Guianas and Central Brazil (Orinoco and Paraná Basins), draining 7 million $km^2$ of land (Sioli 1984). The Brazilian portion of this immense territory is about 5 million $km^2$ and encompasses several ecological systems (Goulding et al. 1996) (Figure 1).

The early discovery and occupation of the Amazon was facilitated by the existence of numerous waterways and a dense river system, which later scientists and explorers also followed. In the mid-1900s a comprehensive picture of the Amazonian ecosystem began to be formed (Sioli 1984). Up to this period, the heterogeneity of the region was obscured by the notion of a vast and homogeneous 'jungle.'

Early studies on the region tried to explain the apparent lack of social complexity by the existence of 'limiting factors,' which would be responsible for relatively low population densities (Behrens 1992). At the risk of being overly simplistic, the rationales behind these debates are briefly mentioned, as extensive literature has already been published about this subject. The classical paper by Meggers (1954) suggested that levels of social complexity are limited by the agricultural potential of soils in the Amazon. Others have argued that protein sources, not necessarily the production of highly caloric crops, has limited population densities throughout the region (Lathrap 1970, Gross 1975, Ross 1978, among others).

Later studies have challenged these views. Archeological evidence has shown the existence of complex prehistoric cultures in the Amazon (Myers 1973, 1989, Roosevelt 1987, 1989a, 1989b). Agronomic and biophysical surveys have found a diversity of soils and land resources, including areas suitable for large-scale agriculture (Falesi 1974, Cochrane and Sánchez 1982, Nicholaides et al. 1984). Beckerman (1979) and Chagnon and Hames (1979) have shown that, in many Amazonian groups, the amount of protein consumed per capita often equals or exceeds amounts consumed in modern Western societies. And, more recently, the process of colonization itself has made it clear that a much more complex picture has to be drawn if we want to understand the potential of the Amazon for development (Moran 1981, 1983, Becker 1982, Schmink and Wood 1984, Bunker 1985, Hecht and Cockburn 1990, Stewart 1994, Almeida 1996).

In general, the trajectory made possible by limiting factors commented above depends on the ability of human cultures to adapt to heterogeneous environmental conditions and to manage these conditions in order to achieve at least the needs of subsistence (Gross et al. 1979, Moran 1982). But the subsistence assumption has also been challenged by the intensification of production systems, as cultural aspects interrelate dynamically with population growth and market demands (Boserup 1965, Netting 1977). Together with the theoretical debates about the potentials and limitations of the Amazon, several regional and local processes were taking place due to governmental, private, or spontaneous initiatives of colonization.

The processes of colonization in the Amazon have attracted a great deal of attention in recent years, mainly because of the deforestation associated with land appropriation. Large-scale deforestation began in the early 1960s with the relocation of the national capital to Brasília and the construction of a network of roads connecting the region with the south and the northeast portions of the country: Belém-Brasília Highway, Transamazon Highway, Cuiabá–Porto Velho Highway (BR-364), Cuiabá-Santarém Highway, and the *Perimetral Norte*, among other ancillary roads (Moran, 1993b). *Calha Norte* and *Avança Brasil* represent the more recent versions of road development projects for the region. During and after the Program of National Integration (PIN), road building was generally attached to development and colonization projects, international funding by the Inter-American Development Bank and the World Bank, credit lines provided by the Amazonian Bank (BASA) and the Amazonian Development Agency (SUDAM), and establishment of rural settlements by the Brazilian Agency for Colonization and Agrarian Reform (INCRA) (Kohlhepp 1984, Moran 1984, Schmink and Wood 1992, Comision Amazonica de Desarrolo y Medio Ambiente 1993, Browder and Godfrey 1997). In the words of Sioli (1984), "...former human interventions in the Amazonian ecosystem were small sized while the modern development plans and enterprises are quantitatively and qualitatively of enormous dimensions. They concern the terrestrial as well as aquatic reaches of the region and consist, as a first step, in total or selective deforestation."

The Amazonian debate has then shifted from limiting factors to the determinants of deforestation. Human and environmental dimensions of the process are also under investigation. Methodological techniques to address these dynamics at a broad scale are becoming available. Estimations about the rate and extension of deforestation, once based on personal perspectives or partial approaches of extrapolation, are now being done with higher accuracy. Studies on vegetation regrowth are showing alternative trajectories in land-use/land-cover (LULC) change. Besides possible deforestation causes, consequences and responses of the process are also being addressed, as a way to suggest scenarios for the future after the learning of the past. Currently, the effects of Amazonian deforestation on global change processes such as atmospheric carbon accumulation are on top of the list. Through a critical literature review, it is evident that the scientific community is now facing similar problems in estimating carbon releases as it faced in the past with quantification of deforestation (Fearnside and Guimarães 1996, Houghton et al. 1998, Salomão et al. 1998). It is virtually impossible to touch on all the issues related to the Amazonian deforestation from the global to the local perspective through the pages dedicated to this chapter. Therefore, the following discussion was restricted to the dynamics of frontier occupation in the Amazon, an already very complex and multi-tiered subject.

After overcoming methodological problems to estimate the amount and rate of deforestation in Amazônia, remote sensing–based studies have shown that the region has been cleared at approximately 0.5% per year since the early 1980s (Malingreau and

Tucker 1988, Skole and Tucker 1993, INPE 1999). Other studies have discussed the social, economic, and ecological processes involved during deforestation dynamics (Conant et al. 1983, Brondizio et al. 1994, 1996, B. Turner et al. 1993, Moran et al. 1994, Gerber 1997).

Slowly, scientific studies in several fields started to recognize a more complex picture (Moran 1993b, 1995). On the one hand, some basic findings were generalized for the entire region as 'unifying principles': a general scarcity of nutrients in the soil (Sombroek 1984); a tightly closed, continuous recycling of nutrients within the biomass of the forest (Herrera et al. 1978, Jordan 1989); extreme diversity of the biota (Prance and Lovejoy 1985); and the regional recycling of a large part of the rainwater, crucial for the maintenance of a climate affected by pluvial processes (Schubart and Salati 1982, Dickinson 1987).

On the other hand, the heterogeneity of such a broad territory was recognized in several fields. Among other regional elements, Amazonian river types were differentiated into whitewater (e.g., Solimões-Amazonas, Madeira), clearwater (e.g., Tapajós, Xingu), and blackwater (e.g., Negro) (Sioli 1984). Sombroek (1984) divided soils into three major categories: well-drained soils of the uplands, imperfectly drained soils in the sedimentary parts of the region, and poorly drained soils in *várzeas* and *igapôs*. Cochrane and Sanchez (1982) provided a more detailed classification and distribution of the Amazonian soils: oxisols (45.5%), ultisols (29.4%), entisols (14.9%), alfisols (4.1%), inceptisols (3.3%), spodosols (2.2%), mollisols (0.8%), and vertisols (0.1%). Gash et al. (1996) and Fisch et al. (1998) revised the regional climate and possible effects of deforestation. Braga (1979), Pires (1984), and Pires and Prance (1985) have described several vegetation types. A myriad of papers have addressed the human dimension behind the environmental heterogeneity (Meggers 1974, Moran 1974, Hames and Vickers 1983, Moran and Herrera 1984, Balée 1989, Posey and Balée 1989, Sponsel 1992).

As a consequence of the increasing knowledge about the region, different development schemes and production systems were described and discussed (Anderson 1990). Among others, shifting cultivation (Beckerman 1983, Denevan et al. 1984, Dufour 1990), agroforestry (Hecht 1982, Nepstad and Schwartzman 1992, Smith et al. 1996, Brondizio and Siqueira 1997), cattle ranching (Falesi 1974), and agriculture with fertilization inputs (Cochrane and Sanches 1982, Nicholaides et al. 1984) are included.

Today, a more reasonable way of thinking about the occupation of the Amazon shifted from 'deforest or not deforest' to 'where, how, and how much to deforest' (Mahar and Ducrot 1998). Embedded in this dynamic process, several modern techniques of environmental assessment were developed. Integration of remote sensing and geographic information systems (GIS) brought the spatial discussion into a broader view of the Amazonian development (Malingreau and Tucker 1990, Conant 1994, Adams et al. 1995, Foody et al. 1996, Hall et al. 1996, Ahern 1998, Moran 1998, Alves 1999). Also, more detailed LULC classifications informed by field data are emphasizing the function of secondary regrowth in Amazonian landscapes (Li et al. 1994, Moran et al. 1994, Lucas et al. 1998). While the deforestation process occurs, secondary vegetation also exists. Thus, issues such as vegetation restoration and succession dynamics should be part of the investigations about land-cover trajectories in the region (Moran et al. 1996).

All these contributions to the knowledge of such a large and diverse region have provided new elements for a better understanding of the colonization process. If we still cannot have a reasonable hope that the rich biodiversity of Amazônia will be saved for future generations, at least we can look at the past and begin to correct the misuse of certain analyses and generalizations. Through this critical approach it may be possible to address complex issues, such as the study of landscape transformation in the State of Rondônia.

## 2.2 - THE FATE OF RONDÔNIA: RURAL DEVELOPMENT VS. LANDSCAPE TRANSFORMATION

Cycles and interests have affected the history of Rondônia. This western portion of the Amazon was originally populated by Tupi-speaking Amerindian societies (Coimbra 1989). By the 1700s, the Portuguese engaged in several expeditions to the region, when occupation was concentrated along the Madeira, Guaporé, and Mamoré Rivers. During the 18th century, Rondônia received its first migration waves, due to gold mines found along the Guaporé River. By the end of the century, mines were abandoned and the local economy faced a period of stagnation until the rubber boom began in the late 1800s. Stimulated by the high prices in the international market, northeastern populations migrated to Rondônia and penetrated deeper into the forest to establish an extractivist economy based on rubber tapping (Rondônia 1981).

By the beginning of the 20th century, the Madeira-Mamoré railway was inaugurated. It connected the town of Guajará-Mirim, located by the Mamoré River, to Santo Antônio (today Porto Velho, the capital of Rondônia) on the Madeira River. By that time, the Brazilian government had launched initiatives to integrate the area with the rest of the country. Telegraphic lines were built, connecting Cuiabá, the capital of Mato Grosso, to Santo Antônio (Porto Velho) and the trails opened for this purpose allowed the establishment of villages. Rondon, for whom the State was later named, led the operation. In 1943, the area was designated 'Federal Territory,' and the highway Cuiabá-Porto Velho (BR-364) was opened. During that same time, rubber extraction had regained importance due to the mobilization for World War II. After the war, the activity declined and was replaced by to diamond extraction during the 1950s and cassiterite mining during the 1960s. By the end of this period, access to different portions of the territory and the demand for development required massive investments and brought about other important changes.

The recent history of Rondônia is embedded in this complex scenario. Following the national strategy of regional occupation and development, colonization projects initiated by the Brazilian government in the 1970s played a major role in LULC change throughout the State (Moran 1984, Fearnside 1989, Schmink and Wood 1992, Matricardi 1996). These projects were implemented to accommodate landless farmers coming from southern Brazil. Two large development projects are particularly relevant, both funded by the World Bank (Pedlowski 1998). The Northwestern Brazil Integration Development Program (POLONOROESTE, 1981-1985) was responsible for paving the BR-364, the main road crossing the State, which improved access in the southeast-northwest direction (World Bank 1987). The Rondônia Natural Resource Management Project

(PLANAFLORO, 1992-1999) funded, among other things, the elaboration of a land zoning for the State (World Bank 1992).

In Rondônia (Figure 2), colonization projects were often designed based on an orthogonal road network, commonly called 'fishbone.' The existence of BR-364 as the backbone of this network drove rural occupation and LULC change into the State. These projects were generally implemented with no consideration for environmental constraints within the landscape or access at the local scale. The combination of a better road infrastructure and huge migration waves from the south with the lack of land-use planning within the settlements was thought to have produced the highest deforestation rates in the Brazilian Amazon during the last twenty years (Alves 1999, Dale and Pearson 1997).

Together with land occupation and landscape transformation, new development trajectories also occurred. Logging has always been associated with road building and land clearing. Cattle ranching still occupies the largest portion of the deforested area (Alves et al. 1999), but, despite earlier predictions, less than 25% of the State has been deforested (Rondônia 1998a). Although most articles written about the State emphasize just the conversion of forest to pasture (60% of the deforested area), Rondônia is the 4$^{th}$ State in terms of national coffee production (Matricardi 1996). Batista (1999) makes an up-to-date socioeconomic analysis based on census data. Rates of population growth have declined drastically during the last decade, due to a decrease in migration and in fertility. Rondônia's gross State product is the 3$^{rd}$ in the north region, after Pará and Amazonas. Agriculture and cattle ranching account for 15%, industry for 15.2%, and services for 69.3%. The largest portion (85%) of all farms are family-managed and have less than 100 ha each. Of the total population, 70% live in urban areas.

Distinct positive forces are present today besides the always-criticized government actions and private initiatives facilitating land speculation. Non-governmental organizations have had a relatively active voice during the land zoning process (Pedlowski 1998). Native communities such as the rubber tappers and indigenous people are having their reserves delimited (Olmos et al. 1999). Conflicts still happen everywhere as reserves are invaded by loggers and road builders, properties are taken over by speculators, county boundaries are still being created, the State government claims for development, and so on (Fearnside and Ferreira 1985). But emergent grassroots organizations are becoming more active in the development process. Also, selected studies about colonization in Rondônia have led to international pressure, national policies, and local initiatives for the preservation of large patches of forest throughout the State (Rondônia 1999a).

Recently, the government of Rondônia decreed the 2$^{nd}$ Approximation of the socioeconomic-ecological zoning (Rondônia 2000). Still obscured by legal obstacles to be effective, the land zoning determines areas with distinct status in Rondônia. The settlements studied in this dissertation — Machadinho and Anari — are assigned to 'areas of agricultural, agroforestry, and forestry' use (Figure 3). The settlements are located at the northeastern portion of the State, adjancent to the borders with Amazonas and Mato Grosso (Figure 4). Studies of farming systems and socioeconomic characteristics at Machadinho have suggested it is a singular model of colonization design (Miranda et al. 1997). Throughout this dissertation, LULC trajectories in each settlement are related to institutional and biophysical aspects underlying landscape transformation.

## 2.3 - WHY MACHADINHO AND ANARI?

The settlements of Machadinho and Anari were founded in the shadow of the emancipation of the State of Rondônia in 1981 when a dramatic population growth was taking place due to migratory waves. The colonization of the southern part of the State attracted a huge crowd from other Brazilian States, creating a demand for new settlement projects to accommodate the accelerating population increase.

Machadinho and Anari are adjacent to each other, and share similar features. They are located approximately 400 km from Porto Velho, the capital of the State, and present comparable biophysical characteristics at the scale of study, as described in the following sections of this chapter. In regard to their establishment, Machadinho and Anari were created by INCRA during the same period (early 1980s) and represented pioneer settlement projects in northeastern Rondônia.

Besides biophysical characteristics, an important commonality between the two settlements is related to the characteristics of initial settlers who shared similar personal traits and assets. The majority of colonists in Rondônia came from the southeast and south regions of Brazil, mainly from the States of Minas Gerais and Paraná (Millikan 1992). In the case of Machadinho and Anari, they were selected from the excessive group of applicants to earlier settlement projects, based on two sets of criteria: eliminatory criteria, including personal attributes of the candidate (i.e., age, conduct, and employment condition) and assets (i.e., income, other properties, and former applications); and classificatory criteria, including household age, family labor force, and farming skills.

The parcels handed to the settlers were about 50 ha each, half the size of other projects in the Amazon during that period. The reduction in parcel size was an attempt to accommodate the dramatic population growth in Rondônia (average of 16% per year between 1970 and 1980) (Rondônia 1996d). In sum, both settlements resulted from political pressure to accommodate landless migrants and settled households with similar socioeconomic characteristics who were granted land titles of similar parcel sizes.

Notwithstanding the similarities in some attributes, Machadinho and Anari had major differences in their architectural and institutional design. They were conceived under very distinct processes as far as farmers' incentives toward land-use decisions were concerned. They strongly differed in the implementation phase in regard to the landscape design and how infrastructure was provided and maintained during the consolidation phase. Anyone driving through the villages can easily observe the differences between the paved major streets in Machadinho with several stores and hotels and the gravel roads in the rural area, compared to the chaotic district of Anari, poorly served by services and infrastructure (Photos 1 and 2). The description underlying the characteristics of each settlement is presented below.

## 2.4 - THE LANDSCAPE IN MACHADINHO AND ANARI: BACKGROUND DATA

### 2.4.1 - Geographic Location, Boundaries, and Settlement Architectures

The settlements of Machadinho and Anari are parts of their respective municipalities. Located in northeastern Rondônia (Figures 2, 3, and 4), they are newer colonization initiatives than areas along BR-364 (Cuiabá-Porto Velho Highway). Furthermore, Machadinho and Anari are adjacent to the borders with the states of Amazonas and Mato Grosso, which may offer potentials and constraints for future conservation and development.

Figure 5 shows the areas including both settlements on a subset of a 1998 Landsat TM image. The adjancency of Machadinho and Anari highlights their different architecture, which was appealing for this comparative research. A cartographic representation of these two designs of colonization is presented in Figure 6. It is striking to compare the orthogonal road network and property grid of Anari with the more organic layout of Machadinho. The former had its roads and property lots laid out without regard to topography and the river network. The latter took into account these variables to allocate infrastructure features and communal forest reserves. Causes, consequences, and responses to landscape transformation and land-use preferences within these two localities so close but so distinct are discussed throughout this dissertation.

### 2.4.2 - Climate

Like the entire Amazon humid region, the State of Rondônia has an equatorial climate, characterized by high precipitation levels, low average annual temperature amplitudes but notable daily temperature amplitudes (Nimer 1989). However, the location of the State in southwestern Amazônia — at approximately $10^{o}$ south of the Equator — produces some distinct characteristics. Perhaps one of the most important differences is the occurrence of two well-defined seasons, with three dry months during the winter — June, July, and August (Figueroa and Nobre 1990). The climate in the study area follows this pattern, being classified as equatorial hot and humid, with tropical transition. According to Koppen's classification, the climate is *Aw*, with average monthly temperatures higher than $18^{o}C$ and a well-defined dry season (Rondônia 1998b).

The lack of meteorological stations with a reliable time series of data in Machadinho or in Anari impedes a more detailed and multi-temporal analysis of climatic variability for the settlements. The closest stations are located in Ariquemes and in the Jaru Biological Reserve, both approximately 80 km from the settlements. The following numbers are derived from analyses of the Jaru data for a period of 20 years (1977 to 1996) and publications about related research projects in Rondônia.

According to Fisch et al. (1998), the average daily solar radiation in Rondônia is 18.3 $MJ.m^{-2}.day^{-1}$ for the dry season and 17.1 $MJ.m^{-2}.day^{-1}$ for the wet season (see also Fisch et al. 1997, Gash and Nobre 1997). The annual average precipitation in Machadinho and Anari is 2,016.6 mm (Table 1). A recent study based on data interpolation for the available network of meteorological stations in the State provides a better gauge of the spatial variability of rainfall (Rondônia 1998b). A map from the study shows an increasing variation in precipitation from the south to the north of Rondônia, including Machadinho and Anari in a range of 2,200 mm to 2,500 mm of rainfall per year.

The annual average temperature is 25.5°C, with the average of maximum temperatures at 32°C and the average of minimum temperatures at 21°C (Table 1). The monthly averages of temperature are very constant throughout the year. Similar regularity occurs for the wind speed (average of 4.5 km/h) (Table 1), predominantly from the south from April to October and from NNE/NE from December to March. Monthly averages for air moisture range from 80 to 85%. These characteristics make the monthly potential evapotranspiration also very constant and, with exception for the dry months, the real and potential evapotranspiration are coincident (Shuttleworth 1998). The climatic diagram shows how each season's definition in the study area is a consequence of monthly precipitation variability rather than of temperature oscillations (Figure 7).

### 2.4.3 - Geology

From the geologic perspective, the State of Rondônia is located in the west portion of the Amazonian Craton in a single tectonic-metamorphic-magmatic domain, the Rondonian Province of San Ignacio (1.45 to 1.30Gy) (Rondônia 1998d). In this area, the Paleoproterozoic metamorphic basement is of medium to high degree, being recovered by:

- A meta-volcanic-sedimentary Mesoproterozoic group, affected by the Rondonian Orogeny;
- A sedimentary Neoproterozoic group;
- Paleozoic-Mesozoic sedimentary basins;
- Cenozoic deposits related to the drainage network and current morphology.

The Mesoproterozoic, Neoproterozoic, Paleozoic, and Mesozoic groups were deposited in successive extensional tectonic events of rifting, being limited by faults and commonly associated with volcanism (Rondônia 1998e).

The area including Machadinho and Anari is basically formed of Cenozoic deposits over the Pre-Rondonian Basement (Paleoproterozoic), the Pre-Rondonian anorogenic suites (Mesoproterozoic), and the Neoproterozoic groups. There are no Paleozoic-Mesozoic sedimentary basins in the area. A brief description of each group or formation, and lithological materials is given below, after compilation from Leal et al. (1978) and Rondônia (1998d, 1998e).

The Pre-Rondonian Basement is formed of gneisses, granulites, anfibolites, migmatites, and calc-silicate rocks. It is a group with medium to high metamorphic degree, constituted more than 1.6 Gy ago (Amazonian Craton), with low permeability and without hydrogeologic interest, except in zones of intense fractures.

The Pre-Rondonian anorogenic suites, formed 1.25 to 1 Gy ago, are plutonic bodies of varied nature (i.e., granites, rapakivi granites, gabbros, and anorthosites). They commonly have low metamorphic degree, low permeability, and low hydrogeologic interest.

The groups Palmeiral-São Lourenço, Prosperança, and Beneficiente, formed approximately 1Gy ago, represent the Neoproterozoic sectors in the study area. Their lithology includes orthoquartizites, arcosian arenites, conglomerates, tuffs, alkaline rocks, and silt or clay horizons. They present a higher hydrogeologic interest and medium to low permeability.

The Cenozoic superficial formations are of the Neogene-Quaternary periods and evolved with the relief as a consequence of tropical meteoric alteration and fluvial dynamics. Because of their detritic nature and the proximity of the sub-surface waters, they frequently present hydrogeologic interest. In general, the Cenozoic formations are 4 to 40 m deep. Two formations occur in the study area. The fluvial terraces and alluvial or colluvial Pleistocene sediments are materials formed by gravel, sand, silt, and clay with different conglomeratic levels but high permeability. The Quaternary-Neogene covertures form other terraces and alteration surfaces showing medium permeability. Some of these features may present laterization.

The relationship of these data to the study of landscape transformation and LULC dynamics in Machadinho and Anari will become clearer after the discussion about their geomorphology, hydrology, and soils, as the potential use of land is directly related to the characteristics of the geological substratum.

### 2.4.4 - Geomorphology and hydrology

Two important concepts have been used to characterize geomorphologic situations in the Amazon: morphostructural unities and morphoclimatic domains (Melo et al. 1978). Morphostructural unities are areas where the geologic conditions created erosive environments under clear control, however without corresponding exactly to the specific sense of geologic provinces (Ab'Säber 1970). Morphoclimatic domains define areas where the geologic influence were practically nullified by erosion systems affected by the soils' evolution and vegetation, under the control of climatic conditions (Ab'Säber 1971).

The delimitation of morphostructural unities cited below was based on the homogeneity of relief forms and their relative topographic locations (Melo et al. 1978). Machadinho and Anari are located in three main unities (Figure 8):

- Southern Amazon Dissected Highland: formed by dissected relief in crests with pronounced slopes, functioning as the residual relief. It includes mainly the southern portion of Anari;
- Occidental Amazon Lowered Highland: this is the largest morphostructural unity in the Amazon Basin and ends exactly at the western limits of the study area. A flattened area with sectors of mild dissection forming tabular interfluves, where the most important rivers have encased valleys, characterizes it.

- Meridional Amazon Interplateau Depression: this unity includes the largest portions of both settlements. It is characterized by a lowered surface, with an incipient drainage, which induces the relief dissection in hills and tabular interfluves.

In terms of the morphoclimatic unities, the study area is very homogeneous, being totally included in Dissected Plateaus and Depressions and Pediplaned Surfaces (Figure 9). The area shows varied relief, including dissected forms in hills, crests, and tabular interfluves, covered by Dense and Open Forest, which minimizes the erosive processes induced by climatic factors.

Three main basins are defined for the State of Rondônia: Guaporé, Mamoré, and Madeira. The latter includes the Ji-Paraná or Machado River sub-basin, which is the longest river in the State and drains both Machadinho and Anari settlements, flowing from south to north (Rondônia 1998f). The Machadinho and Anari rivers are both tributaries of the Ji-Paraná or Machado River. They drain an undulated terrain, which varies in elevation from 100 to 450 meters. Within the boundaries of the study area, the Machadinho River flows from the southwest to the northeast. Its main tributary, the Belém River, crosses the northern portion of the settlement. The Anari River flows in the west-east direction, crossing the Anari settlement in its southern portion. The boundary between the settlements coincides with Machadinho and Anari watershed boundaries. Both watersheds have a dendritic drainage pattern with incised valleys. Figure 10 shows the waterways and elevation ranges within the study area through a digital elevation model based on contour lines and the river network.

### 2.4.5 - Soils

Knowledge about soils should be one of the primary assessments before the establishment of a colonization project. However, detailed studies about this important biophysical variable have been rare before the arrival of colonists in the Amazon (Fearnside 1989). In Machadinho and Anari this pattern persisted. Only regional or exploratory descriptions of soils were available in the early 1980s not allowing the distinction of fertile or infertile soils at the scale of a settlement or property lot (Falesi 1974, Amaral Filho et al. 1978, Cochrane and Sánchez 1982, Sombroek 1984). Even the ecological zoning of the State produced results only at a very coarse scale (1:250,000) (Rondônia 1998g). The most detailed studies about soils at the local scale in the study area are Wittern and Conceição (1982) and, more recently, Bognola and Soares (1999). Their descriptions allow a general characterization about edaphic conditions in Machadinho and Anari. During fieldwork in 1999 and 2000, the characteristics for soil texture and color were confirmed. The paragraphs below summarize the characteristics of seven main soil types present in the area.

- YELLOW LATOSOL (Camargo et al. 1987); YELLOW LATOSOL Cohesive (EMBRAPA 1999); OXISOL (USA 1975)

It is a mineral soil, not hydromorphic, with a latosolic B-horizon, dystrophic, very deep (>200 cm), cohesive, permeable, well drained and very homogeneous, of very clayish texture, with low levels of total iron, $Al_2O_3/Fe_2O_3$ ratio higher than 7.0 and very acidic. The clay levels remain constant along the profile or increase slightly without, however, indicating a textural B-horizon. The transitions between horizons are diffuse, except from horizon A to B, due to the higher level of organic matter found in the former. Its color varies from brown-yellowish to yellow-brownish, yellow, and brown. The soils with latosolic B-horizon occur in places of mild topography, being therefore easily mechanizable. In their natural state, they are resistant to erosion due to the favorable physical conditions and topography. The main agricultural limitation is related to the low natural fertility, strong acidity, and high levels of exchangeable aluminum (saturation higher than 50%).

- RED-YELLOW LATOSOL (Camargo et al. 1987); RED-YELLOW LATOSOL Dystrophic (EMBRAPA 1999); OXISOL (USA 1975)

It is a mineral soil, with sequence of horizons A, Bw, and C, moderate A-horizon and unclear differentiation between horizons, because of the tenuous contrast and ample transitions between them. It is a clayish soil with very low base saturation, saturation for exchangeable aluminum higher than 50%, low cation exchange capacity in the clay fraction, very acidic, well drained, very porous, very permeable, levels of total iron usually between 7 and 15% and molecular relation $Al_2O_3/Fe_2O_3$ between 3 and 7. The Red-Yellow Latosol Dystrophic is also characterized by its high depth, low clay mobility, which denotes a small textural gradient, low silt/clay ratio, high flocculation degree, low percentage of dispersed clay in water and absence of primary minerals of easy decomposition. The Bw horizon is thick and generally presents colors varying from 4YR to 7,5YR, with values 4 or 5 and chromes 6 or 8. The structure presents porous and firm aspect, breaking in subangular and/or granular blocks. This soil type occurs normally in flat and undulated relief. As with the Yellow Latosol, its main agricultural limitation is related to the low natural fertility, strong acidity, and high levels of exchangeable aluminum in Machadinho and Anari. Both of these soils are used for pasture, annual, and perennial agriculture (coffee).

- DARK RED LATOSOL (Camargo et al. 1987); DARK RED LATOSOL Dystrophic (EMBRAPA 1999); OXISOL (USA 1975)

It is a mineral soil, not hydromorphic, with a latosolic B-horizon, dystrophic, very deep (>200 cm), cohesive, permeable, well drained, very homogeneous, and of very clayish texture. It is very similar to the Red-Yellow Latosol described above, differing mainly in the levels of $Fe_2O_3$, which produces a lower $Al_2O_3/Fe_2O_3$ ratio, generally between 1.7 and 2.5. It is a soil with low base saturation and low cation exchange capacity in the clay fraction. The sequence of horizons A, Bw, and C shows poor differentiation. It is also characterized by its low clay mobility, which denotes a small textural gradient, high flocculation degree, and absence of primary minerals of easy decomposition. The morphological characteristics do not vary significantly between horizons, having red-yellow or dark red colors, 5YR and 2.5YR. This Dark Red Latosol occurs normally in flat and undulated relief, associated to the red-yellow latosol and showing similar agricultural limitation and land use.

- RED-YELLOW PODZOLIC (Camargo et al. 1987); YELLOW ARGISOL Dystrophic (EMBRAPA 1999); ULTISOL (USA 1975)

This soil presents profiles with a sequence of horizons A, Bt, and C. It is deep or medium deep, not hydromorphic, clay of low activity, with moderate A-horizon and textural B-horizon, corresponding to the argillic horizon of the American Soil Taxonomy (USA 1975). The yellow shade has a stronger yellow than 5YR in the first 100 cm of the B-horizon (including BA). The A-horizon, with variable thickness of 10 to 30 cm, presents shades that generally vary from 7,5YR to 10YR. The texture varies from sandy to clay-sandy. The transition to the Bt horizon is generally flat and clear and, eventually, flat and gradual. The Bt horizon presents colors with shade varying from 6YR to 10YR, clayish texture, and the structure is weak to moderate. This soil type occurs in relief varying from mild to strongly undulated and is generally used for pasture in Machadinho and Anari. Its main agricultural limitation is related to the undulated topography, low natural fertility, and high acidity.

- DARK-RED PODZOLIC (Camargo et al. 1987); RED NITOSOL Eutrophic (EMBRAPA 1999); ULTISOL (USA 1975)

It is a mineral soil, with shade 2,5YR or redder and with high base saturation ($V > 50\%$) in the first 100 cm of the B-horizon (including BA). It is generally deep, rarely shallow, with moderate A-horizon and brilliant B-horizon, low clay activity and eutrophic. The soil is well drained and occasionally fairly drained and frequently associated with rock outcrops and, sometimes, with rockiness. The moderate A-horizon is between 10 and 30 cm thick, with shade varying from 2,5YR to 5YR, variable clayish texture and transition to B-horizon, normally flat and clear. The brilliant B-horizon, of variable thickness, presents red colors (2,5YR or redder), with predominantly moderate structure, and angular and subangular blocks. This soil type occurs generally in undulated areas. Land use is mainly coffee plantation and pasture in the study area. The most serious limitations of this soil are consequences of topography and the occurrence of rock outcrops and rockiness. Variations to alfisols also occur within these areas.

- *TERRA ROXA ESTRUTURADA* (Camargo et al. 1987); RED NITOSOL Eutroferric (EMBRAPA 1999); ALFISOLS (USA 1975)

It is a mineral soil, not hydromorphic, well drained, deep, with presence of a brilliant B-horizon, clay of low activity immediately below the A-horizon or within the first 50 cm of the B-horizon. Its color is 2,5YR or redder in the first 100 cm of the B-horizon (excluding BA). It originates, in the study area, from the alteration of basic rocks (diabase). Alfisols present clayish texture and are practically free of rockiness. The main variations consist of intermediate profiles looking like the Dark Red Podzolic soil, the difference being detected by higher levels of $Fe_2O_3$ (from 15% to 36%). Despite its high fertility, the limitation of this soil for agricultural purposes is related to its low levels of Phosphorus. The susceptibility to erosion is moderate. The erosion is facilitated mainly in areas of undulated or steep topography. The thinner the superficial horizon and bigger the difference of clay content between horizons A and B, the greater the susceptibility to erosion will be. The infiltration and water clamping capacity is good. The limitation for mechanization varies, depending on the relief and rockiness.

- PLINTOSOL (Camargo et al. 1987); PLINTOSOL ARGILLIC Dystrophic (EMBRAPA 1999); ALLUVIAL SOIL (USA 1975)

It is a mineral soil, with plintic or litoplintic horizon starting at 40 cm, or at 200 cm when immediately below the A or E horizon. It also may underly horizons with a pale color. The shades of this soil type vary considerably and are described in EMBRAPA (1999). The textural B-horizon is present. The alluvial soil has distinct granulometric composition, having low activity clays, slow or moderate permeability and being imperfectly drained. The morphologic features of the underlying layers to the A-horizon may vary a great deal, mainly in function of the water level height and the clay content. The A-horizon, well differentiated, presents variable thickness between 10 and 30 cm. Normally it is sandy, with low to moderate granular structure and with colors varying from 2,5Y to 5Y. The alluvial soil is located in flat areas, occurring also in small depressions, under undulated topography.

### 2.4.6 - Vegetation

The use of a classification system to address the biocomplexity of the Amazonian vegetation is not an easy task. Depending on the scale of analysis, one or another system may be satisfactory. Some publications have addressed the subject looking for regional differentiations by focusing on the entire Amazon Basin (Pires 1984, Pires and Prance 1985) or a specific State (Rondônia 1998h). According to these classifications, the State of Rondônia encompasses several vegetation formations, although the Tropical Open Forest type predominates (Table 2).

Forest formations occurring in Rondônia belong to the so-called tropical rain forests (Richards 1996). Tropical rain forests are the latest in a long line of forest biomes to be heavily altered by mankind. Closed forests of the wetter tropical climates are collectively described as tropical moist forests. Tropical rain forests occur where there is only a short dry season or none (Whitmore 1998). Their main characteristics include:

- Distribution: Neotropics (Central America, northwest South America, Amazon Basin, eastern Brazil near the Atlantic coast), Africa (Central-West) and Southeast Asia (Indo-Malayan region);
- Wettest of all vegetation zones; a month with less than 100 mm of rain is considered relatively dry;
- Temperature and light intensities are always high; rainfall is usually greater than 2,000 mm a year;
- Soils are generally infertile, weathered and poor in nutrients;
- The largest amount of nutrients in the ecosystem is contained in the phytomass;
- Litter decays quickly through mineralization and absorption by roots and mycorrhizae;

- Diversity is very high;
- The largest trees emerge above others; middle and lower layers form a dense canopy;
- Canopy leaves adapt to resist transpiration losses through the thick cuticle;
- The roots are shallow; giant trees are stabilized by large buttresses;
- Lianas exploit trees for support; epiphytes use trees for substrate;
- Distinct forest formations differ in structure and physiognomy;
- Forests consist of a mosaic of gap-phase, building-phase, and mature-phase formations;
- Two contrasting ecological species groups: climax species can germinate and establish seedlings below a canopy (below gaps), whereas pioneer species require full light (big gaps).

Machadinho and Anari are areas of relatively high homogeneity in relation to their original vegetation. Their forest formations follow the characteristics above. However, for the purpose of this description, it is more appropriate to focus on the uniqueness of each local vegetation formation. Four main types of tropical rain forests are found in the area, all of them belonging to the severe subtermaxeric bioclimatic sub-region (Barros-Silva et al. 1978, Rondônia 1998h):

- SUB-MONTANE DENSE TROPICAL FOREST, Sub-Region of the Low Mountain Chains of Southern Amazônia, Low Mountain Chains

The dense forest covers the evidences of basements formed by granites, gneisses, migmatites, and quartzites of several geological formations and of the crystalline basement (Rondônia 1998h). In sub-mountainous areas lower than 600 m it presents, according to soil depth, uniform cover or emergent trees. Its canopy is continuous and closed. Trees dominate the canopy, but they can also occur associated with palms in open valleys and lianas in hillsides and closed valleys (Barros-Silva et al. 1978). It has small spatial distribution in the study area, generally associated with more dynamic topography, such as the northeastern and southeastern portions of Machadinho and the north-central portion of Anari.

- ALLUVIAL OPEN TROPICAL FOREST, Alluvial Sub-Region of Amazônia, Terraces

This type of forest grows over shallow and poorly drained hydromorphic soils, in flat terrain up to 100 m high and in floodplains. The alluvial open forest has medium height, up to 30 m, and less than 5% of deciduous species. The canopy may be uniform with occasional emergent species. The understory is usually dense, with dominance of bushes and herbs. The density may be higher than 600 trees per hectare. In dystrophic soils, the density is higher but the average height of the trees decreases (Rondônia 1998h). The dominant physiognomy is the open forest with palms, such as the forest covering terraces of the Machadinho River. In such sites, trees are often covered by herbaceous lianas, giving the false impression of a liana forest (Barros-Silva et al. 1978).

- SUB-MONTANE OPEN TROPICAL FOREST, Sub-Region of Dissected Surfaces of High Xingu/Tapajós/Madeira, Dissected and Undulated Relief

These two forest types differ only in relation to their substratum (dissected or undulated relief). They are the most representative vegetation formation in both Machadinho and Anari, covering more than 80% of the entire study area before the colonization process took place. The dominant landscape is the open tropical forest with palms covering distinct topographic situations over the crystalline basement (Rondônia 1998h). The dominant soil is the red-yellow podzolic (ultisol), where forests of emergent trees, uniform canopy, bamboo, and lianas also occur. The understory in the forests with palms varies from open to medium, and, from medium to dense in the forests with lianas and forest with bamboos (Barros-Silva et al. 1978). In Machadinho, the sub-montane open tropical forest over undulated relief dominates almost the entire settlement, except at the sources of the Ananas River and in areas to the east of the Machadinho River, where the relief is dissected. In Anari, the sub-montane open forest over dissected relief is more spatially representative, dominating the western and southern portions of the settlement.

### 2.4.7 - Fauna

Landscape fragmentation and its consequences on Amazonian animal habitats have been discussed in several works (Prance and Lovejoy 1985, Dale et al. *Relating* 1994, Laurance et al. 1997). However, there are no data available on fauna resources for the study area. Because of the importance of this biological component on Rondonian landscapes, some comments may be appropriate.

The most recent faunal study covering the entire State is the diagnostic prepared for the second approximation of the socioeconomic-ecological zoning of Rondônia (Rondônia 1998c). Field data was collected for the occurrence of several groups, such as bees, disease vectors, agricultural pests, ictiofauna, herpetofauna, avifauna, and mastofauna. Trying to delimit zoogeographic zones for the State, the authors used the latter three groups as indicators of relatively homogeneous habitats. According to their classification, both Machadinho and Anari belong to a zoogeographic zone of high biodiversity, including endemic, endangered, and threatened species.

The settlements studied differ in terms of conservation management. Machadinho includes sixteen Extractive Reserves in distinct ecological sectors encompassing 33% of its territory. Anari design did not incorporate reserves. In this case, preservation depends solely on a federal rule, stating that 50% of each property lot should be maintained with its forest cover. Ecological consequences of these different strategies are addressed in the next chapters, through the study of LULC dynamics and landscape change.

## 2.5 - PEOPLE, TIME, AND LABOR: THE ANNUAL CYCLE OF RURAL PRODUCTION SYSTEMS IN MACHADINHO AND ANARI

The major actors transforming landscape in Machadinho and Anari are settlers, loggers, and rubber tappers. A critical discussion of their role in affecting LULC change is discussed in Chapter 6. This section describes how they allocate their time through the year, adjusting their activities to seasonality. Information to build this scenario was obtained from archival work and interviews with landowners, loggers, and rubber tappers during fieldwork. Several organizations related to these activities were also visited in 1999 and 2000: farmers' associations, logging companies, the local rubber tappers' association, extension and agricultural research agencies, the agrarian reform agency, governamental offices (e.g., county agricultural sections and banks), and non-governmental organizations. A general overview of farming and extraction activities is summarized in Table 3. The table shows only the most important products and activities.

- SETTLERS

Previous works have described how farming systems have been differentiated in the study area (Miranda and Mattos 1993, Miranda et al. 1997). The trajectory seems to go from an early stage of colonization with all kinds of initial experiences to a more homogeneous situation after a decrease in the variety of farming systems. The pattern indicates agricultural intensification, which is discussed in following chapters. Farming systems are mainly household-based, and little depends on group efforts. Twenty local associations were created within the settlement but most of them are inactive or have little influence on farming decision-making. The only cooperative is an active smallholder organization and currently has 200 members.

After fifteen years of colonization, five main farming systems can be distinguished (Miranda et al. 1997a):

- Perennial agriculture: most farms have just coffee plantations but other land uses include: guarana, coffee/cacao, coffee/guarana, cacao/*Bixa* (*urucum*), coffee/cacao/guarana;
- Cattle ranching: production system in farms where land clearing often means conversion to pasture;
- Perennial agriculture (mainly coffee) and small cattle ranching: combined system including the two most common activities in the rural area;
- Perennial agriculture, annual agriculture, and cattle ranching: this production system mixes different activities in farming management;
- Agrosylvopastoralism: very diversified system including all activities mentioned above plus agroforestry.

The existence of these farming systems was confirmed during fieldwork through interviews with landowners and visits to their properties. The occurrence of cultivation systems within the farming systems is summarized in Table 4.

- RUBBER TAPPERS

Communal forest reserves in Machadinho are State Reserves decreed by the government in 1994 and 1995, legalizing the situation of many families of rubber tappers (Olmos et al. 1999). In 1996 and 1997, governmental and non-governmental organizations established management plans for the reserves (Rondônia 1997). The plans were approved by the local rubber tappers association. Institutional arrangements concerning the reserves and their role in land cover are discussed in Chapter 6. This section mentions just the main activities of families living in those areas.

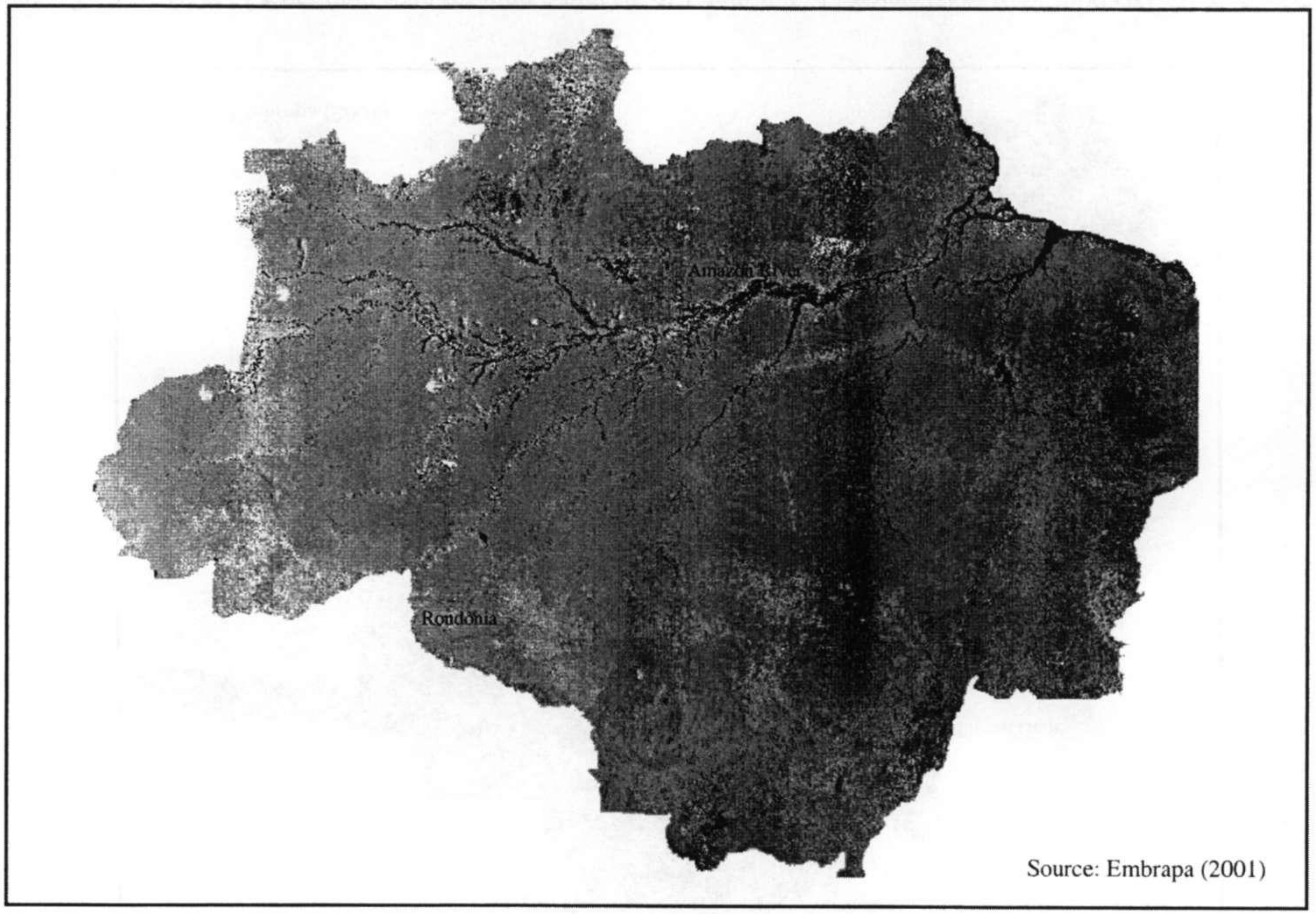
Rubber extraction from native trees is the main source of income of rubber tappers in the study area. In general, each household explores three to six trails containing 100 to 300 trees each. The production of rubber varies from 150 to 300 kg per month per family (Rondônia 1996c). The extraction is made in the early morning and sometimes in the afternoon throughout the year, with exception to the driest months (mainly August) (see Table 3). Other extractive activities, such as copaíba (*Copaifera sp*) oil harvesting and seed collection, are less important in the communities. The communities also plant manioc (their main staple food), subsistence annual crops (corn, rice, and beans), and small coffee plantations.

- LOGGERS

Logging activities were always associated with the opening of new colonization frontiers in the Amazon (Schminck and Wood 1992). Loggers play a major role in providing access to remote areas within the settlement as they open trails through the forest to reach valuable species. Doing so, they also disturb extensive forest patches and increase their flammability (Nepstad et al. *Flames* 1999).

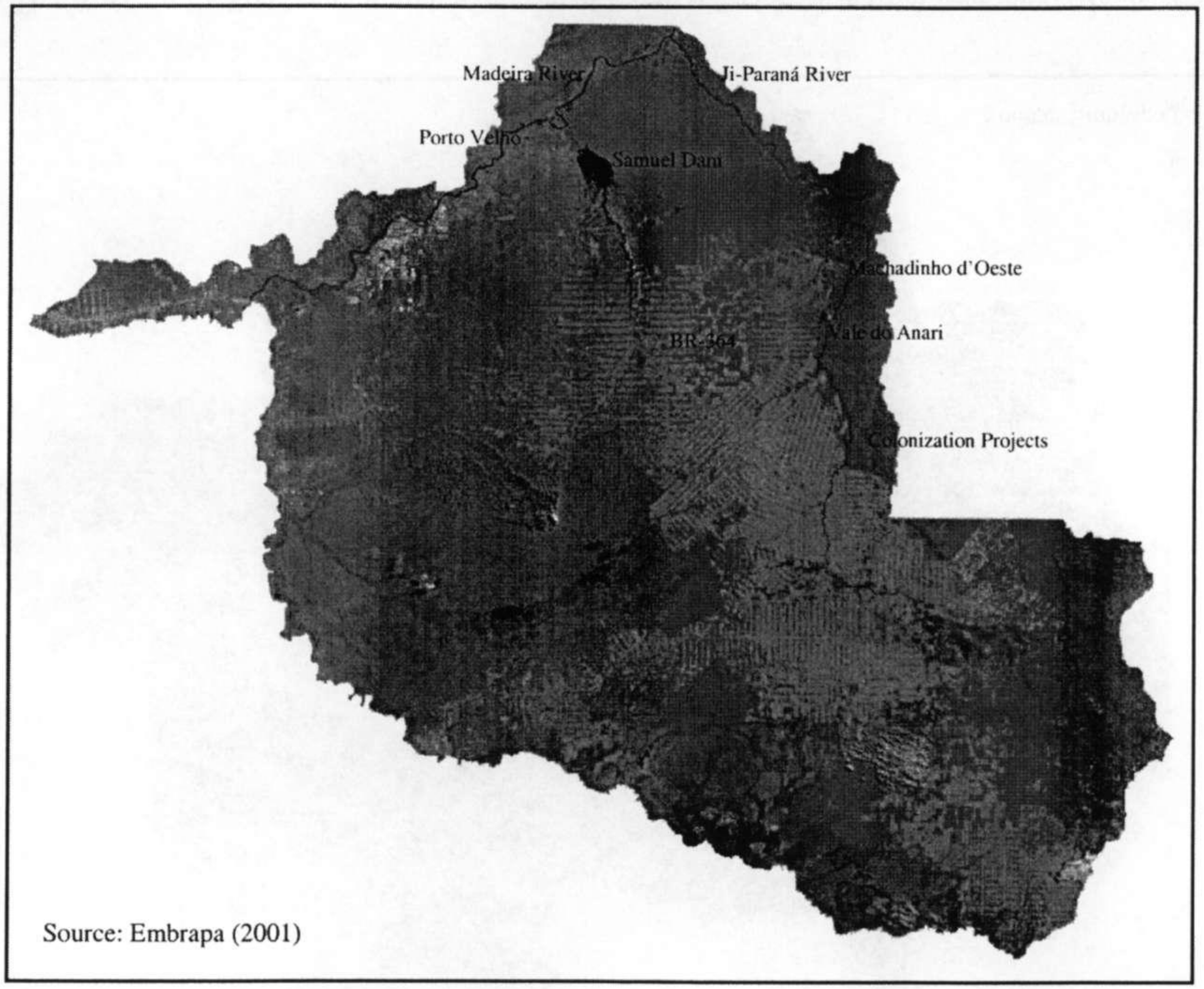
Unfortunately, logging activities in Machadinho and Anari still follow the predatory scheme. Stimulated by market demands, loggers take the larger and most valuable trees without worrying about maintaining the vegetation structure. In general, the leftover vegetation is a forest remnant degraded in structure and species composition (Rondônia 1996a). Only recently, management plans began to be implemented, both in private properties and in communal lands. In all cases, logging is also dependent on access and seasonality because trafficable roads are necessary for taking the wood to sawmills. In the study area, this is usually possible only from May to September, but also in April and October in dryer years (Table 3).

The next chapters discuss in detail how the landscape has been transformed through the introduction of rural production systems in Machadinho and Anari following settlements' implementation. The actions and interactions of settlers, rubber tappers, and loggers are particularly important in generating such outcomes.



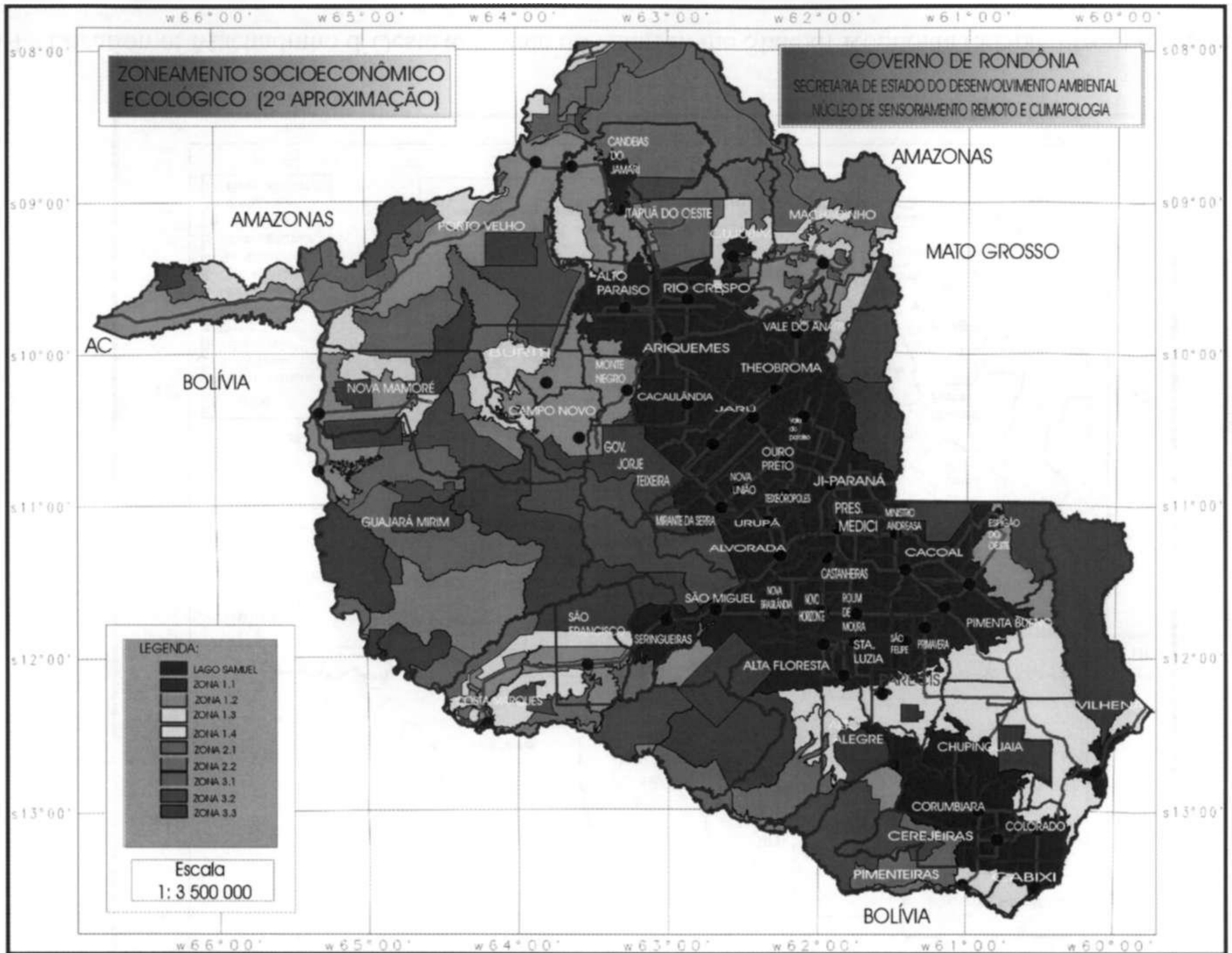

Source: Embrapa (2001)

Figure 1 - The Amazon Region seen through a mosaic of Landsat TM images from year 2000 (Bands 3, 4, and 5).




Source: Embrapa (2001)

Figure 2 - The State of Rondônia seen through a mosaic of Landsat TM images from year 2000 (Bands 3, 4, and 5).




FONTE: GOVERNO DE RONDÔNIA (2000)

Figure 3 - Ecological-Economic Land Zoning of the State of Rondônia, 2nd Approximation (Rondônia 2000).

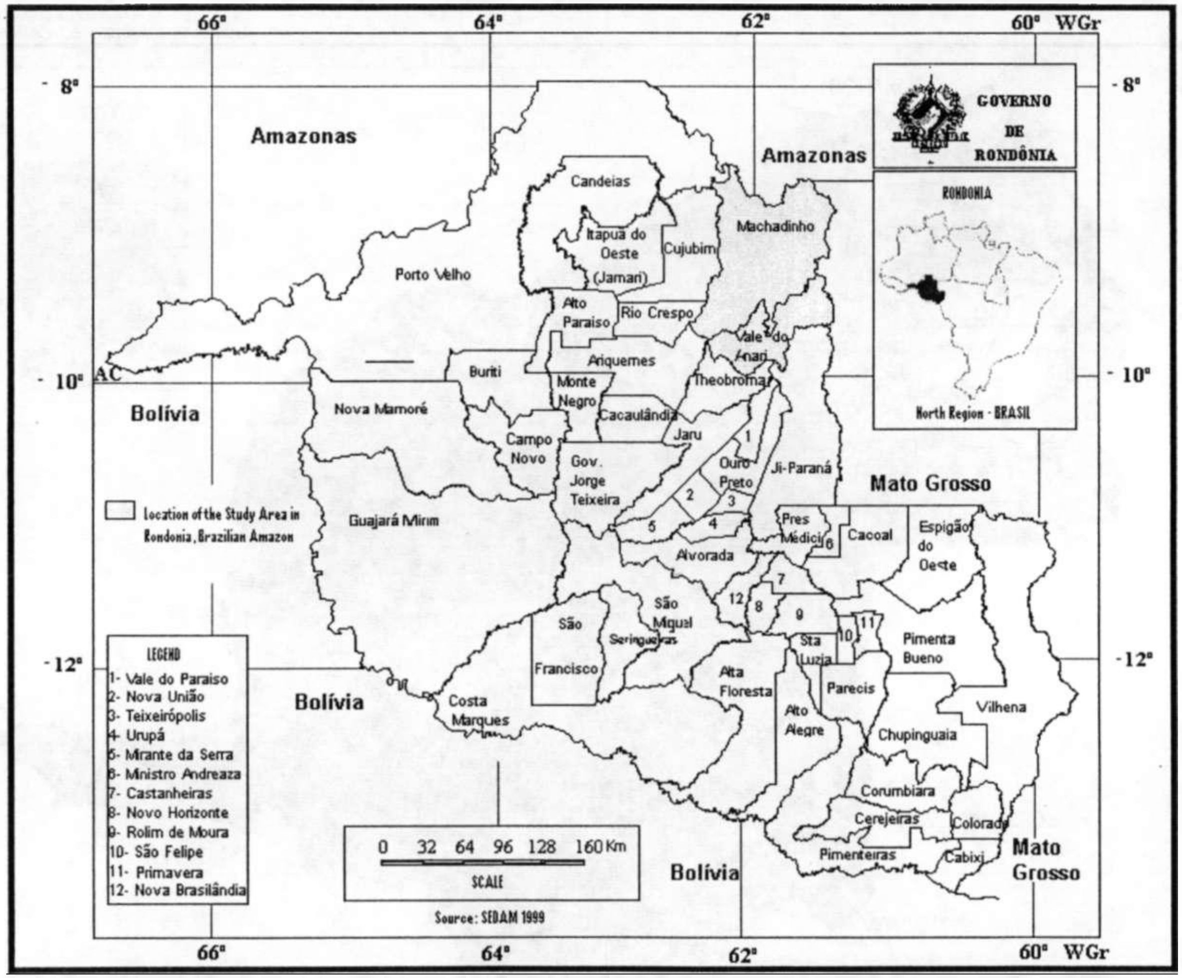



Figure 4 - Location of Machadinho d'Oeste and Vale do Anari in the State of Rondônia (adapted from Rondônia 1999b).

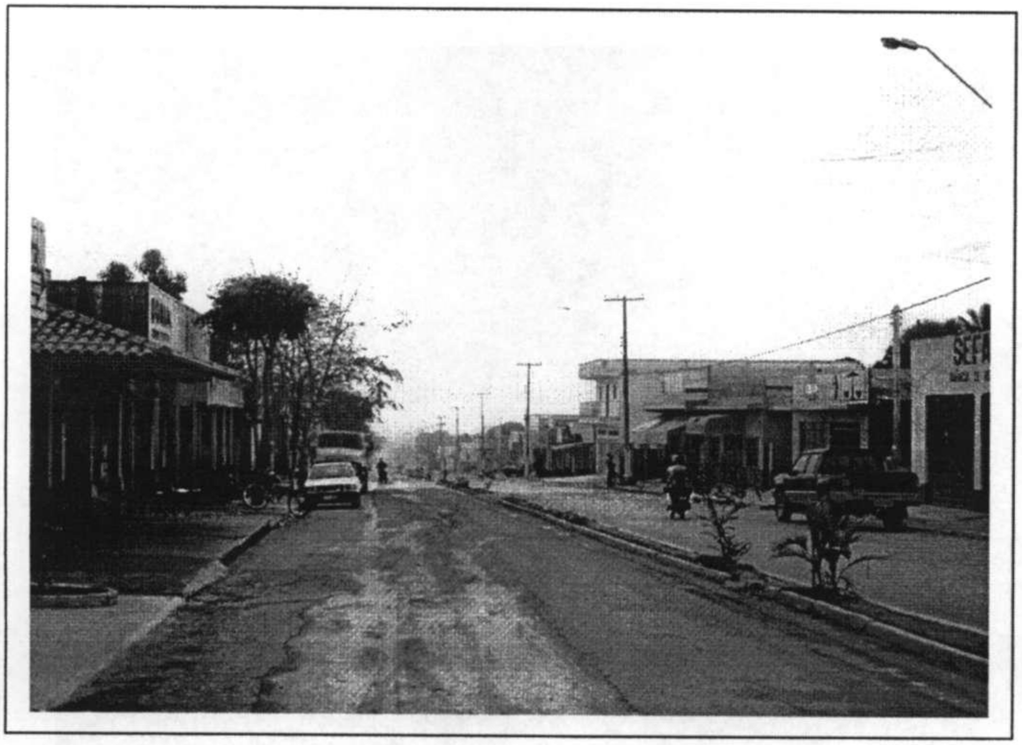


Photo 1 - Partial view of Machadinho d'Oeste (urban area).

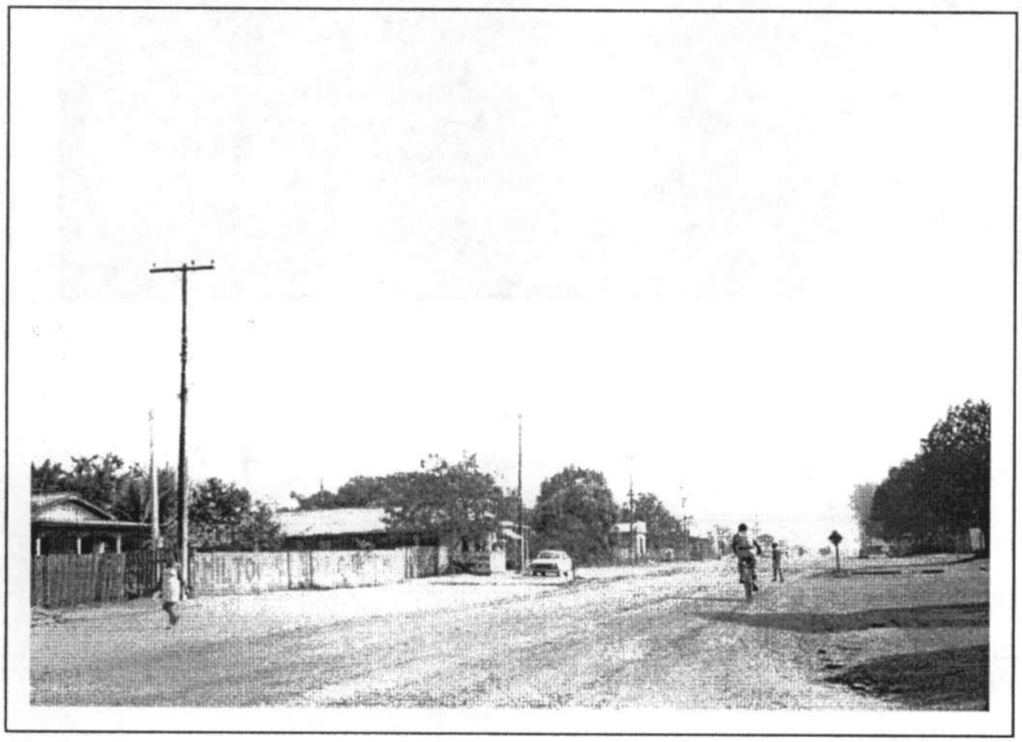


Photo 2 - Partial view of Vale do Anari (urban area).

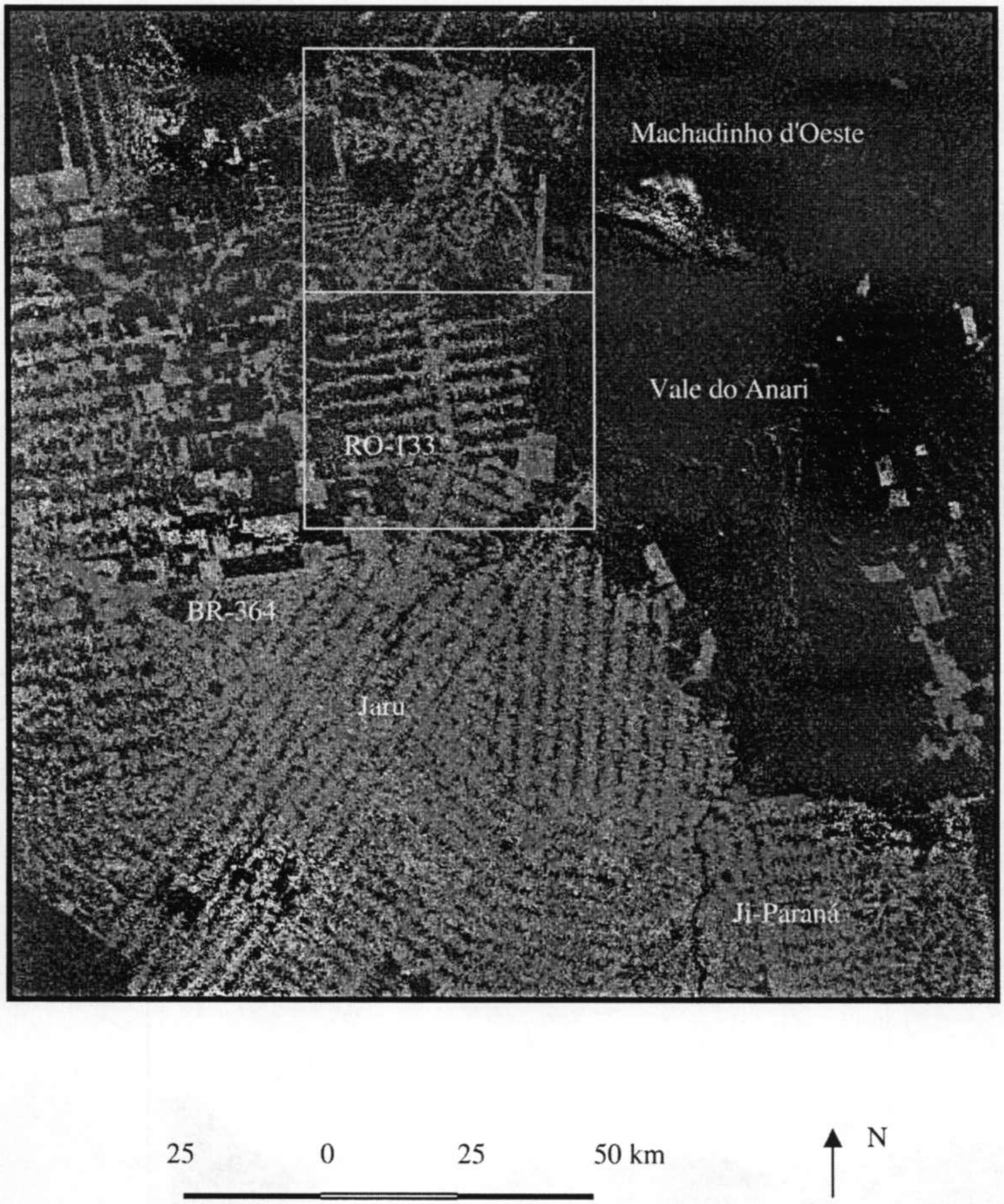



Figure 5 - Landsat TM image from 1998 (bands 3, 4, and 5) showing Machadinho d'Oeste and Vale do Anari distinct designs of colonization.

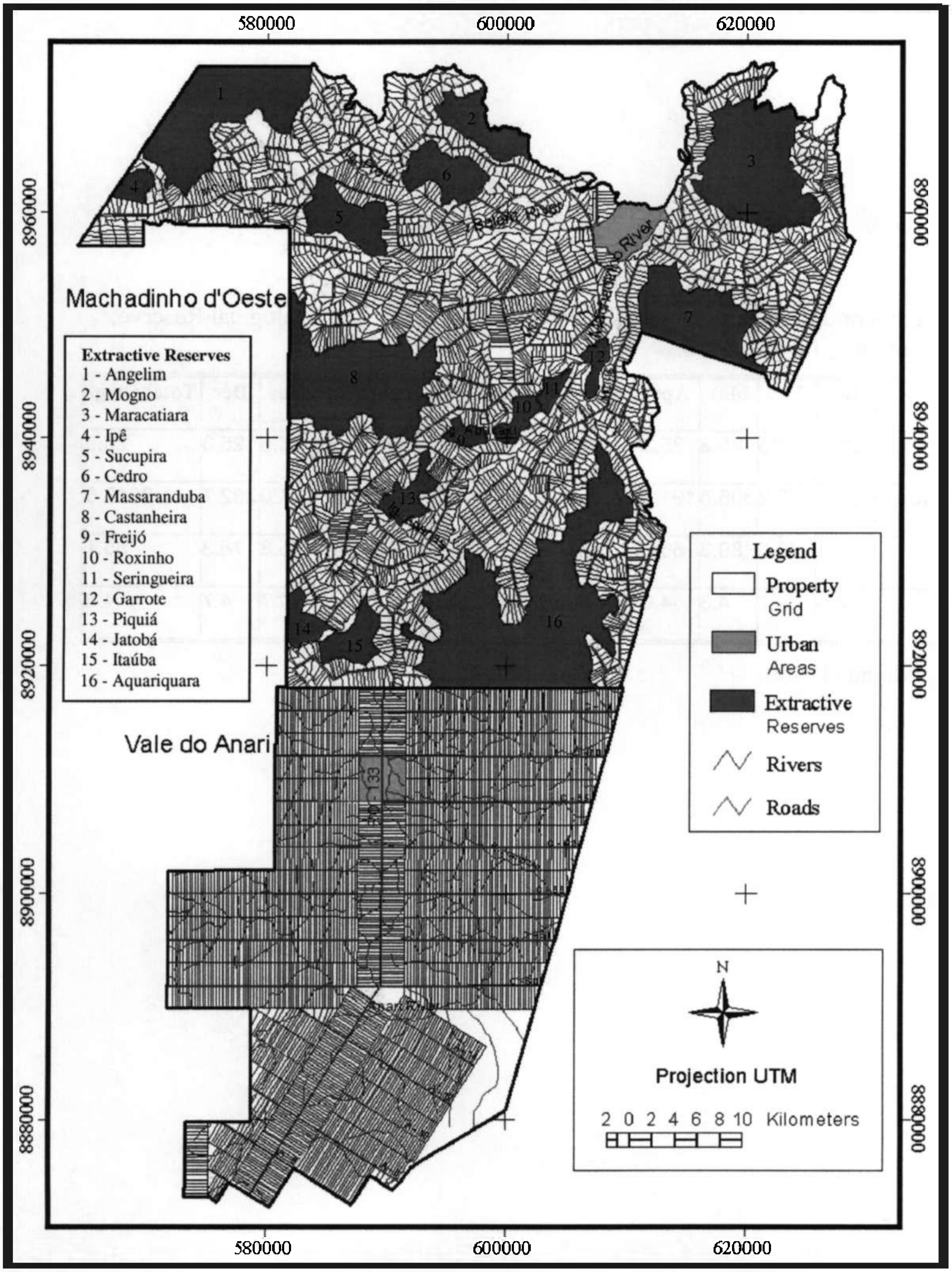
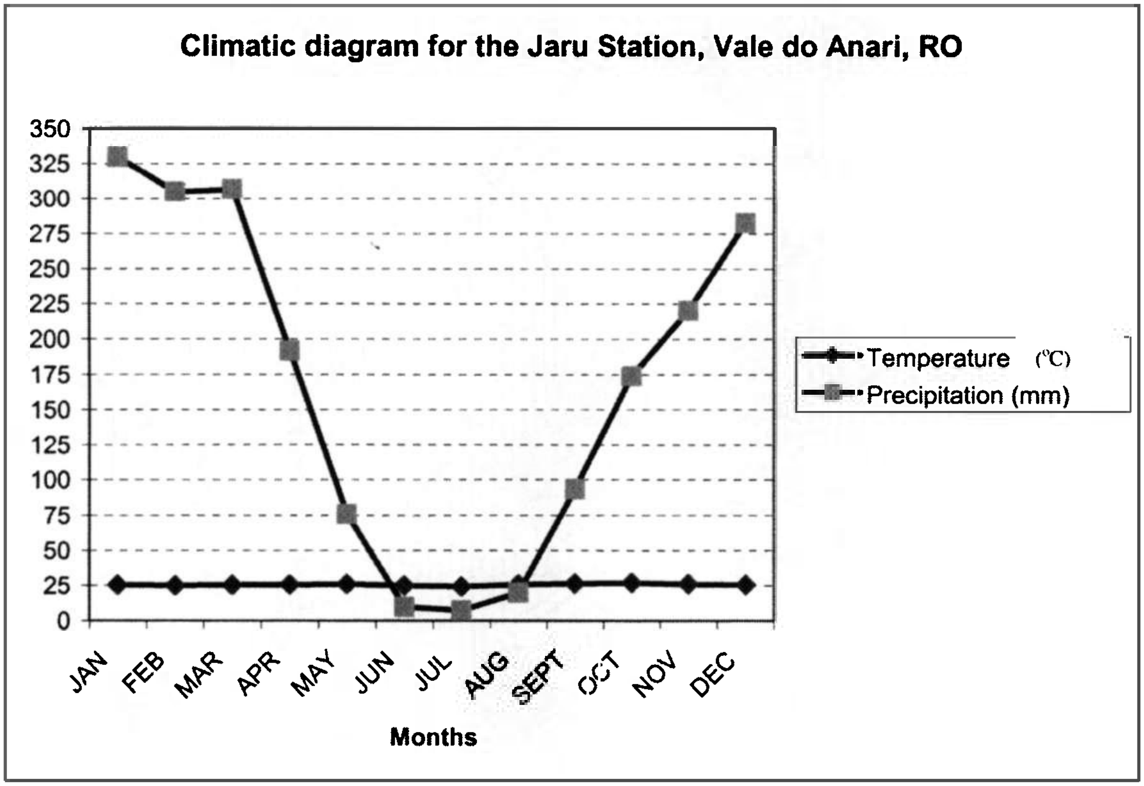



Figure 6 - Machadinho d'Oeste and Vale do Anari - Property Grids, Roads, Rivers, and Extractive Reserves.

Table 1 - Temperature, precipitation, and wind recorded at the Jaru Biological Reserve, Rondônia, 1977 to 1996.

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sept | Oct | Nov | Dec | Total / avg. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Avg. Temp. (°C) | 25.3 | 25 | 25.3 | 25.3 | 25.8 | 24.9 | 24.2 | 25.6 | 26.4 | 26.8 | 25.8 | 25.3 | 25.5 |
| Avg. Prec. (mm) | 329.9 | 305.2 | 306.8 | 191.7 | 76.1 | 9.8 | 7.3 | 19.8 | 93.4 | 173.9 | 220 | 282.7 | 2016.6 |
| S.D. (mm) | 90.4 | 90.5 | 89.3 | 56.9 | 39 | 12.9 | 12.4 | 24.4 | 59.8 | 50.5 | 55.8 | 78.3 | 55.1 |
| Wind (km/h) | 4.8 | 4.7 | 4.3 | 4.0 | 4.4 | 3.6 | 4.9 | 4.7 | 4.6 | 4.7 | 4.7 | 4.7 | 4.5 |

Source: Rondônia (1998b)




Source: Rondônia (1998b)

Figure 7 - Climatic diagram for the Jaru Biological Reserve, Rondônia, 1977 to 1996.

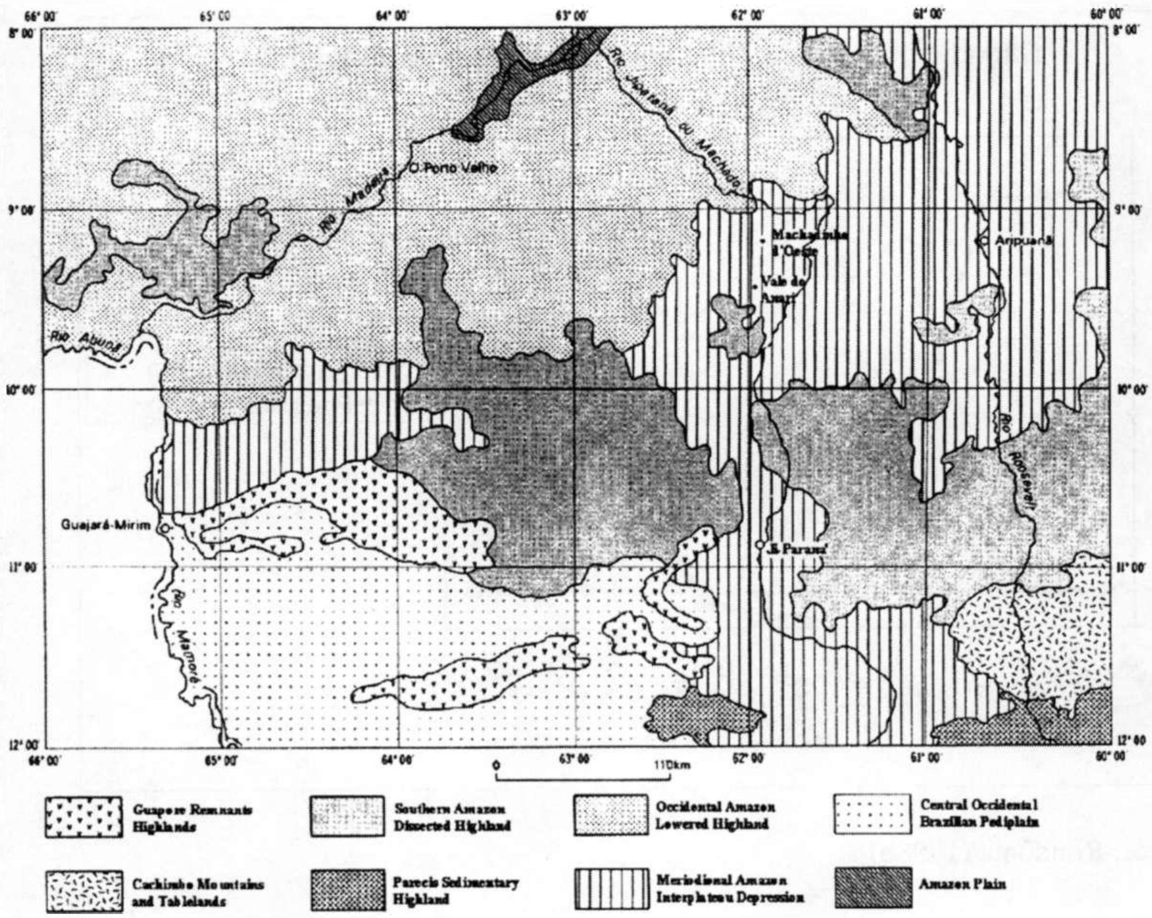



Figure 8 - Morphostructural unities including the study area (adapted from Melo et al.1978).

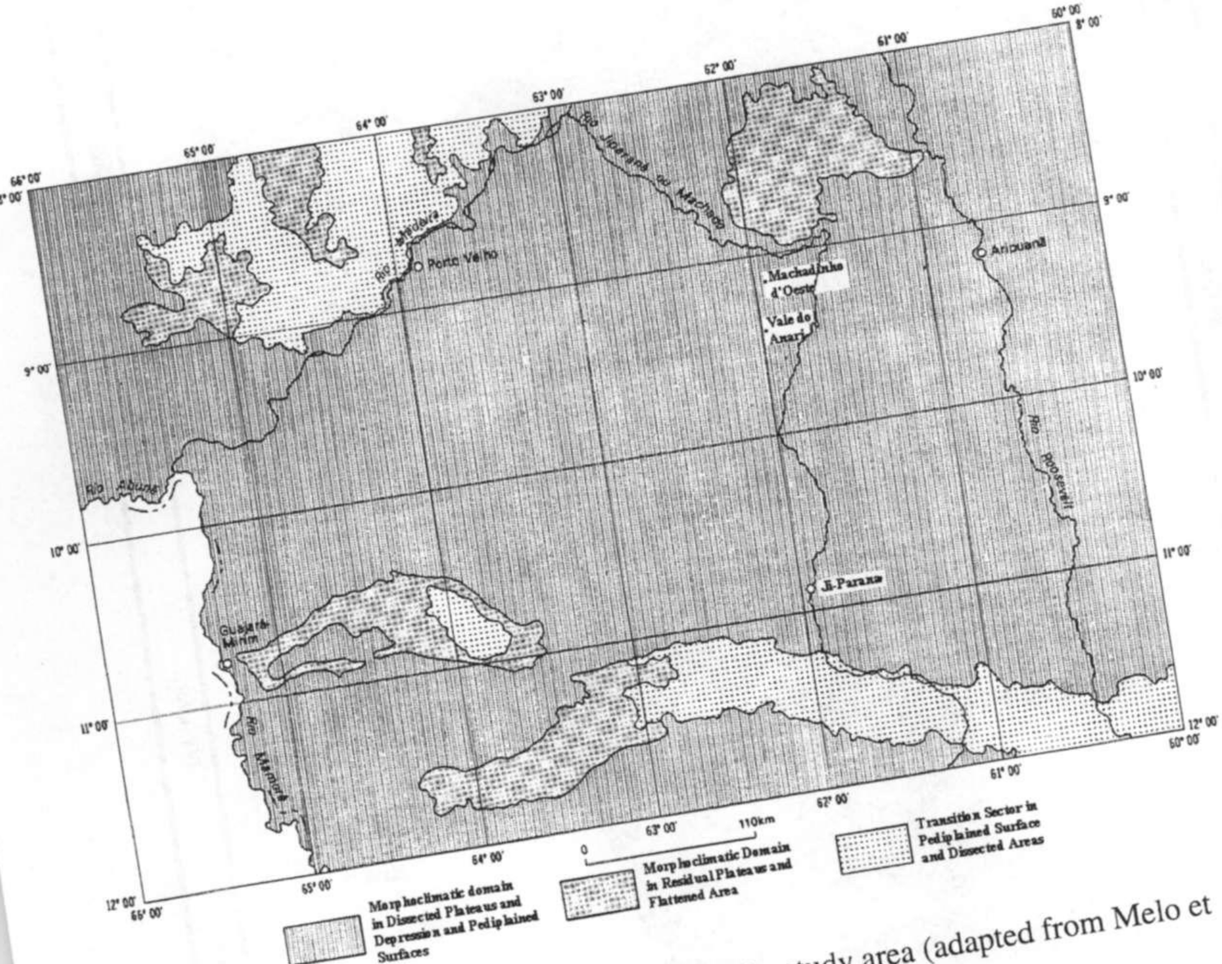



Figure 9 - Morphoclimatic unities including the study area (adapted from Melo et al.1978)

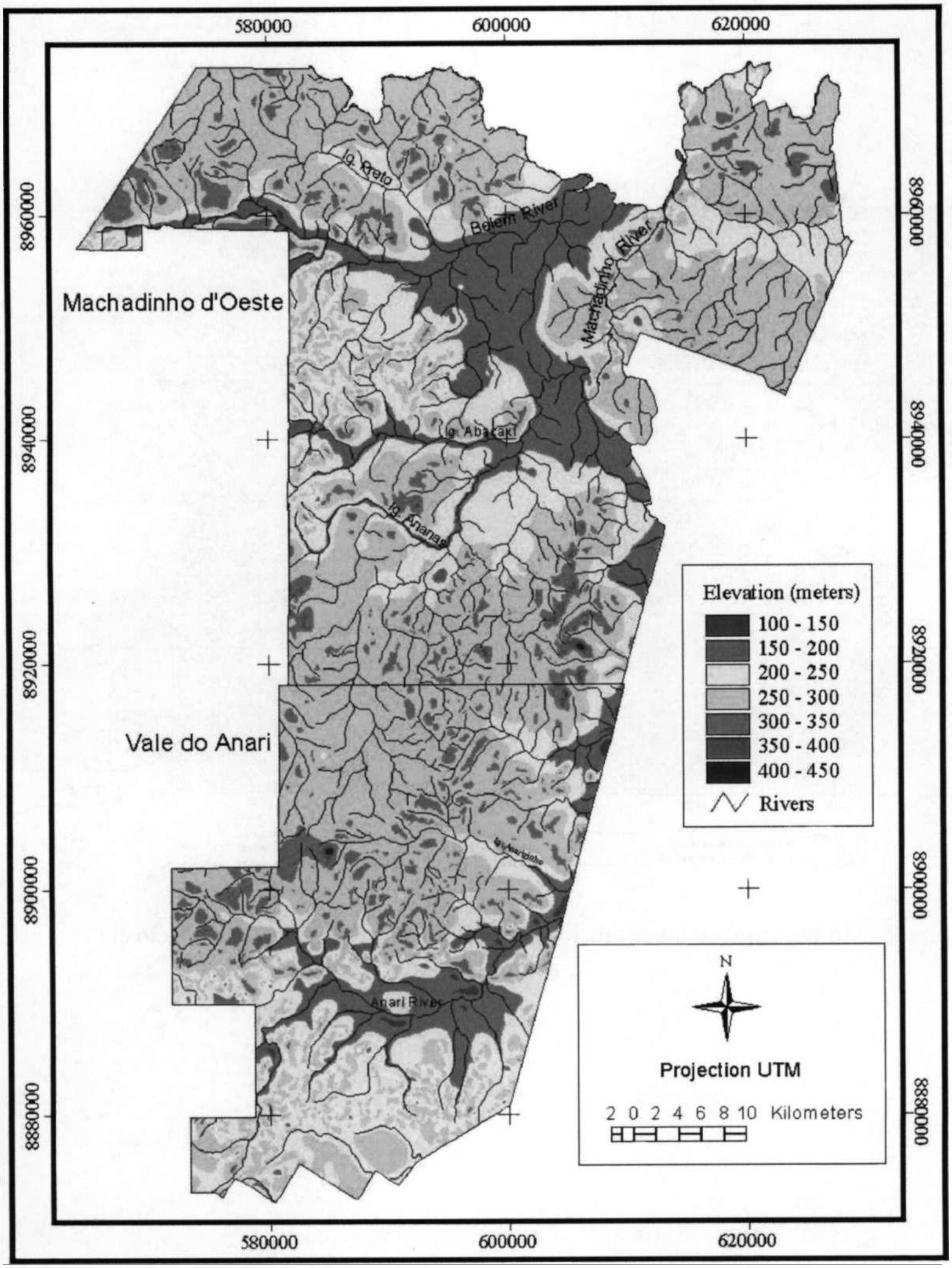



Figure 10 - Machadinho d'Oeste and Vale do Anari – Elevation Classes and Rivers.

Table 2 - Vegetation formations in the State of Rondônia, Brazilian Amazon (Rondônia 1998h).

| Vegetation Formations | Area ($km^2$) | Percent of Total |
|---|---|---|
| **Open Tropical Forest** | 127.620,4 | 53.7 |
| **Dense Tropical Forest** | 9.348,4 | 3.9 |
| **Savanna (*Cerrado*)** | 13.115,2 | 5.5 |
| **Semidecidous Forest** | 5.024,2 | 2.1 |
| **Transition Zone** | 19.809,2 | 8.3 |
| **Pioneer Formation under Fluvial Influence** | 8.743,0 | 3.7 |
| **Alluvial Formation (*Umirizal*)** | 571,1 | 0.24 |
| **White Sand Field (*Campinarana/Campina*)** | 40,8 | 0.02 |
| **Other Formations** | 53.173,7 | 22.4 |
| **Total** | 237.446,1 | 100 |

Table 3 - Farming and extraction activities in the rural areas of Machadinho d'Oeste and Vale do Anari.

| PRODUCT | YEAR | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEPT | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Pastureland** | | | | | | | | | | | | | |
| **Pasture** | 1 | | | slash trees, bushes, vines | slash trees, bushes, vines | fell | fell | | | | *seeding* | *seeding* | |
| | 2 | | | | *cattle introduction* | *cattle introduction* | | | | clearing /burn | clearing/ burn | | slash bushes, weeds |
| | 3-10 | | | | | slash bushes, weeds | | | | | | | slash bushes, weeds |
| **Short Cycle Agriculture** | | | | | | | | | | | | | |
| **Corn** | 1 | | | slash trees, bushes, vines | slash trees, bushes, vines | fell | fell | field preparation/ fallow | burn | burn | *planting* | *planting* | *planting/* weeding |
| | 2 | *harvest (sweet corn)* | *harvest (sweet corn)* | *harvest (sweet corn)* | | | | *harvest (feed corn)* | | | | | |
| **Rice** | 1 | | | slash trees, bushes, vines | slash trees, bushes, vines | fell | fell | field preparation/ fallow | burn | burn | *planting* | *planting* | *planting/* weeding |
| | 2 | *harvest /* weeding | *harvest* | *harvest* | | | | | | | | | |
| **Beans** | 1 | | herbicide | *planting* | *planting* | disease control | *harvest* | | | | | | |
| **Long Cycle Agriculture** | | | | | | | | | | | | | |
| **Manioc** | 1 | | | slash trees, bushes, vines | slash trees, bushes, vines | fell | fell | field preparation/ fallow | burn | burn | planting | planting | *planting/* weeding |
| | 2-3 | *harvest / planting* | *harvest* | *harvest* | *harvest* | *harvest* | *harvest* | *harvest* | *harvest* | *harvest* | *harvest* | *harvest /* replanting | *harvest /* replanting |

Legend: field preparation; *planting/cattle introduction*; maintenance; *harvesting*

Table 3 (continued)

| PRODUCT | YEAR | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEPT | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Perennial Agriculture** | | | | | | | | | | | | | |
| **Coffee** | 1 | | | slash trees, bushes, vines | slash trees, bushes, vines | fell | fell | seedling preparation | burn | burn | liming | liming | fertilization (NPK)/ *planting in holes* |
| | 2 | *planting* | replanting | | | weeding | | | | | weeding/ *planting of rice* | | |
| | 3 | | fertilization | herbicide | | | pest control | | | weeding | weeding/ fertilization | weeding | weeding/ fertilization |
| | 4 | | fertilization | | | | pest control | | | | fertilization | | fertilization |
| | 5-9 | | fertilization | *harvest* | *harvest* | *harvest* | pest control | | | | fertilization | | fertilization |
| | 10 | | | | | | | pruning | pruning | | | | |
| **Cocoa** | 1 | | | slash trees, bushes, vines | slash trees, bushes, vines | fell | seedling preparation | | burn | *planting* | | fertilization (NPK) | *planting in holes* |
| | 2 | *planting in holes* | slash bushes, weeds | | | slash bushes, weeds | | | pruning/ disease control | pruning/ disease control | slash bushes, weeds | | slash bushes, weeds |
| | 3-4 | disease control | slash bushes, weeds/ pest control | slash bushes, weeds/ pest control | disease control | slash bushes, weeds | | | pruning/ disease control | pruning/ disease control | slash bushes, weeds | | slash bushes, weeds |
| | 5 | disease control | slash bushes, weeds/ pest control | slash bushes, weeds/ pest control | disease control/ harvest | *harvest* | *harvest* | | pruning/ disease control | pruning | slash bushes, weeds | | slash bushes, weeds |

Legend: field preparation; *planting / cattle introduction*; maintenance; *harvesting*

Table 3 (continued)

| PRODUCT | YEAR | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEPT | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Perennial Agriculture** | | | | | | | | | | | | | |
| **Guarana** | 1 | | | | | | | | | | | seedling preparation | |
| | 2 | | | slash trees, bushes, vines | slash trees, bushes, vines | fell | fell | | burn | burn | | | *planting in holes* |
| | 3 | *planting in holes* | weeding/ fertilization | | | weeding/ fertilization | | | | | | | |
| | 4 | | weeding/ fertilization | | | weeding/ fertilization | | | | | | | |
| | 5 | | | | | | | | | | *harvest* | *harvest* | *pruning* |
| **Black pepper** | 1 | | | slash trees, bushes, vines | slash trees, bushes, vines | fell | fell | | *seedling preparation* | burn | liming | posting/ fertilization (NPK) | *planting in holes* |
| | 2 | weeding/ fertilization | fertilization (N) | weeding | | weeding/ mulching | | | | | | weeding | |
| | 3 | weeding/ fertilization | fertilization (N) | weeding | | weeding/ mulching | | | | | | weeding | |
| | 4-8 | weeding/ fertilization | fertilization (N) | weeding | | weeding/ mulching | *harvest* | *harvest* | *harvest* | | | weeding | |
| **Cupuacu** | 1 | | | | | | *seedling preparation* | | | | field preparation/ fallow | | *planting in holes* |
| | 2 | slash bushes, weeds/ fertilization | | | | | | | | | slash bushes, weeds/ fertilization | | |
| | 3 | | | | | | | | | | | | |
| | 4 | | | | *harvest* | *harvest* | *harvest* | | | | | | |

Legend: field preparation; *planting / cattle introduction*; maintenance; *harvesting*

Table 3 (continued)

| PRODUCT | YEAR | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEPT | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | |
| **Extraction** | | | | | | | | | | | | | |
| **Rubber** | many | *harvest* | *harvest* | *harvest* | *harvest* | *harvest* | *harvest* | *harvest* | | | *harvest* | *harvest* | *harvest* |
| | | | | | | | | | | | | | |
| **Logging** | | | | | | | | | | | | | |
| **Hard and soft wood** | many | | | | *harvest* | *harvest* | *harvest* | *harvest* | *harvest* | *harvest* | *harvest* | | |

Legend: field preparation; *planting / cattle introduction*; maintenance; *harvesting*

Table 4 - Occurrence of cultivation systems within the farming systems in Machadinho d'Oeste and Vale do Anari.

| | **Perennial** | **Cattle ranching** | **Annual** | **Agroforestry** |
|---|---|---|---|---|
| **Perennial agriculture** | XXXX | | | |
| **Cattle ranching** | | XXXX | | |
| **Perennial agriculture and small cattle ranching** | XXXX | XXXX | | |
| **Perennial agriculture, annual agriculture, and cattle ranching** | XXXX | XXXX | XXXX | |
| **Agrosylvopastoralism** | XXXX | XXXX | XXXX | XXXX |

# CHAPTER 3

# VEGETATION STRUCTURE AS AN INDICATOR FOR LAND-COVER DYNAMICS ASSESSMENT IN THE AMAZON

*'Esse mato tem palmeiras...'*

## 3.1 - DISTURBANCE AND SECONDARY SUCCESSION IN THE AMAZON: SHORT REVIEW AND MOTIVATION

The ecological literature on succession is extensive. Rather than making too broad a review about the topic, the focus is on some concepts related to vegetation regrowth as a background for this study in tropical forests of Rondônia. Since Cowles' observations around the shores of Lake Michigan (Cowles 1911) and Clements'(1916, 1928, 1936) numerous studies, many theoretical ideas about succession in several fields have been argued. According to Drury and Nisbet (1973), in spite of all the different approaches and competing conceptualizations, there is considerable agreement on the general trend of succession. During the 1960s, authors attempted to develop a general theory of structural and functional characteristics of a community's development (Hutchinson 1965, MacArthur et al. 1966, Levins 1968). Odum (1969) proposed a model for the process, discussing how the energy balance in the ecosystem progressively changed. Whittaker (1970) described changes in different vegetation variables through the course of succession ending up in a climax community. Most of these studies focused on temperate regions. The application of the succession concept to tropical forest ecosystems started gaining importance when Richards (1952) called attention to processes following disturbance. Since then, many studies have been carried out in different tropical sites. The paragraphs below describe some findings of works completed in the 1980s and 1990s.

Forest communities show variation due to availability of flora, biophysical differences between formations, and disturbances. Within formations, variation is related to topography, soils, seedling arrival, and success (Whitmore 1998). The fragility or susceptibility to damage from disturbance in a forest ecosystem is a consequence of its ecological characteristics. In tropical rain forests, most soils are infertile, with a low content of nutrients, making the nutrient cycling an important mechanism to maintain the ecosystem. When the process is disturbed, nutrients can be rapidly lost (Jordan 1989).

There are various sorts of forest disturbance. The greater the disturbance of a mature forest the longer it will take to recover. The extreme situation is when disturbance produces intense degradation with no chance for recovery. In this case, the process may be followed by ecosystem degradation (loss of structural and functional integrity), environmental degradation (loss of populations or critical functions), biodiversity degradation (loss of genetic diversity), and agricultural degradation (loss of productivity) (Vieira et al. 1993). Degradation may increase environmental risks such as flammability (Nepstad et al. *Flames* 1999). But when these extremes do not occur, succession starts the recovery of vegetation in a dynamic process. Abandonment brings rapid transformation to a competitive environment that induces successional change (Kellman 1980).

Secondary tropical forests originate from some source of disturbance (Corlett 1995). Succession generally refers to changes in species composition and abundance during or following disturbance of a site. The process is dependent on four main sources of recovery: regeneration of remnant individuals, germination from the soil seed bank, sprouting from cut or crushed roots and stems, and seed dispersion and migration from other areas (Tucker et al. 1998).

Sharp distinctions between successional stages are often artificial (McCook 1994), but useful to differentiate between forest or secondary formations. The most common distinction within forest species is between two contrasting ecological groups: pioneers (short- and long-lived) and climax species (Whitmore 1998). Climax species can germinate and establish seedlings below a canopy, whereas pioneer species require full light. Therefore, succession is the process where pioneer (light-demanding) species establish themselves in big canopy gaps, climax (shade-tolerant) species follow, pioneers die creating small gaps, and mature forest species grow up.

The physiognomic outcome of this continuous process of restoration is a change in vegetation structure, analyzed in this chapter for the study area in Rondônia. Brown and Lugo (1990) enumerate five main structural characteristics typifying secondary forests: high total density but low density of trees > 10 cm diameter at breast height (DBH); low basal area; short trees with small diameters; low woody volume; and high leaf area indices. These characteristics change with time giving place to different stages of vegetation toward a forest formation.

Some succession trends are typical in tropical forests: initial floristic composition influences later stand composition; leaf area index (LAI) and production peak early in succession; and streamwater nutrient losses decline rapidly as biomass accumulates (Uhl and Jordan 1984). Successional vegetation appears to be better adapted than crop plants to the diminishing nutrient availability. Another important adaptation of successful successional species is their high dissemination capability and high sprouting capability after fire, both depending on disturbance intensity and duration (Vieira et al. 1996).

Several studies have been done to understand how characteristics of disturbance influence the rate of recovery. Although no one theory can explain all factors controlling succession, some variables appear to be more important than others. In the Amazon, three main factors control succession: availability of regeneration mechanisms (e.g., sprouts, seeds buried in the soil, seeds dispersed from surrounding areas); availability of seed germination and seedling establishment microhabitats (e.g., fruit trees and slash piles); and availability of nutrients, which may be affected by previous management (Uhl 1987). Tree species diversity and biomass accumulation vary depending on time and intensity of land use before recovering. A key factor retarding succession is the slow rate at which primary forest species become established on abandoned farms (Uhl et al. 1988). Some barriers to tree establishment include low propagule availability, seed predation, seedling predation, seasonal drought, and root competition with old vegetation (Nepstad et al. 1991). Although the natural forest recovery indicates a remarkable resilience, Saldarriaga et al. (1988) estimated that 190 years would be taken by a previously cultivated site to reach mature forest basal area and biomass values. Also, the number of tree species present after 40 years of succession is less than half the number in mature forests (Vieira et al. 1996).

In general terms, soil fertility and land-use history emerge as the critical factors influencing the rate of forest regrowth (Tucker et al. 1998). Uhl et al. (1982) found that the time of recovery depends on land use following removal. Logging, slash/burn/abandon, and slash/burn/agriculture/abandon cycles have increasing secondary succession duration. Large cleared patches, where seed sources are far away, may take hundreds of years to return to primary forest. In another study, Uhl et al. (1988) confirmed these findings. Different regeneration patterns occurred depending on land management following deforestation. Forest regenerated vigorously on sites of previously light use (biomass accumulation of 25% after 8 years.). Tree species richness was also high. Moderately grazed pastures also developed forest, but biomass accumulation and tree species richness were lower. Abandoned pastures subjected to heavy use had the least distinct patterns of succession (eight-year-old site was dominated by grasses and forbs). Only where land has been used too intensively for long periods is reforestation uncertain. Thus, in the absence of fire, forests recover on abandoned sites, accumulating biomass and species at a rate that is inversely related to the intensity of use prior to abandonment (Nepstad et al. 1991).

From the considerations above, it becomes clear that if we want to understand the variables affecting patterns of forest succession, we need to know the disturbance history. Recently, remote sensing and GIS have improved significantly the capability to monitor processes of LULC change (B. Turner 1995, National Research Council 1998). Land-cover classifications using these tools became fundamental to understand and monitor processes of deforestation and secondary succession, particularly in the tropics (Mausel et al. 1993; Moran et al. 1994, 1996; Foody et al. 1996; Steininger 1996). The integration of these methods of analysis, field data about vegetation structure and composition, and ecological research provide new opportunities for the study of dynamic processes such as forest disturbance and recovery at ecosystems and landscapes. For regional and landscape assessments, the study of vegetation structure in tropical forests is even more effective than floristic composition because of general spectral responses to vegetation communities at resolutions such as those in Landsat TM images.

In this chapter, the results for vegetation structure in Machadinho and Anari are presented as a basis for discussing the spectral response of secondary stages when using Landsat TM images. The rationale behind this approach is to follow an itinerary from the continuous vegetation variability found in the field to specific categories of secondary succession useful for LULC classifications such as presented in the next chapter.

## 3.2 - DATA COLLECTION

A number of techniques are available for obtaining quantitative information about the structure and composition of terrestrial plant communities (Randolph 1997). This research focused on vegetation structure rather than composition because of its effects on different spectral responses of tropical secondary forests (Brondizio 1996, Lucas et al. 1998). Since the main goal was to collect vegetation data to inform LULC classifications based on satellite images, some important decisions were necessary when planning fieldwork.

The first step was to perform preliminary satellite image classifications through unsupervised techniques (Jensen 1996, Lillesand and Kiefer 2000). The results provided a general overview about land cover and spectral variability in the area, allowing the stratification of major classes to be sampled. Archival work also indicated the importance of collecting data about different stages of vegetation regrowth, based on structure and land-use history (Uhl 1987, Brondizio 1996).

Fieldwork was carried out during the dry seasons of 1999 and 2000. Assisted by a team of three graduate students and three local workers, 32 surveys were completed encompassing land-cover classes such as forest, initial secondary succession (SS1), intermediate secondary succession (SS2), and advanced secondary succession (SS3). The goal of surveying these classes was to depict major stages of vegetation regrowth regarding their structure and spectral responses.

### 3.2.1 - Sampling Strategy

Once in the field, preliminary image classifications and three-band color composite printouts indicated candidate areas to be surveyed. A flight over the areas provided visual insights about the size, condition, and accessibility of sites. After driving extensively throughout the settlements, field observations provided a sense about the structure of regrowth stages, mainly based on total height and ground cover of dominant species (Lemée 1978, Conant et al. 1983). Indicator species, such as *Cecropia sp.*, *Vismia sp*, palms, grassy vegetation, and lianas also helped in secondary succession stage assignment. To allow integration with spectral TM data, areas smaller than 1 ha were discarded. As a preliminary baseline, maximum tree heights of 8, 10, and 12 m, and maximum ages of 5, 10, and 15 years were suggested for SS1, SS2, and SS3, respectively. These numbers were assigned by approximation to allocate the formations to be surveyed, thus not necessarily indicating the real boundaries between regrowth stages, as it will be developed and discussed later in this chapter. Also, two plot samples served as control sites. Both of them were cleared from primary forest and then allowed to recover without further interference as part of a regrowth experiment conducted by EMBRAPA. In 1999, one control site was 13 years old (SS3) and the other was 3 years old (SS1).

The procedure used for surveying vegetation was a multi-level technique adapted from CIPEC (1998). The surveys were carried out in areas with relatively homogeneous ecological conditions (i.e., topography, distance from water, and surrounding land use) and uniform physiognomic characteristics (Godron et al. 1968). After defining the area to be surveyed (plot sample), three sub-plots were randomly installed to cover the variability within the plot sample. A sub-plot is composed of three nested squares (Figure 11): one for sampling ground cover and tree or woody climber species seedlings (1 $m^2$); one for sampling sapling information (9 $m^2$); and one for sampling trees and woody species (100 $m^2$). The center of each sub-plot was randomly selected. Seedlings were defined as young trees or shrubs with a maximum stem diameter less than 2.5 cm. Saplings were defined as young trees with DBH between 2.5 cm and 10 cm. Trees were defined as woody plants with a DBH greater than or equal to 10 cm. Height, stem height, and DBH were measured for all trees in a 100 $m^2$ area. Height and DBH were measured for all saplings in a 9 $m^2$ area. Ground cover estimation and counting of individuals were carried out for seedlings and herbaceous vegetation in a 1 $m^2$ area.

Based on previous work (Jurdant et al. 1977, Duranton et al. 1982, Brondizio 1996), a survey protocol was used to describe the environment and the vegetation. The protocol encompassed qualitative observations (e.g., topography, soil texture, and land-use history) and quantitative variables (e.g., canopy closure, average canopy height, and vegetation measurements). Some variables were pre-coded in order to maximize the efficiency of data collection in the field (Appendix 1). This procedure provided an objective description about the sites, optimizing later data manipulations. A vegetation profile was also drawn for each sampled plot. Every plot was registered with a Global Positioning System (GPS) device to allow further integration with spatial data in Geographic Information Systems (GIS) and image processing systems. Differential correction was not used because the plot size was larger than the error associated with regular GPS measurements in fieldwork. In-depth interviews with landowners were conducted at each sample location to investigate land-use history and inform classifications of satellite images from previous dates (1994 and 1988). Questions were asked to ascertain when the secondary growth was last cut, clearing and burning procedures, management techniques, types of crop or pasture grown, time since the land was abandoned, and other pertinent land-use information. In total, 32 plots, 96 sub-plots, and 288 nested squares were surveyed.

### 3.2.2 - Database Implementation

A database was built to integrate all vegetation data collected during fieldwork. Its design was based on other studies with the objective of allowing comparisons through different study sites in the Amazon (CIPEC 1998). The main motivation behind this initiative was to maintain the integrity between spatial locations of every surveyed plot with vegetation characteristics as a basis for the integration with spectral data obtained from the analysis of Landsat TM images. A detailed description about image processing is included in the next chapter.

Figure 12 shows the relationships between tables in the database. The vegetation type (i.e., SS1, SS2, SS3, and forest) and spectral data were related to plot data (e.g., location and age) and its local characteristics (i.e., soil and land-use history). Plot data was also related to sub-plot data, which included vegetation structure. The latter was divided in two tables: tree/sapling data for plants with collected DBH and height; and seedling/herbaceous data for plants with collected number of individuals and ground cover.

In total, the database counted 288 records for the sub-plot data table, referring to all squares surveyed in the field. The tree/sapling table included 1075 plants with DBH greater than 2.5 cm (672 trees and 403 saplings). The seedling/herbaceous table included 249 plants.

## 3.3 - DATA ANALYSIS

The steps carried out for data analysis are illustrated in Figure 13. The following sections describe the main procedures implemented. Special attention was given to the definition of vegetation structural variables and the analysis of spectral data in order to achieve a better knowledge about the regrowth stages present in the study area.

### 3.3.1 - Descriptive Comparisons through Photos and Vegetation Profiles

A first picture about the variation in vegetation structure from the early stages after abandonment up to forest is given by visual characteristics. After some training it becomes easier to decide between distinct classes mainly if a small number of possible choices is assigned (i.e., SS1, SS2, SS3, and forest). Of approximate character, the distinction of classes is not very evident in the beginning but becomes consistent after field experience. Following Daget and Godron (1982), the classification is appropriate when the observer hesitates in deciding between two and only two neighbor classes. This hesitation becomes acceptable after preliminary surveys and means that the classes are well adapted to the description of the actual heterogeneity within the plot sample.

Certainly, when making those decisions, an ecologist is intuitively using variables such as height, biovolume, ground cover, dominant and indicator species, among others. To help the analysis, an extensive photo collection was generated. Each photo received the survey number to allow further examination as a register about the ecological condition of each sampling site. On the other hand, several vegetation profiles were drawn to complete the graphic representation of vegetation structure.

### 3.3.2 - Variables Analyzed

Some specific variables were calculated based on collected field data with the purpose of characterizing vegetation stands in a quantitative basis. As the focus was on structure rather than species composition, all variables were calculated for size classes, mainly the dominant strata (i.e., trees and saplings). Literature review about the study of secondary succession in the tropics provided insights about the variables to use. Formulas and definitions were compiled from Mueller-Dombois and Ellenberg (1974), Greig-Smith (1983), Schreuder et al. (1993), and Kent and Coker (1994). In the equations given below, the following abbreviations are used: DBH = diameter at breast height; BA = basal area; H = height; Y = biomass.

- DENSITY

The number of individuals of a size class in the stand is important to characterize vegetation. Density is determined by counting the number of individuals of each size class on each sample plot, and then estimating the average number of stems of each size class per unit area sampled.

- DIAMETER AT BREAST HEIGHT (DBH)

Diameter at breast height is the most frequently measured variable in vegetation surveys and has multiple uses. Overbark diameter measurements at breast height (1.5 m from the ground) are quick, easy, inexpensive, relatively accurate, and usually correlated with other variables, such as basal area, volume or biomass. In the field, DBH was measured with diameter tape and averaged for the classes of interest (i.e., trees and saplings). It is expressed in centimeters.

- BASAL AREA

Basal area is the horizontal (cross-sectional) area occupied by the trunk of a species or size class. It is expressed in square meters per hectare ($m^2/ha$) and its formula is:

$$BA = (DBH/2)^2 * \pi / \text{area sampled}$$

- TOTAL HEIGHT

Total height is a straightforward parameter used for direct measurement purposes and also for the calculation of volume or biomass. It is expressed in meters. Once in a stand, the height of some trees was measured with a hand-held clinometer. The values obtained were used as controls for height estimation of other trees and saplings using a five-meter rod as a reference. The estimation was crosschecked between two or three observers to achieve consensus.

- BIOMASS

Biomass is the equivalent weight of an individual or group of individuals (e.g., trees and saplings). The method of calculation can be destructive (actually cutting and weighing what is being measured) or an estimation, based on allometric equations. It can be measured for aboveground biomass, belowground biomass, wood biomass, leaf biomass, and fruit biomass. In this research, the analysis was restricted to aboveground biomass through the use of two allometric equations for its estimation. Due to its application to forested areas in Rondônia, the equation given by Brown et al. (1995) was used for trees with DBH greater than 10cm, where:

$$Y = 0.0326 * (DBH)^2 * H$$

For saplings (2.5 cm < DBH < 10 cm), the equation given by Honzák et al. (1996) was used, where:

$$Y = \exp[-3.068 + 0.957 \ln (D^2 * H)]$$

Caution should be taken when analyzing aboveground biomass estimations, as they are dependent on several variables such as hollowness, wood density for every species, bark, presence of palms, vines, and dead biomass (Fearnside 1992). The goal of these estimations was to have another parameter for comparison across the size classes (i.e., trees and saplings) and vegetation formations (i.e., SS1, SS2, SS3, and forest) within the study area.

- RATIOS

Some ratios between variables were also calculated. Inspired by previous work (Tucker 1996, Tucker et al. 1998), the goal was to depict the contribution of each major group of plants (i.e., trees and saplings) in relation to values found for the entire vegetation formation or for the other group. Therefore, three ratios are presented in this chapter:

Density of saplings to density of trees

Percent tree contribution to total basal area

Percent sapling contribution to total basal area

### 3.3.3 - Integration of Spectral Data

One of the main goals of fieldwork was to collect sufficient data to carry out the multi-temporal supervised classification of satellite images. For the purpose of image analysis, each plot sample became a 'training sample,' that is, an area of known identity that is used during supervised classification to identify areas of unknown identity (Mausel et al.1990). Each one of these areas was selected as an 'area of interest' (AOI) with specific spectral characteristics. GPS collected points and color composite printouts used in the field allowed the accurate positioning of each of these areas. The mean reflectance for the training samples was extracted for each TM band as well as the value for the Normalized Difference Vegetation Index (NDVI) (Lillesand and Kiefer 2000). The values were exported to the corresponding table in the database to allow their integration with vegetation structure data.

### 3.3.4 - Statistical Analysis

The first step to achieve a better understanding about a specific set of numeric data is to perform an exploratory data analysis (Burt and Barber 1996). There are several methods, techniques, and statistical packages to accomplish this task. The first approach focused on graphic methods of analysis. Quantitative methods were used to inform the discussion in terms of the scientific motivation for this chapter.

Graphs are tools for analysis and communication (Schmid 1983). They provide a different perception about data, summarizing observations based on some defined output. Cleveland and McGill (1985) have shown that graphical methods are successful if the decoding process is effective. Moreover, some methods are better than others in terms of graphical perception. To avoid problems during data interpretation, simple and effective graphical methods such as boxplots and scatterplots were used. A boxplot is a summary plot based on the median, quartiles, and extreme values. The box represents the interquartile range that contains 50% of the values. The whiskers are lines that extend from the box to the highest and lowest values, excluding outliers. A line across the box indicates the median. In the scatterplot, one numeric variable is plotted against another, representing graphically the distribution of both variables (Ott 1993).

After becoming familiar with data through graphic methods, a second type of analysis is done through numeric procedures. Statistics is generally defined as a methodology for collecting, presenting, and analyzing data. Multiple purposes are recognized for the use of statistics, including its capability to summarize data, validate theories, provide forecasts, evaluate trends, and select a particular sample of interest. Descriptive statistics is used to organize and summarize data. Inferential statistics combines descriptive statistics with probability theory, generalizing the results of a study of a few individuals to a larger group. The mean is the most commonly used measure of central tendency. It is the 'center of gravity' or the 'balancing point' of a set of observations. However, the mean does not account for the variability of data in the range of values. To determine how typical the measure of central tendency is in a distribution, it is necessary to analyze measures of dispersion. Standard deviation is the most commonly used measure of dispersion. Mean, standard deviation, minimum and maximum values were used for the study of structural vegetation variables.

Another numeric approach in exploratory data analysis is the study of statistical relations between two variables. Pearson's correlation coefficient and its significance levels were used to measure the strength of association between the variables under analysis.

Finally, analysis of variance (ANOVA) was used as a statistical technique designed to determine whether or not a particular classification of the data is meaningful. Data are decomposed to structure an F-test to test the hypothesis that the between-class variation is large relative to the within-class variation, which implies that there is a significant variation in the dependent variable between classes. The theoretical background about the procedures used and statistical significance of results obtained was based on literature about the topic (among others, Ott 1993, Shaw and Wheeler 1994, Gujarati 1999).

## 3.4 - VEGETATION STRUCTURE OF SECONDARY SUCCESSION AND FOREST IN MACHADINHO AND ANARI

### 3.4.1 - Phyto-Physiognomy and General Patterns of Succession Classes and Forest

This section describes the main characteristics of each vegetation type sampled during fieldwork (i.e., SS1, SS2, SS3, and forest).

- INITIAL SECONDARY SUCCESSION (SS1)

Six sites were sampled to represent SS1. Their ages are three and five years according to information gathered from interviews with landowners. Earlier stages of abandonment (one and two years) were not sampled because of their spectral similarity with other LULC features, such as degraded pasture and perennial agriculture. The discussion about the role of pasture in Amazonian landscapes is an important issue, when related to its different functions in terms of land use or land cover. It is common to see initial stages of secondary succession used for cattle ranching as well as abandoned pastures, where land cover follows the trend of vegetation recovery. To avoid misinterpretation and to keep control over this dichotomy, it was assumed that the percentage ground cover was the variable defining the threshold between the classes 'pasture' and SS1. Thus, areas with grass cover greater than 75% were defined as cultivated pasture. Areas with grass cover between 25 and 75% and used as pasture were assigned as degraded pasture. SS1 was assigned solely to areas where the grass cover was less than 25%, which generally occurs in sites that have been abandoned for more than two years. Each of the six sites sampled has its own history of occupation and abandonment that, together with their different ages and biophysical characteristics, produces an internal variability within the class.

The profile in Figure 14 shows a phyto-physiognomic representation of a SS1 plot. Table 5 summarizes structural characteristics of these sites. Pioneer species such as light-demanding herbaceous plants, grasses, vines, seedlings, and saplings dominate SS1. These species have a short life cycle, high growth rate and high reproductive resource allocation (Gómez-Pompa and Vasquez-Yanes 1981). Some tree species become important after the second or third year of regrowth. Besides palms, species commonly associated with this period include *Vismia sp.* and *Cecropia sp*, as illustrated in Figure 14.

In general, the structural variables show low standard deviation compared to the means, except for density of trees and the ratio between densities of saplings and trees. An important characteristic of this stage is the much higher density of saplings (7460.3 individuals/ha) compared to the density of trees (266.7 individuals/ha). High sapling competition in SS1 is also expressed by its twofold basal area compared to trees. The average DBH for trees is just 1.4 cm above the minimum sampling size (10 cm), indicating the early stage of vegetation recovery. The mean tree height of 7.8 m is relatively high compared to other sites in the Amazon (Tucker et al. 1998). This is due mainly to *Cecropia* trees competing for light and emerging to form the canopy (Figure 14). Despite the high density of saplings, trees are responsible for the greatest part of total stand biomass, which is 29.2 t/ha (metric tons per hectare) (Table 5).

- INTERMEDIATE SECONDARY SUCCESSION (SS2)

The sample for SS2 included ten sites with ages of six, eight, nine, and ten years. Figure 15 shows a profile of this vegetation. Table 6 summarizes the calculated structural variables. The physiognomic difference of this stage in relation to SS1 is evident. Saplings are still important for the stand as a whole (density of 4,814.8 individuals/ha), but the density of trees is three times greater than in SS1 (density of 763.3 individuals/ha). DBH for trees increased to an average of 13.8 cm. Total basal area is 11.5 $m^2$/ha. The sapling contribution of 55.6% to total basal area indicates that saplings are still very important at this stage of regrowth. However, the mean height of trees (10.1 m) is now two times greater than for saplings. Biomass increased twofold in relation to SS1 due to the increase in DBH and height of trees.

In sum, during SS2, young trees are already present but saplings still have a higher density. A closer canopy alters the microclimate, improving conditions for shade-tolerant tree species and creating an unsuitable environment for pioneer species. This profound change sets the path to a more advanced stage of vegetation regrowth.

- ADVANCED SECONDARY SUCCESSION (SS3)

Eight sites with ages of twelve and thirteen years represented SS3. It is useful to remember that the study area started to be colonized between 1981 and 1984, the satellite image was acquired in 1998, and fieldwork was done in 1999. This makes it difficult to find older stages of regrowth, with the main source being only records kept by landowners. Figure 16 illustrates a SS3 stand. The structural variables for this class are described in Table 7.

There are clear differences in vegetation structure. Although large *Cecropia* are still present, most pioneer species gave way to slow-growing, shade-tolerant forest species. Trees dominate the stand as also pointed out by previous studies (Li et al. 1994, Tucker 1996). Tree density increased to 920.8 individuals/ha while density of saplings decreased to 3,750.0 individuals/ha. Average DBH for trees is 17.1 cm and basal area results are now slightly greater for trees than for saplings (6.86 and 6.73 $m^2$/ha, respectively). Total basal area increased to 13.6 $m^2$/ha with a tree contribution of 51.1%. The mean height for trees is 3 m greater than in SS2 stands. Increases in DBH and height doubled the aboveground biomass in relation to SS2. The general appearance of this vegetation type in terms of canopy layers is similar to a forest. However, trees are still not as high or thick, as explained below.

- TROPICAL OPEN FOREST

Seven sites represented the sample for open tropical forest. As illustrated in Figure 17, a clear understory and larger trees characterize these areas. The vegetation formation comprises relatively widely spaced tree individuals, sometimes including palms, bamboo, and lianas, as described by Barros-Silva et al. (1978). These authors also reported a shorter Amazonian forest for eastern Rondônia, with height varying around twenty meters.

The structure of the tropical open forest is quite different from secondary succession stages. Results shown in Table 8 illustrate these findings. The average height is even lower than reported in the literature for other studies: 15.2 m (Barros-Silva et al. 1978, Salomão and Lisboa 1988, Alves et al. 1997). The density of saplings is the lowest of all vegetation classes sampled (2.407,4 individuals/ha). The density of trees (772.1 individuals/ha) is lower than in SS3, certainly because large *Cecropia* individuals and other pioneer species died off during the transition to forest. The mean DBH of trees (22.8 cm) is five times greater than the mean DBH for saplings (4.5 cm) indicating the dominance of trees in these sites. This characteristic is also depicted from values of basal area. Basal area for trees (12.5 $m^2$/ha) represents 69.4% of total basal area. An ultimate indication about the developed structure of the sampled forests in relation to the secondary succession stands is given by their total biomass of 269.2 t/ha. The importance of trees is also noticed here, as their biomass is 268.1 t/ha. Saplings contribute with just 1.1 t/ha.

A complementary way to understand differences and similarities between secondary succession stages and forests in the study area is to analyze structural variables in a comparative fashion. The next section is dedicated to this comparison.

### 3.4.2 - What makes a secondary succession stage?

Overall, the comparative analysis of different succession stages and the tropical open forest indicates a significant separation between the classes sampled in the field. Although the process of vegetation recovery happens on a continuous basis, the decision to choose three categories of regrowth was appropriate to characterize distinct structural phases during the process. The analysis of selected structural variables explaining this distinction is presented below.

- DBH

Figure 18 illustrates the variability in DBH for trees in all classes sampled. It is obvious the trend in increasing DBH from SS1 up to forest. As also expected, there are small overlaps between the extreme values of all classes. The range for DBH of trees in forest sites is the greatest (19.4 to 28.5 cm, Table 8), as well as its distance between the quartiles. The former is explained by the occurrence of emergent individuals competing for light, and the latter indicates the heterogeneity in the average diameter of trees during the first years of recovery. The difference between DBH for all classes is statistically significant at $p<0.001$ (Table 9).

This difference is less significant for DBH of saplings ($p<0.09$). Although it increases from SS1 to SS3, the upper quartile of a previous class is always overlapping with the lower quartile of the next class (Figure 19). It is important to notice the decrease in DBH of saplings in forest sites. This is due to the effect of shading after SS3, when a closer canopy creates an unsuitable environment for sapling development.

- BASAL AREA

Similar trends are found for basal area of trees and saplings, as its calculation is affected by DBH values. Figures 20 and 21 illustrate basal area distributions for these groups of individuals. For saplings, the classification of regrowth stages is not meaningful ($p<0.305$) indicating closer values of basal area from SS1 to forest and mainly at the succession stages (Table 9). Results for total basal area follow the increasing pattern from early secondary stages up to forest (Figure 22). This is explained by tree contribution to total basal area (Figure 23). However, the range and variance for all classes of total basal area are greater than basal area for trees because of sapling heterogeneity for this parameter (Figure 24).

- HEIGHT

Total height of individuals is an important parameter indicating the stage of recovery. Figures 25 and 26 illustrate the observed values for total height of trees and saplings, respectively. The former increases significantly from SS1 to forest ($p<0.001$). Although the height of saplings also increases, overlaps between classes occur more often ($p<0.005$) (Table 9).

Ecologically, these trends are explained by the competition for light within the vegetation community. Trees tend to grow continuously in search of higher canopy layers. As this process occurs, saplings have to deal with the variable availability of light at the understory, which increases their height variance.

- DENSITY

The density of trees increases from SS1 to SS3, but decreases at forest sites (Figure 27). Two factors determine this pattern. First, dominant species at SS3 (e.g., *Cecropia sp.*) die off during the transition to forest. Second, at the forest community level, trees continue to grow in DBH and height but the number of individuals decrease. The trend for density of saplings is the opposite. It constantly decreases from initial stages of regrowth up to forest indicating the importance of trees in more advanced recovery stages (Figure 28). The difference between classes is less significant for trees ($p<0.006$) than for saplings ($p<0.001$) (Table 9).

The relationship of density of saplings and density of trees is depicted by the ratio between these variables. During SS1, this ratio is expressed by a huge variance (Figure 29). Within this stage, the effect of previous land use is more direct, producing different outcomes for vegetation establishment. After SS2, the relationship tends to stabilize as a response to the clear pattern of density change described above.

- BIOMASS

As a function of DBH and height, the trends of aboveground biomass from SS1 to forest are affected by those variables. Biomass for trees increases constantly, achieving its highest values in forest formations (Figure 30). The higher variability for forest biomass is related to the larger range in DBH and total height in this class than in stages of regrowth (Tables 5, 6, 7, and 8). Biomass for saplings shows similar trends to that of DBH for saplings (Figures 31 and 19, respectively). It increases from SS1 to SS3, but decreases for forest, due to the lower importance of saplings in open tropical forest environments. Total biomass values behave similarly to tree biomass (Figure 32).

### 3.4.3 - The Spectral Response to Vegetation Structure

While structural vegetation variables seem to be good indicators of secondary successional stages, the question remains about how spectral Landsat TM bands respond to their variation. Figure 33 illustrates the spectral curves for all areas where vegetation classes were sampled. SS1 and SS2 curves have a higher variability for the mean reflectance in bands 4 and 5 than SS3 and forest. These latter classes have a smaller and well-defined range for reflectance in the near infrared (band 4) and mid-infrared (band 5). The consequences of these spectral responses in terms of distinguishing different regrowth stages and forest are discussed below.

Figure 34 illustrates mean reflectance values for vegetation classes in band 3 (visible). Figure 35 shows these values for band 4 (near infrared), Figure 36 for band 5 (mid-infrared), and Figure 37 for the Normalized Difference Vegetation Index (NDVI).

The significance of the vegetation classification in terms of separability by TM bands is given in Table 10. It is clear how band 5 differentiates regrowth stages better, although all TM bands have $p<0.001$. Band 3 shows poor distinctions in reflectance between SS1 and SS2, while SS3 overlaps with these classes of regrowth and with forest. Band 4 does not distinguish SS1 and SS2. NDVI does not separate any of the vegetation classes ($p<0.502$).

When using graphs to relate structural vegetation variables with reflectance values, other relationships are found. As described above, average total height of trees is a good indicator of succession stages, as it has distinct ranges for all vegetation classes defined (Figure 25). This parameter was used to build scatterplots with visible, near infrared, and mid-infrared TM bands. Band 3 (visible red) does not distinguish vegetation classes properly in terms of the average total height of trees (Figure 38). Infrared bands (4 and 5) show a better response for this structural parameter (Figures 39 and 40, respectively). However, only forest and SS3 are well separated. SS1 and SS2 overlap.

Several other variables reveal similar trends in relation to spectral responses in the infrared. Figures 41, 42, 43, and 44 show these responses for DBH of trees, total basal area, density of trees, and total biomass, respectively. Tridimensional graphs of DBH and total height of trees with reflectance in bands 4 and 5 also suggest that SS1 and SS2 are not well separated spectrally by TM bands (Figures 45 and 46, respectively).

The integration of spectral data with the analysis of field vegetation structure supported the decision-making process when defining classes of land cover used in the next chapters.

## 3.5 - THE ROLE OF VEGETATION STRUCTURE AND REMOTE SENSING FOR THE STUDY OF SECONDARY SUCCESSION DYNAMICS IN COLONIZATION AREAS OF AMAZÔNIA

The study of vegetation structure presented in this chapter confirmed expected trends about secondary succession of tropical forests in Rondônia, which include: increase in density of trees with decrease in density of saplings; increase in DBH of trees and total basal area; increase in total height of trees; and, consequently, increase in total aboveground biomass. In addition, the results obtained for selected vegetation structure variables were depicted by spectral responses in Landsat TM bands, particularly the ones within the infrared portion of the spectrum. This last assertion has already been discussed in the literature and is due to chlorophyll absorption in the visible TM bands (1-3); mesophyll reflectance in the near infrared (band 4); and for both plant and soil water absorption in the mid-infrared bands (5 and 7) (Moran et al. 1994). The balance within and between these three groups of bands permits the differentiation of stages of succession, tropical forest, and other land-cover classes.

The applicability of these findings surpasses the understanding of vegetation recovery processes at local scales. It allows the spatial-temporal monitoring of Amazonian landscapes regarding their land-cover dynamics. Being able to differentiate distinct stages of vegetation regrowth in a landscape makes it possible to draw a better picture about LULC trajectories. The use of remote-sensing techniques has improved this capability by ensuring the investigation of secondary succession in larger areas on a multi-temporal basis. However, such an enterprise is not an easy task, mainly because it artificially reduces the continuous process of vegetation recovery to a selected number of categories.

The dichotomy between natural heterogeneity and the scientific need for generalizations is a major challenge in ecological research. As the knowledge about a phenomenon being studied increases and becomes available for the scientific community, interpolations and extrapolations are readily made. The scales of space, time, and complexity are then reduced to relatively few discrete explanatory categories (Wilson 1998). It is common to see broad generalizations based on local factors and/or grouping of local heterogeneity based on generalizations.

O'Neill et al. (1986), willing to justify such attitude, recognized that some degree of abstraction is required in order to study ecological systems. The rationale behind this statement is that ecology cannot set up a single spatial-temporal scale that will be adequate for all investigations. Space-time dynamics is now understood as a central issue related to ecosystem studies (Kareiva 1994). The scale factor, widely discussed in a variety of studies, has induced the development of a hierarchical view of ecosystems (Allen and Star 1982, Bian 1997). Instead of descriptive and qualitative attempts to analyze natural heterogeneity and dynamics, quantitative approaches have shown the development of complex ecological systems toward new levels of organization (Sklar and Costanza 1991).

These processes range from local to global scales, and the argument is valid for vegetation ecological studies. This chapter focuses on tropical forests in Rondônia and their stages of succession after disturbance. If there is a common sense about what forest is, it relates to a 'vegetation community dominated by trees.' However, even within specific biomes, they may differ in structure, composition, and physiognomy. From the ecologist's standpoint, forests consist of a mosaic of gap-phase, building-phase, and mature-phase formations (Whitmore 1998).

The tentative nature of defining secondary succession classes in Rondônia based on vegetation structure data and remote sensing complies with the need to monitor land cover in the Amazon. But how many final classes need to be defined and how do they correspond with the classes used during field sampling? Do TM spectral bands depict all classes identified by the original sample? If not, which variables can be used to control the process of categorization?

One way to address these questions is to follow the regrowth trajectory in selected sites and assign stages based on age (Uhl 1987, Guariguata et al. 1997, Nelson et al. 1999). This method generally maintains control over site variability but does not allow generalization to other areas within the region due to the small number of samples. In addition, the vegetation classes are difficult to depict in TM images at this level of separation. Another way to address the heterogeneity of vegetation classes of regrowth in the Amazon is to define a range of classes based on vegetation structure (Brondizio 1996, Tucker 1996) or age (Uhl et al. 1988, Steininger 1996). This method may also be affected by the sampling strategy. For instance, if age is considered as an initial parameter to define regrowth classes, gaps between ages sampled may produce additional lack of information in order to identify the final classes. However, using stratified random sample techniques minimizes the potential pitfalls of such strategy by ensuring a broader representation of the natural variability in the study area.

For the research in Rondônia, the sample did not include ages 1, 2, 4, 7, 11, and greater than 14 years. The decision of undersampling the first and second years of succession was discussed above. In this case, the confusion with pasture in terms of land use, vegetation structure (similar to degraded pasture), and spectral responses, indicated that the accuracy of assigning SS1 increases if stands more than 2 years old are considered. The decision was supported by previous studies showing that most class errors were associated with youngest age classes (< 2 years) and with different successional pathways and vegetation composition (Foody et al. 1996). To avoid the problem, Steininger (1996) also assigned classes of regrowth starting at two years old, and included a class called 'pasture with trees' between 'farmland' (agriculture and pasture) and secondary succession.

The confusion between SS1 and degraded pasture is mostly due to a common practice among local landowners. After slashing and burning, they often seed grass for pasture. If not, they plant annual crops, then seed grass. Or they plant annual and perennial crops (mostly coffee), and, if anything goes wrong, planting grass is again seen as an alternative land use. With the use of fire, grasses tend to overcome other pioneer species, playing an important role in initial stages of succession and consequently affecting spectral classifications. After the second year, recovery by saplings and small trees diminish the importance of grasses regarding ground cover. Then, the physiognomy (structure) of a fallow is better characterized.

On the other hand, not including first- and second-year SS1 increased the averages for some key structural variables being analyzed. For example, total height and DBH of trees for SS1 in the study area were greater than reported by other comparable studies (Alves et al. 1997). Besides this initial period of regrowth and a few years of not being present in the sample, other ages were well represented (3, 5, 6, 8, 9, 10, 12 and 13 years old). Secondary succession stands older than 14 years were not sampled due to the settlements' age. Since they were established between 1980 and 1984, and fieldwork was done in 1999, the uncertainty of sampling 15-year-old or older stands would be too high. Moreover, no landowner reported a fallow that old.

The sample variability allowed the comparison of vegetation structure and spectral responses within and across classes. In general, height and DBH of trees, density of saplings, total basal area, and total biomass were good indicators of vegetation regrowth stages. All of them were significantly separated among SS1, SS2, SS3, and forest classes (Table 9). It is important to mention that many of these variables are significantly correlated, indicating that less sampling effort would be needed to depict different classes of succession in broader studies at the regional scale (Table 11). For example, DBH, basal area, height, and biomass of trees are highly correlated. As other studies have shown, height or DBH of trees could be chosen in this case to represent the stage of regrowth (Moran et al. 2000). The advantage of choosing these variables instead of basal area or biomass is the relative simplicity of directly measuring them during fieldwork and perhaps in the future using Light Detection and Ranging (LIDAR) to estimate canopy height for large regional areas.

Despite the clear separation among classes of succession and forest, when graphed against mean reflectance in infrared TM bands (Figures 39 to 46), only three clusters of samples were well differentiated (SS1 and SS2 mixed together, SS3, and forest). These results supported the decision of grouping SS1 and SS2 into a single class of regrowth. In doing that, the accuracy increases in relation to the classification system. Also, the confusion between SS1 and pasture or SS2 and perennial agriculture tends to be minimized. In addition, two classes of succession are still maintained, allowing studies of land-cover dynamics through multi-temporal analyses. In sum, the decision of going from three to two classes of vegetation regrowth was necessary to improve the performance of further analyses of land-cover dynamics.

All these findings confirm the importance of land-use history besides age in defining stages of secondary succession. However, in more recent settlements such as Machadinho and Anari, age also may be significant because there was not enough time to produce the same impact as in older settlements. This is indicated by the significant correlation between age and vegetation structure variables or spectral data mentioned above (table 11). As pointed out by Uhl et al. (1988), site age is a good predictor of aboveground biomass accumulation on light- and moderate-use sites, but not on heavy-use sites. In this chapter, age and physiognomy were used as indicators for field sampling, but, after data collection, age also can become a variable to be analyzed together with vegetation structure variables and spectral responses in TM bands.

Although some studies have attempted to assign age to secondary succession stages based on total stand biomass (Nelson et al. 1999) or canopy geometry (Steininger 1996), what has been measured is the outcome of different trajectories of land use over distinct biophysical features. The stage of regrowth in terms of vegetation structure (and species composition), and not its age, is more useful in possible applications of mapping and monitoring succession classes. However, age may be appropriate as an organizing principle of regrowth stages when sampling vegetation and interviewing local people and landowners or to be used in studying the impact of land-use history on different sites (Moran et al. 2000). In this sense, knowledge of culture and context helps to achieve a better understanding of regeneration processes in the Amazon. Moreover, the study of vegetation structure variables such as total height of trees together with the investigation on biophysical features such as soil fertility and land-use history are better indicators regarding the degree of development of a regrowth stand. The assessment of these variables at local and regional scales and the interpretation of spectral data to depict such variability provide more accurate information about the trajectory of recovery occurring at distinct colonization stages in rural settlements in the Amazon.

## 3.6 - TRENDS IN RESEARCH OF TROPICAL FOREST SECONDARY SUCCESSION

The findings and topics exposed in this chapter illustrate the importance of studying secondary succession in tropical environments. The research also identified many research initiatives regarding the integration of vegetation structure data and the use of satellite images in monitoring land-cover dynamics in the Amazon.

The rapid and aggressive regrowth of secondary vegetation in tropical areas has already been discussed by a number of researchers. The Amazon colonization produces widespread deforestation but also a mosaic of secondary successional vegetation stages. Different regeneration patterns occur depending on land management following deforestation. Although it is clear that secondary vegetation will not preserve the total biodiversity of mature forests, it is also clear that it plays an important role in the Amazonian landscape structure and function (Smith et al. 1997).

Perhaps one important question not covered by this chapter is the role of species composition within the different stages of regrowth. Studies have shown that disturbance from slash-and-burn agriculture affects species composition much more than stand structure and biomass (Uhl 1987). Vieira et al. (1996) have also pointed out that even after 40 years of recovery, richness is less than half of a primary forest. Although such an issue is of central relevance to the maintenance of local and regional biodiversity, we are far from being able to differentiate distinct tropical forest communities based on species composition when using satellite data. Current applications can only recognize different structural patterns and processes.

Research regarding these latter applications includes many new approaches. In terms of the availability of new sensors and data, optical and microwave data provide complementary information about land use and forest fragmentation. Besides overcoming the problem of cloud cover, the use of low frequency radar systems and its integration with other spatial and spectral data is promising for land-cover mapping in the Amazon (Rignot et al. 1997, Saatchi et al. 1997, Yanasse et al. 1997).

A second way of improving the extraction of earth surface feature information for LULC classifications in the Amazon is the use of state-of-the-art techniques for image processing and classification. Among others, spectral mixture analysis (Schweik 1995, Adams et al. 1995), spatial-spectral classifiers (Foody et al. 1996), spectral indices of canopy brightness (Steininger 1996) and GIS-informed classifications (Hinton 1996, Batistella 2000) are among the main trends to improve monitoring of secondary succession.

Recent questions have arisen about the importance of successional land covers to carbon sequestration (Fearnside and Guimarães 1996). Other studies have addressed the process of degradation of Amazonian forests (Nepstad et al. *Flames* 1999, Vieira et al. 1993). Activities such as selective logging have been responsible for the impoverishment of forests. Logging and fire increase forest vulnerability to future burning, 'potentially doubling net carbon emissions from regional land use during severe El Niño episodes' (Nepstad et al. *Large-scale* 1999).

The ecological functions of secondary forests at local and regional scales have just recently been investigated. Besides maintaining one-third of the native species, their role in carbon sequestration seems to be even more important (Vieira et al. 1996). Furthermore, successional vegetation re-evaporates an important part of the rainfall input in spite of the marked seasonal distribution of rainfall (Holscher et al. 1997). Possible regional climatic changes due to deforestation may be less severe in areas where woody secondary vegetation plays an important role in land cover.

At the local scale, the stages of secondary succession are directly associated with cycles of production and abandonment. Slash and burn clearing, cropping, and fallowing correspond to different phases within these cycles and depend on decision-making processes among the landowners. In this sense, monitoring the outcomes in terms of vegetation structure and LULC may also provide information about actions being taken by farmers. The study of LULC dynamics, and its fundamental importance to the understanding of general patterns of landscape transformation, is the goal of the next chapter.

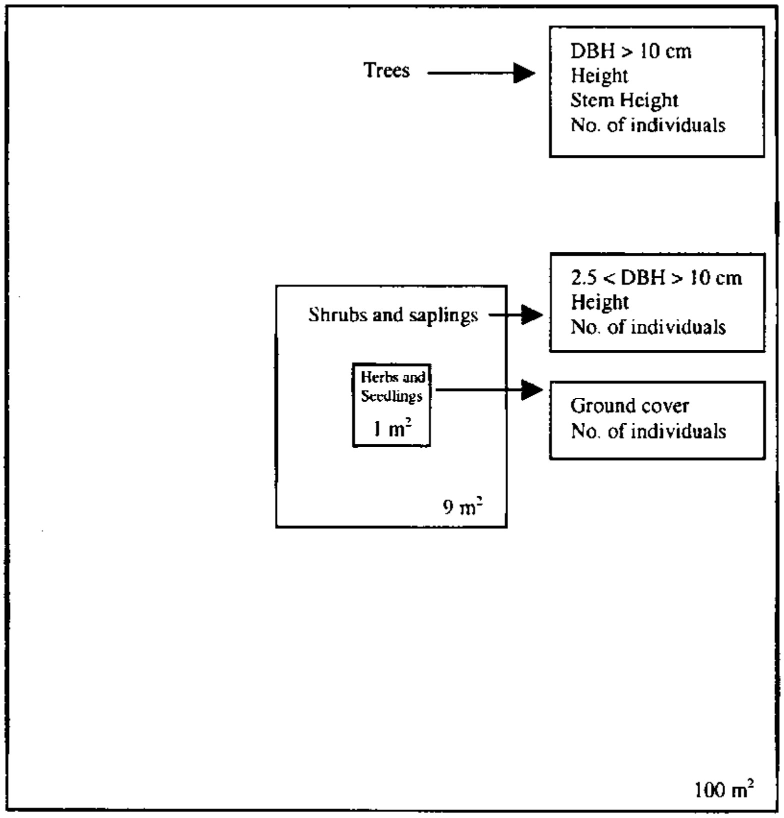



Figure 11 - Diagram of nested squares for vegetation sampling in Machadinho d'Oeste and Vale do Anari.

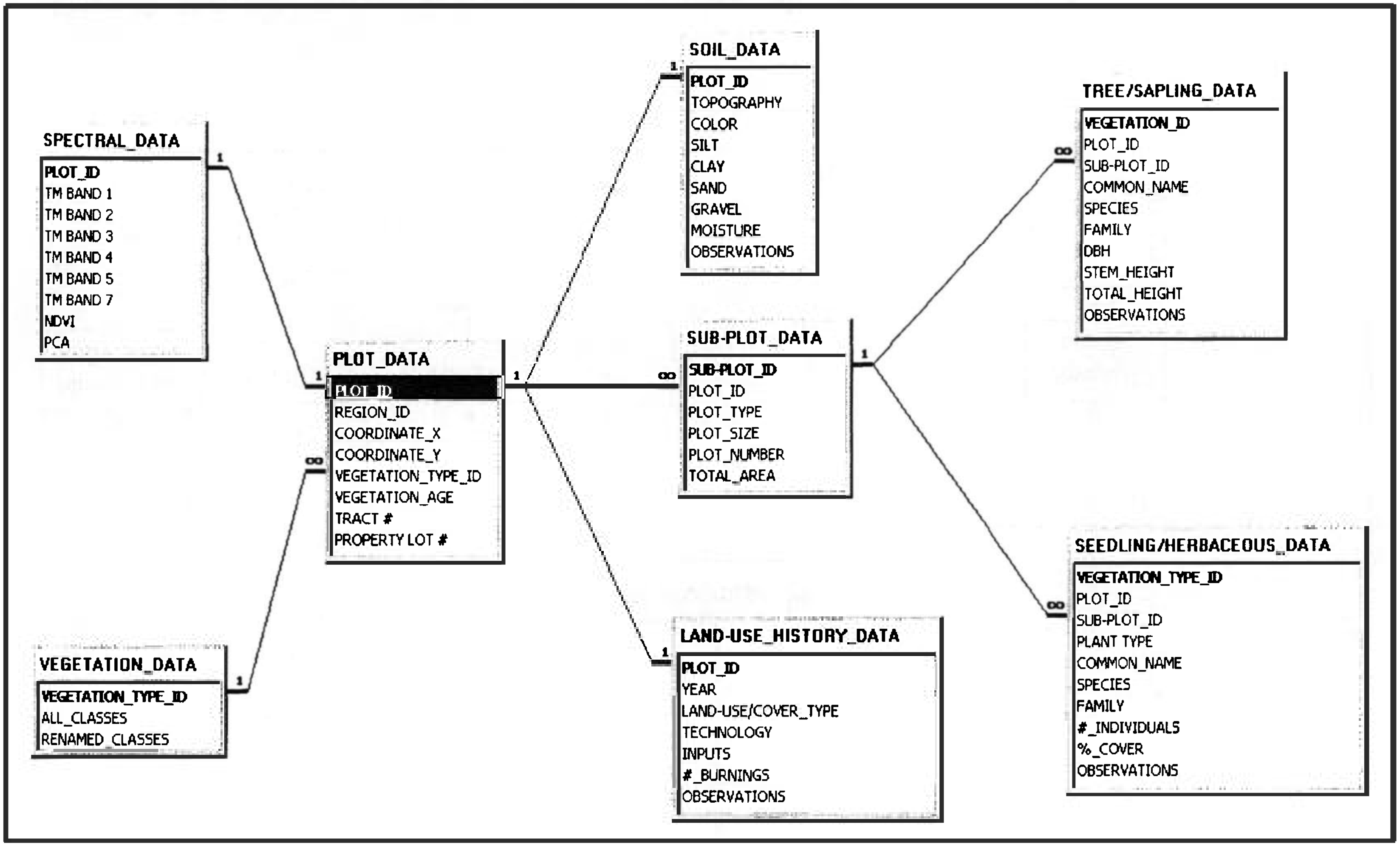



Figure 12 - Relationships between vegetation database tables for Machadinho d'Oeste and Vale do Anari.

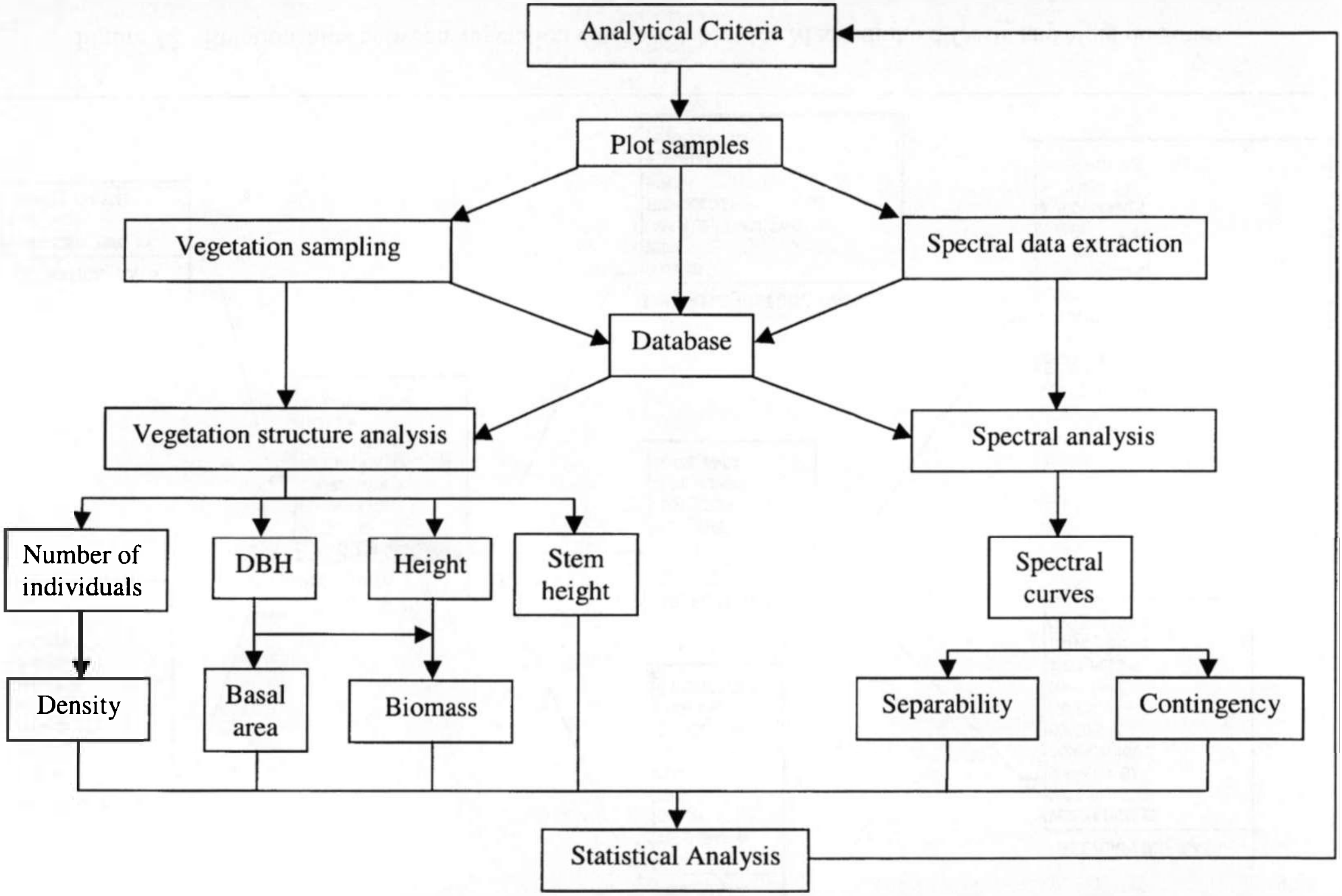



Figure 13 - Integration of vegetation structure and spectral data analysis for Machadinho d'Oeste and Vale do Anari.

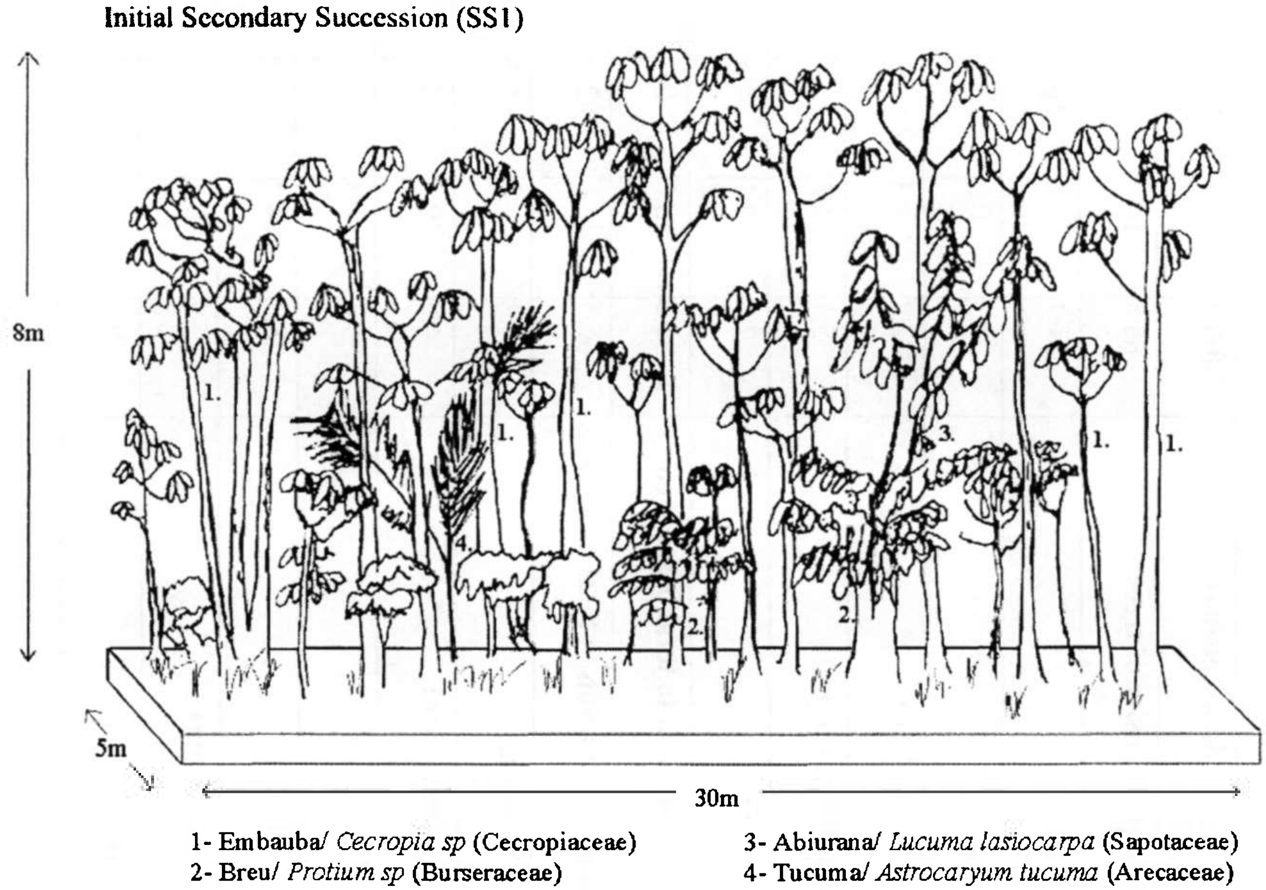
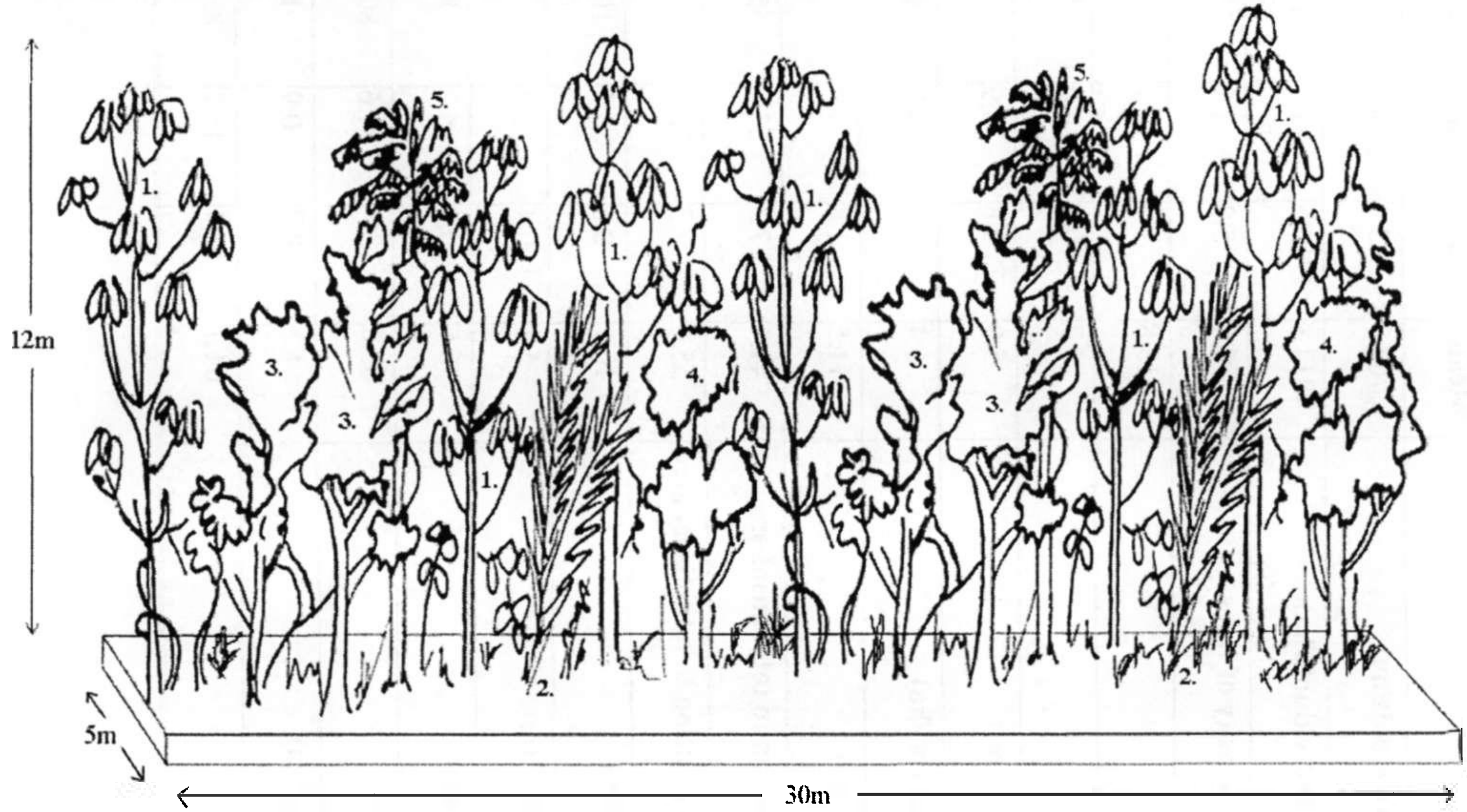



Figure 14 - Vegetation profile of an initial secondary succession stand in Machadinho d'Oeste and Vale do Anari.

Table 5 - Vegetation structural variables for initial secondary succession stands in Machadinho d'Oeste and Vale do Anari.

| | Mean | S.D. | Min. | Max. |
|---|---|---|---|---|
| **Density of trees (individuals/ha)** | 266.7 | 231.9 | 33.3 | 533.3 |
| **Density of saplings (individuals/ha)** | 7460.3 | 2022.1 | 4074.1 | 10000.0 |
| **Density of saplings / density of trees** | 88.8 | 110.7 | 7.6 | 300.0 |
| **DBH of trees (cm)** | 11.4 | 0.8 | 10.0 | 12.4 |
| **DBH of saplings (cm)** | 4.3 | 0.3 | 3.7 | 4.6 |
| **Basal area of trees ($m^2$/ha)** | 2.7 | 1.3 | 0.0 | 4.0 |
| **Basal area of saplings ($m^2$/ha)** | 5.1 | 1.3 | 2.4 | 6.3 |
| **Total basal area ($m^2$/ha)** | 7.8 | 2.1 | 4.6 | 9.8 |
| **Percent tree contribution to total basal area** | 33.5 | 15.6 | 0.0 | 47.7 |
| **Percent sapling contribution to total basal area** | 66.5 | 15.6 | 52.3 | 100. 0 |
| **Total height of trees (m)** | 7.8 | 1.4 | 5.5 | 9.6 |
| **Total height of saplings (m)** | 4.8 | 0.5 | 4.3 | 5.8 |
| **Stem height of trees (m)** | 5.4 | 1.4 | 3.5 | 7.0 |
| **Biomass of trees (t/ha)** | 28.3 | 14.2 | 0.0 | 38.0 |
| **Biomass of saplings (t/ha)** | 0.9 | 0.1 | 0.7 | 1.1 |
| **Total biomass (t/ha)** | 29.2 | 14.3 | 0.9 | 39.1 |

Intermediate Secondary Succession (SS2)



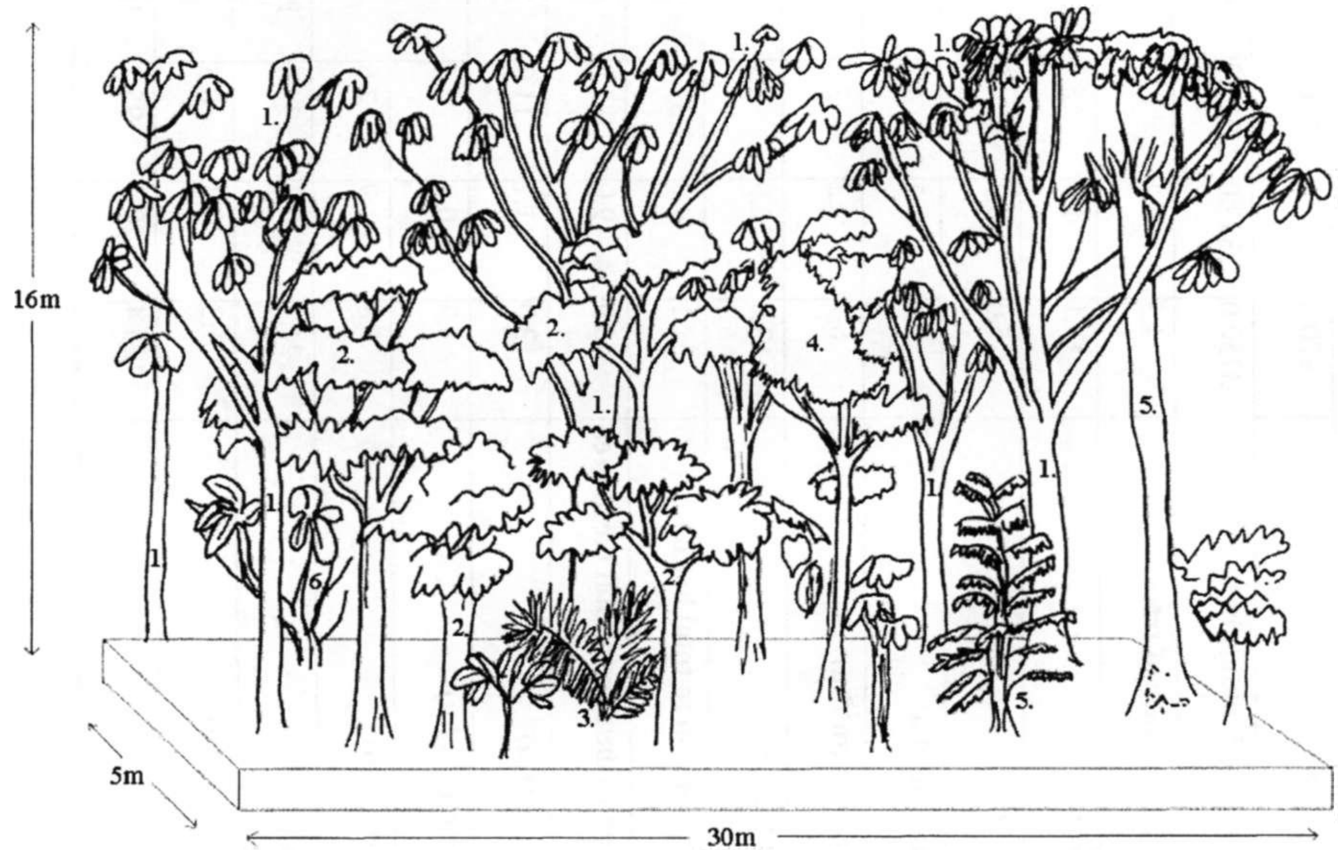

1. Embauba/ *Cecropia sp* (Cecropiaceae)
2. Babacu/ *Orbignya martiana* (Arecaceae)
3. Lacre/ *Vismia sp* (Gutiferae)
4. Goiaba de anta/ *Bellucia imperialis* (Melastomataceae)
5. Breu/ *Protium sp* (Burseraceae)

Figure 15 - Vegetation profile of an intermediate secondary succession stand in Machadinho d'Oeste and Vale do Anari.

Table 6 - Vegetation structural variables for intermediate secondary succession stands in Machadinho d'Oeste and Vale do Anari.

| | **Mean** | **S.D.** | **Min.** | **Max.** |
|---|---|---|---|---|
| **Density of trees (individuals/ha)** | 763.3 | 283.0 | 300.0 | 1233.3 |
| **Density of saplings (individuals/ha)** | 4814.8 | 1719.5 | 1481.5 | 7037.0 |
| **Density of saplings / density of trees** | 7.8 | 5.2 | 1.2 | 19.7 |
| **DBH of trees (cm)** | 13.8 | 1.2 | 12.1 | 15.3 |
| **DBH of saplings (cm)** | 4.7 | 0.6 | 4.0 | 5.7 |
| **Basal area of trees ($m^2$/ha)** | 5.0 | 0.8 | 3.9 | 6.2 |
| **Basal area of saplings ($m^2$/ha)** | 6.4 | 1.6 | 4.7 | 9.5 |
| **Total basal area ($m^2$/ha)** | 11.5 | 1.8 | 9.4 | 15.7 |
| **Percent tree contribution to total basal area** | 44.4 | 7.3 | 33.9 | 55.2 |
| **Percent sapling contribution to total basal area** | 55.6 | 7.3 | 33.9 | 55.2 |
| **Total height of trees (m)** | 10.1 | 0.6 | 8.7 | 10.7 |
| **Total height of saplings (m)** | 5.1 | 0.4 | 4.4 | 5.6 |
| **Stem height of trees (m)** | 6.6 | 0.9 | 5.2 | 8.0 |
| **Biomass of trees (t/ha)** | 63.6 | 13.4 | 44.6 | 80.7 |
| **Biomass of saplings (t/ha)** | 1.1 | 0.2 | 0.9 | 1.5 |
| **Total biomass (t/ha)** | 64.7 | 13.4 | 45.7 | 82.2 |

Advanced Secondary Succession (SS3)

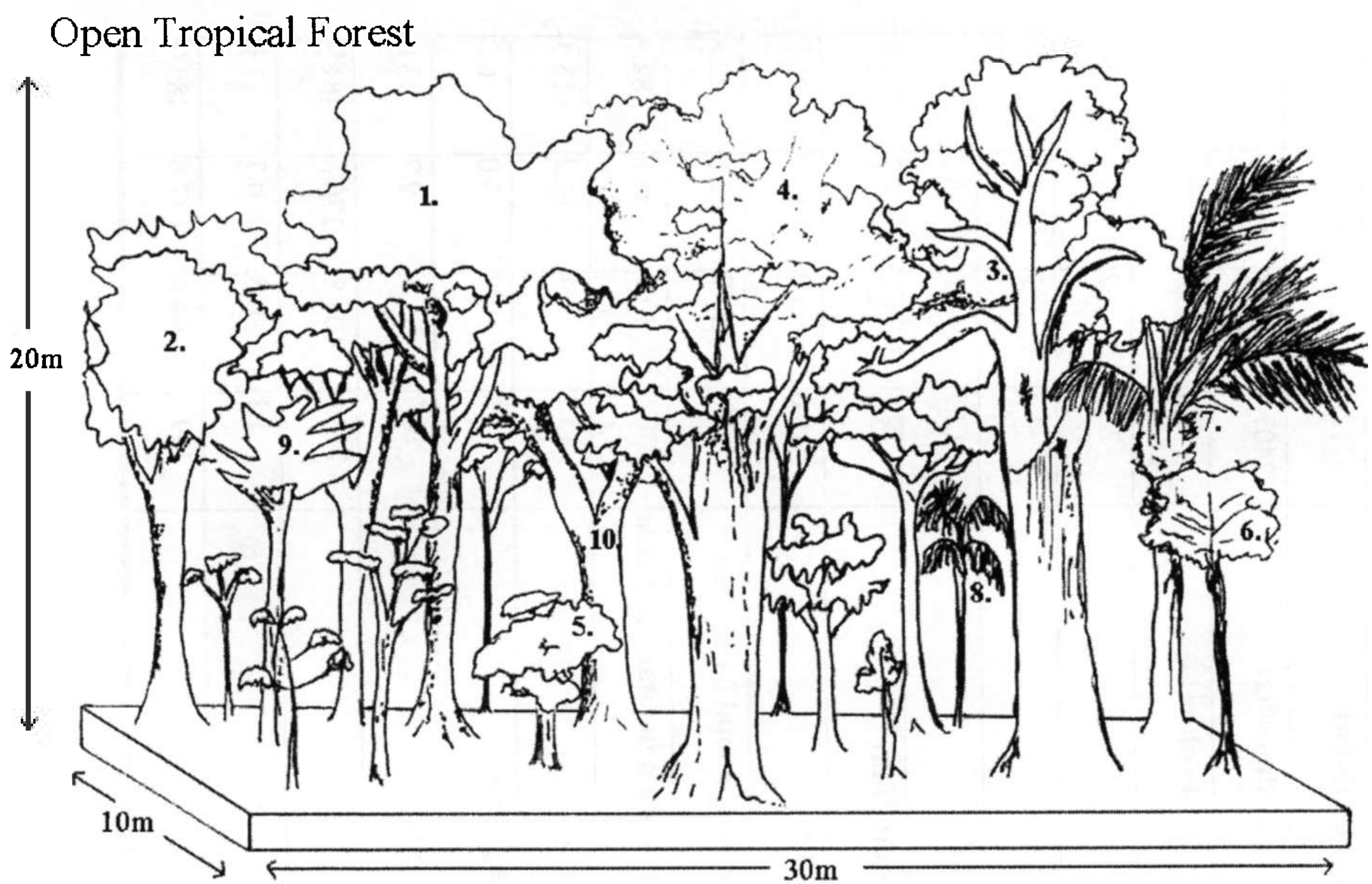



1- Embauba/ *Cecropia sp* (Cecropiaceae)
2- Goiaba de anta/ *Bellucia imperialis* (Melastomataceae)
3- Babacu/ *Orbignya Martiana* (Arecaceae)
4- Lacre/ *Vismia sp* (Gutiferae)
5- Breu/ *Protium sp* (Burseraceae)
6- Abiurana/ *Lucuma lasiocarpa* (Sapotaceae)

Figure 16 - Vegetation profile of an advanced secondary succession stand in Machadinho d'Oeste and Vale do Anari.

Table 7 - Vegetation structural variables for advanced secondary succession stands in Machadinho d'Oeste and Vale do Anari.

| | Mean | S.D. | Min. | Max. |
|---|---|---|---|---|
| Density of trees (individuals/ha) | 920.8 | 276.0 | 666.7 | 1333.3 |
| Density of saplings (individuals/ha) | 3750.0 | 1392.0 | 2222.2 | 6666.7 |
| Density of saplings / density of trees | 4.5 | 2.4 | 1. 7 | 9.1 |
| DBH of trees (cm) | 17.1 | 1.1 | 15.2 | 18.6 |
| DBH of saplings (cm) | 5.0 | 0.7 | 3. 9 | 6.1 |
| Basal area of trees ($m^2$/ha) | 6.9 | 1.5 | 4.5 | 9.1 |
| Basal area of saplings ($m^2$/ha) | 6.7 | 2.2 | 3.8 | 10.8 |
| Total basal area ($m^2$/ha) | 13.6 | 2.9 | 8.9 | 17.4 |
| Percent tree contribution to total basal area | 51.1 | 9.0 | 37.9 | 64.2 |
| Percent sapling contribution to total basal area | 48.9 | 9.0 | 35.8 | 62.1 |
| Total height of trees (m) | 13.0 | 1.1 | 11.3 | 14.8 |
| Total height of saplings (m) | 5.7 | 0.8 | 4.4 | 6.9 |
| Stem height of trees (m) | 9.8 | 1.9 | 7.6 | 12.9 |
| Biomass of trees (t/ha) | 124.1 | 20.8 | 94.5 | 151.3 |
| Biomass of saplings (t/ha) | 1.3 | 0.3 | 0.8 | 1.7 |
| Total biomass (t/ha) | 125.4 | 20.7 | 95.7 | 152.4 |




1-Itaubarana/ *Heisteria sp* (Olacaceae)
2-Matamata/ *Eschweilera sp* (Lecythidaceae)
3-Jatoba/ *Hymenaea sp* (Caesalpiniaceae)
4-Itauba/ *Mesilaurus itauba* (Lauraceae)
5-Guariuba/ *Clarisia racemosa* (Moraceae)
6-Roxinho/ *Peltogyne paniculata* (Caesalpiniaceae)
7-Babacu/ *Orbignya martiana* (Arecaceae)
8-Acai/ *Euterpe oleraceae* (Arecaceae)
9-Louro/ *Acrodiclidium brasiliense* (Lauraceae)
10-Massaranduba/ *Manilkara huberi* (Sapotaceae)

Figure 17 - Vegetation profile of a tropical open forest stand in Machadinho d'Oeste and Vale do Anari.

Table 8 - Vegetation structural variables for tropical open forest stands in Machadinho d'Oeste and Vale do Anari.

| | Mean | S.D. | Min. | Max. |
|---|---|---|---|---|
| **Density of trees (individuals/ha)** | 772.1 | 449.6 | 466. 7 | 1766. 7 |
| **Density of saplings (individuals/ha)** | 2407.4 | 1296.3 | 1481.5 | 5185.2 |
| **Density of saplings / density of trees** | 3.2 | 0.7 | 2.0 | 4.3 |
| **DBH of trees (cm)** | 22.8 | 3.2 | 19.4 | 28.5 |
| **DBH of saplings (cm)** | 4.5 | 0.7 | 3.5 | 5.8 |
| **Basal area of trees ($m^2$/ha)** | 12.5 | 4.3 | 8.3 | 21.3 |
| **Basal area of saplings ($m^2$/ha)** | 5.5 | 2.4 | 2.6 | 9.7 |
| **Total basal area ($m^2$/ha)** | 18.0 | 5.0 | 11.2 | 26.8 |
| **Percent tree contribution to total basal area** | 69.4 | 10.7 | 55.8 | 82.8 |
| **Percent sapling contribution to total basal area** | 30.6 | 10.7 | 55.8 | 82.8 |
| **Total height of trees (m)** | 15.2 | 1.4 | 14.2 | 18.1 |
| **Total height of saplings (m)** | 5.8 | 0.5 | 5.0 | 6.3 |
| **Stem height of trees (m)** | 10.7 | 1.3 | 9.7 | 13.6 |
| **Biomass of trees (t/ha)** | 268.1 | 104.8 | 176.5 | 481.9 |
| **Biomass of saplings (t/ha)** | 1.1 | 0.3 | 0.7 | 1.6 |
| **Total biomass (t/ha)** | 269.2 | 104.8 | 177.6 | 483.0 |

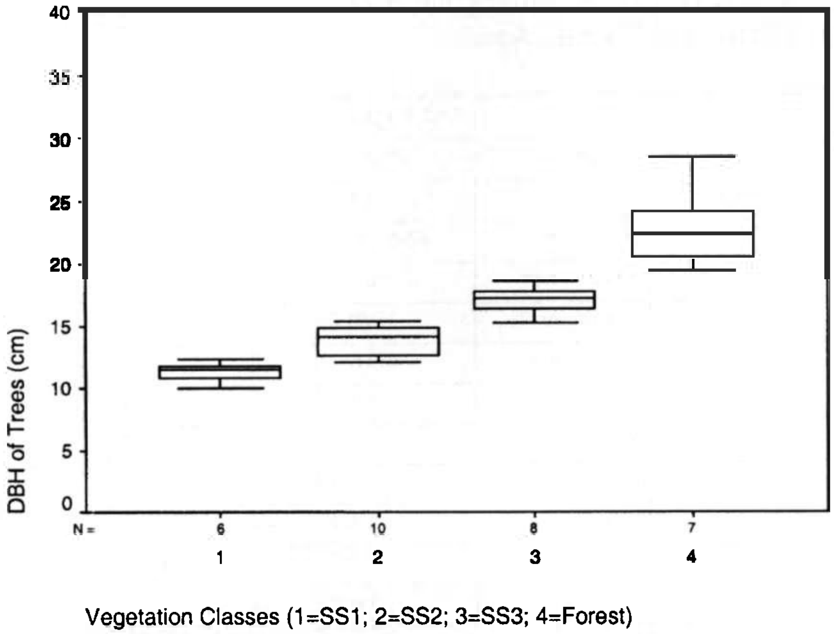



Figure 18 - Distribution of DBH of trees within vegetation classes sampled in Machadinho d'Oeste and Vale do Anari.

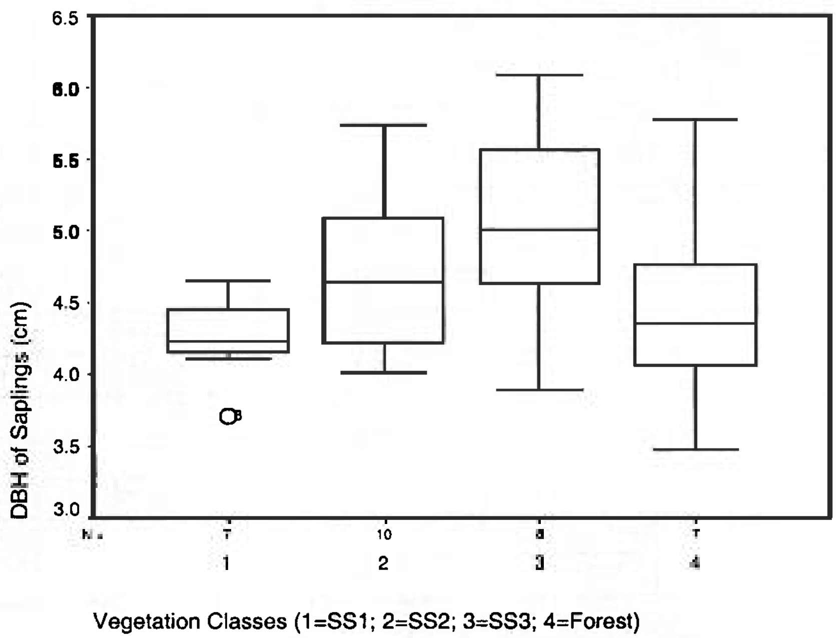



Figure 19 - Distribution of DBH of saplings within vegetation classes sampled in Machadinho d'Oeste and Vale do Anari.

Table 9 - Analysis of variance (ANOVA) for vegetation structural variables sampled in Machadinho d'Oeste and Vale do Anari.

| | | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|---|
| **Density of trees (individuals/ha)** | Between Groups | 1590306.48 | 3 | 530102.16 | 5.23 | 0.006 |
| | Within Groups | 2736146.60 | 27 | 101338.76 | | |
| **Density of saplings (individuals/ha)** | Between Groups | 97164561.17 | 3 | 32388187.06 | 12.13 | 0.000 |
| | Within Groups | 74791871.49 | 28 | 2671138.27 | | |
| **Density of saplings / density of trees** | Between Groups | 33691.26 | 3 | 11230.42 | 4.93 | 0.007 |
| | Within Groups | 61549.15 | 27 | 2279.60 | | |
| **DHB of trees (cm)** | Between Groups | 510.36 | 3 | 170.12 | 52.13 | 0.000 |
| | Within Groups | 88.11 | 27 | 3.26 | | |
| **DBH of saplings (cm)** | Between Groups | 2.59 | 3 | 0.86 | 2.39 | 0.090 |
| | Within Groups | 10.12 | 28 | 0.36 | | |
| **Basal area of trees ($m^2$/ha)** | Between Groups | 373.88 | 3 | 124.63 | 24.36 | 0.000 |
| | Within Groups | 143.25 | 28 | 5.12 | | |
| **Basal area of saplings ($m^2$/ha)** | Between Groups | 13.82 | 3 | 4.61 | 1.27 | 0.305 |
| | Within Groups | 101.82 | 28 | 3.64 | | |
| **Total basal area ($m^2$/ha)** | Between Groups | 389.11 | 3 | 129.70 | 13.72 | 0.000 |
| | Within Groups | 264.63 | 28 | 9.45 | | |
| **Percent tree contribution to total basal area** | Between Groups | 4831.07 | 3 | 1610.36 | 14.17 | 0.000 |
| | Within Groups | 3181.83 | 28 | 113.64 | | |
| **Percent sapling contribution to total basal area** | Between Groups | 4831.07 | 3 | 1610.36 | 14.17 | 0.000 |
| | Within Groups | 3181.83 | 28 | 113.64 | | |
| **Total height of trees (m)** | Between Groups | 218.51 | 3 | 72.84 | 59.44 | 0.000 |
| | Within Groups | 33.08 | 27 | 1.23 | | |
| **Total height of saplings (m)** | Between Groups | 5.00 | 3 | 1.67 | 5.25 | 0.005 |
| | Within Groups | 8.89 | 28 | 0.32 | | |
| **Stem height of trees (m)** | Between Groups | 135.47 | 3 | 45.16 | 22.67 | 0.000 |
| | Within Groups | 53.77 | 27 | 1.99 | | |
| **Biomass of trees (t/ha)** | Between Groups | 243799.89 | 3 | 81266.63 | 31.68 | 0.000 |
| | Within Groups | 71837.89 | 28 | 2565.64 | | |
| **Biomass of saplings (t/ha)** | Between Groups | 0.42 | 3 | 0.14 | 2.48 | 0.082 |
| | Within Groups | 1.58 | 28 | 0.06 | | |
| **Total biomass (t/ha)** | Between Groups | 243937.55 | 3 | 81312.52 | 31.75 | 0.000 |
| | Within Groups | 71704.42 | 28 | 2560.87 | | |

Note: df = degrees of freedom; F = F test of significance; Sig. = Significance

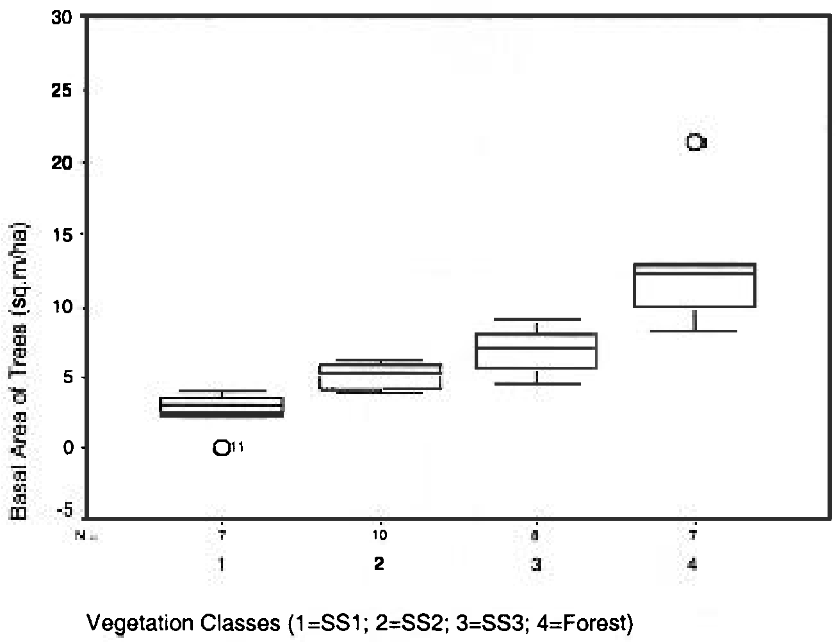



Figure 20 - Distribution of basal area of trees within vegetation classes sampled in Machadinho d'Oeste and Vale do Anari.

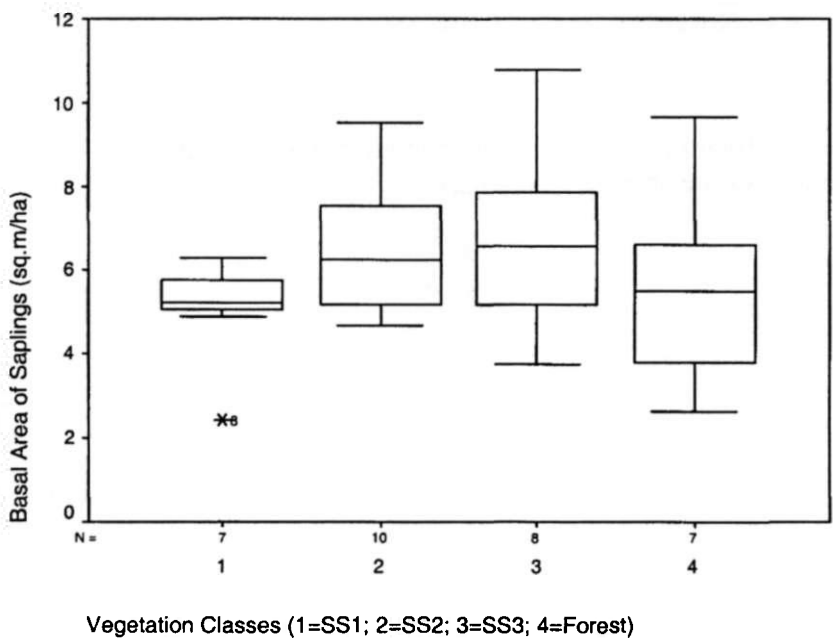



Figure 21 - Distribution of basal area of saplings within vegetation classes sampled in Machadinho d'Oeste and Vale do Anari.

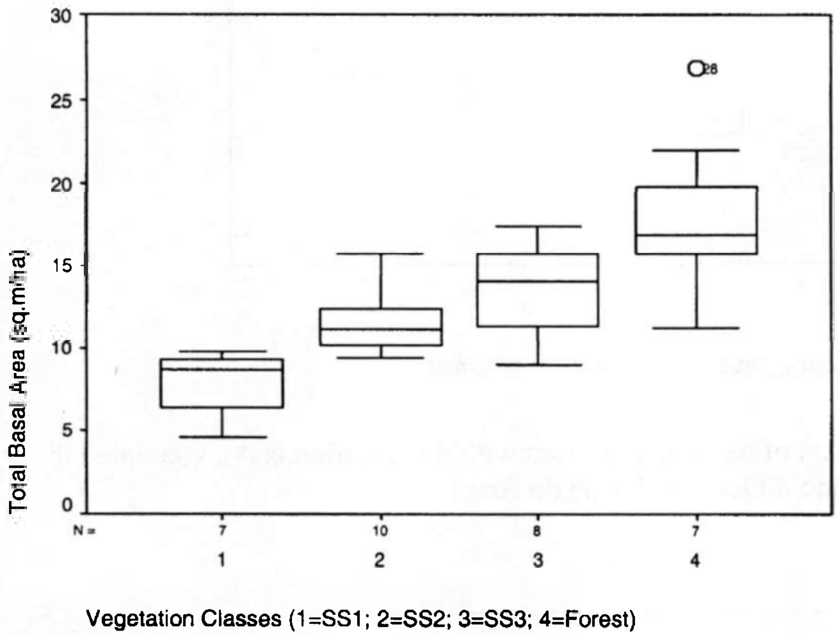



Figure 22 - Distribution of total basal area within vegetation classes sampled in Machadinho d'Oeste and Vale do Anari.

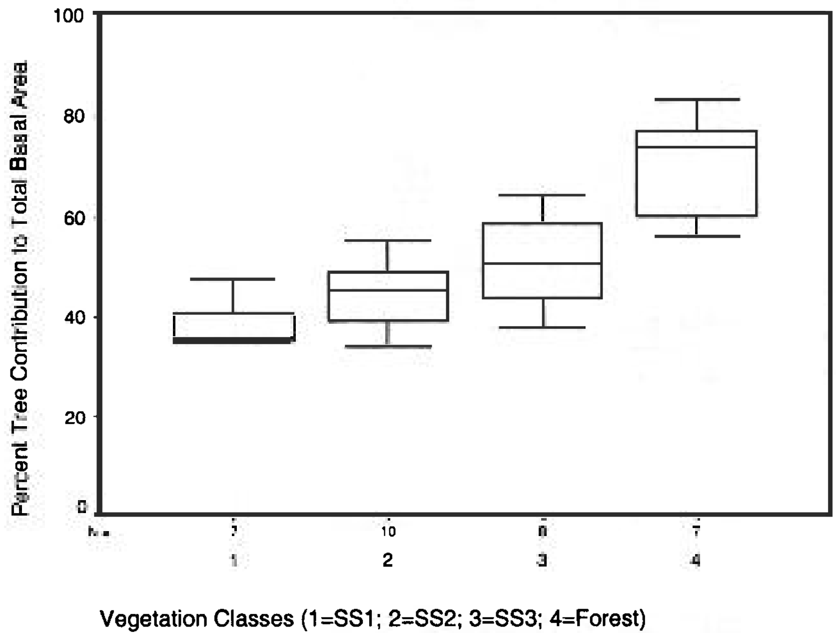



Figure 23 - Distribution of percentage tree contribution to total basal area within vegetation classes sampled in Machadinho d'Oeste and Vale do Anari.

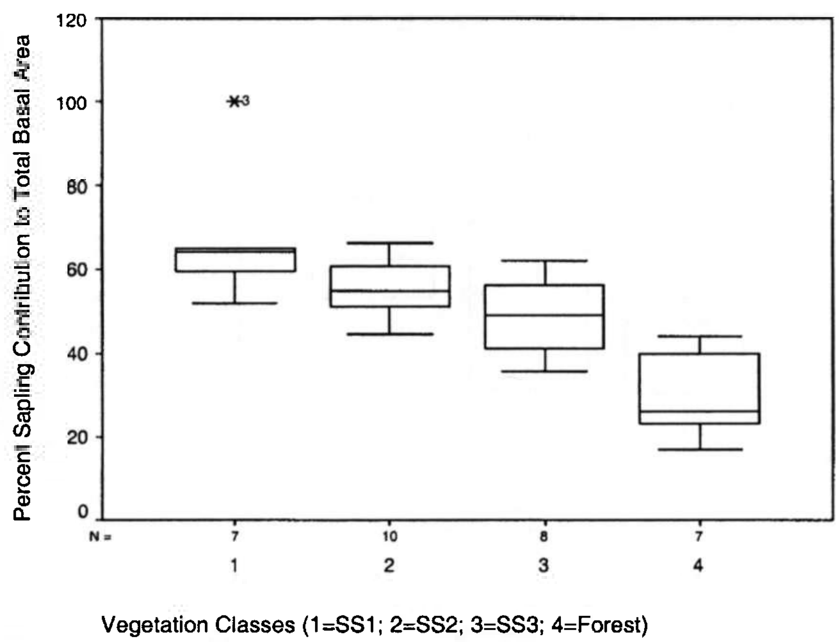



Figure 24 - Distribution of percentage sapling contribution to total basal area within vegetation classes sampled in Machadinho d'Oeste and Vale do Anari.

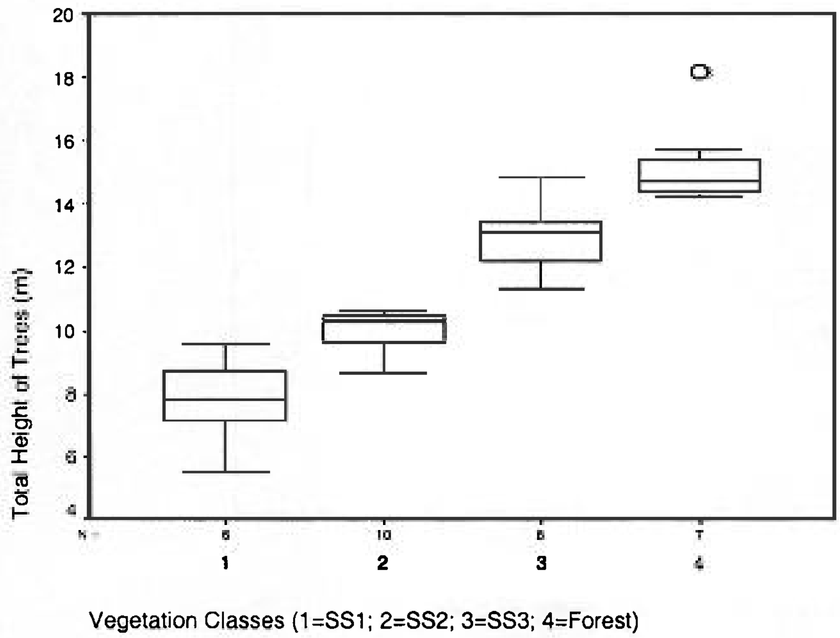



Figure 25 - Distribution of total height of trees within vegetation classes sampled in Machadinho d'Oeste and Vale do Anari.

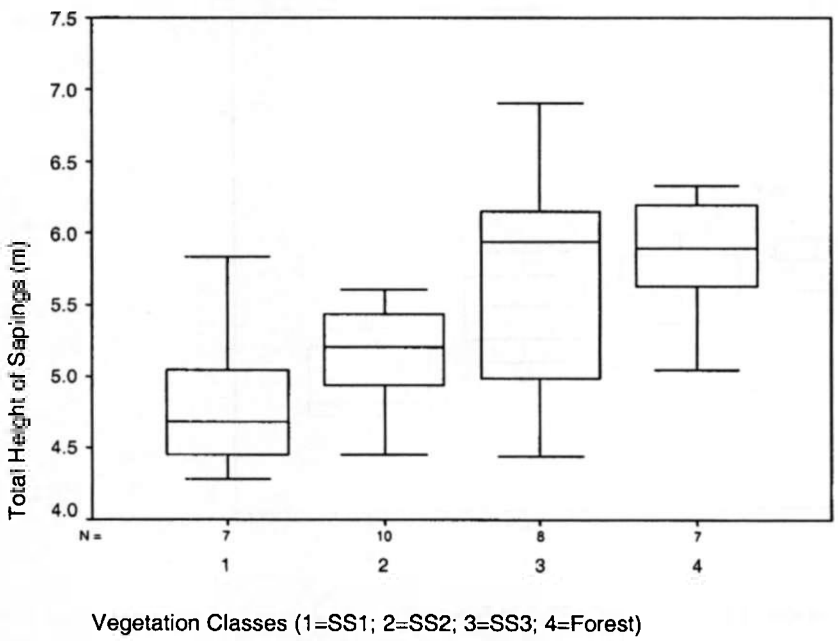
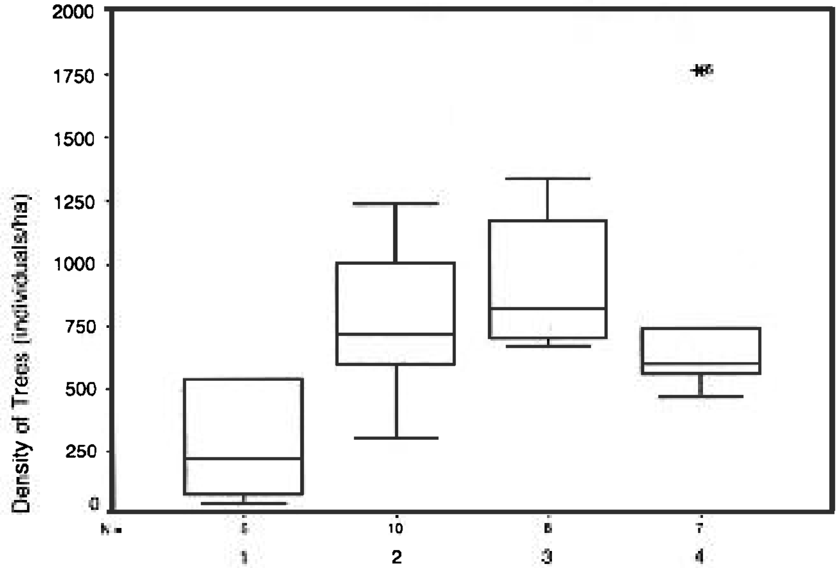
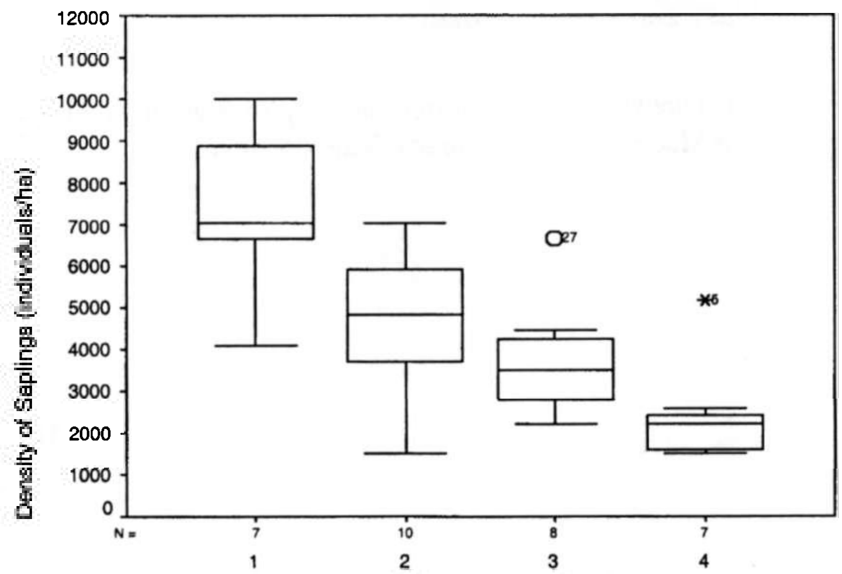



Figure 26 - Distribution of total height of saplings within vegetation classes sampled in Machadinho d'Oeste and Vale do Anari.




Vegetation Classes (1=SS1; 2=SS2; 3=SS3; 4=Forest)

Figure 27 - Distribution of density of trees within vegetation classes sampled in Machadinho d'Oeste and Vale do Anari.




Vegetation Classes (1=SS1; 2=SS2; 3=SS3; 4=Forest)

Figure 28 - Distribution of density of saplings within vegetation classes sampled in Machadinho d'Oeste and Vale do Anari.

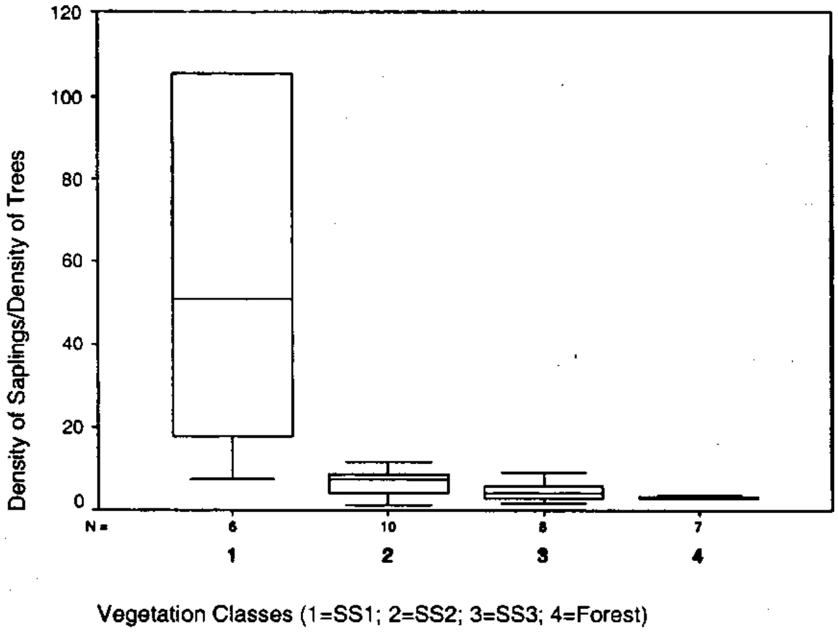



Figure 29 - Distribution of ratio between density of trees and saplings within vegetation classes sampled in Machadinho d'Oeste and Vale do Anari.

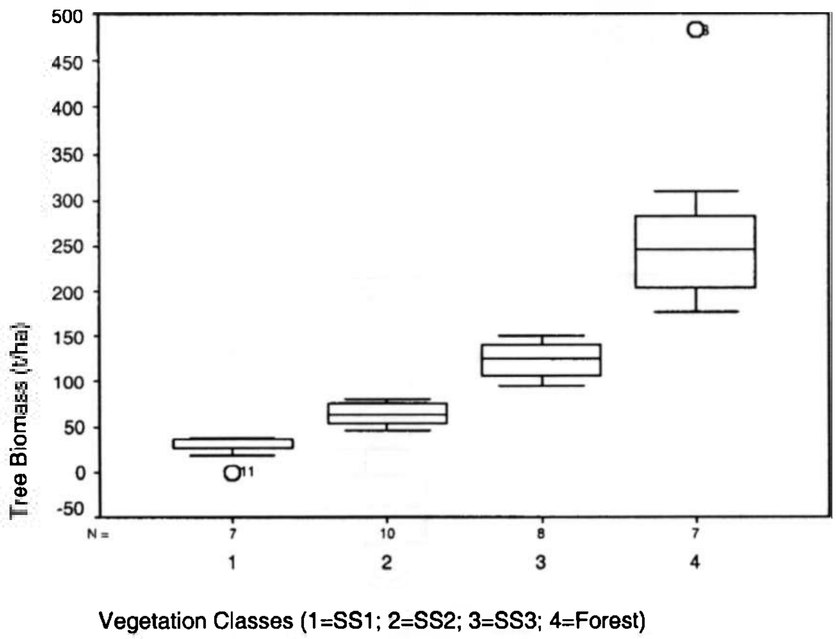



Figure 30 - Distribution of biomass of trees within vegetation classes sampled in Machadinho d'Oeste and Vale do Anari.

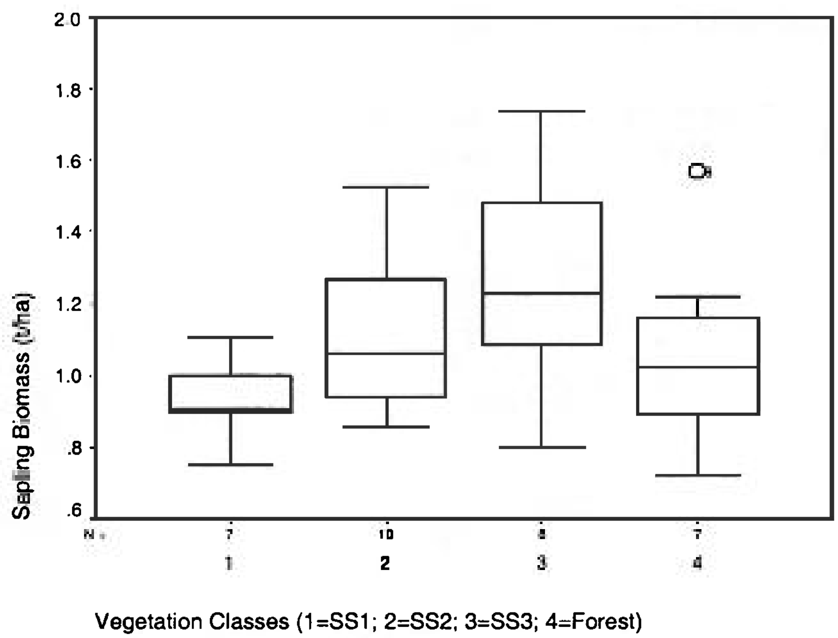



Figure 31 - Distribution of biomass of saplings within vegetation classes sampled in Machadinho d'Oeste and Vale do Anari.

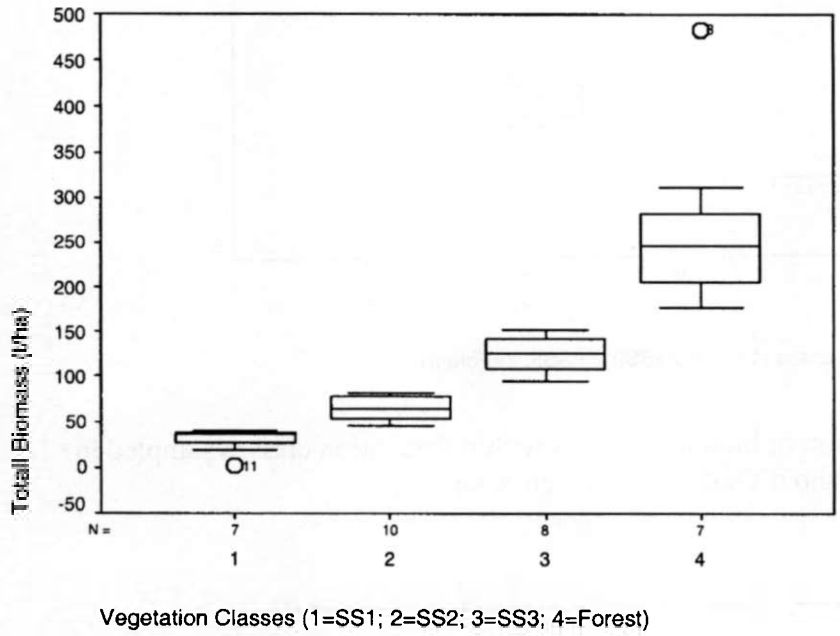



Figure 32 - Distribution of total biomass within vegetation classes sampled in Machadinho d'Oeste and Vale do Anari.

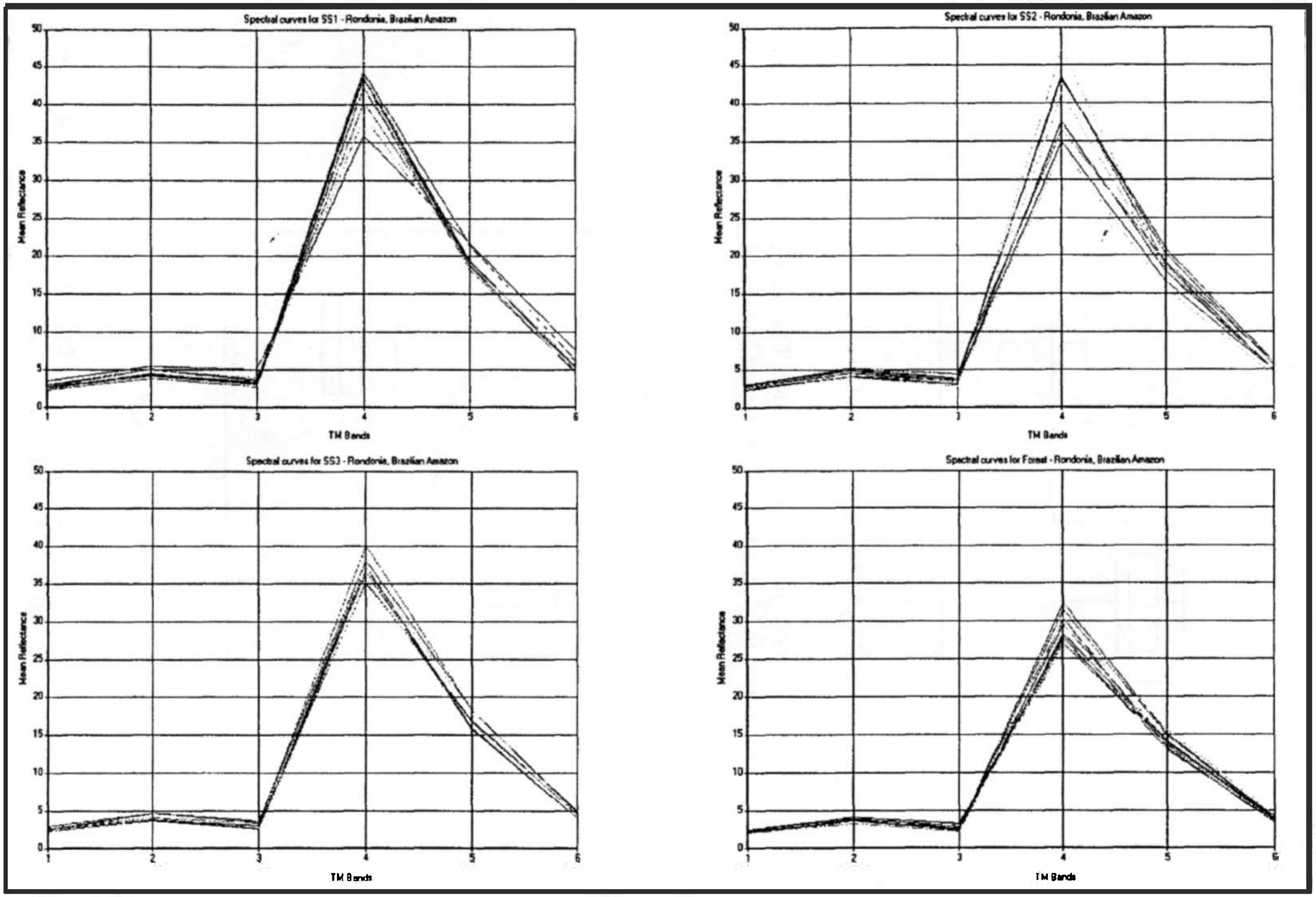



Figure 33 - Spectral curves for each group of plot samples in Machadinho d'Oeste and Vale do Anari (SS1, SS2, SS3, and forest).

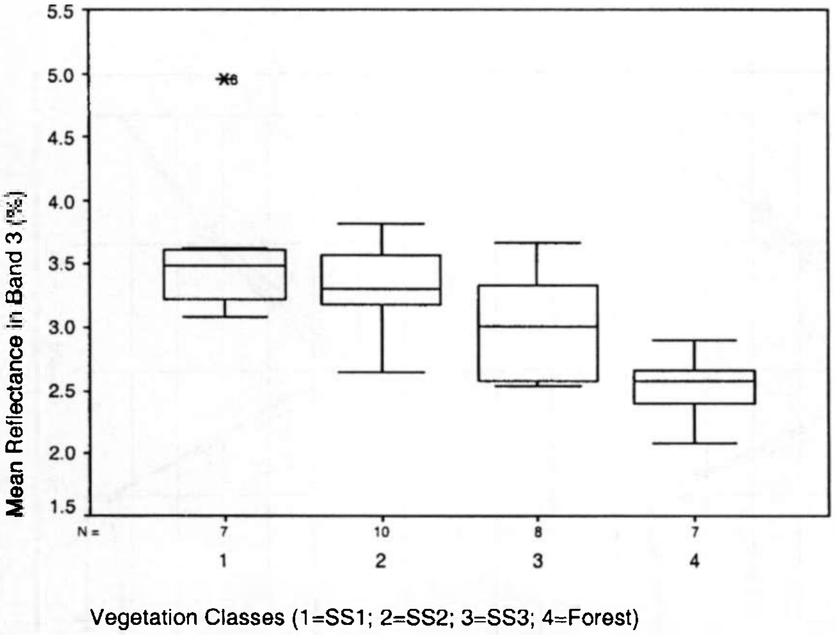



Figure 34 - Distribution of mean reflectance in Landsat TM band 3 within vegetation classes sampled in Machadinho d'Oeste and Vale do Anari.

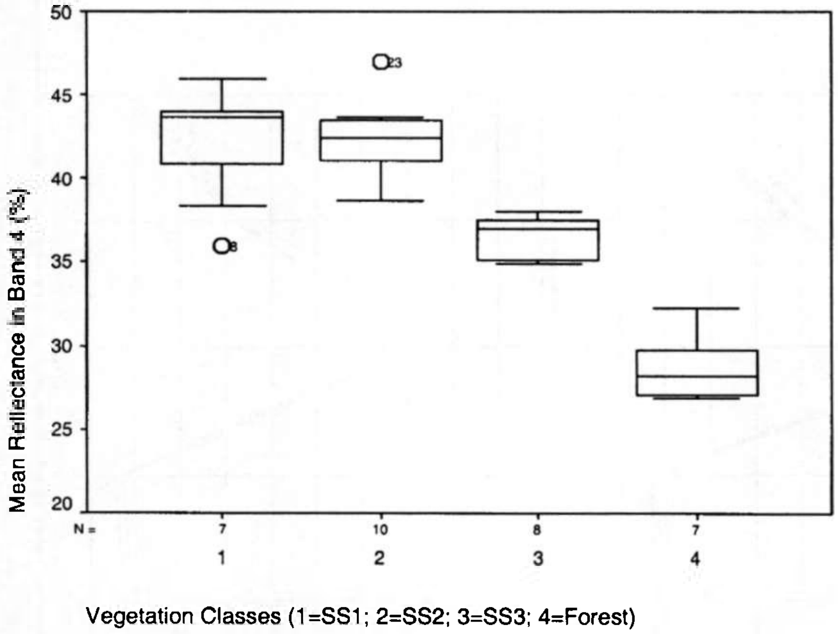



Figure 35 - Distribution of mean reflectance in Landsat TM band 4 within vegetation classes sampled in Machadinho d'Oeste and Vale do Anari.

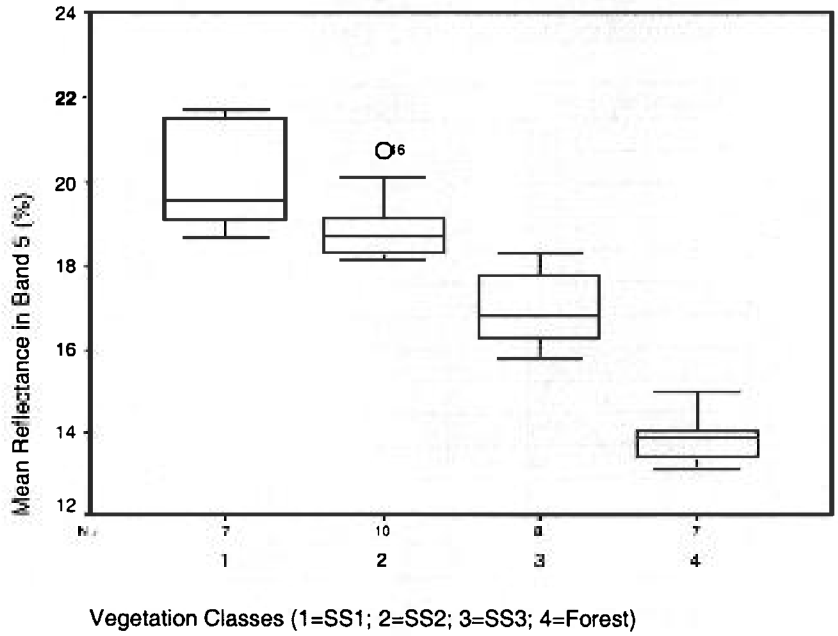



Figure 36 - Distribution of mean reflectance in Landsat TM band 5 within vegetation classes sampled in Machadinho d'Oeste and Vale do Anari.

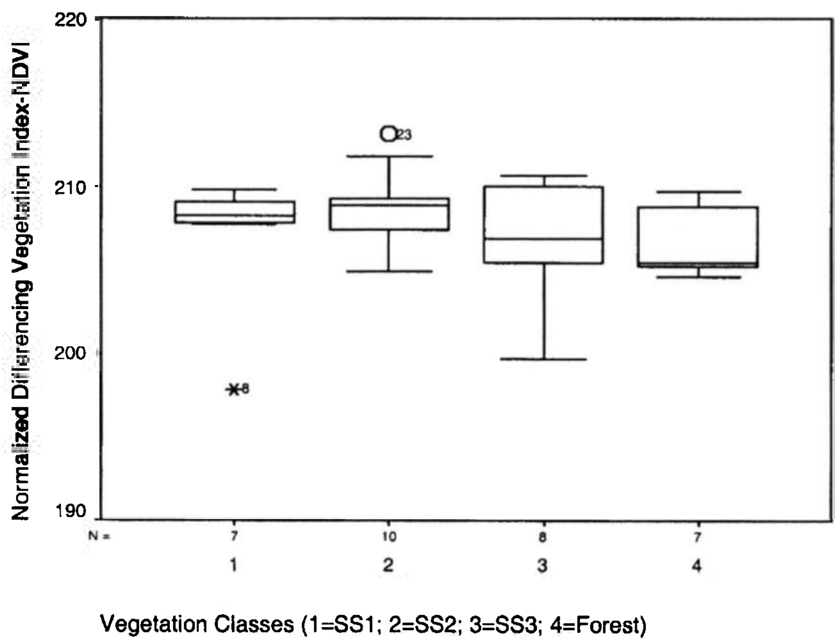



Figure 37 - Distribution of mean reflectance in Landsat TM NDVI within vegetation classes sampled in Machadinho d'Oeste and Vale do Anari.

Table 10 - Analysis of variance (ANOVA) for mean reflectance in Landsat TM bands and NDVI of sites sampled in Machadinho d'Oeste and Vale do Anari.

| | | Sum of squares | df | Mean square | F | Sig. |
|---|---|---|---|---|---|---|
| **Band 1** | Between Groups | 1.408 | 3 | .469 | 7.935 | .001 |
| | Within Groups | 1.656 | 28 | 5.914E-02 | | |
| **Band 2** | Between Groups | 5.889 | 3 | 1.963 | 14.456 | .000 |
| | Within Groups | 3.802 | 28 | .136 | | |
| **Band 3** | Between Groups | 4.436 | 3 | 1.479 | 7.383 | .001 |
| | Within Groups | 5.607 | 28 | .200 | | |
| **Band 4** | Between Groups | 925.239 | 3 | 308.413 | 53.620 | .000 |
| | Within Groups | 161.050 | 28 | 5.752 | | |
| **Band 5** | Between Groups | 167.230 | 3 | 55.743 | 61.877 | .000 |
| | Within Groups | 25.225 | 28 | .901 | | |
| **Band 7** | Between Groups | 17.214 | 3 | 5.738 | 16.530 | .000 |
| | Within Groups | 9.719 | 28 | .347 | | |
| **NDVI** | Between Groups | 23.357 | 3 | 7.786 | .804 | .502 |
| | Within Groups | 271.255 | 28 | 9.688 | | |

Note: df = degrees of freedom; F = F test of significance; Sig. = Significance

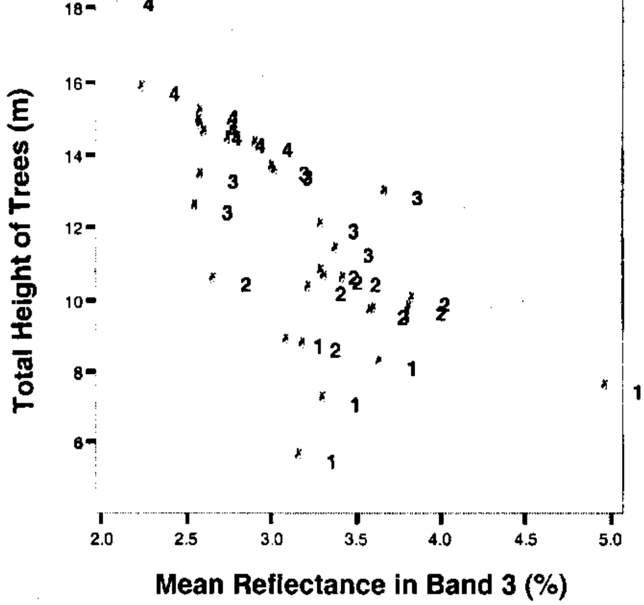



Figure 38 - Total height of trees and mean reflectance in Landsat TM band 3 within vegetation classes sampled in Machadinho d'Oeste and Vale do Anari.

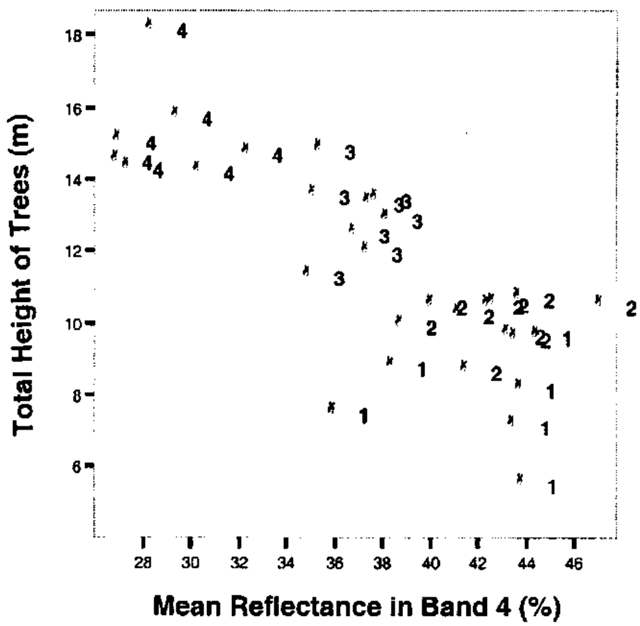



Figure 39 - Total height of trees and mean reflectance in Landsat TM band 4 within vegetation classes sampled in Machadinho d'Oeste and Vale do Anari.

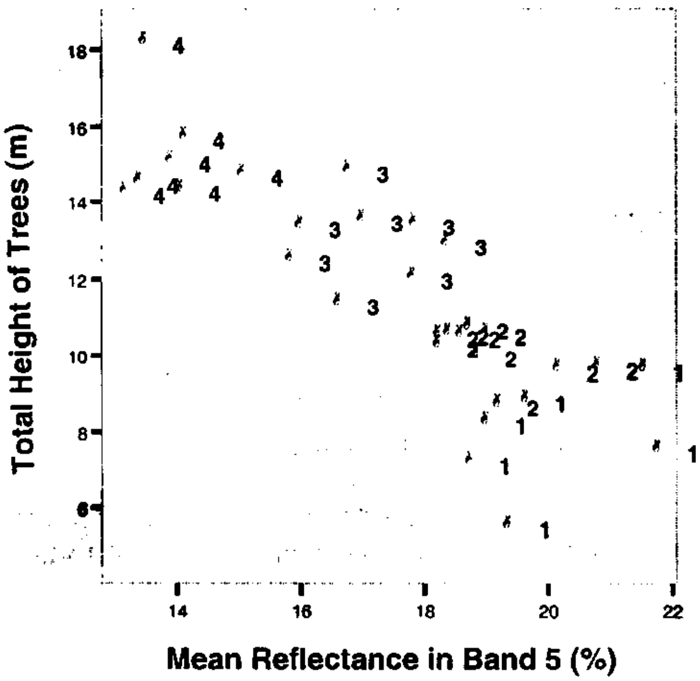



Figure 40 - Total height of trees and mean reflectance in Landsat TM band 5 within vegetation classes sampled in Machadinho d'Oeste and Vale do Anari.

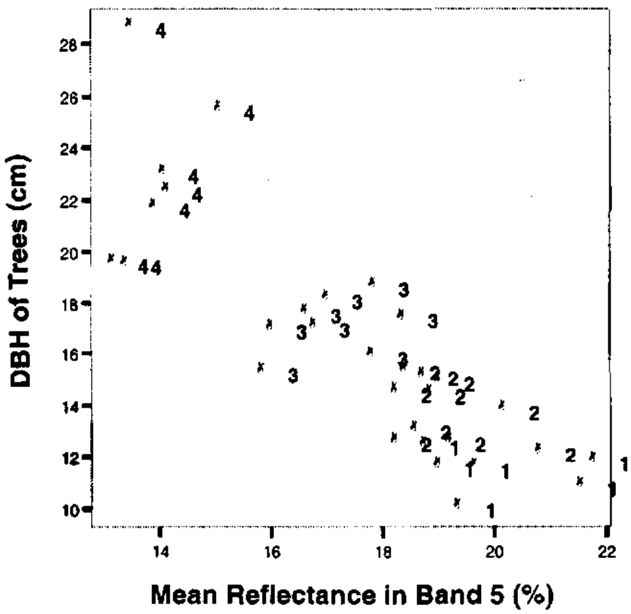



Figure 41 - DBH of trees and mean reflectance in Landsat TM band 5 within vegetation classes sampled in Machadinho d'Oeste and Vale do Anari.

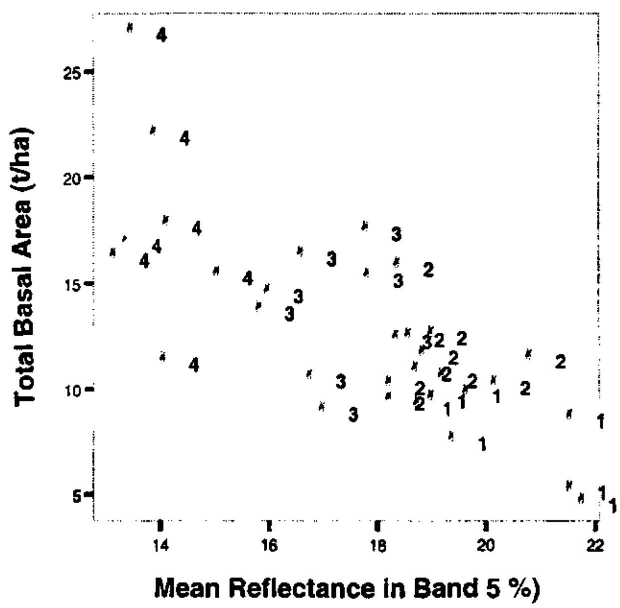



Figure 42 - Total basal area and mean reflectance in Landsat TM band 5 within vegetation classes sampled in Machadinho d'Oeste and Vale do Anari.

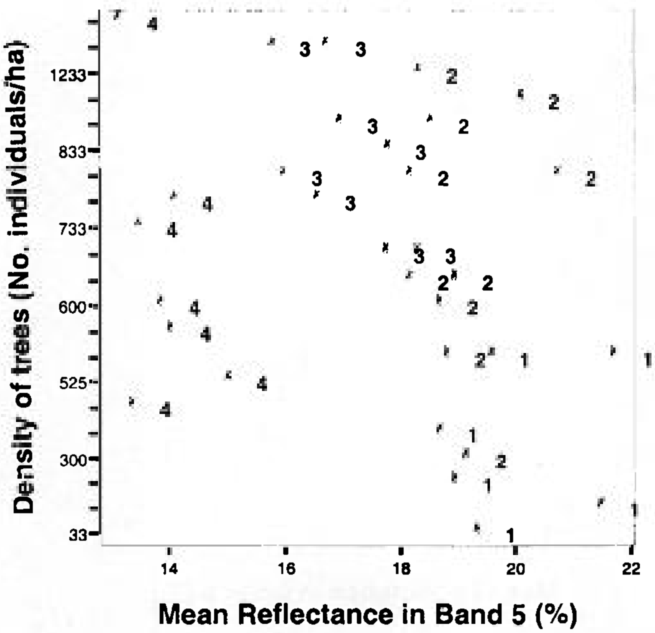



Figure 43 - Density of trees and mean reflectance in Landsat TM band 5 within vegetation classes sampled in Machadinho d'Oeste and Vale do Anari.

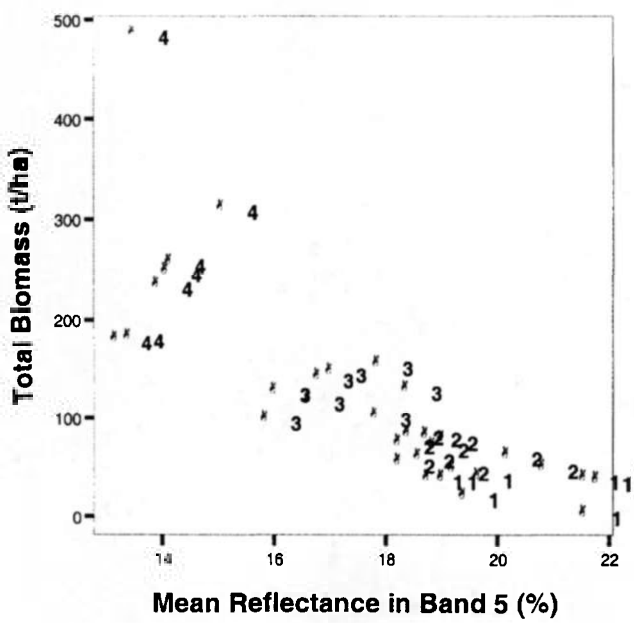



Figure 44 - Total biomass and mean reflectance in Landsat TM band 5 within vegetation classes sampled in Machadinho d'Oeste and Vale do Anari.

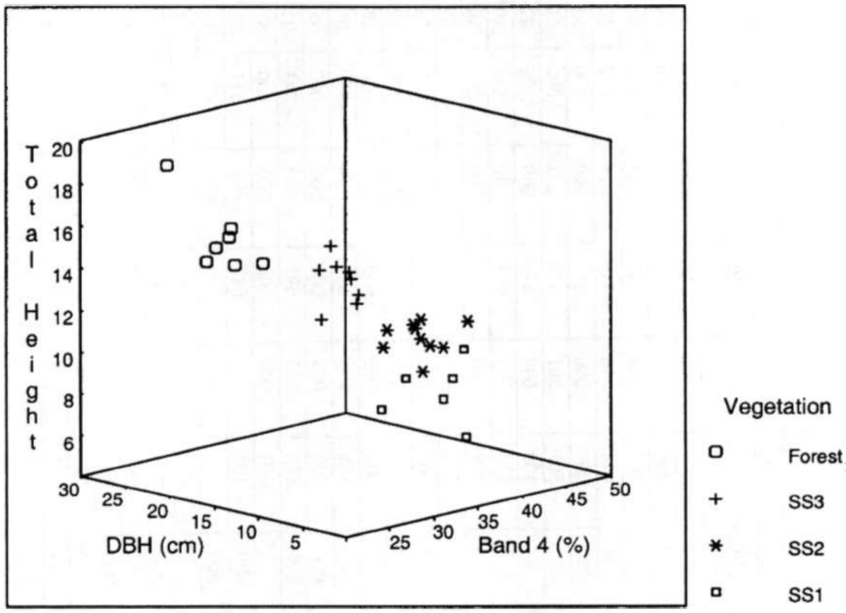



Figure 45 - Total height, DBH, and mean reflectance in Landsat TM band 4 within vegetation classes sampled in Machadinho d'Oeste and Vale do Anari.

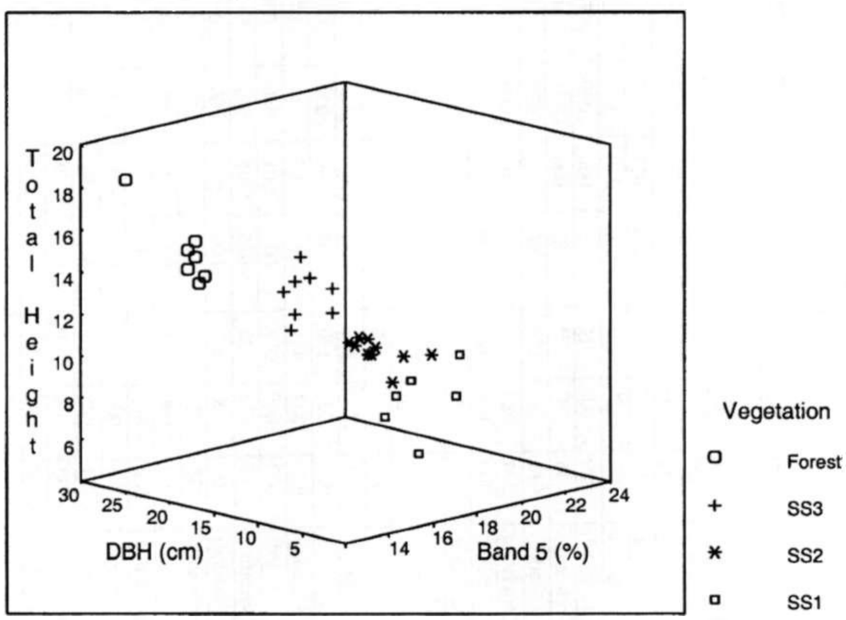



Figure 46 - Total height, DBH, and mean reflectance in Landsat TM band 5 within vegetation classes sampled in Machadinho d'Oeste and Vale do Anari.

Table 11 - Pearson correlation coefficients for selected vegetation structure variables, mean reflectance in TM bands, and NDVI for sites sampled in Machadinho d'Oeste and Vale do Anari.

| | | Class | Age | Density of trees | Density of Saplings | Density Ratio | DBH of Trees | Basal Area of Trees | % Tree Basal Area | Total Basal Area | Height of Trees | Biomass of Trees | Total Biomass | Band 3 | Band 4 | Band 5 | NDVI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Class** | Correlation | 1.000 | .906 | .432 | -.732 | -.445 | .904 | .818 | .760 | .764 | .931 | .835 | .835 | -.660 | -.854 | -.912 | -.119 |
| | Sig. (2-tailed) | | .000 | .015 | .000 | .012 | .000 | .000 | .000 | .000 | .000 | .000 | .000 | .000 | .000 | .000 | .516 |
| **Age** | Correlation | .906 | 1.000 | .351 | -.688 | -.335 | .868 | .801 | .701 | .730 | .847 | .833 | .834 | -.615 | -.905 | -.900 | -.150 |
| | Sig. (2-tailed) | .000 | . | .053 | .000 | .066 | .000 | .000 | .000 | .000 | .000 | .000 | .000 | .000 | .000 | .000 | .413 |
| **Density of trees** | Correlation | .432 | .351 | 1.000 | -.431 | -.521 | .270 | .187 | .153 | .265 | .444 | .190 | .191 | -.269 | -.226 | -.350 | .051 |
| | Sig. (2-tailed) | .015 | .053 | . | .015 | .003 | .142 | .313 | .410 | .150 | .012 | .307 | .304 | .143 | .221 | .054 | .785 |
| **Density of Saplings** | Correlation | -.732 | -.688 | -.431 | 1.000 | .589 | -.673 | -.574 | -.573 | -.525 | -.731 | -.616 | -.616 | .419 | .614 | .618 | .108 |
| | Sig. (2-tailed) | .000 | .000 | .015 | . | .000 | .000 | .001 | .001 | .002 | .000 | .000 | .000 | .017 | .000 | .000 | .557 |
| **Density Ratio** | Correlation | -.445 | -.335 | -.521 | .589 | 1.000 | -.401 | -.312 | -.347 | -.331 | -.505 | -.301 | -.301 | .133 | .331 | .296 | .150 |
| | Sig. (2-tailed) | .012 | .066 | .003 | .000 | . | .025 | .088 | .056 | .069 | .004 | .100 | .099 | .476 | .069 | .106 | .421 |
| **DBH of Trees** | Correlation | .904 | .868 | .270 | -.673 | -.401 | 1.000 | .930 | .902 | .777 | .914 | .971 | .971 | -.631 | -.830 | -.851 | -.101 |
| | Sig. (2-tailed) | .000 | .000 | .142 | .000 | .025 | . | .000 | .000 | .000 | .000 | .000 | .000 | .000 | .000 | .000 | .589 |
| **Basal Area of Trees** | Correlation | .818 | .801 | .187 | -.574 | -.312 | .930 | 1.000 | .809 | .907 | .839 | .952 | .952 | -.628 | -.754 | -.810 | -.051 |
| | Sig. (2-tailed) | .000 | .000 | .313 | .001 | .088 | .000 | . | .000 | .000 | .000 | .000 | .000 | .000 | .000 | .000 | .780 |
| **% Tree Basal Area** | Correlation | .760 | .701 | .153 | -.573 | -.347 | .902 | .809 | 1.000 | .575 | .763 | .816 | .815 | -.453 | -.720 | -.726 | -.196 |
| | Sig. (2-tailed) | .000 | .000 | .410 | .001 | .056 | .000 | .000 | . | .001 | .000 | .000 | .000 | .009 | .000 | .000 | .281 |
| **Total Basal Area** | Correlation | .764 | .730 | .265 | -.525 | -.331 | .777 | .907 | .575 | 1.000 | .763 | .795 | .796 | -.614 | -.654 | -.759 | .011 |
| | Sig. (2-tailed) | .000 | .000 | .150 | .002 | .069 | .000 | .000 | .001 | . | .000 | .000 | .000 | .000 | .000 | .000 | .954 |
| **Height of Trees** | Correlation | .931 | .847 | .444 | -.731 | -.505 | .914 | .839 | .763 | .763 | 1.000 | .879 | .880 | -.692 | -.792 | -.841 | -.026 |
| | Sig. (2-tailed) | .000 | .000 | .012 | .000 | .004 | .000 | .000 | .000 | .000 | . | .000 | .000 | .000 | .000 | .000 | .888 |
| **Biomass of Trees** | Correlation | .835 | .833 | .190 | -.616 | -.301 | .971 | .952 | .816 | .795 | .879 | 1.000 | 1.000 | -.647 | -.801 | -.811 | -.054 |
| | Sig. (2-tailed) | .000 | .000 | .307 | .000 | .100 | .000 | .000 | .000 | .000 | .000 | . | .000 | .000 | .000 | .000 | .771 |
| **Total Biomass** | Correlation | .835 | .834 | .191 | -.616 | -.301 | .971 | .952 | .815 | .796 | .880 | 1.000 | 1.000 | -.648 | -.801 | -.812 | -.053 |
| | Sig. (2-tailed) | .000 | .000 | .304 | .000 | .099 | .000 | .000 | .000 | .000 | .000 | .000 | . | .000 | .000 | .000 | .772 |
| **Band 3** | Correlation | -.660 | -.615 | -.269 | .419 | .133 | -.631 | -.628 | -.453 | -.614 | -.692 | -.647 | -.648 | 1.000 | .476 | .772 | -.519 |
| | Sig. (2-tailed) | .000 | .000 | .143 | .017 | .476 | .000 | .000 | .009 | .000 | .000 | .000 | .000 | . | .006 | .000 | .002 |
| **Band 4** | Correlation | -.854 | -.905 | -.226 | .614 | .331 | -.830 | -.754 | -.720 | -.654 | -.792 | -.801 | -.801 | .476 | 1.000 | .856 | .364 |
| | Sig. (2-tailed) | .000 | .000 | .221 | .000 | .069 | .000 | .000 | .000 | .000 | .000 | .000 | .000 | .006 | . | .000 | .041 |
| **Band 5** | Correlation | -.912 | -.900 | -.350 | .618 | .296 | -.851 | -.810 | -.726 | -.759 | -.841 | -.811 | -.812 | .772 | .856 | 1.000 | -.026 |
| | Sig. (2-tailed) | .000 | .000 | .054 | .000 | .106 | .000 | .000 | .000 | .000 | .000 | .000 | .000 | .000 | .000 | . | .887 |
| **NDVI** | Correlation | -.119 | -.150 | .051 | .108 | .150 | -.101 | -.051 | -.196 | .011 | -.026 | -.054 | -.053 | -.519 | .364 | -.026 | 1.000 |
| | Sig. (2-tailed) | .516 | .413 | .785 | .557 | .421 | .589 | .780 | .281 | .954 | .888 | .771 | .772 | .002 | .041 | .887 | . |

# APPENDIX 1

# SURVEY PROTOCOLS USED DURING FIELDWORK IN MACHADINHO D'OESTE AND VALE DO ANARI

Plot Sample Protocol for Rondônia, Brazilian Amazon

RESEARCH ID: ________ COUNTRY ID:____________ SITE ID:__________
CASE #:_______ PLOT #:_________ MANAGEMENT UNIT ID:_____
TODAY'S DATE (mm/dd/yr): _____/_____/_____
COLLECTOR'S NAME:____________________& email______________________________
TS AREA/OWNER NAME:______________________________________________

IMAGE PRODUCTS USED:
Image ID/date: ____TM June 1998_______ Color Composite Used: R = 5 G = 4 B = 3
(3 letter airport code, TM or MSS, m/d/ y) (MSS or TM bands)

Map only: Y/N _N_ Unsupervised Classification: Y/N _Y_ Unsupervised Class for TS reference:_____
(cluster name related to this T.S.)

DIAGRAMS OF GENERAL OBSERVATIONS: Show location of GPS points and major features.

Aerial View | Profile Diagram (parallel to maximum slope)

(include land marks, north arrow and scale bar) | (overall draw of vegetation, slope, and vertical scale)

GEOGRAPHIC COORDINATES:
UTM Northing (X ):_______ [m]; UTM Easting (Y):_______ [m] ; UTM Zone: 20; Datum: SAD 69 (or)

Latitude (N/S)____°, ____', ____" Longitude (E/W)____°, ____', ____" (or)

Decimal Degrees (N/S)_____ . ________ (E/W)_____ . _________

GPS INFO: FILE NAME:____________________________; PDOP:___________

TOPOGRAPHY: Ridge_____ Slope______ Flat______ Steepness of Slope:______° (0-90°)
Azimuth (downhill direction of maximum slope in which water would naturally run)_____ (0-360°)

SOIL:
Local Name: ________________________________ Color:_______________________

Texture: Silt:___ Clay:___ Sand:___ Gravel: ___ Mix:____ Observations:________________

Moisture: Dry: _____ Moist: _____ Saturated:_____ Observations:________________

LAND COVER TYPE (put a check mark next to land cover type or write in others):

| | | | | | |
|---|---|---|---|---|---|
| VEGETATION TYPE | | DISTURBED: | | FARMLAND: | |
| Tropical forest (upland) | | SS 3 (advanced succession) | | Wood perennial fruit crop | |
| Tropical forest (floodplain) | | SS 2 (intermediate succession) | | Agroforestry/crops | |
| Tropical forest (open) | | SS 1 (initial succession) | | Agroforestry/pasture | |
| Gallery forest | | | | | |
| | | Disturbed forest (logging) | | Plantation (eg. Eucaliptus) | |
| Woodland (Savanna) | | Burned field | | | |
| Herbaceous/Shrub Savanna | | Quarry | | Annual: | |
| | | Forest with cleared understory | | | |
| | | | | | |
| Grassland (Woody) | | (others-use space below): | | Pasture | |
| Grassland (Herbaceous) | | | | Pasture-Degraded | |
| | | | | | |
| Marsh Wetland | | INFRASTRUCTURE | | Agricultural-Bare soil | |
| Seasonal wetland | | Roads | | Non-Agricultural- bare soil | |
| Tall Grasses and Shrubs | | Dense urban residential | | Stubble field | |
| Dry woody shrub | | Open urban residential | | Plowed field | |
| Mangrove | | Commercial | | (others-use space below): | |
| Palm forest | | Industrial | | | |
| Bamboo | | Lawn | | | |
| | | Concrete | | WATER | |
| | | Blacktop | | | |
| | | Gravel | | OBS: | |
| | | Pavement | | | |

VEGETATION STRUCTURE ESTIMATES:

%Herbaceous ___; % litter, ___; % soil ___; % rock ___ (to the nearest 5%)

Canopy closure: ______% cover  Average canopy height: ____m, Height of emergent trees: ____m

Avg. DBH of trees: 2-10 cm_; 10-20 cm_; 20-30cm_; 30-50 cm_; 50-70 cm_; 70cm-1m_; > 1m__

Avg. DBH of emergent trees: 10-20 cm__; 20-30cm __; 30-50 cm__; 50-70 cm__; 70cm-1m__; > 1m__

Presence of Saplings: Absent_____, Few _____, Moderate_____, Abundant _____

Presence of Seedlings: Absent_____, Few _____, Moderate_____, Abundant _____

Presence of Lianas: Absent_____, Few _____, Moderate_____, Abundant _____

Presence of Epiphytes: Absent_____, Few _____, Moderate_____, Abundant _____

Presence of Palms: Absent_____, Few _____, Moderate_____, Abundant _____

Presence of Succulents: Absent_____, Few _____, Moderate_____, Abundant _____

Presence of Others: _________________Absent_____, Few _____, Moderate_____, Abundant _____

If secondary vegetation, give original vegetation if known (see land cover table above):_____________

PRESENCE OF DOMINANT SPECIES:_________________________________________

Trees:____________________________________________________________

Saplings: _________________________________________________________

Seedlings: ________________________________________________________

Herbaceous: ______________________________________________________

PRESENCE OF MANAGED SPECIES (including forest management, plantation, agroforestry):

Number of managed species (including planted): _____;

Sci. Name (Family/Genus/Species)______________________________

Common Name:_______________ Density: Absent____, Few ____, Moderate____, Abundant ____

Sci. Name (Family/Genus/Species)______________________________

Common Name:_______________ Density: Absent____, Few ____, Moderate____, Abundant ____

Landscape Change and LULC Dynamics in Rondônia, Brazilian Amazon
Plot Sample Protocol

# of Plot Sample:____________ Date:________________________
# of Sub-Plot:_______________ Size of the Sub-Plot:____________

B. Inventory Data Sheet for Trees:

| TREE # | DBH (cm) | STEM HEIGHT (m) | TOTAL HEIGHT (m) | OBSERVATIONS[1] |
|---|---|---|---|---|
| 1 | | | | |
| 2 | | | | |
| 3 | | | | |
| 4 | | | | |
| 5 | | | | |
| 6 | | | | |
| 7 | | | | |
| 8 | | | | |
| 9 | | | | |
| 10 | | | | |
| 11 | | | | |
| 12 | | | | |
| 13 | | | | |
| 14 | | | | |
| 15 | | | | |
| 16 | | | | |
| 17 | | | | |
| 18 | | | | |

[1] For **observation**, note morphological characteristics and/or life form. Ex: tree, liana, palm, succulent, bamboo, others.

# of Plot Sample:__________________ Date:______________________

# of Sub-Plot Sample:________________ Size of the Sub-Plot:______

C. Inventory Data Sheet for Saplings (1), Seedlings (2), Herbaceous (3), and Lianas (4):

| PLANT TYPE (1, 2, 3, 4) | N°. OF INDIV. | % COVER | DBH (cm) | TOTAL HEIGHT (m) | OBSERVATIONS[1] |
|---|---|---|---|---|---|
| | | | | | |
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| | | | | | |

[1] For **observation**, note morphological characteristics and/or life form. Ex: shrub, sapling, woody liana, climber, grass, palm, succulent, bamboo, others.

<u>Landscape Change and LULC Dynamics in Rondônia, Brazilian Amazon</u>
<u>Plot Protocol</u>

# of Plot:__________________ Date:_________________________

A. Plot History:

| YEAR | LAND USE/COVER TYPE (#) | TECH. @ | INPUTS* | # BURNINGS |
|---|---|---|---|---|
| 1998 | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| 1994 | | | | |
| | | | | |
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| | | | | |
| | | | | |
| | | | | |
| 1990 | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| 1988 | | | | |
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| 1986 | | | | |
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| 1984 | | | | |
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| 1982 | | | | |
| | | | | |
| 1980 | | | | |

(#) Land use type: 1-Mature Forest (1.1-Upland; 1.2-Floodplain; 1.3-Open); 2-Savanna (2.1-Woodland; 2.2-Herbaceous/Shrub); 3-Grassland (3.1-Woody; 3.2-Herbaceous/Shrub); 4-Secondary Succession (4.1-Advanced; 4.2-Intermediate; 4.3-Initial); 5-Agricultural Land (5.1-Perennial; 5.2-Agroforestry; 5.3-Annual; 5.4-Pasture); 6-Barren Land (6.1-Agricultural Exposed Soil; 6.2-Non-Agricultural Exposed Soil); 7-Built-up Land (7.1-Road; 7.2-Urban Area); 8-Water.
@ Technology: Manual-MAN or Mechanized-MEC.
* Inputs: Fertilizer-FER; Lime (calcareo)-LIME; Ash-ASH

# CHAPTER 4

# LULC DYNAMICS: THE COLONIZATION IMPACT

*'A época da rapadura passou. Agora é a do chimarrão.*
*Mas o chimarrão é amargo, a rapadura é doce.*
*Só que a rapadura é doce, mas não é mole...'*

## 4.1 - GEOTECHNOLOGIES AND LULC DYNAMICS IN AMAZÔNIA: POTENTIALS AND PITFALLS

The enhanced capabilities in terms of data production and methods of analysis for Earth surface feature information have led to new approaches and to a more integrative vision about LULC change within and across research sites (Burrough and Frank 1995). Using multi-temporal satellite data allows a better understanding about the dynamics of deforestation, land abandonment, pasture conversion, agriculture, and secondary succession within rural landscapes in transformation (Lambin 1997). In Amazônia, the study of LULC change and its human dimensions through the use of geotechnologies may contribute to a more sustainable development of communities under investigation.

Remote sensing and geoprocessing techniques have allowed the integration of spatial data at several scales (Quattrochi and Pelletier 1991, Fotheringham and Rogerson 1995). The generation of global- and local-scale data, the reworking of historical data sets, and some programmatic aspects of land database development have become fundamental themes to the research community (Goodchild et al. 1992, Justice et al. 1995). This has highlighted the mutual benefits of closer links between Geographic Information Systems (GIS) and methods of spatial data analysis. The evolution of these tools has consolidated important elements to solve environmental problems and help decision-making tasks (Coulson et al. 1991). The possibility of testing spatial models through the use of georeferenced databases and algorithms to measure spatial heterogeneity has opened new pathways to research issues such as LULC dynamics in Amazônia.

The increasing interest in ecosystems spatial dynamics have led to the need for new quantitative methods capable of analyzing patterns, determining the importance of spatial processes, and developing models about landscapes (Gardner and Turner 1991, Fortin 1999). Thus, ecological studies have described landscape features in terms of number, diversity, distribution, complexity, and dispersion of their spatial elements (Jurdant et al. 1977, Domon et al. 1989, Robbins and Bell 1994).

Advanced airborne and satellite technologies, image processing and analysis, and extensive capabilities to analyze spatial data through GIS and associated software has catalyzed the development and test of new quantitative methods of spatial assessment (Goodchild et al. 1993, Sample 1994, Burrough and McDonell 1998). The variety of aerial and orbital data in distinct spatial, temporal, and spectral resolutions have required the generation of digital image processing techniques in applications related to the characterization and management of natural resources (Johannsen and Sanders 1982, Szekielda 1988, Richards 1993, Jensen 2000, Lillesand and Kiefer 2000). By the same token, GIS packages have integrated an always increasing and diverse amount of spatial information (Maguire et al. 1991, Dangermond 1992, ESRI 1997, DeMers 2000).

In the Amazon, several applications have been implemented at regional and local scales. The first systematic survey about natural resources for the entire region used side-looking airborne radar (Radambrasil 1972). Experts interpreted an impressive number of images to map geology, geomorphology, soils, vegetation, and other themes. This multi-task survey took more than ten years to accomplish the manual compilation of data in several layers for 335 sheets at 1:250,000 scale. Since that initiative, the technological advances mentioned above have taken place, together with the pressing need to understand and monitor recent ecological changes occurring in the region in the wake of development efforts.

Many Amazonian issues have attracted a great deal of attention during the last thirty years. Deforestation is among the most important of them. The Brazilian Amazon has been deforested at an average rate of approximately 0.5% per year (Skole and Tucker 1993, INPE 2000) as a result of several factors, including road building, colonization programs, land speculation, and demographic and geopolitical reasons. Besides being a very large area, the process is complex due to environmental heterogeneity, distinct socioeconomic factors affecting LULC outcomes, and strategic interests at several decision-making levels.

GIS and associated software provide a data structure to efficiently store and manage ecosystems data for large areas; enable aggregation and disaggregation of data between multiple scales; locate study plots and/or environmentally sensitive areas; support spatial statistical analysis of ecological distributions; improve remote sensing information-extraction capabilities; and provide input data and parameters for ecosystem modeling (Haines-Young et al. 1996). Aware of the potential of integration between remote sensing, GIS, and associated software, and based on an international concern about possible broad-scale environmental effects due to the conversion of tropical rain forests, research teams have carried out distinct initiatives. These initiatives include the study of climatic and meteorological mechanisms of interaction between the rain forests and the atmosphere; the rates; extension and possible consequences of deforestation processes; the biogeochemical cycles in the region; the 'greenhouse effect' of trace gases; the human dimensions of LULC change; and landscape structure, function, and dynamics (Hall et al. 1996).

Several questions have arisen: When, where, and why is deforestation taking place in Amazônia and what are its consequences? What happens after deforestation? Is the amount of carbon uptake from secondary successional vegetation comparable to the amount of carbon released by deforestation? When and where is deforestation and secondary succession likely to be detected by using remotely sensed digital data? Which sensors and techniques will be necessary to achieve accurate results for these research questions?

The integration of statistical numeric and georeferenced spatial data is an important topic in geographic information science and has been one of the bases of broad-scale research initiatives in the Amazon. Procedures take into account the relationships of predefined regions in space with attributes derived from numeric variables (Bastedo and Theberge 1983, Goodchild and Brusegard 1989, Kareiva 1994). This is not a trivial question when working with the Amazon, mainly due to the diversity of data, inconsistency between different sources, heterogeneity of data collection methods, and differences in presentation of data (scale, legend, material, format, and quality) (Davis et al. 1990, Wickhman and Norton 1994, Burrough and Frank 1995).

Recent development of remote sensors, GIS tools, and associated software (e.g., database management, programming languages, and spatial analysis) has facilitated the achievement of results with significant precision and accuracy, based on objective procedures (Burrough and McDonnel 1998, Lillesand and Kiefer 2000). These techniques have allowed assessment of the spatial organization of Amazonian agroecosystems and natural resources, defining potentials for conservation and development (Coulson et al. 1991).

From this point of view, land zoning is one of the most important recent applications of GIS and associated software, yielding a better management of natural resources in Amazônia. Some states (e.g., Rondônia, Tocantins, and Maranhão) already have an extensive database generated in a GIS and based on 1:250,000 maps. They include several layers of information and synthetic maps defining areas with distinct potentialities for conservation, management, agriculture development, and urbanization (Bognola and Miranda 1999, Miranda 1999, Olmos et al. 1999, Rondônia 2000). All these initiatives used Landsat TM images to produce LULC maps.

Other examples of GIS applications include the spatial analysis done by Alves (1999) and Alves et al. (1999). Making use of maps produced through visual interpretation of Landsat TM images at 1:250,000 scale (INPE 2000), the authors analyzed geographical patterns of deforestation for states, municipalities, and road buffers. Twenty-five percent of the total deforestation was found in less than 4% of the cells and 50% of the total deforestation in less than 10% of the cells. Forty percent of the cells amassed 95% of the deforestation, and 86% of the total deforestation in Amazônia was found within 25 km from areas already deforested in 1978. This is the typical case where geotechnologies were central for the achievement of results at regional scale, showing the concentration of processes of LULC change along roads.

Skole and Tucker (1993), also using Landsat TM images and GIS integration, mapped LULC change for the entire Brazilian Amazon. Deforestation, fragmented forest—defined as areas smaller than 100 $km^2$ surrounded by deforestation—and edge effects—within 1 km into forest from adjacent areas of deforestation—were measured for 1978 and 1988. The results showed that deforestation increased from 78,000 $km^2$ in 1978 to 230,000 $km^2$ in 1988, while tropical forest habitat, severely affected with respect to biological diversity, increased from 208,000 $km^2$ to 588,000 $km^2$. Besides reaffirming the concentration of deforestation processes, the findings supported analyses on the human dimensions of colonization within the region (Skole et al. 1994).

Miranda et al. (1994) used a grid approach to monitor Amazonian fires. They have followed the spatial-temporal magnitude of the phenomenon for almost ten years, counting burning spots indicated by the thermal bands of (National Oceanographic and Aerospace Administration (NOAA) satellites. Although technical problems are always associated with these estimates (Setzer and Pereira 1991, Setzer and Verstraete 1994), the results achieved so far have defined the seasonality, timing, and interannual variations of fires in the region. Recent initiatives are using a multiple sensors for estimating biomass burning at a regional scale (Eva and Lambin 1998).

Another recent application for the entire region is the link of satellite, census, and survey data done by Wood and Skole (1998). The project looks for general trends in deforestation, using regression analysis on socioeconomic variables and GIS database links to census data.

Several other research initiatives using remote sensing and GIS techniques have taken place at distinct sites and more detailed scales in the Amazon. Studies of physical, biological, and social processes have helped understand how human decisions affect local and regional land use (Mausel et al. 1993, Moran et al. 1994, Skole et al. 1994, Brondizio et al. 1996). Nepstad et al. (*Flames* 1999) show the role of logging and fire on the impoverishment of Amazonian forests. A myriad of articles discuss the use of new sensors and techniques to monitor LULC within the region (Adams et al. 1995, Foody et al. 1996, Steininger 1996, Rignot et al. 1997, Saatchi et al. 1997, Yanasse et al. 1997, Lucas et al. 1998).

Following this literature, my research about colonization impacts in Rondônia is a contribution to the use of geotechnologies in spatial-temporal assessments of LULC. Producing multi-temporal information about two distinct settlement designs (i.e., Machadinho and Anari) may improve the capability to include detailed LULC information in regional- and global-scale simulation models through the use of accurate landscape- and property-based data. My goal is to use this research to stimulate a rethinking of settlement designs in the Amazon.

## 4.2 - METHODOLOGICAL APPROACH

Few political initiatives have had the social, economic and environmental impact of rural colonization projects in the Brazilian Amazon. Despite its importance, examples of planning and monitoring of settlements in the region using geoprocessing techniques to understand the trajectory of those landscapes in transformation are rare. This chapter builds on research carried out at Indiana University, through a framework based on the integration of remote sensing data and anthropological and ecological research in a geographic information system that allows spatial and temporal analyses in several levels and scales. The main goal of this initiative is to understand LULC dynamics in Machadinho and Anari, enriching the debate about planning and monitoring strategies of rural settlements in Amazônia.

In general terms, the methodological approach involved the need to investigate colonization processes within the study area and their environmental implications regarding LULC change. Thus, I intend to explain relationships between LULC dynamics and agroecological processes underlying landscape transformation. Remote sensing, GIS, and spatial analysis played a central role in providing elements for discussion. But how should one distinguish different units of analysis composing a settlement? This hierarchy depends on consideration of the mosaic of patches characterizing the settlement. In

Amazonian rural settlements, the biophysical compartments, the socioeconomic context, and the spatial-temporal arrangements of occupation delimit fundamental units of analysis. Within this chapter, findings are presented with emphasis on settlement landscapes, reserves, buffers around roads, and property lots. The analytical strategy, summarized in Figure 47, includes several modules described as follows:

- Questions to be addressed, units of analysis, and level of detail for collection and integration of data;
- Remote Sensing Module: data definition and processing techniques for extraction of information related to LULC in a multi-scalar and multi-temporal basis;
- Statistical Module: numeric analysis of data through descriptive and inferential statistics;
- GIS Module: manipulation of spatial databases generated by the previous modules;
- Analysis and Synthesis Module: integration of spatial and numeric data to answer the research question.

### 4.2.1 - Multi-Temporal Analysis: What need have I for this?

It has been shown that deforestation trajectories in Amazonian settlements follow cycles related to stages of establishment, expansion, and consolidation of rural properties. The magnitude of these pulses is a function of lot allocation and condition, time of occupation, structure and composition of the domestic unity, and credit policies (Brondizio et al. in press).

In order to capture the spatial-temporal dynamics regarding LULC changes in Machadinho and Anari, I used satellite images beginning in 1988. This allowed the detection of earlier stages of lot occupation and deforestation, five years after the settlements' implementation. Starting with 1988, a ten-year period was defined to carry out the multi-temporal analysis. The choice of image dates and period of analysis was dependent on several factors. The goal was to depict deforestation processes and conversion to farmland, as well as vegetation regrowth to older stages of secondary succession. For this purpose, images dated 1988, 1994, and 1998 were used. The images were selected after a careful analysis of Landsat TM data availability, cloud cover, and data quality. All images were acquired in June, during the dry season, to allow a better differentiation between forest lands, areas in succession, and farmlands. Collection of training samples during fieldwork was carried out in 1999 and 2000 from June to August, also during the dry season.

### 4.2.2 - Pre-Classification Techniques

Several pre-processing techniques were carried out prior to LULC classification. The first step was to correct geometric distortions present in the raw Landsat TM images. Geometric rectification is the process of image adjustment to a pre-established coordinate system (Lillesand and Kiefer 2000). A multi-step procedure was used to maintain consistency during the rectification process. First, the three images were registered together based on control points identifiable in all of them. Then, all bands of all images were combined in a single file and geometrically rectified based on control points taken from topographic sheets at 1:100,000 scale using a UTM projection. The algorithm used for coordinate transformation was *nearest neighbor*, which applies a regression model to determine the coefficient for the transformation equations in $x$ and $y$. The resampling technique directly assigns the digital number (DN) in the input file that most overlaps the pixel in the output file, maintaining its value (Richards 1993). The RMS (Root Mean Squared) error in all steps was always smaller than a half pixel.

Once geometrically rectified, the images were separated to perform atmospheric correction. When using multi-temporal TM data, atmospheric conditions can vary significantly both spatially and temporally as a result of molecular scattering and absorption. The objective of atmospheric correction was to convert remotely sensed digital numbers (DN) to ground surface reflectance in order to make the data spectrally comparable (Green et al. 2000). There are several methods addressing atmospheric correction issues (Markham and Baker 1986; Chavez 1988, 1996; Vermote et al. 1997). Some of the most accurate methods involve physically based models, which require atmospheric data coincident with remote sensing data acquisition. However, when these data are unavailable, image-based models are recommended. So, the Improved Image-Based Dark Object Subtraction (DOS) model was used (Lu et al. in press). The algorithm takes the atmospheric scattering and absorption into account, correcting the effects caused by path radiance and part of the atmospheric transmittance. The process can be used for atmospheric correction of remotely sensed data, especially for historical image data when atmospheric data are not available. The model is expressed by:

$$R_\lambda = \pi * (L_{\lambda\ sensor} - L_{\lambda.haze})/(TAUv * Esun_\lambda * COS(\theta) * TAUz),$$ where:

$R_\lambda$ is the surface reflectance

$\lambda$ is the wavelength

$\pi$ is a constant (3.141592)

$L_{\lambda.sensor}$ is the apparent at-satellite radiance

$L_{\lambda.haze}$ is the path radiance

TAUv is the atmospheric transmittance along the path from the ground surface to the sensor

$Esun_\lambda$ is the exo-atmospheric solar irradiance

$\theta$ is the sun zenith angle (or 90° – sun elevation angle)

TAUz is the atmospheric transmittance along the path from the sun to the ground surface

After geometric rectification and atmospheric correction, subsets were produced using the settlements' boundaries. Figure 48 summarizes the procedures described so far.

### 4.2.3 - LULC Classification

The transformation of spectral data into information through the extraction of thematic features has been traditionally done through classification techniques. Several textbooks present techniques for *supervised* or *unsupervised* classification, but they do not always indicate the need of emphasizing specific characteristics of each application (Woodcock and Strahler 1987).

The main difference between supervised and unsupervised classification is that the former requires the identity and location of some of the land cover to be known (Mausel et al. 1990), while the latter is based on automatic clustering of pixels with similar spectral characteristics according to statistically determined criteria (Jensen 1996).

The unsupervised classification requires only a minimal amount of initial input from the analyst. However, knowledge about the spectral characteristics of the terrain is necessary to label certain clusters as representing land-cover classes (Landgrebe and Biehl 1995). The supervised classification requires much more input from the analyst, including the collection of training samples, the generation of graphic methods for feature selection, and the selection of appropriate classification algorithms (Lillesand and Kiefer 2000).

Results obtained from the single use of standard classification techniques are not always sufficient, mainly in studies involving complex LULC features (Myers et al. 1989). An alternate approach to increase information content from original and enhanced data is to implement improved classification techniques and methods of analysis. It has been demonstrated that hybrid classification systems are frequently appropriate not only to track past deforestation, but also to see future trends of new agroecological processes (Lucas et al. 1998, McCracken et al. 1999, Brondizio et al. in press).

The method used for LULC classification in Machadinho and Anari was an example of hybrid solutions. The first step was to build a hierarchical classification system based on vegetation structure and physiognomy. The criteria for class definition used a multi-level approach (Anderson et al. 1976) and an official Brazilian classification system for vegetation features (Veloso et al. 1991). Table 12 summarizes LULC classes encountered during fieldwork. For the final classification, the first-level classes were adopted, except for secondary succession, for which two classes were used, as indicated by the results presented in Chapter 3. So, the final classes were: mature forest, advanced secondary succession, initial secondary succession, pasture, agriculture, bareland, infrastructure, and water. In 1988, just one class of regrowth was used. After just five years of settlement implementation, the advanced secondary succession stage would not be present.

The hybrid classification approach consisted of building spectral signature files derived from both unsupervised ISODATA techniques (ERDAS 1998) and supervised classification using training samples collected during fieldwork. All training samples were accurately integrated in the GIS/remote sensing environment through the use of a GPS (Global Positioning System) and associated software. The training sample protocol and fieldwork data collection was already described in Chapter 3. An important part of the process was to carry out interviews with local people to inform the classification of images dated 1988 and 1994.

Separability analysis on the signature files (ERDAS 1998) and analysis of vegetation structure (Brondizio 1996) were used to select the best signatures during the classification process. The spectral curves for all classes in each date show the responses obtained after all techniques used (Figures 49, 50, and 51). Once the best signatures had been selected, a maximum likelihood classification (Jensen 1996) was carried out for each date.

### 4.2.4 - Post-Classification Procedures and GIS Manipulation

One of the main problems when classifying complex LULC features in the Amazon is related to the spatial configuration of agricultural fields, pasture, and different stages of secondary succession. Both the relatively small size of these patches and the mixed spectral responses of pixels representing their classes are responsible for data misclassifications. Recently, several initiatives have been implemented to overcome these limitations, including the use of data with higher spatial resolution (e.g., IKONOS), non-optical sensors (Rignot et al. 1997, Saatchi et al. 1997), the integration of detailed field data to support the classification process (Mausel et al. 1993, Li et al. 1994, Brondizio et al. 1996, Lucas et al. 1998), the use of spectral mixture analysis (Adams et al. 1995), object-based classifiers (Foody et al. 1996), indices (Steininger 1996), and hybrid techniques. Other problematic land covers to differentiate in the study area are the road network and urban areas. They are often confused with agricultural bare soil because most roads and urban areas are unpaved.

After going through the procedures described in the previous section, some adjustments were necessary to achieve a higher accuracy for the final LULC classifications. First, a 3 x 3 pixels neighborhood filter based on the majority rule was used to remove isolated pixels (ERDAS 1998). The procedure was carried out for all dates using identical rules and produced better cartographic results for the scale of study. To better map roads, urban areas, and rivers, topographic maps and visual interpretation were used to improve the classification in a GIS environment. Field notes and observations about LULC in the study area were always useful to inform decisions about the technical procedures to use.

The results were tested through accuracy assessment. A common method for classification accuracy assessment is the error matrix. The error matrix compares the relationships between ground-truth data (reference data) and classified results category-by-category. From the error matrix, some important measures can be derived, such as overall accuracy, producer's accuracy, and user's accuracy. Many works have provided the meanings and calculation methods for these measures (Congalton 1991, Richards 1993, Janssen and Wel 1994, Campbell 1996, Jensen 1996). Another method to interpret the classification accuracy is to calculate Kappa coefficients (Ma and Redmond 1995, Jensen 1996, Kalkahan et al. 1997). It measures the difference between the agreement between reference data and classification results and the chance of agreement between the reference data and a random classifier. The Kappa coefficient is computed as

$$KAPPA = \frac{N\sum_{i=1}^{r} X_{ii} - \sum_{i=1}^{r}(X_{i+} * X_{+i})}{N^2 - \sum_{i=1}^{r}(X_{i+} * X_{+i})},$$

where r is the number of rows in the error matrix, $X_{ii}$ is the number of observations in row $i$ and column $i$ in the error matrix (i.e., the corrected classified number), $X_{i+}$ and $X_{+i}$ are the marginal total in row $i$ and column $i$ respectively, and $N$ is the total number of observations included in the error matrix.

The results for the accuracy assessment of LULC classifications are listed in Table 13. Relatively higher values were found for the 1988 and 1998 classifications. The higher accuracy in 1998 is certainly due to the greater control over field data collected in 1999 and 2000. A considerable number of training samples were selected for this date based on ground truthing. In 1988, the use of just one class of secondary succession was responsible for a better discrimination between classes.

After accuracy assessment, the classifications were integrated in a GIS to allow further manipulations and analyses. Areas were tabulated for each class and date. Transition matrices were performed to answer specific questions on LULC dynamics in Machadinho and Anari. Buffers of 100 m, 200 m, 400 m, and 800 m were created around the road network for manipulations and area calculations within these landscape corridors. Analyses with and without the extractive reserves in Machadinho were performed. Property grids were digitized for both settlements, allowing the extraction of LULC information at the property level. Layouts, tables, and graphics were produced, as presented in the next sections.

## 4.3 - LAND-USE/LAND-COVER (LULC) DYNAMICS

### 4.3.1 - Machadinho and Anari: General Spatial Trends in LULC

Comparison of LULC classes between the two settlements reveals striking differences in landscape change (Table 14). During the early stage of implementation, both settlements had similar percentages of forest and pasture (about 87% and 6%, respectively). Ten years later, forest cover dropped to 51% in Anari in contrast to 66% in Machadinho. Figure 52 shows the forest cover through time in Machadinho and Anari.

Forest conversion was also different in both areas. In Anari, pastureland increased threefold, while in Machadinho it increased less than twofold (10% of the landscape). While agricultural areas are also larger in Anari (10.3%), Machadinho shows a faster growth of this activity (just 1% in 1988 in comparison to 7% in 1998). According to landowners in both settlements, the condition of agricultural fields is better in Machadinho. This is confirmed by official indices, suggesting a better management of cropland by landowners at this settlement. For example, the productivity of corn in Machadinho is 1,200 kg/ha while in Anari it is just 1,000 kg/ha (IBGE 2000b).

An indication of a slightly higher percentage of abandonment of agricultural fields as well as pasture areas in Anari is indirectly depicted by the total percentage of vegetation regrowth (initial and advanced secondary succession): 16.8% in Anari opposed to 13.5% in Machadinho. If we consider that a remarkable amount of area under vegetation recovery is effectively used for cattle ranching, the trend of Anari for pasture extensification becomes even clearer. Figure 53 shows the dominance of pasture conversion in Anari in contrast to more balanced relationships between LULC categories in Machadinho.

Cartographic outputs and field data reveal LULC spatial patterns within the settlements. In Machadinho, small agricultural fields (mainly coffee plantations) predominate at the central portion of the settlement, on both sides of the Machadinho River. The extractive reserves play an important role in maintaining forest cover (Figure 54). Larger patches of pasture occur mainly within the peri-urban area, in the northern portion of the settlement and along main roads MC-06 (east) and MC-07 (north). Patches of initial secondary succession are often associated with these locations (Figure 55).

In Anari, larger patches of pasture are found in the south and along the main road. Secondary succession is also associated with these areas. The largest patch of pasture at the southeastern border of the settlement indicates land aggregation processes. To the north, along the boundary with Machadinho, small agricultural fields occur, as well as pasturelands in the intersection of the main road and the feeder roads (Figure 54).

### 4.3.2 - Deforestation, Production, and Secondary Succession: Different Processes

Different agroecological processes occur in Machadinho and Anari. Deforestation represents the human action to clear the land for production or speculation. Secondary succession is the continuous response of nature through vegetation regrowth whenever humans abandon cleared areas or gaps are formed within forests. The section above showed how LULC changed through time but did not analyze processes of change themselves. This section answers specific questions related to deforestation, production, and succession. What is the pace of deforestation in Machadinho and Anari? Is the deforested land under production or abandonment? How much and when was the deforested land abandoned for succession?

The cartographic result showing land-clearing processes in the study area is illustrated in Figure 56. Areas in southern Anari with no data for 1988 and 1994 represent only 11% of the settlement. It is obvious how the process is associated with the road network, as described further in Section 4.3.4 through buffer analysis. Deforestation before 1988 follows the roads consistently. Colonists in both settlements started to clear their properties as soon as they had access to the land along these paths. The urban area of Machadinho, located in the northeastern limits of the settlement, was also established before 1988. The village of Anari was embedded in a square located between the second and third feeder roads from the north. Deforestation during 1988-1994 and 1994-1998 expanded from the patches cleared before 1988.

Figure 57 illustrates graphically the different paces of deforestation in Machadinho and Anari. Water was not represented (less than 0.5% in both settlements). The period between 1988-1994 showed higher rates of deforestation (13% in Machadinho and 19% in Anari). This is due in part because this period is longer than the period from 1994 to 1998. For the entire period of analysis, Anari's rates of deforestation are always higher than Machadinho's. Moreover, in Machadinho the rates are the same before 1988 and between 1994 and1998 (11%). In Anari, these rates increased from 13% to 16% during the same periods.

The recoding process to answer questions about secondary succession was more complicated. To answer these questions, the original LULC classifications were recoded to four classes: forest, secondary succession (SS1 and SS2), production (pasture, agriculture, and bareland), and others (infrastructure and water). Then, these classes were combined using transition matrices (ERDAS 1998). Secondary succession in Machadinho and Anari follows cycles of clearing and abandonment of production fields. Thus, these two processes (i.e., expansion of production fields and vegetation regrowth) were used as guidelines for the definition of final transition classes (Table 15).

Following deforestation, patches for production since 1988 and 1994 are located closer to roads, in areas cleared for this purpose (Figures 56 and 58). Areas of recent clearing are often located further from roads, as a consequence of the expansion of production activities within the properties. In areas of both settlements, where lots were often not occupied or were abandoned, large areas of recent clearing occur (central-eastern portion of Machadinho and end of eastern feeder roads in Anari). Field observation showed that pasture conversion and land aggregation has occurred in these areas. In Anari, the settlement design facilitates the visual perception of these processes. Other processes occur within areas in succession (i.e., long-fallow cycle, short-fallow cycle, and recent abandonment). They often predominate further from roads, functioning as buffers between areas in production and areas covered by forest (Figure 58).

Figure 59 illustrates the percentage of the settlements covered by each transition class of production or succession. Machadinho has 5% of its area in long-fallow cycles and 3% in short-fallow cycles. In Anari, these succession areas cover 4% of the settlement each. However, recent abandonment is significantly higher in Anari (13%) than in Machadinho (10%), also indicating a better maintenance of production fields in the latter. Percentages of areas in production since 1988, since 1994, and recently cleared are always higher in Anari (7%, 9%, and 9%, respectively) than in Machadinho (4%, 5%, and 6%, respectively).

#### 4.3.3 - Do communal forest reserves make a difference in Machadinho?

The existence of communal forest reserves managed by local rubber tappers in Machadinho is an important factor in producing a distinct outcome in terms of LULC change, as shown above by the difference in forest cover between the two settlements. However, when only private lots are considered, Machadinho's forest cover is similar to Anari's: 83% in 1988, 65% in 1994, and 51% in 1998. These results clearly indicate how the combination of private lots and communal reserves can produce significant effects in the maintenance of forest cover when considering the entire settlement as the unit of analysis.

Machadinho had fifteen State Extractive Reserves decreed in 1995 and one State Forest for Sustainable Management decreed in 1996 (Olmos et al. 1999). However, all of them had already been implemented as reserves during the settlement creation by INCRA in 1983. Figure 6 illustrates their location within the settlement. Five reserves are responsible for 75% of the area decreed as reserves: Aquariquara (25%), Castanheira (15%), Maracatiara (14%), Angelim (13%), and Massaranduba (8%). Figure 60 illustrates graphically the percentage of each forest reserve in relation to the total area of reserves in Machadinho.

The total area of these reserves in Machadinho encompasses 68,477.6 ha, approximately 33% of the entire settlement. Their forest cover in 1998 represented 46.5% of the total forest cover in Machadinho. A population of 401 individuals lives in scattered locations within fourteen reserves (Table 16). Their main activity is rubber extraction, which has maintained forest cover, as indicated by the LULC results. Figures 54, 56, and 58 show that the largest portions of these reserves are still covered by forests.

In Chapter 6, institutional factors are related to the management of forest reserves in Machadinho and their role in interactions among actors within the settlement. The importance of these reserves in maintaining lower levels of landscape fragmentation is also discussed.

### 4.3.4 - Roads: The Path for Lot Occupation

Access to land is an important variable affecting LULC change in Amazônia. For this reason, distance from roads is often associated with the pace of deforestation and land colonization (Browder and Godfrey 1997, Alves 1999, Alves et al. 1999, Laurance et al. 2001). However, the establishment of road systems in the region is a very complex process, varying regionally and locally. At the regional scale, programs for road building have opened major paths for Amazonian occupation. Towns, rural settlements, and secondary roads have flourished from these roads, making the human footprint visible within the landscape.

The case of Rondônia is singular. As mentioned in Chapter 2, beginning in the early 1970s, the state has been intensively occupied through settlement programs to accommodate migrants from other Brazilian states. The process was accelerated by the building and paving of BR-364, the main road in Rondônia crossing the State from Mato Grosso (southeast) to Acre (northwest). RO-133, the main road crossing Anari from south to north, is a secondary road starting at BR-364, in Jaru. Going further to the north, it reaches the road system of Machadinho (Figures 5 and 6).

This section shows how LULC has changed in distinct and contiguous buffers around roads in Machadinho and Anari. The motivation here is to understand if road system design affected the pattern of LULC change. In this case, the bias caused by reserves increasing the percentage of forest cover within the settlement is attenuated, as the buffers chosen (100 m, 200 m, 400 m, and 800 m) barely reach the reserves' boundaries (Figure 61). [1] So, we can assume that the results are related to LULC change at the property lots.

Figure 62 illustrates trends of deforestation until 1998. The spatial pattern varies depending on which buffers are being analyzed. For the 100-meter buffers, the patterns in Machadinho and Anari are very similar, but deforested areas in 1988 are already larger in the latter. Within the 200-meter buffers, the difference begins to be visible. The

[1] In Machadinho, because of its curvilinear design, areas between the road buffers filled with the color of a buffer class are related to the smallest buffer necessary to fill the polygon.

percentage of area covered by forests or where recent clearing occurred is lower in Anari, indicating the faster process of lot occupation from roads. Within the 400- and 800-meter buffers, the differences become even clearer. Forest cover within the 800-meter buffers is just 25% in Anari and 44% in Machadinho, showing that deforestation processes extend further from roads in Anari.

When analyzing the numbers for production and succession, one can see similar patterns but different magnitudes in Machadinho and Anari. In general, the results for succession (i.e., SS since 1988, long-fallow cycle, short-fallow cycle, and recent abandonment) are about 2% higher in Anari at all distances. Areas in production since 1988 and 1994 are 5% and 3% larger in Anari in all distances, respectively. The main difference between the settlements occurs in areas of recent clearing. They are practically constant in Machadinho in all buffers but increase from 3% to 10% in Anari as they get further from roads. This also indicates that the process of clearing in Anari is more intense than in Machadinho, even after 15 years of colonization.

### 4.3.5 - Property-Based Analysis of LULC

The property-based analysis of LULC was possible by overlaying the property grid to the LULC classifications and tabulating areas for each polygon using a GIS. Descriptive statistics and graphic outputs were then produced based on these data. The importance of this procedure relies on the fact that excluding Machadinho's communal forest reserves from the analysis allows a better comparison between the settlements regarding lot occupation and establishment. As mentioned in Chapter 2, Machadinho was implemented in 1982-1984 and Anari in 1980-1982. The two-year separation may produce a subtle difference in the final numbers but do not affect the study of LULC dynamics within the settlements. Moreover, the results show that this difference in time did not blur the picture of property lots within the settlements. Results are presented in hectares (ha) and percentages to facilitate the analysis (Tables 17-22). Boxplots illustrate the distribution of data for LULC classes in all periods (Figures 64-69).

The first important finding to mention is the mean property size of 43.8 ha in Machadinho (Tables 17, 18, and 19) and of 50.0 ha in Anari (Tables 20, 21, and 22). This number per se already provides a sense of property size homogeneity in Anari due to its fishbone design. Rectangular properties of 2,000 by 250 meters make the blueprint of this settlement. In Machadinho, properties vary in size and shape, being 6 ha smaller than in Anari on average, as a consequence of the settlement design being based on topography and the fact that communal forest reserves encompass 33% of the total settlement area (Figure 6).

The percentage and area of forest cover within the properties add new information to the results presented in the sections above. Landowners cleared about the same percentage of their lots in Machadinho (Tables 17, 18, and 19) and in Anari (Tables 20, 21, and 22). However, the area cleared in Anari was larger than in Machadinho. At the former settlement, farmers deforested 1.4 ha/year between 1988 and 1994 and 2.2 ha/year between 1994 and 1998. In Machadinho, they cleared 1.3 ha/year and 1.7 ha/year, respectively (Table 23). In both settlements, deforestation of properties was higher between 1994 and 1998. Standard deviation and variance for forest cover are always higher in Machadinho, indicating a higher heterogeneity in land clearing and different strategies of land use among owners.

Advanced secondary succession had similar patterns in percentage of area in Machadinho and Anari. These areas are relatively small, not exceeding an average of 1 ha per property in 1994 and 2.3 ha per property in 1998 (Tables 17 to 22). Initial secondary succession showed a more dynamic picture. Machadinho has more area and percentage of area per property in SS1 than Anari in all dates. In 1998, this stage of succession covered 15.3% of the properties in Machadinho and 12.5% in Anari (Tables 19 and 22, respectively). Opposite trends occurred with pasture. They started with equal area in 1988 in both settlements (Tables 17 and 20), but in 1994 the higher pasture conversion in Anari is already clear (Tables 18 and 21). In 1998, properties had 8.1 ha (16%) of pasture in Anari (Table 22) and 5.9 ha (13.4%) in Machadinho (Table 19). Figures 65, 66, 68, and 69 illustrate the opposite trends of SS1 and pasture within the settlements.

Agricultural fields had similar land cover in both settlements in 1994 and 1998: about 5.5% of the properties in 1994 (Tables 18 and 21) and about 10% in 1998 (Tables 19 and 22). In 1988, agricultural land was three times larger in Anari (Tables 17 and 20), suggesting that the priority for pasture came with experience and time.

Bareland can be interpreted as a proxy for agriculture and pasture increment. In Machadinho, landowners prepared 1 ha of land in 1988 (Table 17) and 1.3 ha in 1994 and 1998 (Tables 18 and 19, respectively). In Anari, bareland was just 0.4 ha in 1988 against 1.9 ha in 1994 and 1.3 ha in 1998. Although it is risky to draw conclusions solely from these numbers, they indicate a higher homogeneity in farming decision-making in Machadinho through time. Next section discusses the results presented so far trying to relate trajectories of LULC in Machadinho and Anari with the spatial organization within the settlements.

## 4.4 - THE COLONIZATION IMPACT IN MACHADINHO AND ANARI

In the beginning of this chapter, I called attention to the importance of geotechnologies in supporting the study of LULC dynamics in Amazônia. Through a brief literature review, the need of spatial-temporal assessments related to the subject was emphasized and the research was included in this methodological context. After going through the results achieved at distinct units of analysis (i.e., settlement, buffers around roads, reserves, and rural properties), this section discusses the impact of this research for a better understanding about trajectories of LULC in the study area and in Amazonian frontiers of colonization. For this purpose, the section is divided in three main aspects: the methodological and operational issues; the main findings and their meanings; and the trajectories of LULC and trends for the near future.

### 4.4.1 - Methodological and Operational Issues

LULC classification in Amazônia is a complex task and its degree of difficulty increases with the number of classes one wants to distinguish. Spectral signatures detected by TM images often include mixed responses for the heterogeneous tropical environment. More than just distinct vegetation types, LULC cover classes represent scenarios within the complex dynamics of vegetation clearing or recovering. In addition, the process occurs at remote and large areas, sometimes of difficult access. Lack of data, such as soil and topographic maps at detailed scale, also complicates the process of classification. In sections 3.5 and 4.1, aspects related to the use of spectral analysis and vegetation structure for understanding LULC dynamics in the Amazon are mentioned. This section discusses some operational and methodological issues faced when tracking the colonization impact in the study area using remote sensing tools.

Some problems are merely operational (e.g., the lack of image data for the southern portion of Anari in 1988 and 1994 or detailed soil maps). Other questions are methodological, such as to use a reasonable classification system to describe the variance of LULC dynamics at the scale and complexity of study. One way to surpass such difficulty is to increase the fieldwork effort by gathering more ground-truth data. In the case of Machadinho and Anari, the total area to be covered (3,383 $km^2$) was reasonably large to include multiple scenarios within the distinct landscapes and LULC outcomes. During fieldwork, overview flights were carried out in small planes. I also drove through all dirt roads, and walked through properties and forest reserves. The challenge was not just to acquire training data to inform image classifications. It was also to understand the responses of local people to processes of LULC change and landscape transformation. For this reason, interviews with local people were carried out, helping to achieve a better conceptual approach about local heterogeneity in LULC.

Accuracy assessment of LULC classifications brought attention to some aspects. In areas of steeper topography, mainly along orthogonal roads of Anari crossing ridges and valleys, ground truthing indicated that some agricultural fields and bareland should have been classified as pasture. The confusion between bareland and pasture becomes worse with overgrazing during the dry season, when soil spectral response contributes more significantly to the signature of sparsely covered grassy vegetation. On the other hand, degraded pasture in the process of vegetation recovery often has high densities of *Vismia sp.* and *Orbignya sp.*, generating confusion with the spectral response for SS1 or even perennial agriculture. Spectral responses for perennial agriculture can also be confused with SS1, mainly in areas of initial recovery of disturbed gallery vegetation. One way of reducing the risk of misclassification would to group classes such as pasture, agriculture, and bareland as a class named 'production,' or collapsing the stages of secondary succession into just one class, which was done for the computation of transition matrices and for the calculation of landscape metrics described in the next chapter. This produces more accurate classifications but at a cost of generalizing LULC classes drastically, not allowing the generation of results such as the ones presented in this chapter.

To overcome possible problems related to the chosen classification system, extensive fieldwork during the dry seasons of 1999 and 2000 and previous studies supported the description of LULC categories and production systems in the area (Miranda and Mattos 1993; Miranda et al. 1997, 1997a). The proximity of Machadinho and Anari also made the study possible by easing the access to most portions of the area under investigation. Also, possible methodological problems related to image classification can be assumed to be similar in both settlements.

### 4.4.2 - Main Findings and Their Meanings

The results presented in this chapter were produced at distinct units of analysis. This method allowed addressing LULC dynamics in a multi-scale manner, from the landscape (settlement) to the property. The landscape-based analysis provided a general picture about the process in Machadinho and Anari. As expected and assumed at the beginning of this research, both settlements had similar LULC in 1988. This holds for all classes mapped, except for agriculture and bareland. Despite the fact these classes had small land cover at the time, the percentage of agricultural lands in Anari is three times greater than in Machadinho, and the percentage of bareland is twice greater in the former settlement (Table 14). As explained in Chapter 2, Anari settlement was started about two years before Machadinho. These numbers indicate that the process of farm occupation was a little more advanced in Anari in 1988. In 1998, after experiencing many production systems and coping with distinct policies, incentives, and local biophysical heterogeneity, farmers produced a different outcome, with Anari showing a clear trajectory toward higher rates of deforestation and pasture conversion.

As far as intra-settlement spatial patterns are concerned, some findings deserve attention and were corroborated during fieldwork. In Machadinho, larger patches of pasture occur mainly along two roads: MC-7 and MC-6, at the northern and eastern portions of the settlement, respectively. According to local landowners and extensionists, these are zones within the settlements where the less fertile soils occur. Although there are no detailed soil maps available for the area, it makes sense to expect that the rate of abandonment by original landowners and land aggregation for pasture conversion by speculators will be higher in less fertile areas. Within the center of the settlement, properties remain with their original sizes and are mainly cultivated with coffee plantations or mixed production systems including agriculture and pasture.

In Anari, other important patterns were found. Large patches of pasture occur along the main road and at the ends of secondary roads. Here, besides soil fertility, access is also affecting the process of pasture conversion and land aggregation. Along the main road, first colonists and opportunists took over the land with better access and converted it rapidly to pasture to ensure their tenure status. In marginal areas at the border of the settlement, speculators took over abandoned lots, as they did in Machadinho. In these areas, access is poor through dirt roads trafficable only during the dry season, making cattle the only choice of production. Interesting enough, the sector of Anari called 'line of agriculture' by the local population is located at the northern portion of the settlement in mild topography. Besides better access to the urban area and proximity with Machadinho, better soils occur in this area, according to landowners and extensionists.

Section 4.3.2 presented the results for the study of agroecological processes using transition matrices between the multi-temporal classifications. Deforestation processes are clearly associated with roads, urban areas did not grow significantly, production patches follow the deforestation patches, and secondary succession patches often occur further from roads.

The results for production and succession (Figures 58 and 59) do not allow conclusions about intensification or extensification of production systems in Machadinho and Anari. All that can be said is that area in production (pasture and agriculture) is greater in Anari. However, a careful analysis of the results at the settlement- and the property-level indicates a trend. At the settlement level, Table 14 shows that Anari has more pasture in 1998, both in area and percentage. The numbers for agriculture show a different picture. Although the percentage of the settlement covered by this land use is greater in Anari, the rate of agriculture conversion in Machadinho is higher. These opposite trends are clearly shown by the areas of pasture and agriculture per property (Tables 17-22). In Machadinho, the area of agriculture increases from 0.5 ha in 1988 to 4.4 ha per property in 1998, while the area of pasture goes from 2.8 ha to 5.9 ha during the same period. In Anari, the numbers for agriculture are 1.4 ha in 1988 and 5.2 ha in 1998 (higher, but not very different from Machadinho), while pasture area grew rapidly from 2.8 ha to 8.1 ha per property during the same period. This analysis at the property level avoids misinterpretations of results obtained for the entire settlement, as Machadinho has more properties than Anari and properties in Anari are on average larger than in Machadinho.

Still through the transition matrices, it was possible to depict spatial patterns for recent clearings in both settlements. Large areas being cleared are often associated with pasture conversion and are adjacent to other pasture areas. Smaller areas being cleared are located further from roads and are generally associated with the expansion of agricultural fields. Interviews with Anari landowners during fieldwork shed some light on this pattern. According to them, agricultural fields develop better in areas closer to forests because of a cooler microclimate. Moreover, they try to keep these fields at a certain distance from pastures, as the latter are frequently managed through the use of fire. In Machadinho, this pattern is not so clear, as the curvilinear road design does not follow an orthogonal distribution of production fields as in Anari. In addition, this finding is valid only for properties with mixed production systems including agriculture and cattle ranching.

Section 4.3.3 showed the relative importance of communal forest reserves in maintaining a higher percentage of forest cover in Machadinho. The institutional aspects regarding rules in use and interactions among different actors within the settlement are discussed in Chapter 6. The important point here is to reaffirm that the percentage of forest cover in Machadinho in 1998 would be the same as in Anari if the reserves did not exist (i.e., 51%). This brings up an important discussion about the limits of deforestation in Amazônia and in Rondônia, also valid for the results at the property level. Arguments about a reasonable 'Forestry Code' ruling the region are currently in debate. The Brazilian Congress seeks to determine a percentage of deforestation allowed by law. This percentage was of 50%, but recent discussions have vacillated between reducing and increasing this number.

Moreover, land zoning laws often conflict with the 'Forestry Code', making the subject a complicated issue affected by political and economic interests. The contribution of this research to the topic is that multi-temporal analysis using remote sensing has proved to be an effective tool when comparing the trajectories of settlements in Rondônia. In addition, comparative analysis, such as the one carried out during this research, makes it possible to draw a better picture of the heterogeneity of LULC dynamics in the Amazon, particularly in areas of rural settlements with distinct architectural and institutional designs.

Another aspect analyzed in this chapter is the impact of road system design in LULC change patterns. The results show that deforestation extends further from roads in Anari, which is also reaffirmed by higher rates of recent clearing at the 800-meter buffers around roads within this settlement. Deforested areas tend to percolate first in Machadinho because secondary roads are closer to each other than in Anari. The communal reserves play an important role in maintaining large patches of forest encompassed by the road system. However, the discussion about the importance of road system design to the magnitude of deforestation still requires more research. On one hand, questions related to access may affect the process significantly. In general, marginal areas of difficult access at the end of secondary roads tend to be converted to pasture. This happens for two main reasons. First, as mentioned above, speculators take over these abandoned or underused areas and assure tenure by planting grass and introducing cattle. Second, agriculture is often unviable in these areas because secondary roads are too bad for transportation of produced goods. This process is more visible in Anari, where the orthogonal road design and poor maintenance of roads leads to higher rates of pasture conversion. On the other hand, besides infrastructure, incentives toward specific land uses may affect the decision-making process at the property level, generating a spatial pattern at the settlement level. Farmers in Machadinho had several incentive programs for agricultural production, including coffee, cacao, and agroforestry. Despite their questionable success in terms of economic return for the farmers, the LULC outcome was a more heterogeneous mosaic of production systems at variable distances from roads. Institutional aspects related to farmers' decision making and their possible impacts in LULC dynamics and landscape transformation will be discussed in Chapter 6.

The final unit of analysis was at the property level. Results in both percentage of lot and area, and rates of land conversion to different LULC features, provided a better understanding of the colonization process in Machadinho and Anari. Property results showed a higher percentage and area of deforestation per year in Anari after 1988 (Table 23). Higher rate of deforestation in Machadinho's properties before 1988 is probably due to the fact that this settlement was implemented with infrastructure and incentives for production already in place. In Anari, the implementation phase was more chaotic, as discussed further in Chapter 6. Landowners had to cope with difficulties in access to their lots and to incentives. Once they had adapted to these problems, they started clearing the land rapidly (after 1988), at a rate of deforestation higher than Machadinho. A higher pasture conversion rate was also confirmed for Anari. The variance in terms of area tends to increase with time in all classes in both settlements, indicating different farming strategies implemented by landowners.

Perhaps, property-based analyses for transition matrices and the study of a time series with more intervals could provide a better picture of specific trajectories within the lots. The integration of these results with household data for socioeconomic and agroecological variables may also be a valuable approach to take. However, cloud-free images for other dates and household data for Anari were not available. So, the results were based on the multi-temporal data available and the use of geotechnologies to bring light to general LULC dynamics in Machadinho and Anari. Together with the feedback from local people, some trajectories and trends of LULC may be drawn.

### 4.4.3 - Trajectories of LULC and Trends for the Near Future

The human occupation defined different outcomes in terms of LULC in Machadinho and Anari during the period of study. In 1998, after about 15 years of colonization, properties in both settlements reached an average of approximately 54% of deforestation. The pathways of LULC change underlying the colonization impact is illustrated in Figure 70. Infrastructure and water are not in the graph because they are poorly represented in terms of area in both settlements and their surface did not show significant changes through time (Table 14). However, it is important to mention that the trajectory toward infrastructure and water is diverse. Their patches can be originated from the conversion of any LULC class. Infrastructure includes roads and urban areas. The latter have grown slowly during the period of study through the conversion of forest, SS2, SS1, pasture, agriculture, and bareland. The roads were primarily built during settlement implementation through forest clearing. Newer road building, although rare, may have been converted from any LULC class. The return of infrastructure to other classes is also spatially unimportant but may occur. Water includes rivers and lakes. The former may change their path over time but the effect in terms of area of LULC change is also very small. The lakes, which include water ponds, are generally built for cattle ranching. Their number has increased but their extent is also small.

A more dynamic process occurs between forest, SS2, SS1, pasture, agriculture, and bareland. The trajectories between these classes are associated with cycles of vegetation clearing, degradation, or recovery through the portfolio of strategies among colonists. Forest can be cleared to bareland, converted to pasture or agriculture, and degraded to SS2. Pasture can be cleared or degraded to bareland, converted to agriculture or recovered by SS1. Agriculture can be cleared to bareland, converted to pasture, and recovered after abandonment by SS1. Bareland can be converted to agriculture or pasture, and recovered by SS1. SS1 can be cleared to bareland, converted to pasture or agriculture, or develop to SS2. And SS2 can be cleared to bareland, converted to pasture or agriculture, degrade to SS1, or develop to forest.

A range of factors influences these trajectories and was confirmed during interviews. Local biophysical features can drive LULC changes, mainly because of soil fertility and topography. Distance from roads and urban areas may also affect LULC changes, as mentioned throughout this chapter when explaining higher rates of pasture conversion in Anari. Socioeconomic variables can also impact the outcomes in LULC. Access to credit and incentives, household labor force, previous farming experiences, and available assets are among the most important drivers for land management or abandonment.

Another important consideration to point out is the meaning of each LULC during the time frame being studied. This not only explains specific trajectories toward LULC change, but also defines trends for the near future. In 1988, for instance, agriculture meant annual crops and young perennial plantations (i.e., coffee, rubber, cacao). SS1 was the only class of vegetation recovery at this early stage of colonization, resulting from abandonment of lots or fields. SS2 did not exist because not enough time had passed for vegetation recovery to occur. Forest, pasture, bareland, infrastructure, and water had the same characteristics as in 1994 and 1998. However, in these two latter years, agriculture was mainly represented by older coffee plantations, secondary succession included different stages of recovery, and more dynamic trajectories were taking place as the internal variance in area of each LULC increased within properties (Tables 17-22 and Figures 64-69). Pearson correlation also indicates the relationships between changes in forest cover and selected LULC classes. In Anari, loss of forest cover is strongly associated with the pasture extent. Values of –0.618, -0.700, and –0.626 ($p<0.01$) were found for 1988, 1994, and 1998, respectively. Correlations for SS1, agriculture, and bareland are also higher in Anari, where the deforested area for production at farm lots is greater than in Machadinho (Table 24).

Despite major LULC trajectories presented in this chapter, some other trends deserve attention, particularly in agricultural production. In general, trends are represented by experiences with different crops. These crops have attractive economic returns, but also some uncertainty related to market demands. Black pepper is one example. Many farmers have tried to produce it, but they claim it is a difficult and expensive crop to implement. Guaraná (*Paulinnia cupana*) is relatively difficult to cultivate with high productivity. Palm heart production and *mamona* seeds for oil production are not reliable crops because market demand and access are questionable for farmers in Machadinho and Anari. Tree plantations for lumber depend on a very long cycle. On the other hand, cacao and rubber tree producers are not happy with the results.

For these reasons, coffee is still the most common option when farmers choose a type of agriculture. Productivity and quality of coffee plantations are often low, but they provide extra income for landowners, who came mostly from southern and southeastern Brazil, and are used to coffee production systems. Last but not least, trends of LULC change for the near future may also be affected by rural and urban development. Rural power lines, mechanization, irrigation, better rural extension practices, and the use of better crop varieties are already being discussed and implemented.

All LULC processes described in this chapter affect landscape transformation in Machadinho and Anari. But the analysis of LULC change by itself does not allow a comprehensive approach about the effect of these processes in the spatial pattern of landscapes, classes, and patches within the settlements. Chapter 5 addresses this matter.

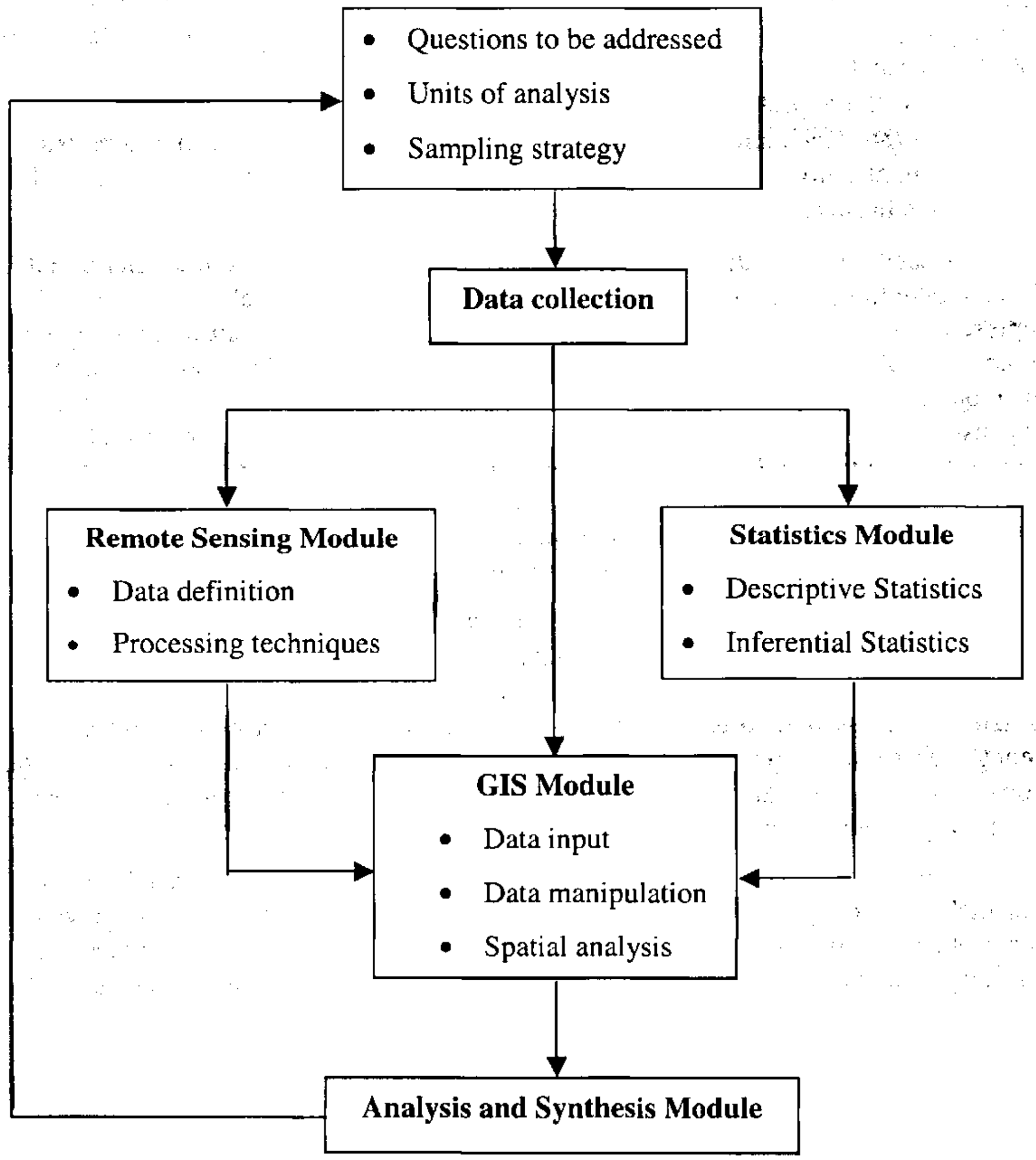



Figure 47 - Methodological steps for the study of LULC dynamics in Machadinho d'Oeste and Vale do Anari

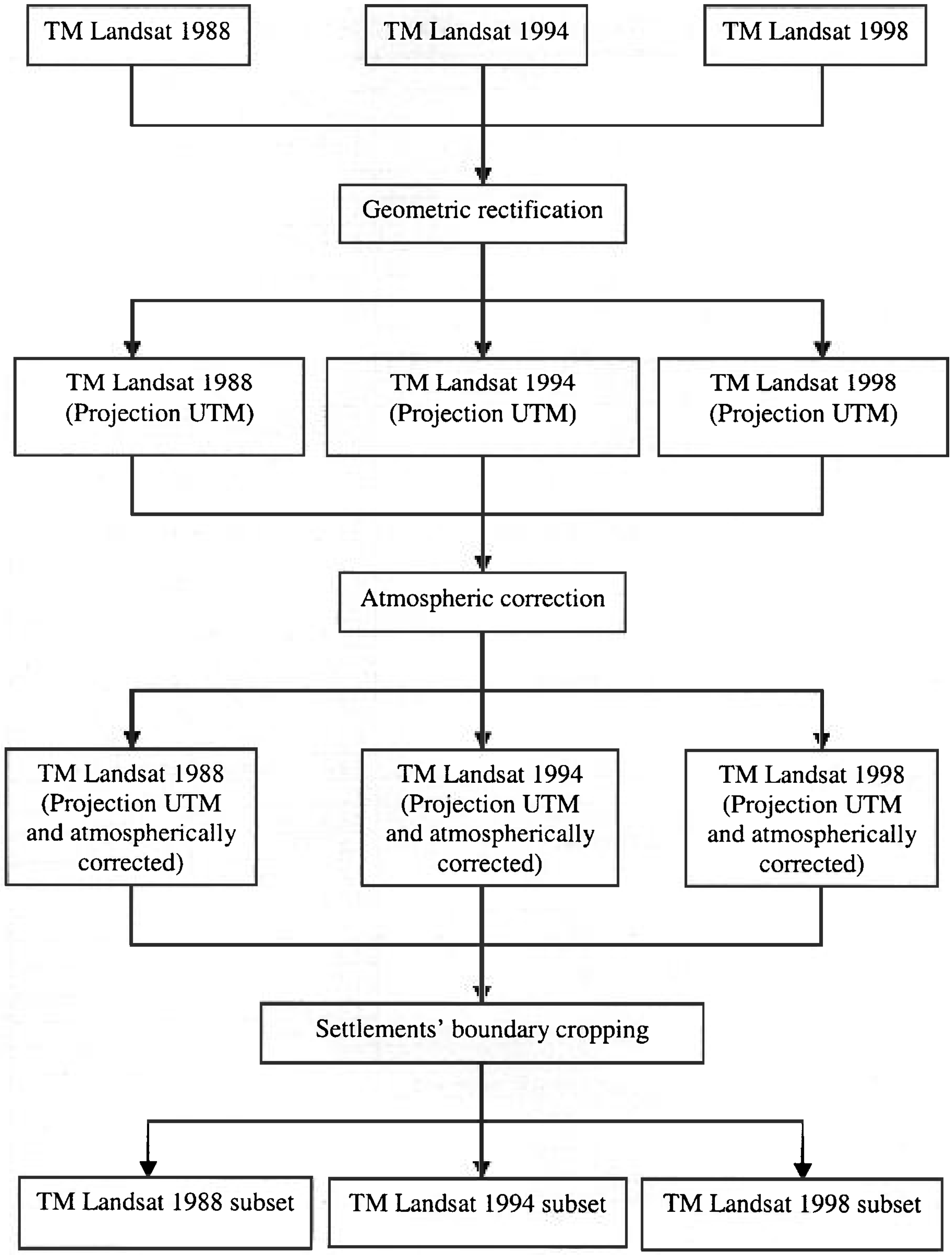



Figure 48 - Pre-classification techniques used for the study of LULC dynamics in Machadinho d'Oeste and Vale do Anari

Table 12 - LULC classification system for Machadinho d'Oeste and Vale do Anari

| LEVEL 1 | LEVEL 2 | LEVEL 3 |
|---|---|---|
| **1. Mature Forest** | 1.1. Open Forest | 1.1.1. Open Forest w/Palms |
| | | 1.1.2. Open Forest w/Bamboo |
| | | 1.1.3. Open Forest w/Lianas |
| | 1.2. Floodplain Forest | 1.2.1. *Varzea* |
| | | 1.2.2. Gallery |
| **2. Secondary Succession** | 2.1. Advanced Secondary Succession | |
| | 2.2. Initial Secondary Succession | |
| **3. Pasture** | 3.1. Degraded Pasture | 3.1.1. Degraded Pasture with Palms |
| | | 3.1.2. Degraded Pasture with Stumps |
| | | 3.1.3. Degraded Pasture with *Vismia sp* |
| | 3.2. Cultivated Pasture | 3.2.1. Cultivated Pasture with Palms |
| **4. Agriculture** | 4.1. Agroforestry | 4.1.1. Coffee/*Cecropia* |
| | | 4.1.2. Coffee/Rubber |
| | | 4.1.3. Cacao/Rubber |
| | | 4.1.4. Coffee/Cupuaçu/Cacao/*Guarana* |
| | | 4.1.5. Coffee/Rubber/Guarana |
| | | 4.1.6. Coffee/*Cecropia*/Other tree sp. |
| | | 4.1.7. Coffee/Rubber/Banana/Cacao |
| | | 4.1.8. Coffee/Other tree species |
| | 4.2. Perennial | 4.2.1. Coffee |
| | | 4.2.2. Cacao |
| | | 4.2.3. Rubber |
| | | 4.3.4. Banana |
| | 4.3. Annual | 4.3.1. Corn |
| | | 4.3.2. Rice |
| | | 4.3.3. Beans |
| | | 4.3.4. Manioc |
| **5. Bareland** | 5.1. Agricultural Exposed Soil | |
| | 5.2. Exposed Rock | |
| **6. Built-up Land (Infrastructure)** | 6.1. Road | |
| | 6.2. Urbanized Areas | |
| **7. Water** | 7.1. Running Water | |
| | 7.2. Lakes | |

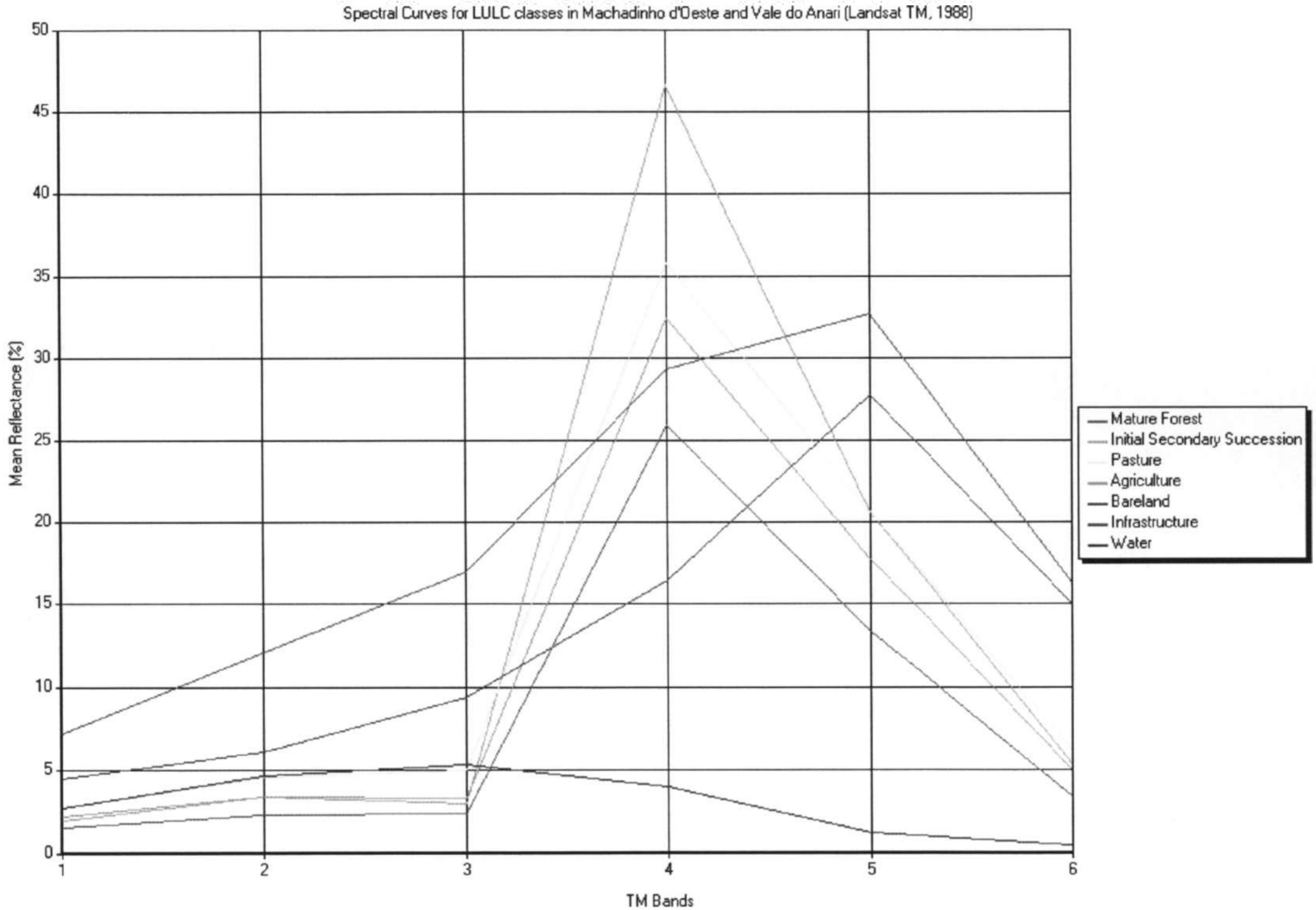



Figure 49 - Spectral curves for LULC classes in Machadinho d'Oeste and Vale do Anari (Landsat TM 1988)

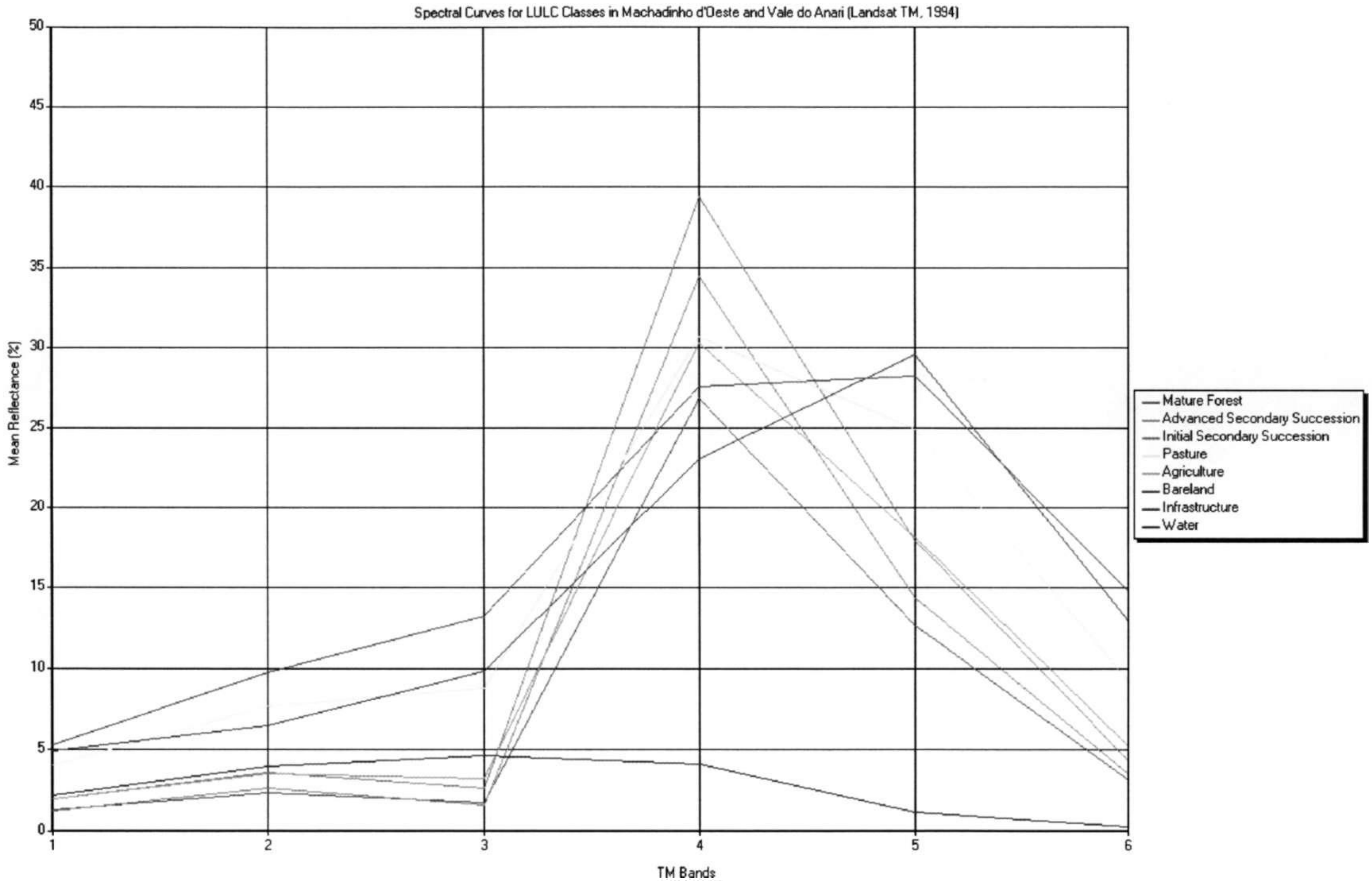



Figure 50 - Spectral curves for LULC classes in Machadinho d'Oeste and Vale do Anari (Landsat TM 1994)

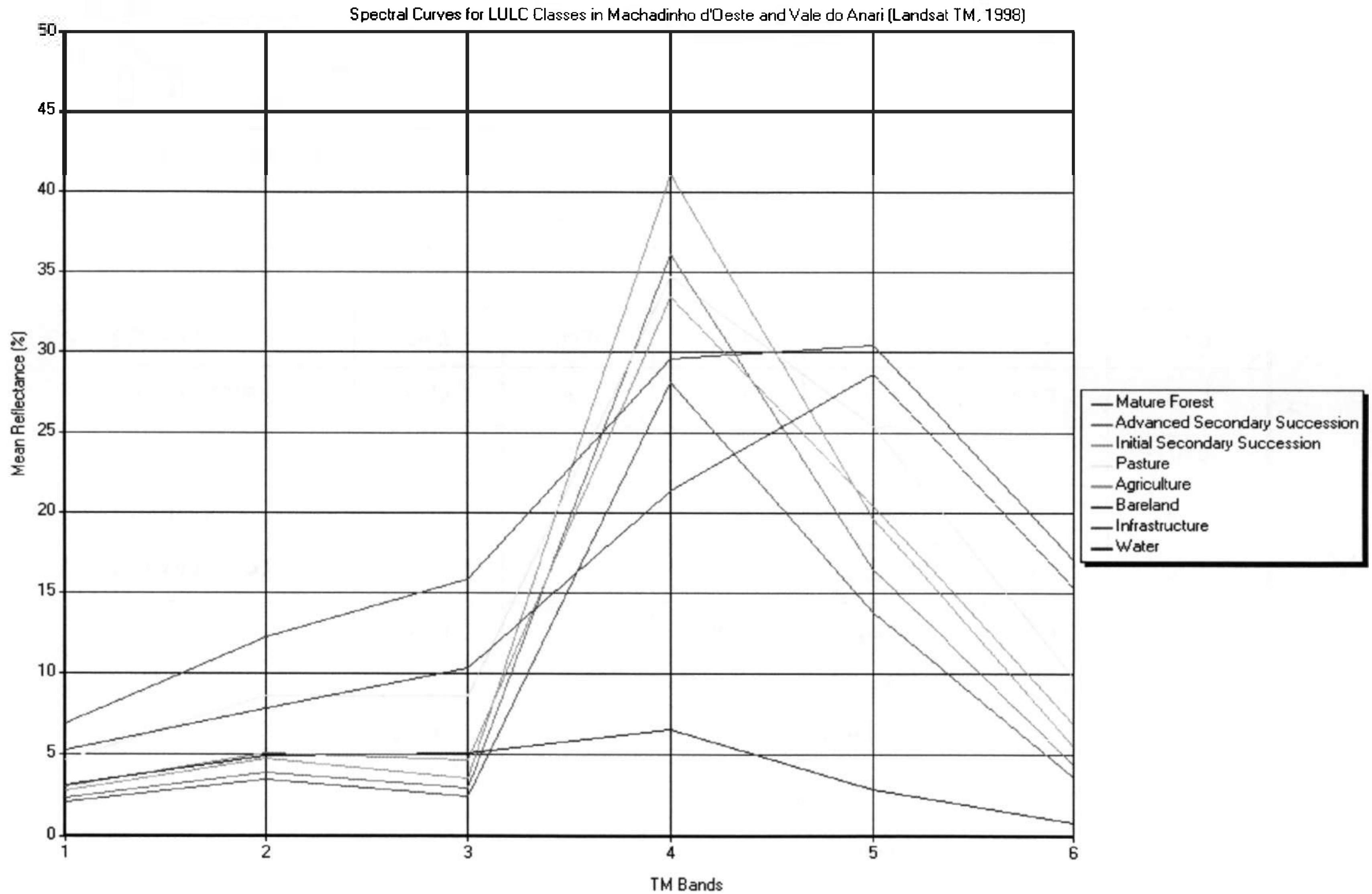



Figure 51 - Spectral curves for LULC classes in Machadinho d'Oeste and Vale do Anari (Landsat TM 1998).

Table 13 - Accuracy assessment for LULC classifications in Machadinho d'Oeste and Vale do Anari

| | 1988 | | 1994 | | 1998 | |
|---|---|---|---|---|---|---|
| | **User's Accuracy** | **Producer's Accuracy** | **User's Accuracy** | **Producer's Accuracy** | **User's Accuracy** | **Producer's Accuracy** |
| **Forest** | 89.4 | 86.3 | 80.2 | 95.8 | 81.9 | 97.3 |
| **Advanced SS** | -- | -- | 48.1 | 46.7 | 54.0 | 57.2 |
| **Initial SS** | 68.4 | 83.3 | 65.9 | 85.9 | 71.3 | 89.4 |
| **Pasture** | 87.7 | 72.0 | 90.5 | 66.4 | 95.3 | 70.5 |
| **Agriculture** | 80.5 | 66.7 | 85.1 | 77.8 | 86.5 | 82.3 |
| **Bareland** | 79.7 | 94.6 | 75.1 | 90.3 | 77.9 | 94.0 |
| **Infrastructure** | 82.4 | 100.0 | 81.0 | 83.6 | 81.0 | 85.0 |
| **Water** | 71.4 | 87.0 | 81.7 | 100.0 | 86.4 | 100.0 |
| **Overall Accuracy** | 79.5 | | 76.8 | | 81.1 | |
| **Kappa Coefficient** | 74.7 | | 70.1 | | 75.6 | |

Table 14 – Land Use/Land Cover in Machadinho d'Oeste and Vale do Anari in 1988, 1994, and 1998

| | MACHADINHO D'OESTE | | | | | | VALE DO ANARI | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Land-Use/ Land-Cover | Area in 1988 (km$^2$) | % in 1988 | Area in 1994 (km$^2$) | % in 1994 | Area in 1998 (km$^2$) | % in 1998 | Area in 1988 (km$^2$) | % in 1988 | Area in 1994 (km$^2$) | % in 1994 | Area in 1998 (km$^2$) | % in 1998 |
| Forest | 1879.3 | 88.4 | 1620.1 | 75.8 | 1402.7 | 65.7 | 951.1 | 86.8 | 748.5 | 68.5 | 632.7 | 50.8 |
| Advanced SS | 0.0 | 0.0 | 27.8 | 1.3 | 63.5 | 3.0 | 0.0 | 0.0 | 14.7 | 1.3 | 55.3 | 4.4 |
| Initial SS | 34.4 | 1.6 | 151.8 | 7.1 | 224.5 | 10.5 | 16.1 | 1.5 | 71.9 | 6.6 | 154.6 | 12.4 |
| Pasture | 121.0 | 5.7 | 169.0 | 7.9 | 208.8 | 9.8 | 71.7 | 6.5 | 137.3 | 12.6 | 230.2 | 18.5 |
| Agriculture | 20.8 | 1.0 | 83.9 | 3.9 | 152.1 | 7.1 | 35.6 | 3.2 | 64.7 | 5.9 | 129.1 | 10.3 |
| Bareland | 37.4 | 1.8 | 44.0 | 2.1 | 44.8 | 2.1 | 10.2 | 0.9 | 43.5 | 4.0 | 31.4 | 2.5 |
| Infrastructure | 26.0 | 1.2 | 26.9 | 1.3 | 28.1 | 1.3 | 9.4 | 0.9 | 11.1 | 1.0 | 11.2 | 0.9 |
| Water | 7.9 | 0.4 | 12.8 | 0.6 | 11.9 | 0.6 | 1.2 | 0.1 | 1.4 | 0.1 | 2.0 | 0.2 |
| Total | 2127.0 | 100.0 | 2136.4 | 100.0 | 2136.4 | 100.0 | 1095.5 | 100.0 | 1093.2 | 100.0 | 1246.5 | 100.0 |

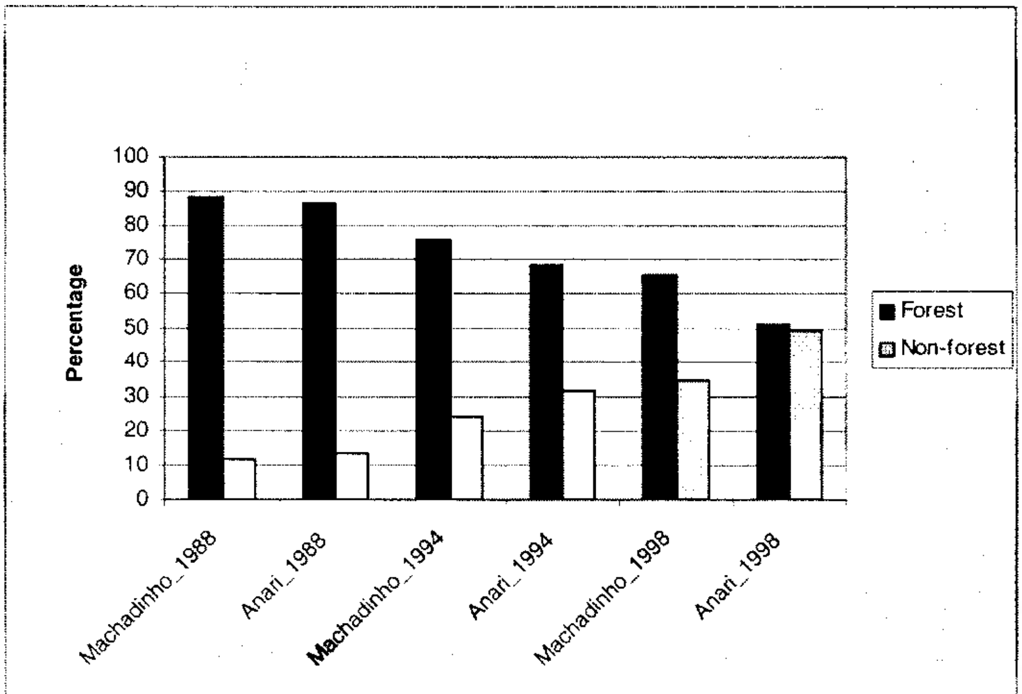



Figure 52 - Percentage of forest and non-forest in Machadinho d'Oeste and Vale do Anari in 1988, 1994, and 1998

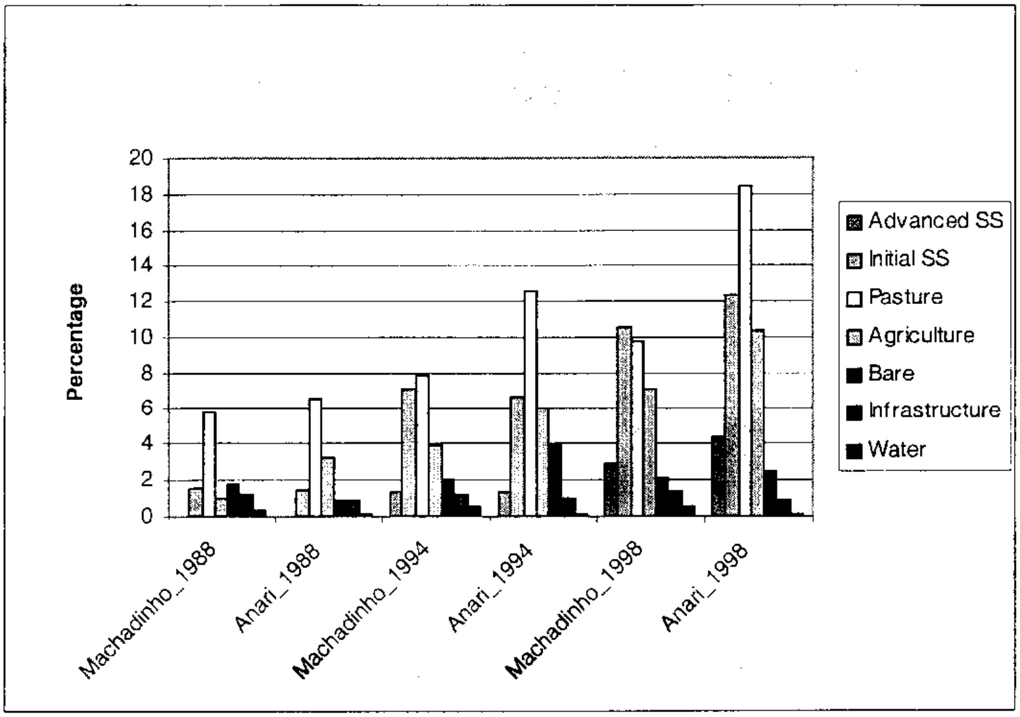



Figure 53 - Percentage of non-forest classes in Machadinho d'Oeste and Vale do Anari in 1988, 1994, and 1998

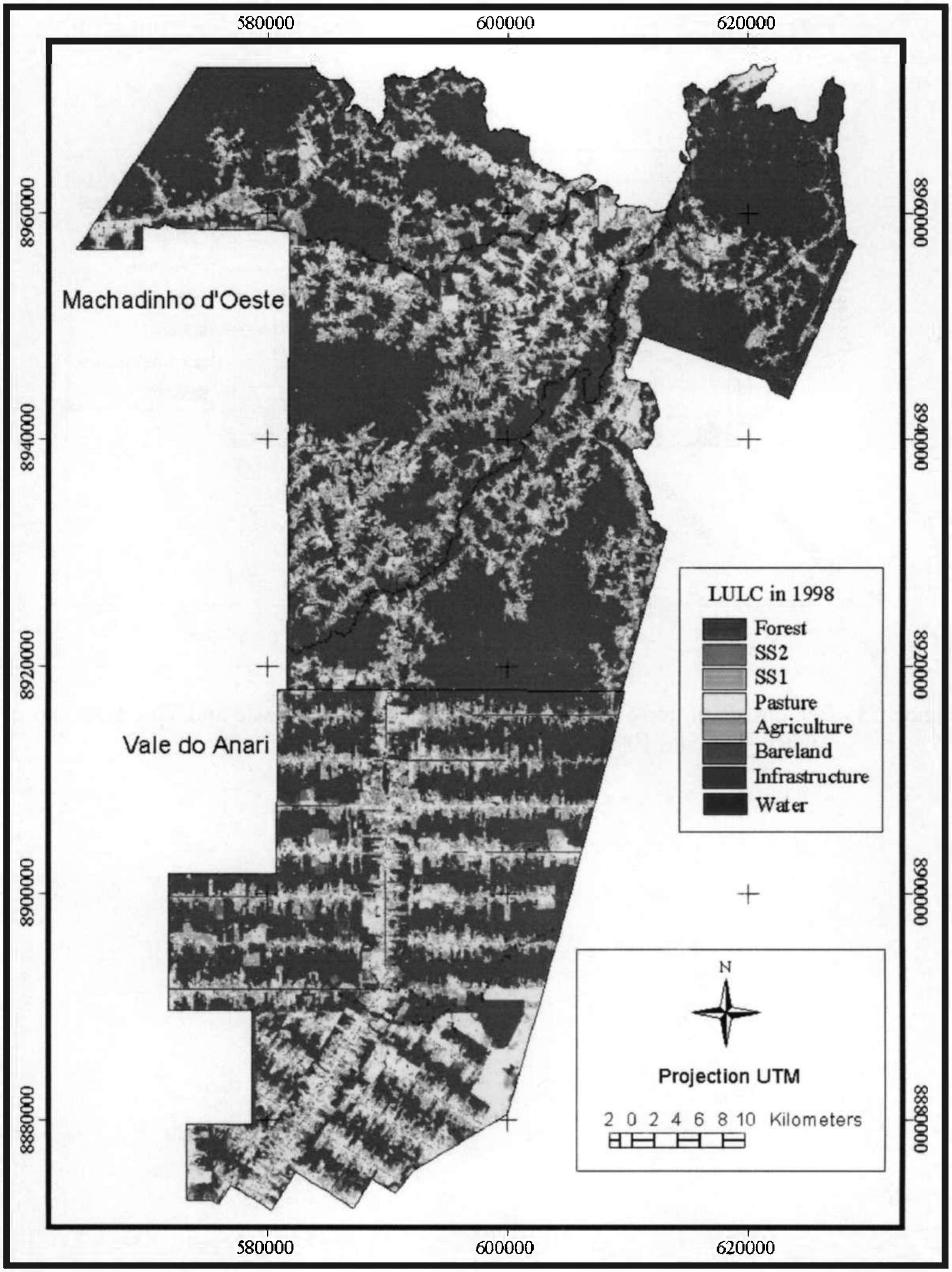



Figure 54 - Machadinho d'Oeste and Vale do Anari – Land Use/Land Cover in 1998

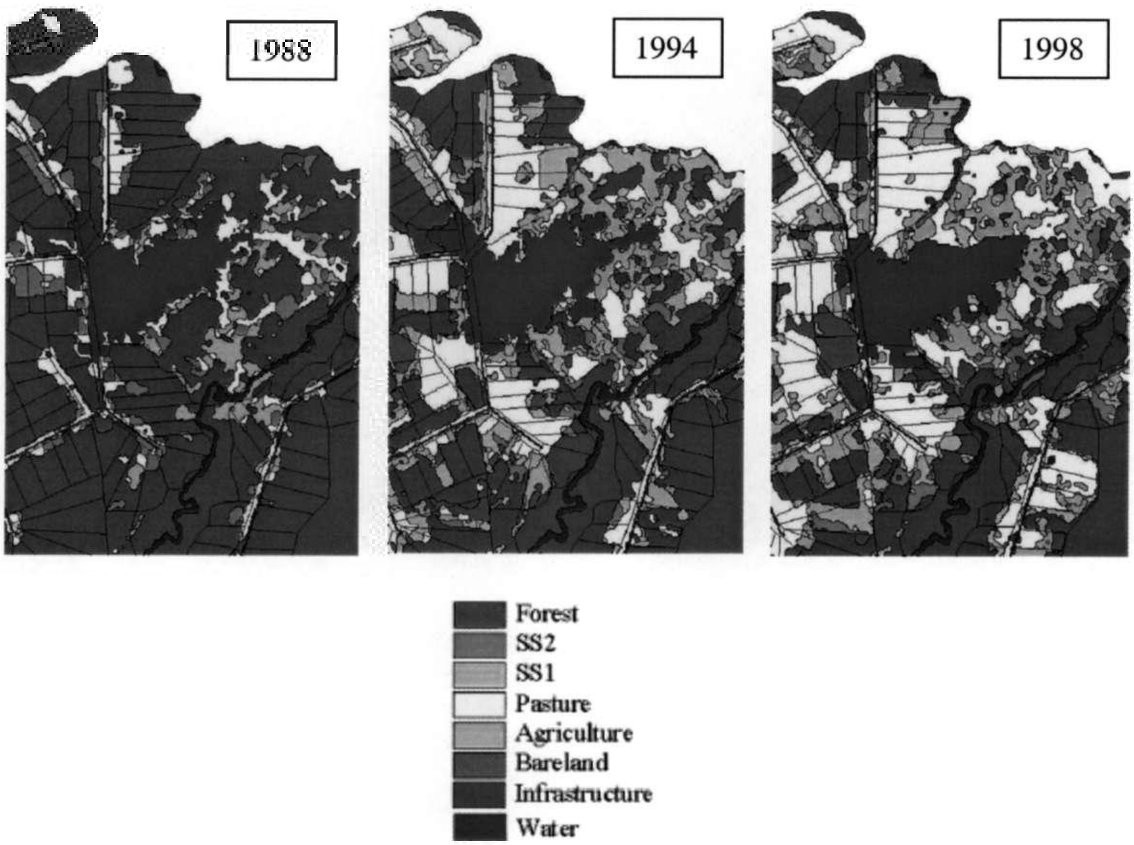



Figure 55 - Pasture conversion in peri-urban areas of Machadinho d'Oeste

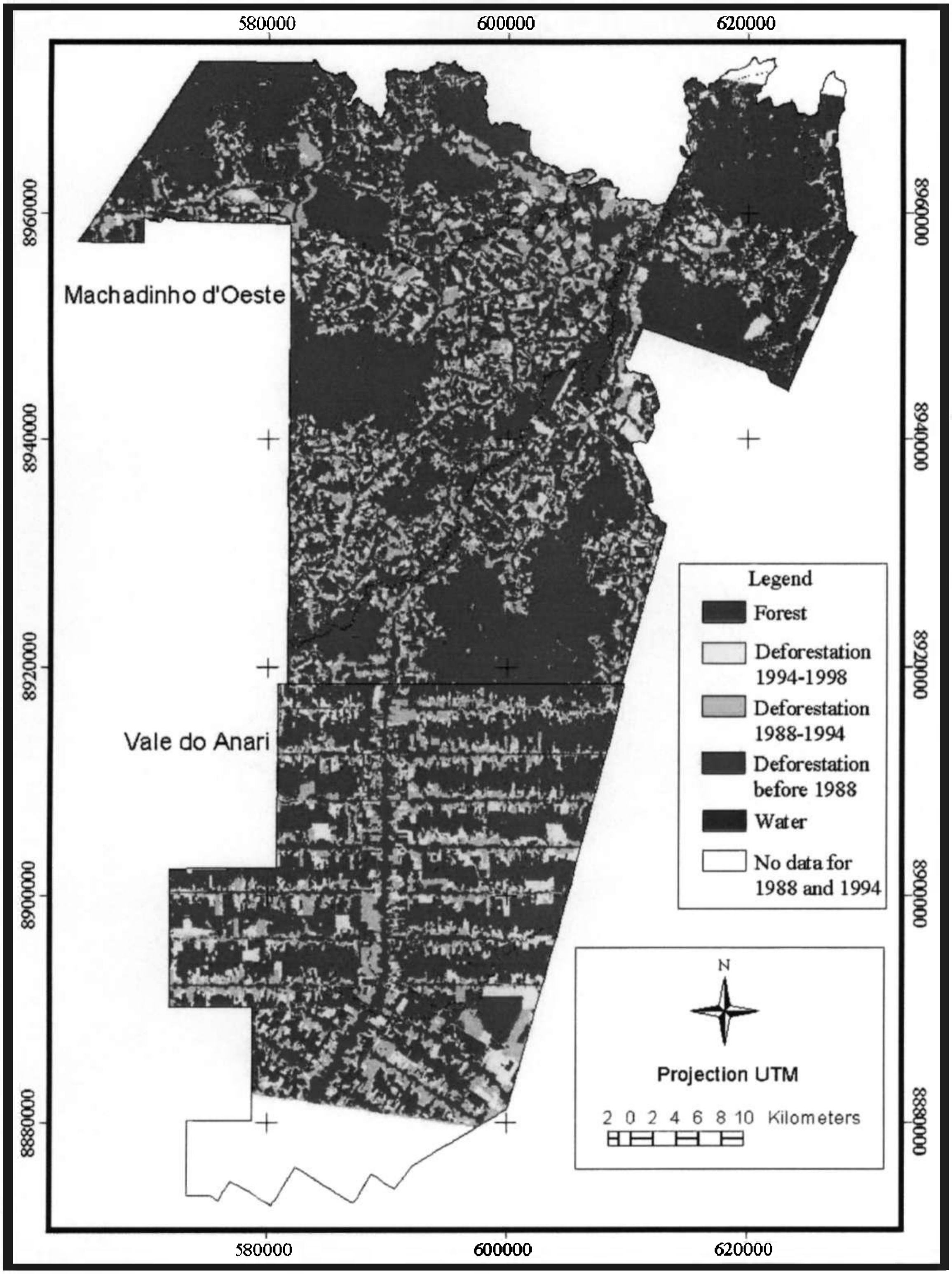
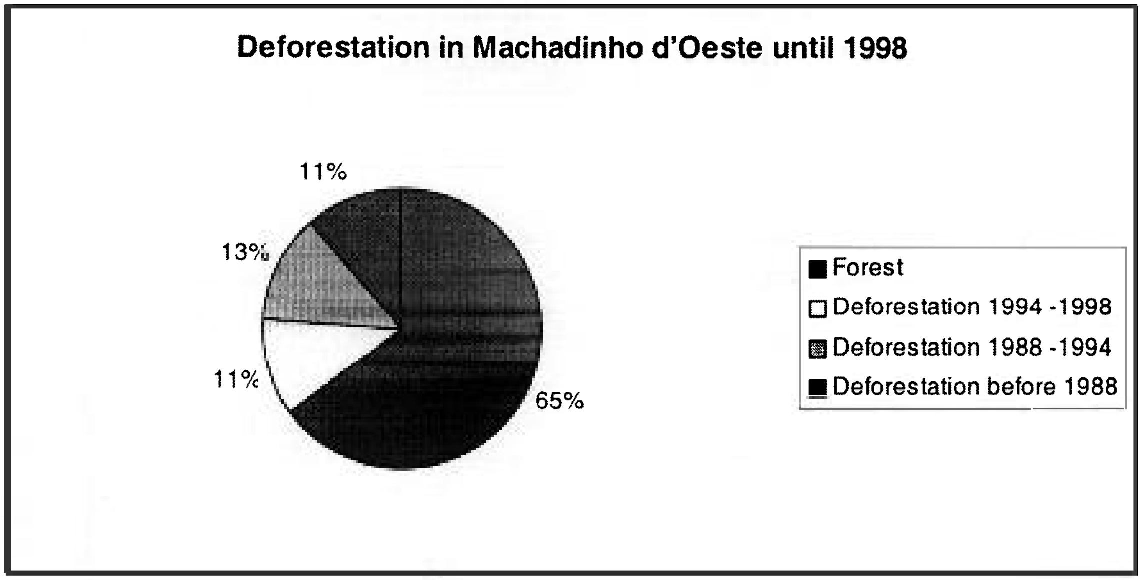



Figure 56 - Machadinho d'Oeste and Vale do Anari – Deforestation until 1998



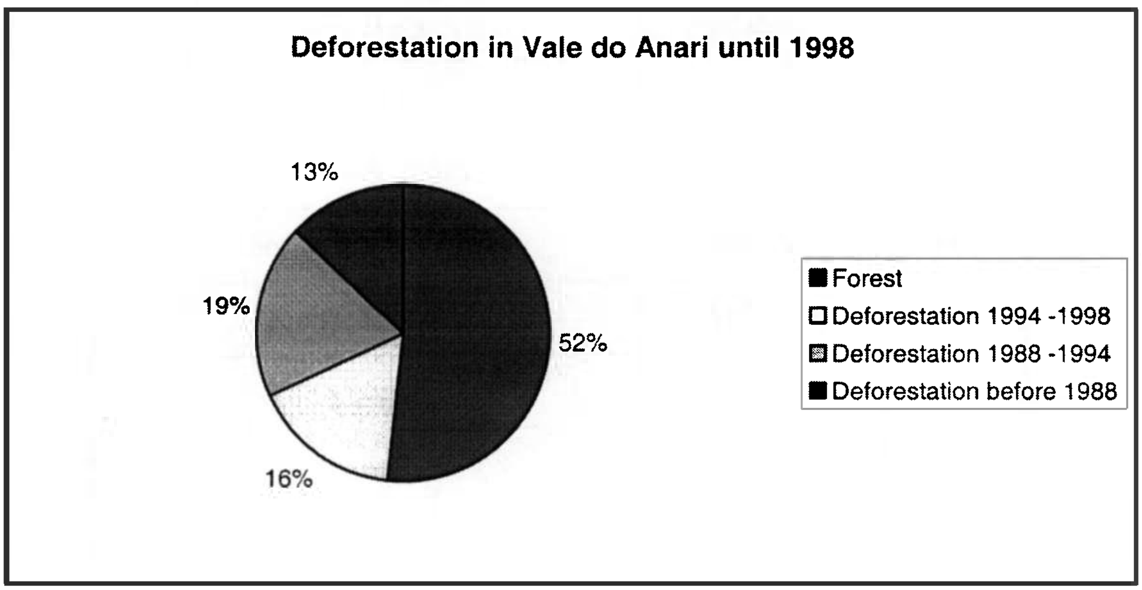




Figure 57 - Percentages of classes of deforestation and forest in Machadinho d'Oeste and Vale do Anari until 1998

Table 15 - Definition of transition classes for production and secondary succession in Machadinho d'Oeste and Vale do Anari

| TRANSITION CLASS | CLASSES IN 1988 – 1994 - 1998 |
|---|---|
| **Forest since 1988** | F - F - F |
| **SS since 1988** | SS - SS - SS |
| **Long Fallow Cycle** | F - SS - SS or F |
| | SS - SS - Prod |
| | Prod - SS - SS or F |
| **Short Fallow Cycle** | F - SS - Prod |
| | SS - Prod - SS |
| | Prod - SS - Prod |
| **Recent Abandonment (SS in 1998 only)** | F - F - SS |
| | F - Prod - SS |
| | Prod - Prod - SS |
| **Production since 1988** | Prod - Prod - Prod |
| **Production since 1994** | F - Prod - Prod |
| | SS - Prod - Prod |
| **Recent Clearing (Production in 1998 only)** | F - F - Prod |
| **Others** | Infrastructure and water |

F = Forest; SS = Secondary Succession; Prod = Production

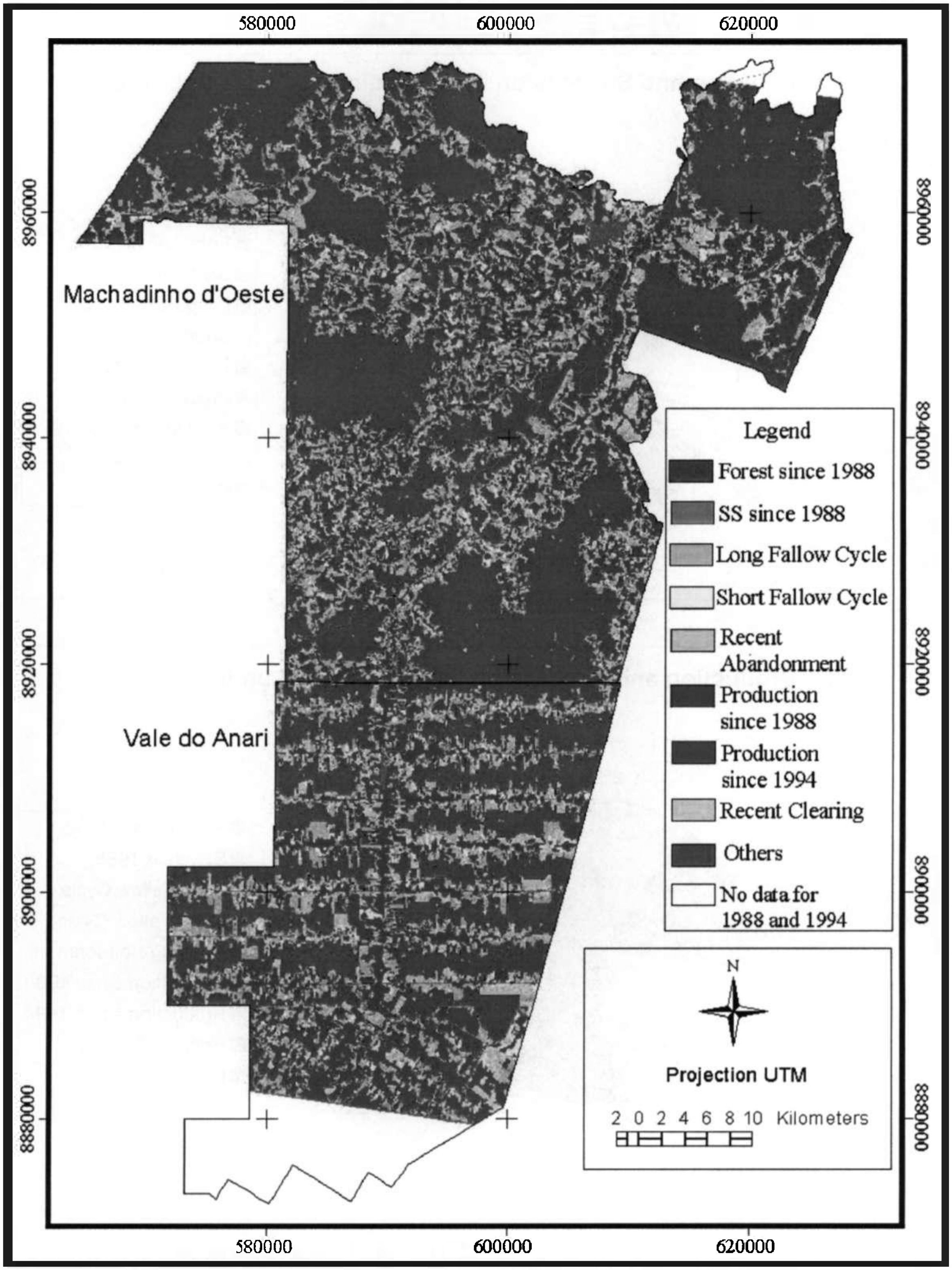
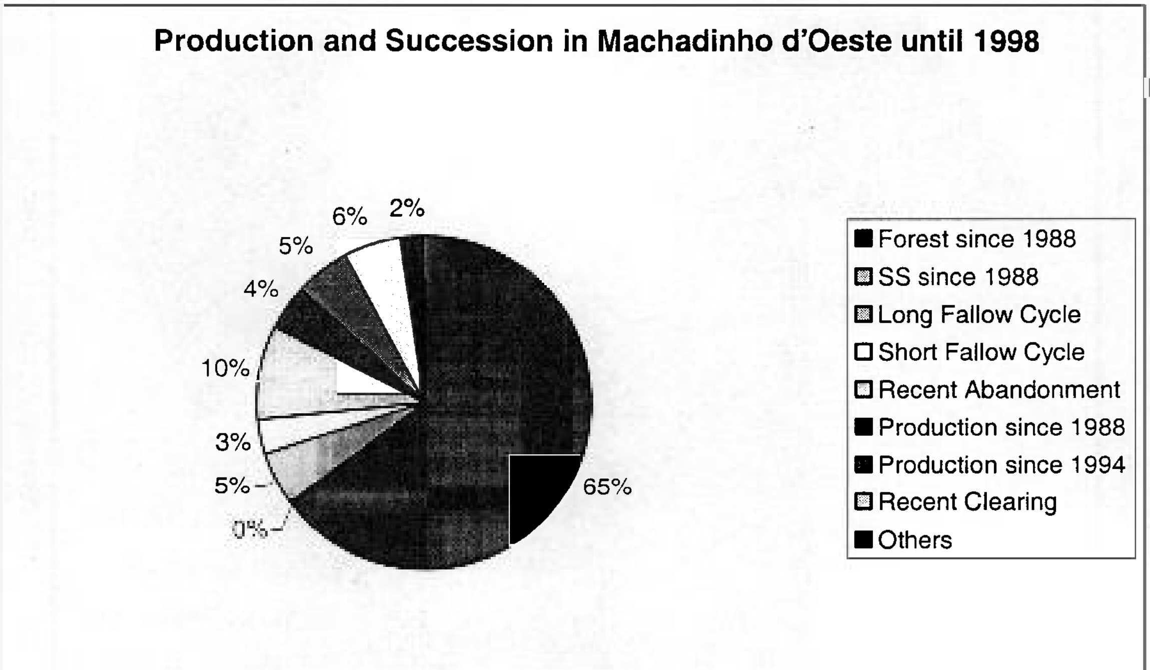



Figure 58 - Machadinho d'Oeste and Vale do Anari – Production and secondary succession until 1998



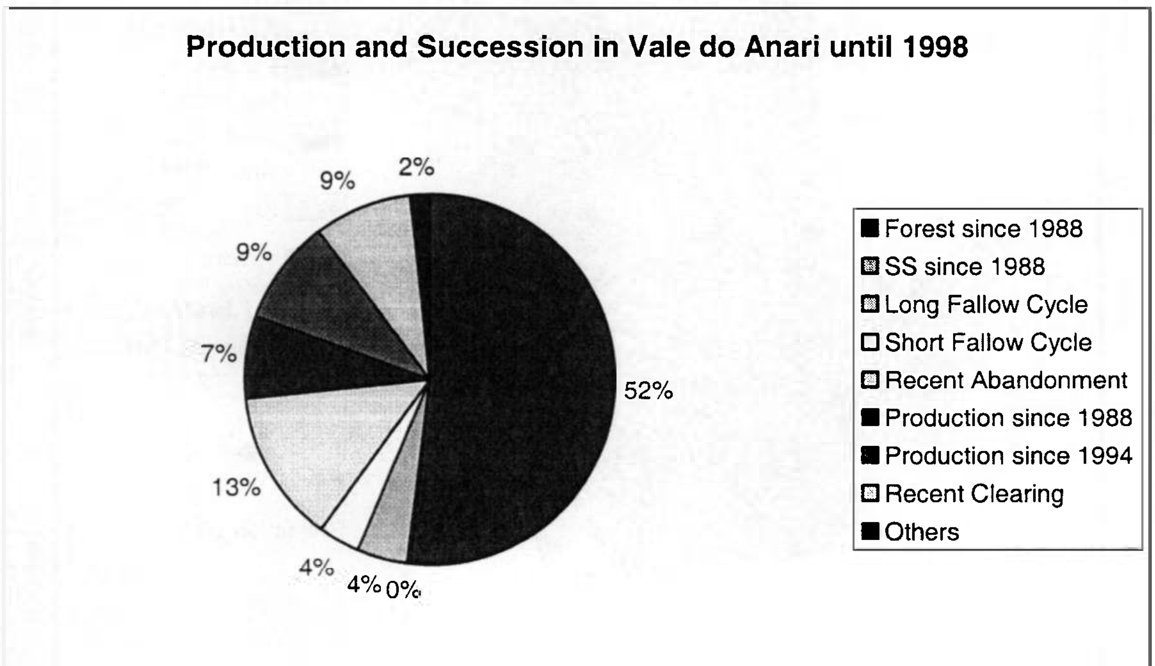




Figure 59 - Percentages of classes of production and secondary succession in Machadinho d'Oeste and Vale do Anari until 1998

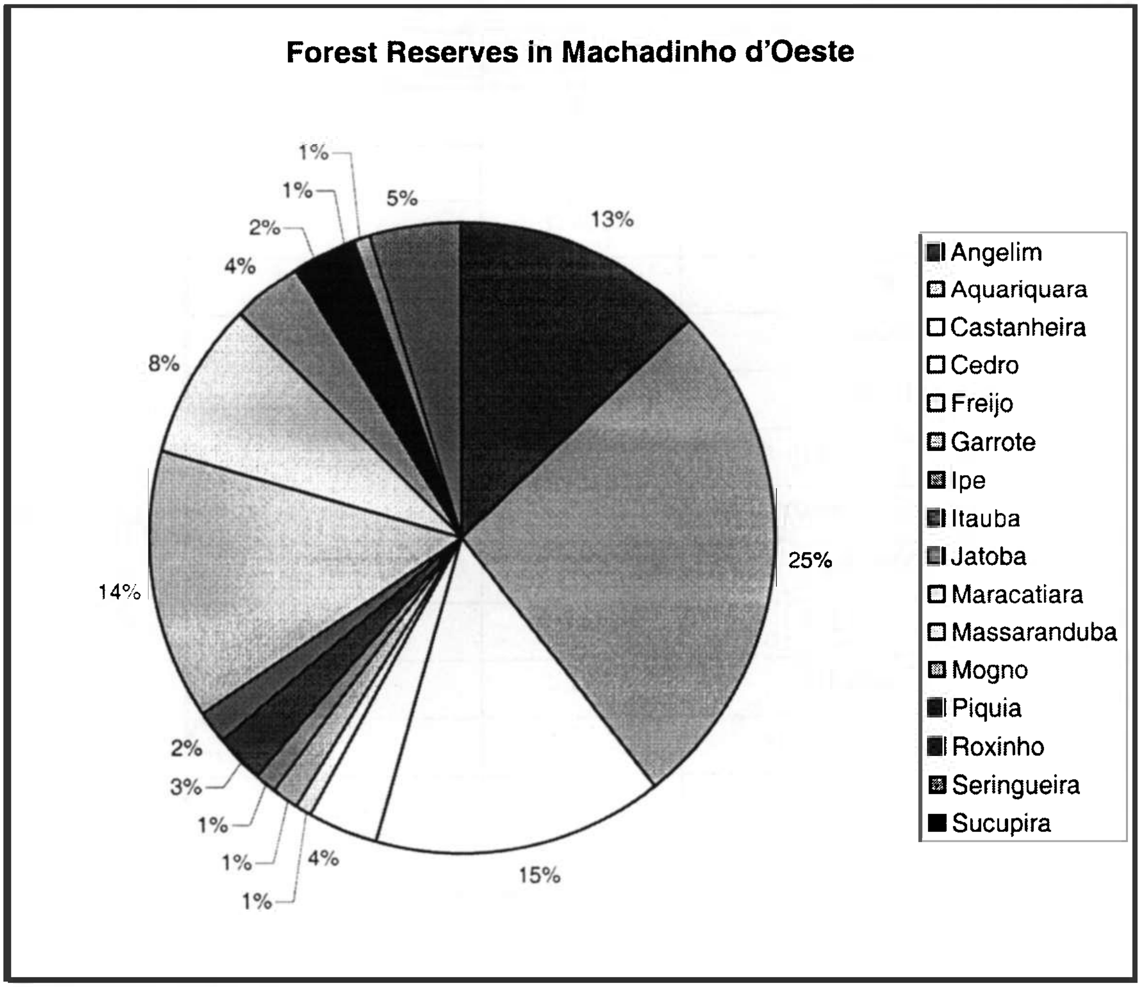



Figure 60 - Percentages of each forest reserve in relation to the total area of reserves in Machadinho d'Oeste

Table 16 - Forest reserves in Machadinho d'Oeste

| RESERVES | AREA (ha) | POPULATION |
|---|---|---|
| **Angelim** | 8923.2 | 10 |
| **Aquariquara** | 18100.0 | 181 |
| **Castanheira** | 10200.0 | 27 |
| **Cedro** | 2566.7 | -- |
| **Freijó** | 600.4 | 4 |
| **Garrote** | 802.5 | 9 |
| **Ipê** | 815.5 | 28 |
| **Itaúba** | 1758.1 | 13 |
| **Jatobá** | 1135.2 | 3 |
| **Maracatiara** | 9503.1 | 66 |
| **Massaranduba** | 5566.2 | 18 |
| **Mogno** | 2450.1 | 13 |
| **Piquiá** | 1448.9 | 16 |
| **Roxinho** | 882.2 | 9 |
| **Seringueira** | 537.5 | 4 |
| **Sucupira** | 3188.0 | -- |
| **Total** | 68477.6 | 401 |

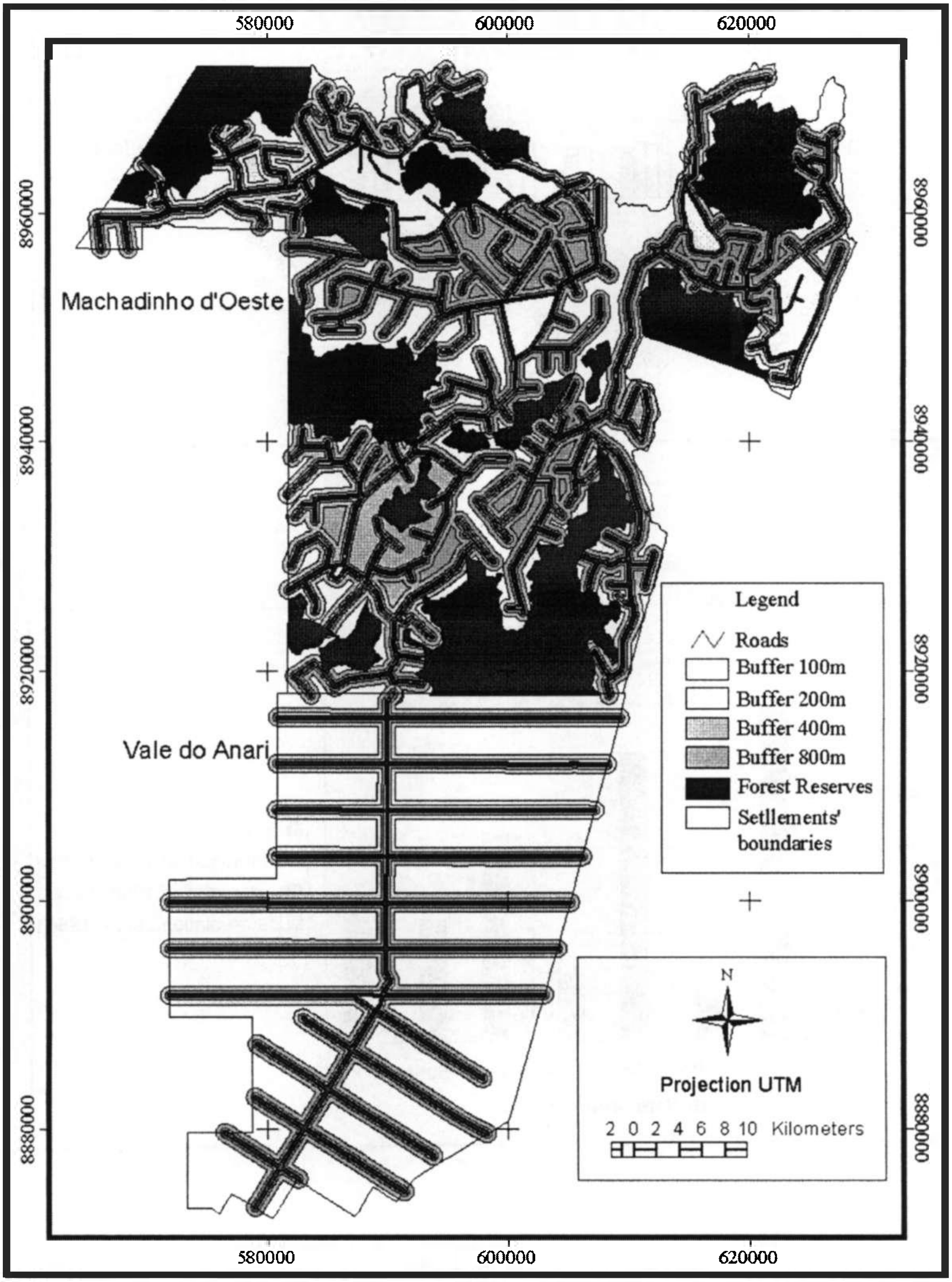
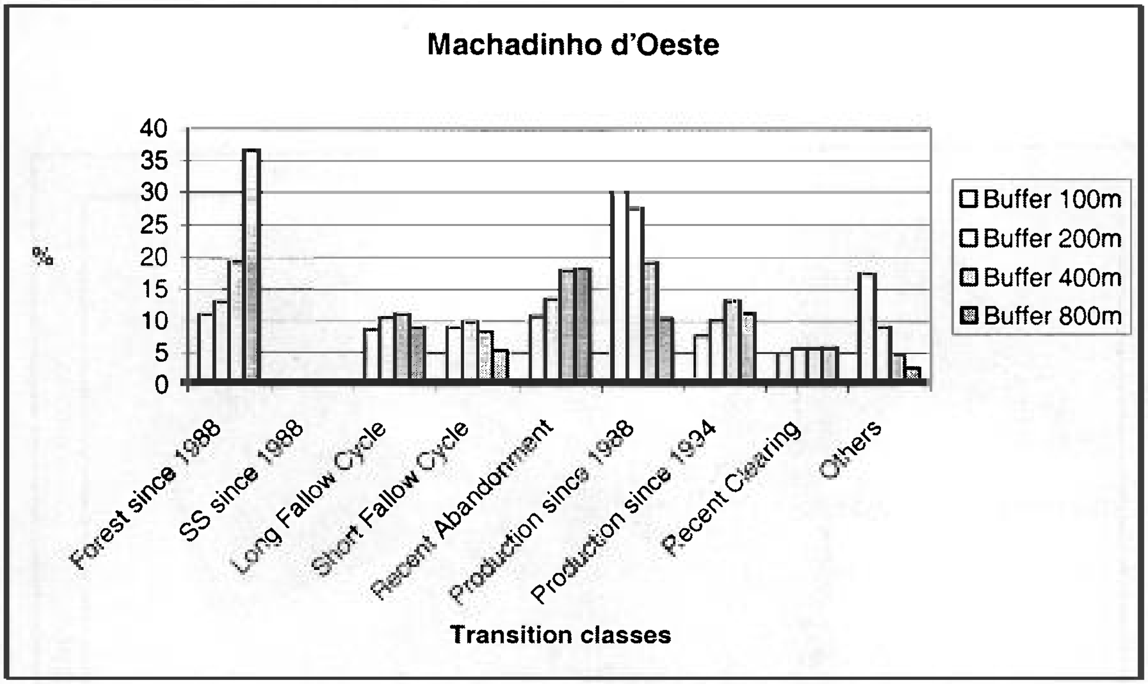



Figure 61 - Machadinho d'Oeste and Vale do Anari – buffers around roads



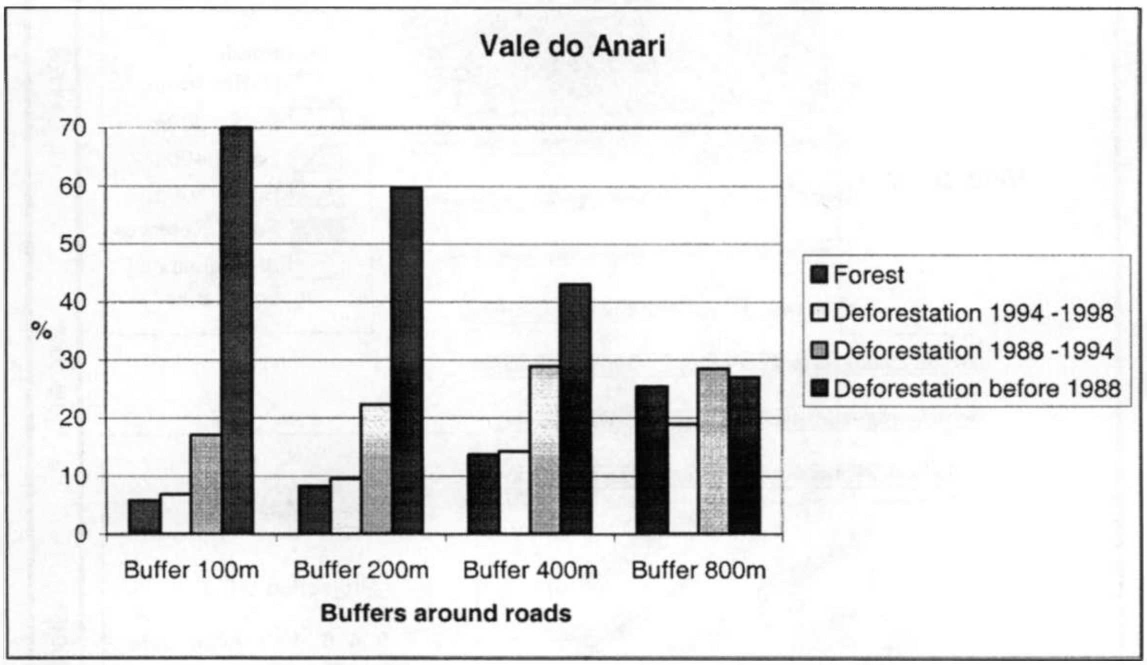
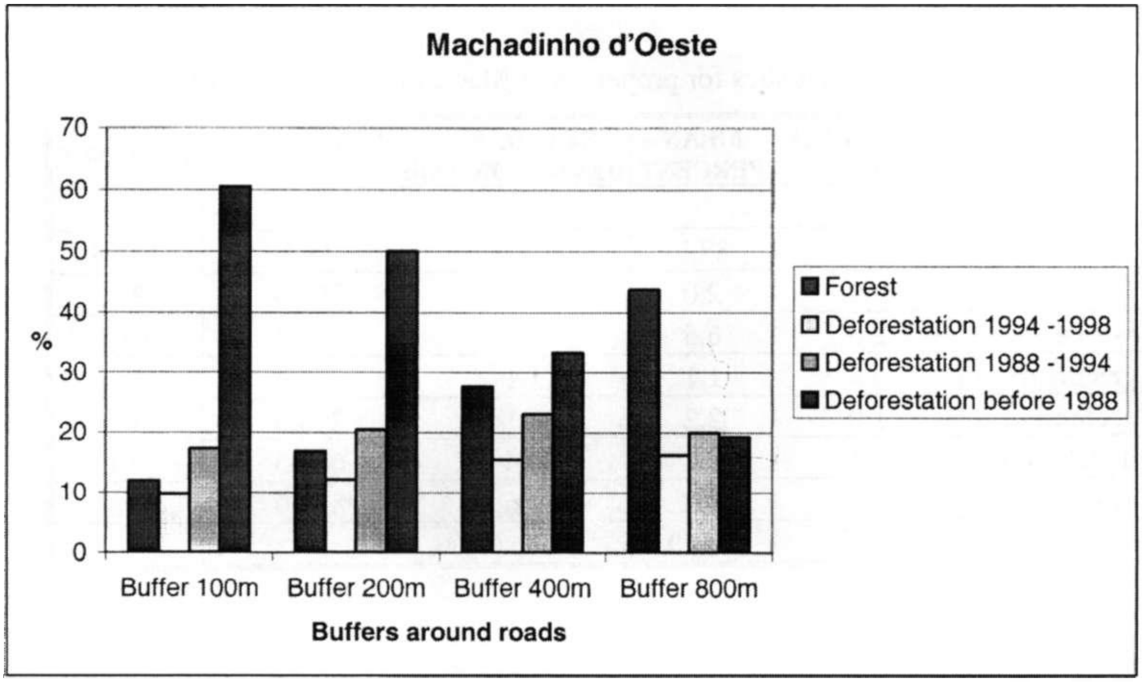




Figure 62 - The route of deforestation around roads in Machadinho d'Oeste and Vale do Anari until 1998



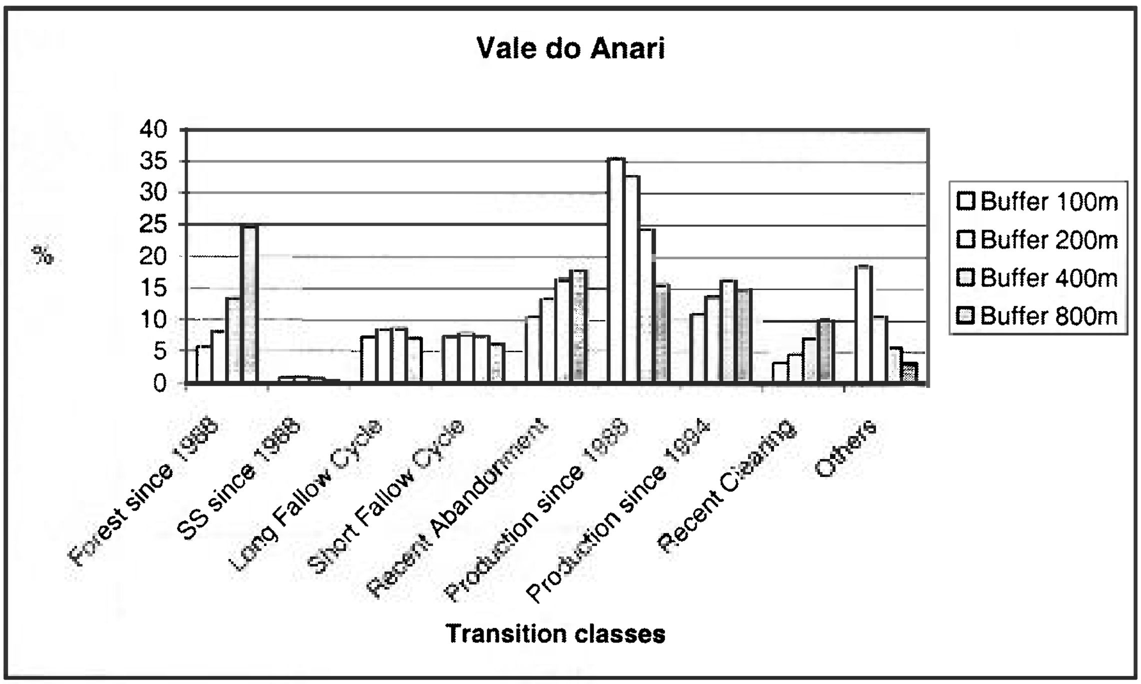




Figure 63 - Production and secondary succession around roads in Machadinho d'Oeste and Vale do Anari until 1998

Table 17 - LULC statistics for properties of Machadinho d'Oeste in 1988

| | MEAN AREA (ha) | MEAN PERCENT | STANDARD DEVIATION (ha) | STANDARD DEVIATION (%) | VARIANCE |
|---|---|---|---|---|---|
| | | | | | |
| **Forest** | 38.5 | 87.9 | 13.5 | 35.2 | 183.3 |
| **SS1** | 0.9 | 2.0 | 1.8 | 200.0 | 3.1 |
| **Pasture** | 2.8 | 6.5 | 3.3 | 116.3 | 10.8 |
| **Agriculture** | 0.5 | 1.1 | 1.1 | 232.4 | 1.2 |
| **Bareland** | 1.0 | 2.2 | 2.1 | 218.5 | 4.5 |
| **Infrastructure** | 0.1 | 0.1 | 0.4 | 684.5 | 0.1 |
| **Water** | 0.1 | 0.2 | 0.6 | 811.0 | 0.3 |
| **Total** | 43.8 | 100.0 | | | |

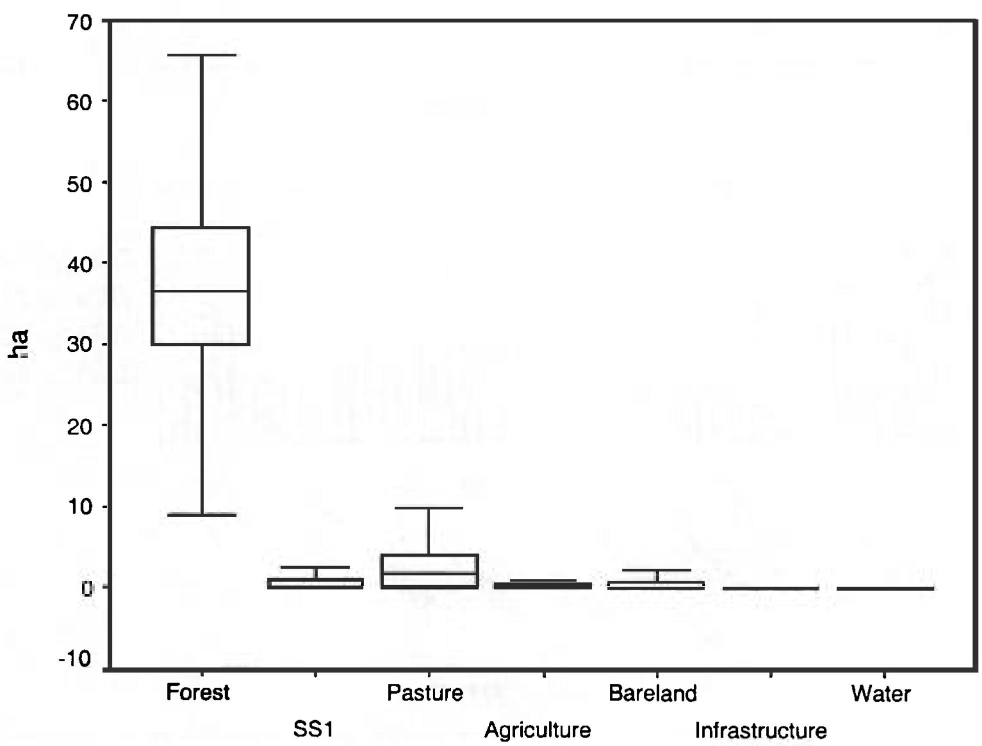



Figure 64 - LULC boxplots for properties of Machadinho d'Oeste in 1988

Table 18 - LULC statistics for properties of Machadinho d'Oeste in 1994

| | MEAN AREA (ha) | MEAN PERCENT | STANDARD DEVIATION (ha) | STANDARD DEVIATION (%) | VARIANCE |
|---|---|---|---|---|---|
| | | | | | |
| **Forest** | 30.4 | 69.5 | 14.7 | 48.4 | 217.4 |
| **SS2** | 0.8 | 1.7 | 1.4 | 183.1 | 1.9 |
| **SS1** | 4.3 | 9.8 | 5.1 | 120.2 | 26.5 |
| **Pasture** | 4.5 | 10.4 | 6.9 | 151.2 | 47.0 |
| **Agriculture** | 2.3 | 5.2 | 3.0 | 130.4 | 9.0 |
| **Bareland** | 1.3 | 3.0 | 2.6 | 196.0 | 6.7 |
| **Infrastructure** | 0.1 | 0.2 | 0.6 | 832.8 | 0.3 |
| **Water** | 0.1 | 0.2 | 0.7 | 785.5 | 0.5 |
| **Total** | 43.8 | 100.0 | | | |

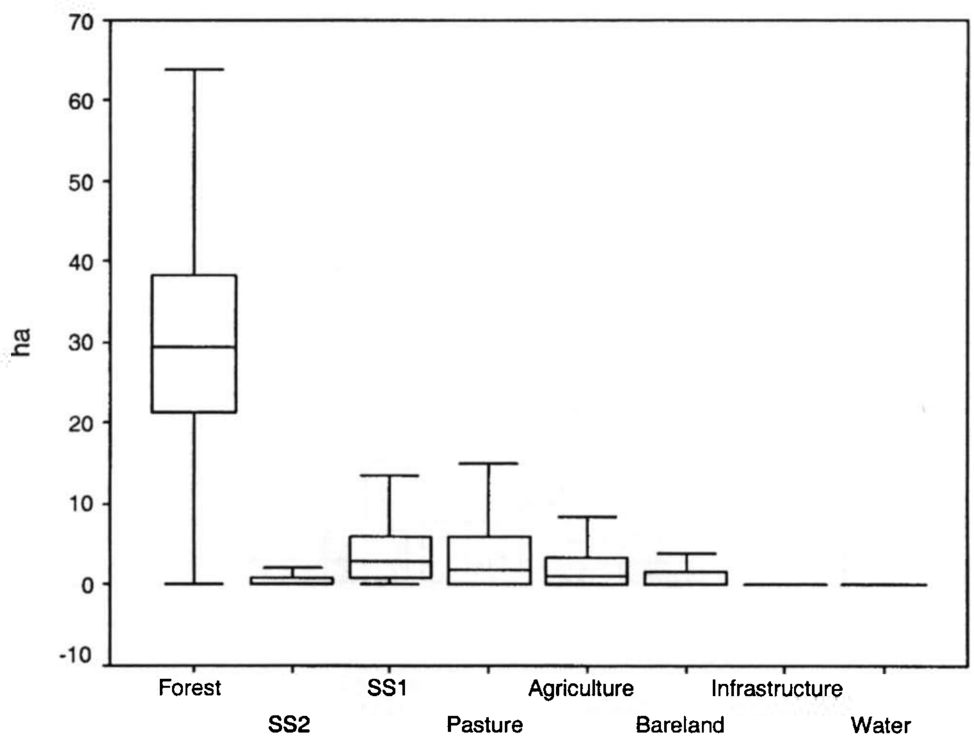



Figure 65 - LULC boxplots for properties of Machadinho d'Oeste in 1994

Table 19 - LULC statistics for properties of Machadinho d'Oeste in 1998

| | MEAN AREA (ha) | MEAN PERCENT | STANDARD DEVIATION (ha) | STANDARD DEVIATION (%) | VARIANCE |
|---|---|---|---|---|---|
| | | | | | |
| **Forest** | 23.5 | 53.8 | 15.2 | 64.5 | 230.2 |
| **SS2** | 1.8 | 4.0 | 2.5 | 139.8 | 6.0 |
| **SS1** | 6.7 | 15.3 | 6.8 | 102.0 | 46.6 |
| **Pasture** | 5.9 | 13.4 | 8.8 | 150.0 | 77.7 |
| **Agriculture** | 4.4 | 10.0 | 5.2 | 117.5 | 26.6 |
| **Bareland** | 1.3 | 3.1 | 3.1 | 229.4 | 9.4 |
| **Infrastructure** | 0.1 | 0.2 | 1.0 | 1451.8 | 1.0 |
| **Water** | 0.1 | 0.3 | 0.7 | 622.2 | 0.5 |
| **Total** | 43.8 | 100.0 | | | |

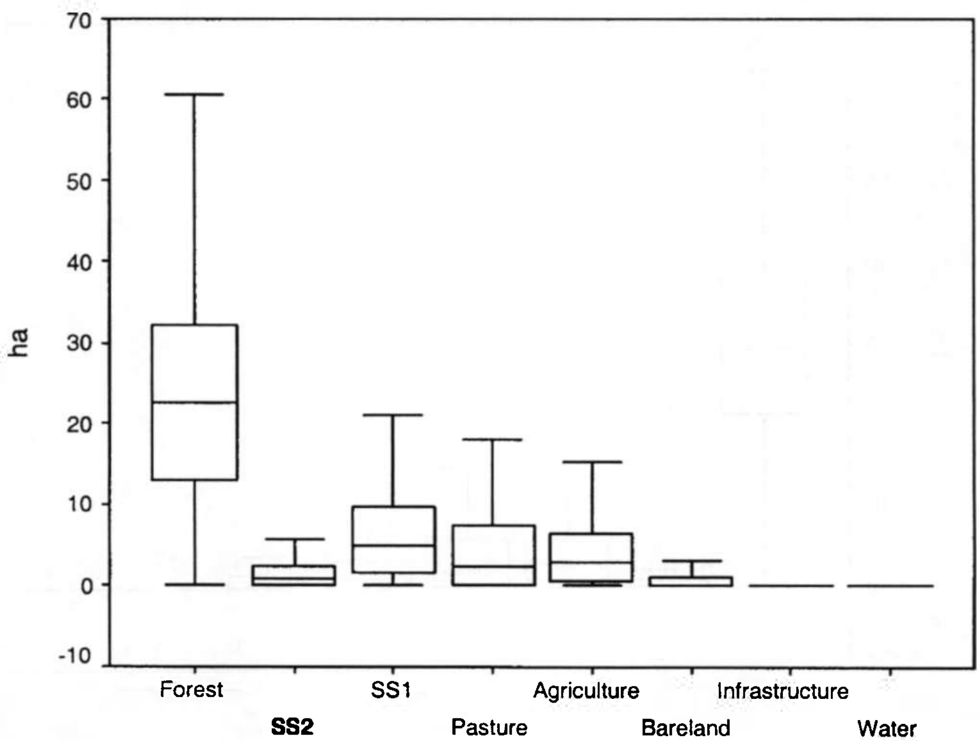



Figure 66 - LULC boxplots for properties of Machadinho d'Oeste in 1998

Table 20 - LULC statistics for properties of Vale do Anari in 1988

| | MEAN AREA (ha) | MEAN PERCENT | STANDARD DEVIATION (ha) | STANDARD DEVIATION (%) | VARIANCE |
|---|---|---|---|---|---|
| | | | | | |
| **Forest** | 44.5 | 89.0 | 7.3 | 16.5 | 53.9 |
| **SS1** | 0.7 | 1.3 | 1.5 | 224.8 | 2.1 |
| **Pasture** | 2.8 | 5.6 | 4.0 | 141.7 | 15.9 |
| **Agriculture** | 1.4 | 2.7 | 2.1 | 153.5 | 4.4 |
| **Bareland** | 0.4 | 0.8 | 1.2 | 299.3 | 1.5 |
| **Infrastructure** | 0.2 | 0.4 | 0.5 | 245.0 | 0.2 |
| **Water** | 0.1 | 0.1 | 0.3 | 539.1 | 0.1 |
| **Total** | 50.0 | 100.0 | | | |

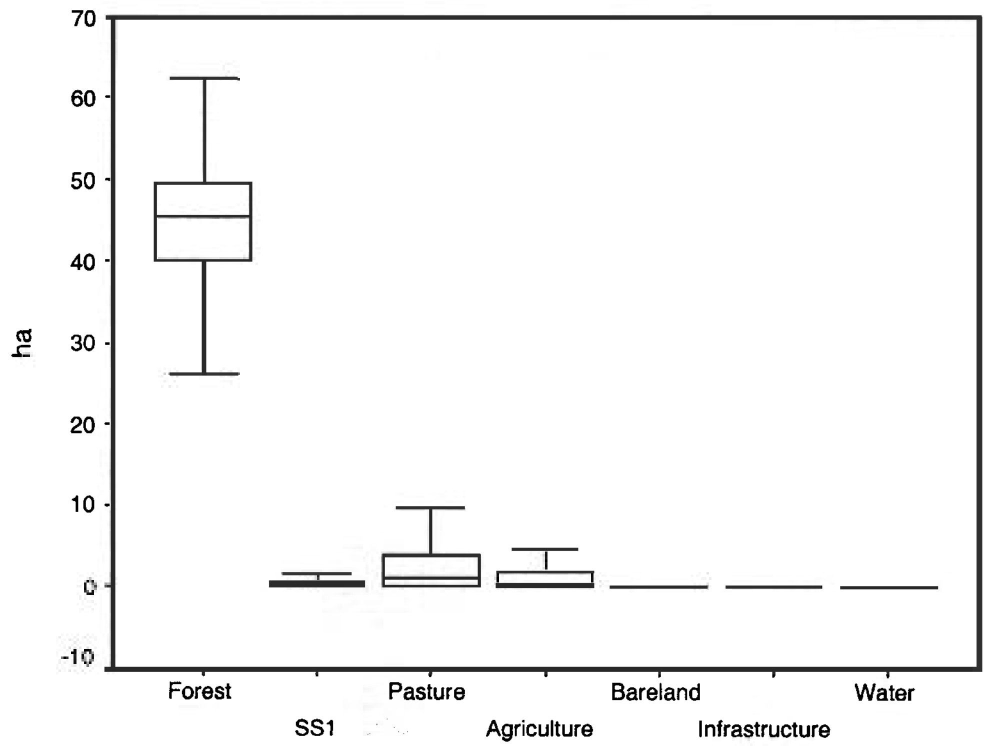



Figure 67 - LULC boxplots for properties of Vale do Anari in 1988

Table 21 - LULC statistics for properties of Vale do Anari in 1994

| | MEAN AREA (ha) | MEAN PERCENT | STANDARD DEVIATION (ha) | STANDARD DEVIATION (%) | VARIANCE |
|---|---|---|---|---|---|
| | | | | | |
| **Forest** | 35.9 | 71.7 | 11.4 | 31.8 | 130.6 |
| **SS2** | 0.6 | 1.3 | 1.1 | 174.4 | 1.3 |
| **SS1** | 3.2 | 6.3 | 4.1 | 128.5 | 16.5 |
| **Pasture** | 5.4 | 10.8 | 7.0 | 130.3 | 49.3 |
| **Agriculture** | 2.8 | 5.5 | 3.5 | 127.6 | 12.5 |
| **Bareland** | 1.9 | 3.8 | 3.6 | 189.0 | 12.9 |
| **Infrastructure** | 0.2 | 0.4 | 0.5 | 244.7 | 0.2 |
| **Water** | 0.1 | 0.2 | 0.5 | 538.1 | 0.2 |
| **Total** | 50.0 | 100.0 | | | |

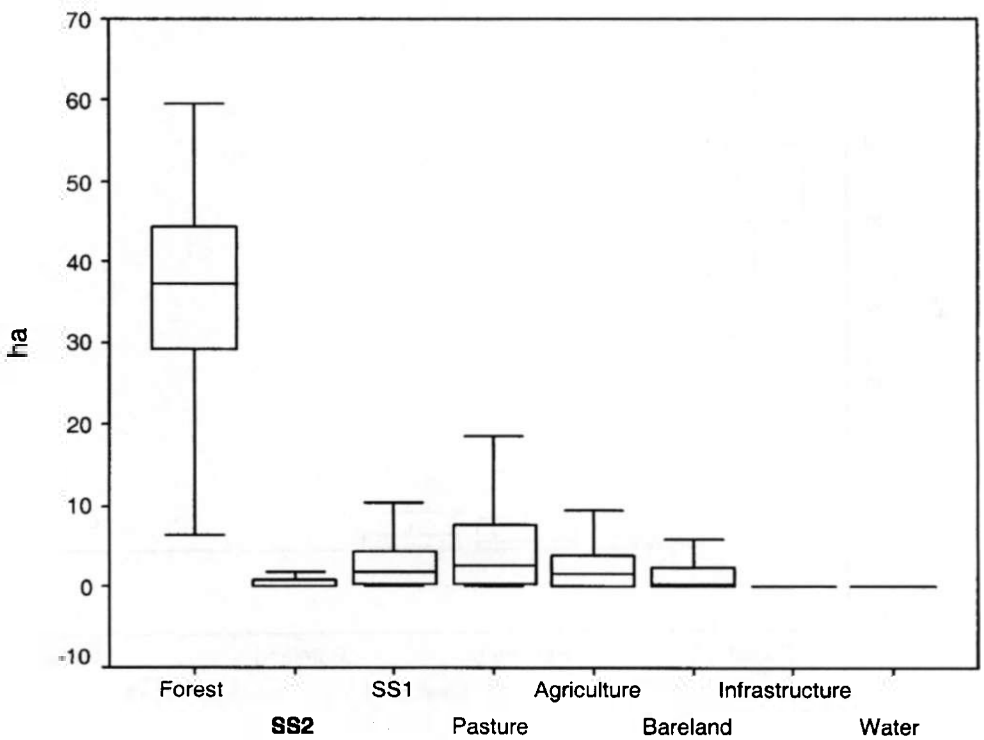



Figure 68 - LULC boxplots for properties of Vale do Anari in 1994

Table 22 - LULC statistics for properties of Vale do Anari in 1998

| | MEAN AREA (ha) | MEAN PERCENT | STANDARD DEVIATION (ha) | STANDARD DEVIATION (%) | VARIANCE |
|---|---|---|---|---|---|
| | | | | | |
| **Forest** | 27.1 | 53.6 | 12.6 | 46.6 | 159.5 |
| **SS2** | 2.3 | 4.5 | 3.1 | 136.6 | 9.6 |
| **SS1** | 6.3 | 12.5 | 6.1 | 95.7 | 36.8 |
| **Pasture** | 8.1 | 16.0 | 9.4 | 116.1 | 87.8 |
| **Agriculture** | 5.2 | 10.3 | 5.0 | 96.5 | 25.4 |
| **Bareland** | 1.3 | 2.5 | 2.8 | 214.0 | 7.6 |
| **Infrastructure** | 0.2 | 0.3 | 0.5 | 279.2 | 0.2 |
| **Water** | 0.1 | 0.2 | 0.4 | 459.0 | 0.1 |
| **Total** | 50.0 | 100.0 | | | |

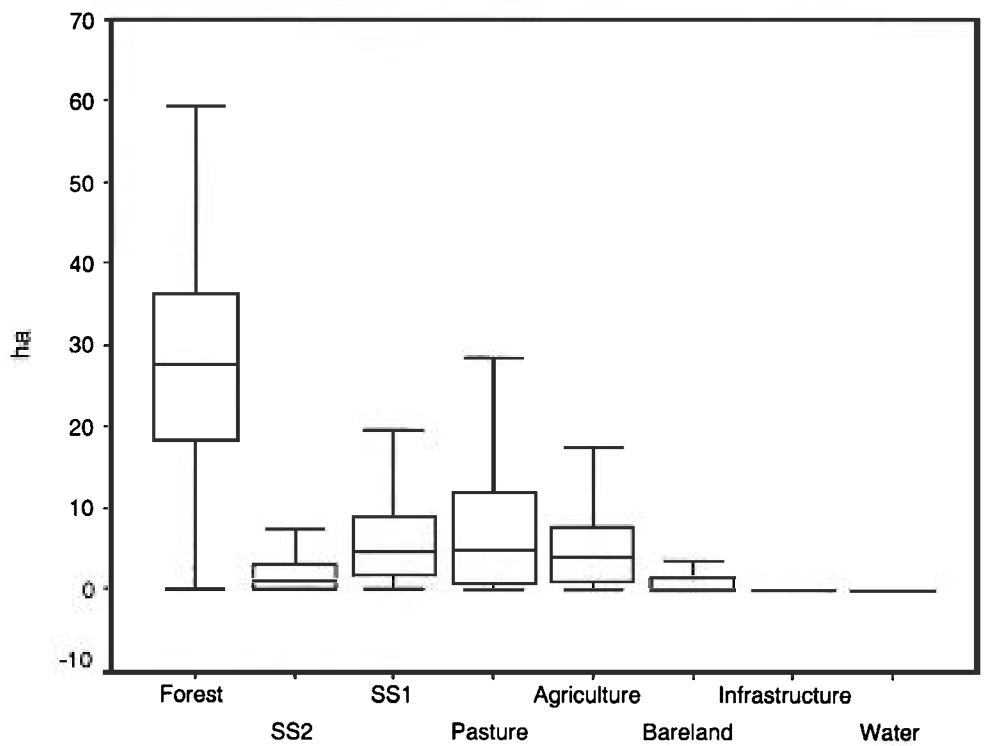



Figure 69 - LULC boxplots for properties of Vale do Anari in 1998

Table 23 - Rates of deforestation in Machadinho d'Oeste and Vale do Anari until 1998

| Deforestation | MACHADINHO D'OESTE | | VALE DO ANARI | |
|---|---|---|---|---|
| | % per year | ha/year | % per year | ha/year |
| **Before 1988** | 2.4 | 1.1 | 1.6 | 0.8 |
| **1988 - 1994** | 3.1 | 1.3 | 2.9 | 1.4 |
| **1994 - 1998** | 3.9 | 1.7 | 4.5 | 2.2 |

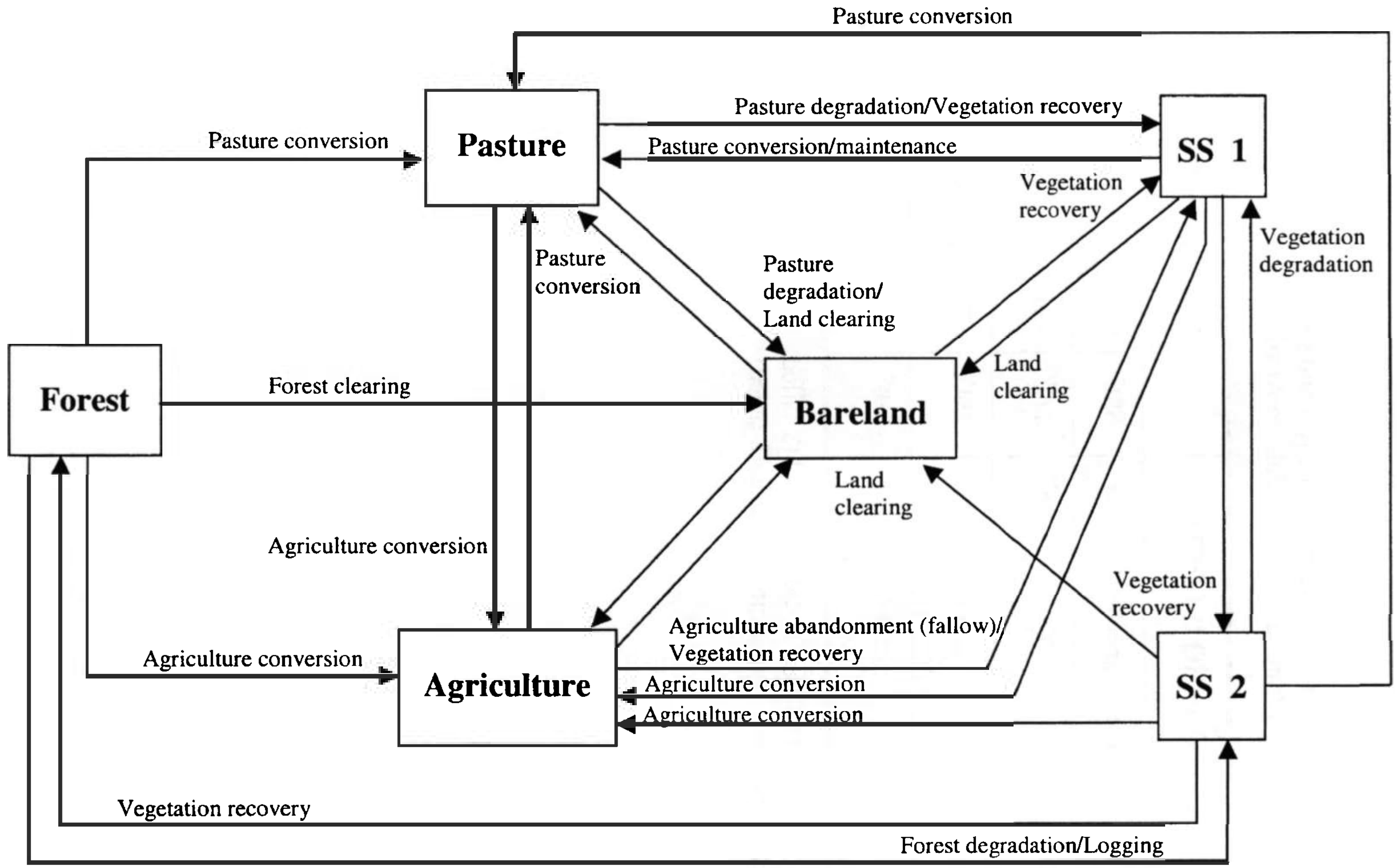



Figure 70 - Trajectories of Land Use/Land Cover in Machadinho d'Oeste and Vale do Anari until 1998

Table 24 - Pearson correlation between forest cover and selected LULC classes in farm lots of Machadinho d'Oeste and Vale do Anari

| | MACHADINHO D'OESTE | | | | VALE DO ANARI | | | |
|---|---|---|---|---|---|---|---|---|
| | SS1 | Pasture | Agriculture | Bare | SS1 | Pasture | Agriculture | Bare |
| 1988 | -.039* | -.182** | -.077** | -.126** | -.179** | -.618** | -.390** | -.274** |
| 1994 | -.225** | -.425** | -.271** | -.172** | -.384** | -.700** | -.499** | -.394** |
| 1998 | -.239** | -.434** | -.280** | -.160** | -.388** | -.626** | -.367** | -.131** |

** Correlation is significant at the 0.01 level (2-tailed)
* Correlation is significant at the 0.05 level (2-tailed)

# CHAPTER 5

# LANDSCAPE CHANGE DESCRIBED BY SELECTED METRICS

*'Quando eu percebi, isso aqui tava tudo mudado'*

## 5.1 - WHY STUDY LANDSCAPE CHANGE IN RONDÔNIA?

The interest of naturalists and ecologists in landscape spatial patterns is extensive (Urban et al. 1987, Turner et al. *Predicting* 1989). This approach, responsible for an ecological perspective about the geographic space, is today represented by landscape ecology. The term was initially proposed by Troll (1939) and used by Schmithusen (1942) and Neef (1956), among others. The tradition in regional geography and vegetation ecology studies was in the origin of this recent science (Bertrand 1968, Godron et al. 1968, Long 1974, Jurdant et al. 1977). Its historical development was widely reviewed by Naveh (1982) and Naveh and Lieberman (1984).

The concept of landscape was always present in the history of civilization, induced by artistic motivation, as a complementary descriptor on the delimitation of territories. Recently, landscapes became objects of study, analysis, and synthesis, including new perspectives about the distribution of ecological systems. The landscape is no longer considered just 'a portion of the earth surface captured by human eyes' (Amandier 1973). It is now understood as a spatially heterogeneous mosaic (Forman and Godron 1981) to be studied from the reciprocal effects among spatial patterns and ecological processes (Pickett and Cadenasso 1995). Others have emphasized the human dimension underlying landscape outcomes (Naveh and Lieberman 1994). The study of these relations confers a practical dimension to landscape ecology, through the establishment of scientific bases for planning, management, conservation, and development of territories (Leser and Rodd 1991).

Since the expression of such studies is spatially represented, the issue of scale and resolution is central (Allen and Starr 1982, Meentemeyer and Box 1987, Pickett and Candenasso 1995). Recent empirical tests have focused on the role of scale and resolution for understanding relations among patterns and processes of landscape change. Changing spatial resolutions, for instance, may affect our ability to extrapolate information across different scales (Turner and Gardner 1991). Traditionally, many researchers have assumed that ecological processes affecting populations and communities operate at local scales (Dunning et al. 1992). Meanwhile, habitat variations respond to different scales (Wiens 1989), making the problem of spatial dynamics one of the frontiers of ecology (Levin 1992, Kareiva 1994). The current interest in biodiversity, within the landscape context, unites the research on population dynamics and ecological processes (Ricklefs 1987, Norton and Ulanowicz 1992, M. Turner et al. 1995). Perhaps, an important methodological problem for landscape ecological studies may be the difficulty of repeating observations through time and space. For this reason, quantitative approaches, through models of analysis and simulation, still dominate (Sklar and Costanza 1991).

In landscape ecology, the need for studies at multiple scales suggests the use of spatial data analysis (Turner et al. *Predicting* 1989). This has been done through modern approaches to address spatial patterns and ecological processes (Turner et al. *Effects* 1989, Turner 1990, Flamm and Turner 1994, Wickham and Norton 1994). The parallel development of geographic information science (Goodchild 1992) and landscape ecology (Forman and Godron 1986) provides new opportunities for multi-disciplinary studies on ecological modeling of spatial data (Raper and Livingstone 1995). However, the nature of spatial data is diverse and such applications must take the actual nature of the ecological phenomena into account instead of just testing algorithms. Like the 'illusion of objectivity' inherent to analyses of statistical data (Berger and Berry 1988), the analysis of spatial data also includes a variety of pitfalls. However, the need for quantitative methods is an incentive to search for standards. In a world of constant change from global to local scales, it is urgent to overcome the limitations of spatial representations and find better ways to handle their intrinsic problems.

One of the primary steps of spatial analytical initiatives is to identify their underlying assumptions. Frequently, the assumptions are so strong that even the choice of methodological techniques to be used is affected. For example, Anselin (1989) emphasized that the uniqueness of spatial data is expressed by three characteristics. First, it is primarily based on two continuous dimensions (x,y). Second, it presents spatial dependence: 'the propensity for nearby locations to influence each other and to possess similar attributes'. Third, geographical data is distributed over the curved surface of the Earth (from projections to the sphere). The field of geostatistics has followed the assumptions of continuity and spatial dependence (Rossi et al. 1992). It is reasonable to expect such characteristics when dealing with spatial data, until there is a boundary. As human-altered landscapes are full of sharp boundaries (Forman 1997), difficulties have been faced to integrate geostatistics and landscape ecology.

Another relevant issue when dealing with spatial data is that spatial representation can assume multiple forms. Areal data, point data, network data and directional data are the most common ones (Burt and Barber 1996). The purpose of these spatial representations is to mimic a range of phenomena. Thus, examples include land-use/land-cover maps as areal data, vegetation samples as point data, drainage systems as network data, and wind or water flow as directional data.

Several representation techniques have been tested through statistical approaches to allow integration of distinct spatial distributions. Although there are methods to convert data from different spatial representations (e.g., point data into areal data and vice-versa), the procedure is not always recommended. Recently, development efforts are willing to integrate this distinct group of techniques in a more friendly way to handle spatial data (Goodchild et al. 1992, Burrough and Frank 1995). Geostatistics techniques (Issaks and Srivastava 1989), spatial analysis (Burrough 1990, Baker and Cai 1992, Fotheringham and Rogerson 1995, McGarigal and Marks 1995), and GIS capabilities (Burrough and McDonnell 1998, DeMers 2000) have provided new opportunities to explore spatial- and scale-related matters (Withers and Meenteneyer 1999).

The potential of such an integrative approach to handle spatial phenomena for the study of landscapes is promising. However, this functionality is still not implemented in a friendly way that allows a reasonable manipulation of different spatial data representations through complementary techniques. Also, although the integration has been frequently suggested, it is rare to see studies in landscape ecology dealing with point data, for example. This is probably related to the rationale behind the study of landscape structure, based on the concepts of matrix, patch, and corridor (Forman and Godron 1986, Forman 1997). Landscape mosaics imply discreteness of elements and the existence of clear boundaries between neighboring patches (Hansson et al. 1995). Thus, spatial statistics has been used to describe the degree of spatial autocorrelation or spatial dependency between values of a variable that has been sampled at various geographic coordinates, while landscape metrics characterize the geometric and spatial properties of a mosaic of patches (Fortin 1999).

The applicability of these concepts to spatially explicit ecological studies is clear. In a world where human-altered landscapes are increasingly created, processes of disturbance need to be spatially quantified and understood. Disturbance can be defined as any relatively discrete event in time that disrupts the ecosystem, community, or population structure and changes resources, substrate availability, or the physical environment (Pickett and White, 1985). The propagation of disturbance in heterogeneous landscapes depends on the structure of the landscape, as well as on the intensity and frequency of disturbances. M. Turner et al. (1995) highlighted the importance of new conceptual approaches when studying disturbance within landscapes. For instance, a broader view of the equilibrium concept should expect a return to normal dynamics rather than to an artificial 'undisturbed' state. Moreover, as disturbed sites recover deterministically through succession, stability must be assessed through multi-temporal and -spatial approaches, taking into account the scale-dependent nature of concepts of landscape equilibrium (M. Turner et al. 1993).

When studied through the landscape ecology approach, the structure of 'disturbance landscapes' is controlled by characteristics of the disturbance regimes, including the distribution of disturbance sizes and intervals, and the rotation time. In this case, the structure of mosaics of disturbance patches (e.g., patch size and shape) is an important parameter to assess landscape structure (Forman and Godron 1981). Both the number and size of patch births (i.e., patch turnover) govern the response of landscapes to changing disturbance regimes (Baker 1995).

Several methods based on the concept of landscape structure have been developed to address processes of disturbance within landscapes. Landscape metrics have been widely used for this purpose (Baker and Cai 1992). The integration of spatial data in GIS has improved this approach (Haines-Young et al. 1996, Forman 1997, Frohn 1998). Using GIS and landscape metrics to relate disturbance and spatial heterogeneity allows the study of environmental composition and configuration at scales broader than the community or ecosystem (Sample 1994). There are metrics related to landscape composition, referring to features associated with the presence and amount of each patch type within the landscape but without being spatially explicit. Others are related to landscape configuration, referring to the physical distribution or spatial character of patches within the landscape (Burrough 1981, Mandelbrot 1983, McGarigal and Marks 1995).

Perhaps, one of the most frequent examples of landscape disturbance in the tropics is derived from LULC change, particularly forest fragmentation. The process occurs when forested areas are progressively subdivided into smaller and more isolated forest fragments, mainly as a result of human land-use activities. Landscape heterogeneity can either increase or decrease, depending on the parameter and spatial scale examined (Krummel et al. 1987). In general, the disturbed landscape has more small forest patches and fewer large, matrix patches than the intact landscape (Lovejoy et al. 1986, Mladenoff et al. 1993, Malcolm 1994, Lovejoy 1997).

Taking this assertion as a hypothesis, this research examines landscape structure in Rondônia through derived LULC classifications. Machadinho and Anari are analyzed in terms of their composition and configuration in a multi-temporal basis. Results for both sites are compared, trends are described, and methodological issues are discussed.

## 5.2 - CONCEPTUAL AND METHODOLOGICAL APPROACH

The ecological concept of landscape has been extensively discussed. More than trying to coin an ultimate meaning for the term, this research addresses landscape as an interacting mosaic of patches or ecosystems relevant to the phenomenon under consideration (McGarigal and Marks 1995). Building on findings described in the last chapter, LULC change is used as a proxy for landscape transformation to understand how Machadinho and Anari have evolved from little disturbed environments covered by forests to a fragmented mosaic of human-induced agroecosystems.

Three other characteristics define a landscape: its elements are under the influence of the same broad climate, similar geomorphology, and similar disturbances. In addition, landscape structure is defined by the spatial relationships among ecosystems. Landscape function is related to the interactions among the spatial elements (i.e., flows of energy, materials, and species). Landscape change is the alteration in the structure and function of the ecological mosaic over time (Forman and Godron 1986). This chapter does not focus on the function of landscapes or patch mosaics within the study area, although its findings may be used for this purpose. It rather concentrates on the structure of those landscapes and how they have changed since the settlements were implemented in Rondônia. Additionally, this research is not an empirical test about the behavior of metrics measuring landscape structure, but a comparison between agroecological processes and spatial patterns in Machadinho and Anari through the use of quantitative methods. LULC is the most important variable affecting structure, function, and change within landscapes in the study area. Other variables, such as topography and soils were assumed to be similar at the scale of analysis.

After Turner et al. (*Predicting* 1989) and Silbernagel (1997), the following definitions are used. Scale is the temporal or spatial dimension of an object or process, characterized by both grain and extent. Resolution is the precision of measurement (grain size, if spatial). Grain is the finest level of spatial resolution possible with a given data set (pixel size for raster data). Extent is the size of the study area or the duration of time under consideration. These parameters were kept under control to allow the comparative analysis of landscape structure and change in Machadinho and Anari. As presented in Chapter 4, LULC was classified through the lens of Landsat TM images and both settlements are in the same scene. Thus, grain size is equivalent. The extent of each landscape was defined by the settlement boundary, as also mentioned before. The goal of this study is to compare the two different designs of colonization in terms of landscape structure and change: fishbone design encompassing just private properties versus topography-based design including private properties and communal reserves. The next section describes the methods of analysis and data used.

Last but not least, three concepts characterizing landscape structure deserve attention: patch, corridor, and matrix. Their definitions were borrowed from Forman and Godron (1986). Patch is a 'nonlinear surface area differing in appearance from its surroundings' and created by mechanisms involving disturbance, environmental heterogeneity, and human activity. Within the study area, the mosaic of patches evolves and changes according to two major processes: land occupation and secondary succession. Land occupation can generate 'disturbance patches,' for example, by logging or burning. It also creates 'introduced patches,' such as pasture, agriculture, bareland, and built-up land such as urban areas and roads. Succession gives place to 'regenerated patches' according to different stages of vegetation regrowth. Forest and water are what is left from land occupation and succession. The former represents the original landscape matrix and tends to evolve to 'remnant patches' within the settlements. Water is represented by natural lotic environments (i.e., rivers and streams) or manmade lentic environments (i.e., lakes and water ponds). The latter are 'environmental resource patches' but could also be classified as 'disturbance patches,' as they were artificially created. The former are best understood as landscape corridors because of their shape and function.

Corridors are 'narrow strips of land which differ from the matrix on either side'. Roads and watercourses represent landscape corridors within the study area. Roads are 'disturbance corridors' and watercourses are 'environmental resource corridors.' This research does not emphasize the study of landscape corridors, particularly because they represent small portions within the landscapes. However, further studies should investigate the role of corridors as functional elements interfering in LULC change processes.

Matrix is the 'most extensive and most connected landscape element type, and therefore plays the dominant role in the landscape' functioning. Forman and Godron (1986) established three criteria to define a matrix: relative area of landscape element types, level of connectivity present, and degree of control over landscape dynamics. The element type within the landscape with higher values for these three parameters would be the landscape matrix. In the study area, forest could be assumed to be the matrix. It was for sure in early stages of colonization, when a large contiguous forested landscape dominated Machadinho and Anari. After landscape change following colonization and land clearing, forest still has the largest areal extent, but other landscape elements tend to take its place (i.e., succession and production areas, for example). For comparative purposes through this multi-temporal study, forest was treated as another landscape element type composed of patches, instead of being designated as the landscape matrix. Operationally, this decision did not affect measurements of landscape structure although the function of the forest element within the landscape boundaries may have changed. On the other hand, assigning forest as a patch type (class) allowed a useful comparison between processes of fragmentation between the study sites.

Landscape ecologists have recently pointed out the need of new developments and standardization for quantitative analysis of landscapes (Wiens and Moss 1999). With this study in Rondônia, my goal is to contribute to the rain forest fragmentation debate through a better understanding of spatial pattern and process by using a set of comparable metrics.

## 5.3 - DATA AND METHODS

A multi-temporal approach was used to characterize landscape change in Machadinho and Anari in 1988, 1994, and 1998. LULC classifications were similarly recoded for both settlements to facilitate interpretation of landscape pattern and change (Table 25). The recoded classes were based on the main processes occurring in the study area and affecting landscape transformation, that is forest fragmentation through deforestation, vegetation recovery through succession, and land occupation through pasture and agriculture conversion.

The delimitation of landscape boundaries for calculation of metrics is central, as discussed later in section 5.5.2. In Chapter 4, the largest settlement area with available satellite data was used for the calculation of LULC percentages. In this chapter, the settlement boundaries are still assigned as landscape limits. However, for Anari the boundary of the smaller subset (1994) was used to clip the classifications for other dates. The procedure left 11% of the Anari settlement out of the analysis, but allowed consistency during calculation and comparison of metrics. For Machadinho, metrics were calculated for the entire settlement, including and excluding the communal reserves. For this latter case, the reserves were considered as background with no class value.

Metrics were computed at three levels of analysis, that is landscape, class, and patch (McGarigal and Marks 1995). Each settlement was assigned as one landscape. Thus, the study differentiates the landscape of Anari with its orthogonal design of roads and parcels, and the landscape of Machadinho following topographic features. Class is the patch type (i.e., forest, succession, production land, or others). Patch was already defined in the section above and operationally corresponds to each polygon of the vector coverages. Areas smaller than 900 $m^2$ were not computed to keep consistency with the pixel size of satellite images used for LULC classifications (30 x 30 m). By the same token, the buffer area for core metrics calculations was 90 m wide. This width was chosen based on various studies about edge effects on tropical forest remnants in the Amazon (Laurance and Bierregaard 1997).

Several metrics were computed at the landscape, class, and patch levels of analysis. Table 26 lists these metrics and their respective acronyms. At the patch level, additional descriptive statistics were computed for the population of patches. Tables and graphic outputs allowed comparisons between the two landscape patterns and changing processes within the ten-year period (1988-1998). Appendix 2 describes the metrics used for each level of analysis. Formulas and descriptions were compiled from McGarigal and Marks (1995).

## 5.4 - SPATIAL PATTERN AND PROCESS IN MACHADINHO AND ANARI: METRICS AND TRENDS

The following sections present the results for landscape, class, and patch metrics.

### 5.4.1 - Landscape: A Broad Comparison between the Study Sites

Landscape metrics should be considered with caution, as they average values obtained for patches and classes within the landscape. However, when comparing two distinct architectural designs of colonization in the Amazon on a multi-temporal basis, an overview of these metrics can provide a first indication about landscape structure and change. The following paragraphs comment the results presented in Table 27.

The Largest Patch Index (LPI) quantifies landscape composition through the percentage of total landscape area encompassed by the largest patch. LPI has been widely used as an indicator of landscape fragmentation. LPI decreases in both settlements as deforested areas expand through time. In Anari, LPI decreases threefold, while in Machadinho it decreases less than twofold. However, when excluding the communal reserves from Machadinho's design, LPI decreases abruptly to 2.6% of the landscape.

Patch density, patch size, and variability metrics also serve as indicators of fragmentation processes within landscapes. Patch density (PD) is greater in Machadinho in all dates, but increases at a lower rate than in Anari. Mean Patch Size (MPS) is larger in Anari, but much more stable in Machadinho through time. As both PD and MPS are functions of the number of patches and total landscape area, these results are somewhat redundant and indeed show the same process. MPS is more informative when interpreted together with a measurement of dispersion. Patch Size Standard Deviation (PSSD) and Patch Size Coefficient of Variation (PSCV) are variability metrics and indicate aspects related to landscape heterogeneity. Thus, landscapes with greater PSSD and PSCV are more heterogeneous and landscapes with lower PSSD and PSCV are more uniform. For the three cases being analyzed, PSSD and PSCV tend to decrease over time and particularly at a higher rate in Machadinho when excluding the reserves. This tendency is largely influenced by values for PSSD and PSCV for classes, as will be shown below.

Another group of indicators of landscape fragmentation is represented by edge metrics. Edge Density (ED) was chosen for comparative purposes between Machadinho and Anari because Total Edge (TE) is directly affected by the size of landscapes under analysis. ED is a measurement of landscape configuration with applications to the study of edge effects. Values for ED in Machadinho, including reserves, and in Anari are roughly similar in all dates. When excluding the reserves, ED in Machadinho is much greater in all dates.

Shape metrics are as important as patch size metrics for the understanding of landscape configuration (Milne 1988). Two shape metrics were used for landscapes within the study area, both derived from comparisons to a circular shape at the patch level (Appendix 2). The Landscape Shape Index (LSI) increases over time in all cases, although it has lower values in Anari and higher values in Machadinho when excluding reserves. In Machadinho, the Area Weighted Mean Shape Index (AWMSI) decreases from 1988 to 1998. It starts with the same value with or without reserves and decreases more abruptly when reserves are not included for the calculations. In Anari, AWMSI increases from 1988 to 1994 and is stable from 1994 to 1998.

Core area was defined as the area within a patch beyond the distance of 90 m from its edge. Also important for the study of edge effects, core area metrics were selected for the research in Rondônia. These metrics indicate both aspects related to composition and configuration. For landscapes, the Total Core Area Index (TCAI) was used. It quantifies core area for the entire landscape as a percentage of total landscape area. TCAI decreases 20% in Machadinho over time. When excluding reserves, TCAI decreases 27% during the period of study, as it does in Anari.

Diversity metrics quantify landscape composition by measuring richness and evenness of patch types. Richness refers to the number of patch types and evenness refers to the distribution of area among different types. The Modified Simpson's Diversity Index (MSIDI) was used to reflect differences in patch richness over time. The Modified Simpson's Evenness Index (MSIEI) quantified evenness among the landscapes. Although MSIDI and MISEI increase approximately threefold for all landscapes under analysis over time, Machadinho is less diverse and less even in all dates. When excluding reserves from the analysis, diversity metrics in Machadinho are closer to values observed in Anari.

The nterspersion and Juxtaposition Index (IJI) measures how intermixed patch types are within a landscape and, therefore, are related to configuration. IJI is calculated in percentage units and approaches 100% when all classes are equally adjacent to all other classes. Machadinho shows higher IJI values in all dates, followed by the less interspersed landscapes of Anari and Machadinho without reserves. An interesting finding is a higher IJI value for all cases in 1994. The next section presents the results for metrics calculated at the class level and provides a more detailed perspective about pattern and processes within landscapes in Machadinho and Anari.

### 5.4.2 - Class: Understanding LULC Change through Spatial Metrics

Selected metrics were computed for classes within Machadinho and Anari landscapes. Results for forest are particularly emphasized in this section, as they play an important role in defining landscape structure and fragmentation within the study area. Percentage of Landscape (PLAND) and Largest Patch Index (LPI) provide results in terms of percentage of total landscape covered by all patches of a class and by the largest patch of a class, respectively (Appendix 2). As pointed out in Chapter 4, PLAND of forest in Machadinho dropped from 88.4% in 1988 to 65.7% in 1998, while in Anari these values were 86.8% and 52.9%, respectively. When excluding the communal reserves from the analysis, Machadinho shows the same rate of deforestation as Anari. Areas in succession increased about 11.9% in Machadinho, 16.7% if excluding the reserves, and 15.4% in Anari during the period of study. For production areas, these figures were 10.7%, 15.4%, and 18.3%, respectively. PLAND for other areas (water and built-up land) stayed stable over time (Table 28). These trajectories were also discussed in Chapter 4 and complemented by property-based data analysis, although a more disaggregated classification system was used at that point.

The examination of LPI for each class allows a better understanding about the behavior of this metric than when analyzed for the entire landscape (Table 29). LPI for forest decreases with time down to 10.7% in Machadinho, 4.5% in Anari, and only 2.6% in Machadinho without reserves. Anari shows consistently higher values of LPI for succession and production areas in all dates.

Patch density, patch size, and variability metrics were also calculated for landscape classes (Tables 30 to 33). Patch Density (PD) of forest increases more than 2.5 times in Anari during the period of study. In Machadinho, it increases at a much lower rate. Higher values of PD are observed for forest in Machadinho when excluding reserves. PD of areas in succession increases at a similar rate for all cases although its values are higher in Machadinho, particularly when excluding reserves. In Machadinho, PD of areas in production decreases from 1988 to 1994 and increases from 1994 to 1998. In Anari, it just increases over time (Table 30).

In Machadinho, Mean Patch Size (MPS) of forest fragments dropped from 319.0 ha (n=592) in 1988, to 219.1 ha (n=741) in 1994, and to 167.4 ha (n=838) in 1998. In Anari, these metrics were 556.4 ha (n=170) in 1988, 224.9 ha (n=332) in 1994, and 126.7 ha (n=455) in 1998. In Machadinho without reserves, MPS of forest is considerably smaller in all dates (Table 31). Values of MPS for succession areas, production areas, and other features are unaffected by the exclusion of forest reserves. MPS of succession areas in both landscapes are similar in 1988 and 1994, but larger in Anari in 1998. MPS of areas in production are always larger in Anari.

Patch Size Standard Deviation (PSSD) and Patch Size Coefficient of Variation (PSCV) were also computed for landscape classes (Tables 32 and 33). In succession areas, production areas, and other features, PSSD and PSCV values are also unaffected by the exclusion of forest reserves. PSSD of forest decreases in all cases. In Machadinho, the exclusion of reserves from the analysis causes an abrupt drop in PSSD values for forest. PSSD of succession areas is greater in Anari in 1998, while PSSD of production areas is always greater in all dates (Table 32). PSCV of forest in Machadinho decreases slowly over time but rapidly if reserves are excluded. In Anari, PSCV of forest increases from 1988 to 1998 (Table 33).

Results for Edge Density (ED) of forest are roughly similar for all dates in Machadinho and Anari. When excluding the reserves in Machadinho, PD of forest is greater. Similar trends were found for ED of succession and production classes. In all cases, PD increases over time (Table 34).

Landscape Shape Index (LSI) and Area Weighted Mean Shape Index (AWMSI) were also computed for all classes. As done for landscapes, these metrics quantify the amount of edge present in a class relative to what would be present in a class of the same size but with a circular shape. In other terms, these metrics provide a relative measurement of shape complexity. The particularity about AWMSI is that larger patches are weighted more heavily than smaller patches in calculating the average patch shape (Appendix 2). LSI increased for all classes in Machadinho and Anari over time. LSI of forest increased 1.5 times in Machadinho and twofold in Anari. However, values in Anari are lower than in Machadinho in all dates. The highest LSI values for forest were found for Machadinho without the reserves. LSI results for succession, production, and other features were unaffected in Machadinho when excluding reserves from the analysis. In general, Machadinho has higher values of LSI for these classes, but both landscapes present the similar ascendant trend (Table 35).

AWMSI results reveal other interesting findings (Table 36). AWMSI of forest shows opposite trends within the two landscapes, decreasing in Machadinho and increasing in Anari over time. When Machadinho reserves are excluded, AWMSI also decreases, but at a higher rate than when the landscape is complete. AWMSI of succession areas increases similarly in both landscapes. Production areas otherwise have higher AWMSI values in Anari in all dates. AWMSI results for other features (water and built-up land) are notably stable and higher in Anari, while they increase in Machadinho during the period of study.

Opposite trends were found for the Mean Core Area Index (MCAI) of forest. It increases in Machadinho and decreases in Anari over time. MCAI of succession and production areas increases in all cases during the period of study and is always higher in Anari (Table 37).

The last metric calculated for classes within Machadinho and Anari landscapes was the Interspersion and Juxtaposition Index (IJI) (Table 38). This metric defines how class patches are located in relation to other patches of the same class and to patches of other classes within the landscape. IJI of forest is greater in Machadinho in all dates, followed by Anari and Machadinho without reserves. In all cases, values of IJI of forest are similar in 1988 and 1998, peaking in 1994. IJI of succession areas decreases 4% in Machadinho, 3.2% in Machadinho without the reserves, and 9.2% in Anari. IJI of production areas also increase in 1994 in all cases, decreasing in 1998 but at a higher level than in 1988. A similar trend occurs for other features (water and built-up land). The next section describes the results found for patch metrics.

### 5.4.3 - Patch: Polygon-Based Descriptive Statistics

Patch-based metrics were also computed for Machadinho and Anari landscapes. The paragraphs below present results for area of patches (AREA), perimeter of patches (PERIM), shape index of patches (SHAPE), and fractal dimension of patches (FRACT) (Appendix 2; Figures 71–82). Results for forest, succession, and production patches are emphasized. Patches of other features (i.e., water and infrastructure features including roads and urban areas) show little variation over time and are not discussed.

For the patch-based analysis, it is important to remember that the box within boxplots represents the interquartile range and contains 50% of all values. The line crossing the box is the median. Whiskers represent the highest and lowest values, excluding outliers. Unfortunately, for the sake of producing readable and comparable graphs for all dates and cases of study, extremes and outliers were hidden from the output. This weakens the analysis for particular questions but allows a better picture of the majority of values within the statistical population (Ott 1993).

Values for area of patches are presented in Figures 71, 72, and 73. The interquartile range for patches of forest increases in Machadinho over time, either including or excluding reserves. In Anari, this interval is more stable through time although greater in 1988. The distribution of values for area of succession and production patches is similar in both cases analyzed for Machadinho in all dates, with the interquartile ranges for both classes tending to increase over time. In Anari, the distribution of successional areas is also similar to Machadinho in 1988 and 1994. In 1998, the interquartile range and highest value are slightly greater. The range and highest value of production areas in Anari are slightly greater than in Machadinho in 1988, distinctively greater in 1994, and slightly smaller in 1998.

The interquartile range for perimeter of forest patches increases in Machadinho during the period of study. In Anari, it decreases from 1988 to 1994 and slightly increases in 1998. The range is obviously greater in Anari in 1988, similar but with higher median in 1994, and smaller but with similar median in 1998. Including or excluding reserves do not affect results for perimeter of succession or production patches in Machadinho. In both cases, the range increases slightly in 1994 and remains stable in 1998. In Anari, the median of perimeter of succession patches is often higher than in Machadinho, while the interquartile range is greater only in 1998. For production areas, the median and range are greater in Anari than in Machadinho in 1988 and 1994. In 1998, the range is smaller in Anari and the median is equivalent in both settlements (Figures 74, 75, and 76).

Some points deserve consideration for the shape index and fractal dimension, as shown in figures 77 to 82. The interquartile range of the shape index for forest patches is slightly greater in Machadinho when excluding reserves from the analysis. The presence of reserves does not affect values for succession and production patches. In Anari, the range for forest is greater than in Machadinho in 1988, but smaller in 1994 and 1998. The median is also smaller in 1998. Shape index for succession patches in Anari has similar ranges and medians as Machadinho in all dates. For production areas, the shape index in Anari is similar to Machadinho in 1988 and 1994. In 1998, its range and median are smaller.

Fractal dimension measures shape complexity for each patch within the landscape. It ranges from 1 to 2, with 1 meaning Euclidian geometric shapes such as circles and squares, and 2 meaning a very complex patch shape. In Machadinho, the median fractal dimension of forest patches decreases as its range increases over time. When excluding reserves, the trend is similar, although the upper quartile and highest values are greater in 1998. In Anari, the median for forest patches decreases from 1988 to 1994 but increases slightly in 1998. The interquartile range also decreases from 1988 to 1994 and remains stable in 1998. Fractal dimension of patches of succession and production areas are unaffected when excluding reserves from the analysis in Machadinho. The median slightly increases for succession areas from 1988 to 1994 and stays stable in 1998. In Anari, values for fractal dimension of succession patches are very similar for all dates. The median and range of fractal dimension of production patches decreases in 1994 in Machadinho and remains equivalent in 1998. A similar trend was found for Anari although the median values are lower.

## 5.5 - LANDSCAPE TRANSFORMATION IN MACHADINHO AND ANARI

### 5.5.1 - Metrics and Meanings

This chapter presents results for landscape, class, and patch metrics, in a multi-temporal approach, for two distinct settlement designs in Rondônia, Brazilian Amazon. Perhaps, the most intuitive analysis of metrics occurs at the class level. Landscape metrics average values of all classes and can lead to misleading conclusions if not analyzed with caution. However, when comparing two landscapes of distinct structure, such as Machadinho and Anari, landscape metrics provide important elements for a description about the general pattern within the settlements. Patch metrics are too disaggregated and can be more useful when analyzing single patches for specific purposes (e.g., habitat studies, reserves delimitation, edge effects, and so on). The importance of patch metrics is mainly related to their role in providing the basis for class- and landscape-level calculations, as depicted by the formulas for these latter metrics (Appendix 2). However, the analysis of distribution of values for specific patch metrics can also contribute to a better understanding about the spatial pattern of landscapes, as patches are the primary elements defining landscape structure. When averaged to the class level, specific patterns within the landscape become clearer, particularly when analyzing LULC change as the most important process leading to landscape transformation.

Other techniques could be used to overcome the limits of this research. A promising study would be to measure the importance of specific groups of patches to processes causing changes in landscape pattern. In the case of roads and watercourses, for example, analysis of connectivity instead of patch distribution would be more appropriate since the design of these corridors ultimately affects landscape patterns and processes of change, as indicated by the analysis of buffers around roads in Chapter 4. Another empirical exercise would be to fill the reserves in Machadinho with a similar pattern found in property areas and simulate the inclusion of permanent reserves within the Anari landscape to test the actual contribution of reserves and architectural design to landscape fragmentation processes. Until these studies are carried out, the paragraphs below discuss the results produced so far, as a contribution to rethinking settlement design in the Amazon.

Results for Percentage of Land (PLAND) are redundant with the ones presented in Table 14, but in this chapter they are aggregated for the recoded classes (i.e., forest, succession, production, and others). Slight differences between these numbers and results presented in Chapter 4 are due to the use of an adjusted boundary for Anari when calculating landscape metrics.[2] The classes used for this research have distinct functions within the landscapes. Further studies may be more specific about their role in flows of materials, energy, and species within landscape elements. PLAND is a very useful metric when comparing same classes between landscapes of different sizes, such as Machadinho and Anari. It is not inappropriate to reaffirm the importance of communal reserves in

[2] As explained before, the adjusted boundary was used to maintain consistency during the multi-temporal comparison in Anari, as 11% of the landscape had no data available for 1988 and 1994.

maintaining a higher percentage of forest cover in Machadinho. Without them, the rate of deforestation becomes similar in both landscapes (Table 28).

The Largest Patch Index (LPI) is one of the most effective metrics measuring landscape fragmentation (Dale 2001). At the landscape level, LPI decreases in all cases, but more abruptly in Machadinho without reserves and Anari (Table 39). This result is actually reflecting what happened to forest class, which shows an equivalent trend (Table 29). The relatively large size of the Aquariquara Reserve in Machadinho is affecting LPI results positively for this landscape. Certainly, the reserve itself and contiguous private forest areas make up the LPI value for forest in Machadinho. Interestingly, because of this communal reserve, this metric tends to remain stable in Machadinho, while it keeps decreasing in Anari.[3] This has significant ecological implications, as some species need a single large patch as their primary habitat for maintenance and reproduction (Burkey 1989). LPI values for succession, production, and other features have relatively less importance because their largest patches are too small in comparison with the landscape's extent. However, the higher values of LPI for succession and production areas in Anari indicate that land aggregation (for pasture conversion, for example) and land speculation (through relative abandonment) is more current in the fishbone scheme.

Patch density, patch size, and patch variability metrics are other important quantitative measurements to assess landscape transformation and fragmentation because the total amount of energy and nutrients in a patch is proportional to its area (Forman and Godron 1986). The consequences of these matters to species composition and abundance within the landscape are clear. As pointed out by the island biogeographic theory, species diversity or richness is related directly to an island's area, its isolation, and its age (MacArthur and Wilson 1967). Patch size can stand for an island's area for analyses of species habitat (Harris 1984). It is out of the scope of this chapter to discuss the effects of patch size and variability on species. But it is important to mention that the study of landscape structure can effectively contribute to the understanding of occurrence and distribution of organisms (Ricklefs 1987).

Within the study area, results for Patch Density (PD) have to be considered with caution. Although higher in Machadinho at the landscape level (Table 27), this finding reflects the fragmentation of succession and production areas more than of forest stands. This is corroborated by the results of PD at the class level, which are more informative (Table 30). Production fields and succession areas in Machadinho are smaller and more numerous, increasing PD despite the lower level of fragmentation of forests within this landscape. When excluding reserves from the analysis, values of PD of forest in Machadinho are higher because the large patches of forest are not being considered in the calculation. Results also indicate trends in rates of forest fragmentation. PD of forest increased more than 2.5 times in Anari during the period of study, indicating a faster process of forest fragmentation (Table 40). PD is ultimately measuring landscape and class heterogeneity, providing important quantitative information for land zoning and management initiatives.

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[3] The largest forest patch in Machadinho has 22,892 ha. The Aquariquara Reserve has 18,100 ha (Table 16). As soon as the areas contiguous to the reserve are cleared, the reserve will be the largest patch itself, stabilizing the LPI at 8.5%.

Mean Patch Size (MPS) is derived from patch-based area metrics and also indicates fragmentation. The first important finding within all cases under analysis is that MPS averaged for the entire landscape decreases over time (Table 39). Also, landscape MPS is lower in Machadinho, but decreases at a faster rate in Anari. To better understand these rates of fragmentation and which landscape elements are contributing to the process, analyses at the class level are more helpful. In general, MPS decreases for forest and increases for all other classes (Table 40). Moreover, a lower pace of forest fragmentation is indicated for Machadinho when compared to Anari. Although MPS of forest was smaller in Machadinho in 1988, it ended up larger after a decade of landscape transformation. This occurred because MPS of forest decreased 1.9 times in Machadinho and 4.4 times in Anari during the period of study! The fishbone scheme tends to show lower levels of fragmentation during the early stages of colonization due to the large elongated patches of forest located between roads. However, when forest clearing advances, these patches are subdivided into several smaller patches. In Machadinho, communal forest reserves combined with private property forests produced a more stable landscape. If the reserves are excluded, MPS of forest drops abruptly, suggesting a much more fragmented class than even the fishbone design. Obviously, the exclusion of reserves in Machadinho was just an empirical exercise. Nevertheless, the results offer an alert for further initiatives trying distinct settlement designs in the Amazon. MPS of successional vegetation and cropland are always greater in Anari through time. These trends are affected by the increase in pasture areas and associated secondary vegetation within the fishbone settlement. Results for MPS of succession, production, and other areas are unaffected when excluding reserves in Machadinho because these three classes are barely absent within the reserves. Conversely, results for patch-based and class-based area metrics for forest are always affected by the exclusion of reserves, indicating the importance of their patches for the statistical population and distribution of forest class within Machadinho's landscape (Figures 71, 72, and 73).

As an average, MPS is sensitive to extreme values. Thus, its results are better interpreted when analyzed together with measurements of dispersion. The behavior of Patch Size Standard Deviation (PSSD) and Patch Size Coefficient of Variation (PSCV) follows the trends observed for MPS. In general, these dispersion metrics decrease as MPS for forest decreases and increase as MPS for the other classes increases over time (Tables 39 and 40). In other terms, the variability in patch size of forest and landscapes as a whole is decreasing, making the distribution of these metrics more uniform. The only exception refers to PSCV of forest. As it is calculated as a percentage of MPS, it increases in Anari, reflecting a higher relative variability in size of forest patches within the fishbone landscape in 1998, even with a lower absolute variability measured by PSSD. On the other hand, PSSD and PSCV of production and succession classes increase over time, indicating that these areas are becoming larger, with different sizes (Tables 27, 32 and 33).

The next two groups of metrics (i.e., edge metrics and shape metrics) have important applications for the study of edge effects, which certainly affect the dispersal and foraging of organisms (Ranney et al. 1981, Laurance and Bierregaard 1997). Edge effects are important ecological phenomena and particularly useful for the study of rain forest fragments (Lovejoy et al. 1986, Malcolm 1994, Kapos et al. 1997, Laurance 1997). The amount of edge and the shape of patches dictate the interactions between distinct patch types and, consequently, the flow of species throughout the landscape. In this sense, a large but elongated patch, such as the strips of forest between roads in Anari, could become completely edge habitat. More than explore scenarios about edge effects occurring within the landscapes of Machadinho and Anari, this research provides a preliminary analysis of edges and shapes as a basis for further studies regarding ecotones and transitions among patch types. Comparative studies of species diversity and abundance in Machadinho and Anari, for instance, could offer new elements for discussion about settlement design.

The similarity found in Edge Density (ED) for classes in Machadinho and Anari suggests that fragmentation is taking place within both landscapes (Tables 34 and 40). In general, ED is increasing for all classes as the process of occupation and LULC change advances. The abrupt increase in ED when excluding reserves in Machadinho should not guide us to misleading conclusions. In this case, the results are affected by the reserves' edges, considered as background for calculations. Further studies about edges within those landscapes should explore the role of contrasts between different patch types. The absence of results for edge contrast metrics minimized the potential of indicators to analyze ecotones. Depending on the land-cover class adjacent to forest patches, for example, different effects may be observed in terms of ecological processes. If forest patches border open vegetation, such as production areas, this fragment may become more susceptible to disturbances in its structure and composition. Conversely, if forest patches are adjacent to succession areas, secondary regrowth may be accelerated. Investigating these relationships would bring a better understanding about the functional significance of each patch type. Such inferences go beyond the purposes of this study, but the exploratory results obtained for edge contrast metrics justify the use of these quantitative approaches in further ecological analyses within Amazonian landscapes under processes of LULC change.

Edge contrast and nearest-neighbor metrics were not calculated due to the computer intensity when processing large and complex data sets such as those used for this research. However, exploratory runs for different dates and subsets confirmed what was expected. Edge contrast metrics measure the degree of contrast between a patch and its neighbors by assigning different weights to classes within the landscape. Nearest-neighbor metrics reflect configuration by measuring the distance between nearest patches of the same class, based on edge-to-edge distance. In other terms, they indicate the degree of isolation of patches within the landscape. The following three metrics were used during this exploratory approach (McGarigal and Marks 1995). In general, Contrast Weighted Edge Density (CWED) tends to increase and Mean Edge Contrast Index (MECI) tends to decrease within Machadinho and Anari landscapes over time. Mean Nearest Neighbor (MNN) also tends to decrease, as these landscapes become more fragmented. The exploratory analysis of edge contrast and nearest-neighbor metrics at the class level indicated similar behavior for both landscapes, as found for landscape metrics. Although the magnitude of each metric for all dates was not computed, some general trends can be mentioned. CWED tends to increase for all classes while MECI tends to decrease, mainly for forest. Mean Nearest Neighbor (MNN) increases for forest and decreases for succession and production areas, as expected for an ecological process where a pristine landscape matrix is progressively subdivided into more isolated remnant fragments.

Shape metrics are also related to edge effects, as patch shape and size dictate perimeter extent and edge with neighbor patches. These perimeter-area relations are intricate to quantify concisely in a metric and often are difficult to interpret (McGarigal and Marks 1995). Patch perimeter distribution was represented in Figures 74, 75, and 76. Perhaps, the most important finding was that perimeter for forest patches in Anari shows a similar pattern in all dates, while in Machadinho it increases over time. The results obtained for the computed shape metrics show relevance related to some particular trends. Landscape Shape Index (LSI) increases over time for all classes and landscapes due to the formation of more irregular shapes (Tables 39 and 40). Values are higher for Machadinho because it has a more complex design. When excluding the reserves, these values are even higher for the same reason explained above for Edge Density (Tables 27 and 35). By the same token, lower LSI values in Anari indicate a lower complexity in patch shape within this landscape. When analyzing these results, it is important to consider that LSI is not measuring shape morphology. In this sense, a large elongated patch could have the same LSI value as a smaller convoluted patch. What LSI is in fact indicating is that the configuration of classes and landscape in Anari is less complex because its design is based on an orthogonal road network. In Machadinho, the design based on topography produces a more complex outcome in landscape shape structure.

When weighted by areas of patches, not just the magnitude but also the trends of shape metrics are different within the settlements. Area Weighted Mean Shape Index (AWMSI) for forest and the entire landscape decreases in Machadinho and increases in Anari during the period of study (Tables 27, 36, 39, and 40). The size and perimeter-to-area relationship of forest patches within the landscapes is certainly affecting the results, as AWMSI increases similarly for all other classes over time. Other quantitative analyses such as the interior-to-edge ratio relating edge and shape metrics could provide an easier intuitive interpretation. Although these relationships were not computed for this study, it is expected that communal reserves in Machadinho tend to increase the interior-to-edge ratio of forest while the narrow elongated forest remnants in Anari tend to lower the ratio for this patch type.

The analysis of shape metrics at the patch level is difficult to interpret, as even radical changes in the shape of some patches may have little effect on the distribution of patch shape values for the class as a whole. For metrics such as area and perimeter this is minimized because they are absolute values without limit and not ratios as the shape metrics are. However, results for the shape index of forest patches indicate a lower shape complexity of forest stands in Anari (Figures 77, 78, and 79). In addition, results for fractal dimension of patches of forest, succession, and production areas behaved as expected and described in previous studies (Frohn 1998). Forest patches tend to have more complex shape than agricultural or successional fields (Figures 80, 81, and 82).

Core-area metrics are the counterpart of edge metrics. They are related to the concept of 'interior habitat,' which is very relevant for a number of species (Patton 1975, Saunders et al. 1991). My decision to choose Total Core Area Index (TCAI) and Mean Core Area Index (MCAI) was to avoid redundancy with patch size, density, and variability metrics, as core area is generally a function of these latter measurements. TCAI and MCAI are relative indices that quantify core area as a percentage of total area (Appendix 2). All these metrics are based on the selection of an edge width, which should be associated with the phenomenon under investigation. As this research is related to processes of LULC change, the choice of an edge width of 90 m was based on potential responses of plants and the environment when subjected to LULC edge effects (Kapos et al. 1997). This decision is somewhat arbitrary, and empirical tests could clarify the effects of changing edge width to core-area metrics values. However, for the comparative purpose of this study, the results are already valuable.

Within the study area, TCAI decreases for all cases (Table 39), suggesting that the landscapes are losing interior habitat as they become more fragmented. Although TCAI is greater in Anari in 1988 because of the large elongated patches of forest, it decreases more slowly in Machadinho including reserves (Table 27). Also, lower values of TCAI in Machadinho when excluding reserves indicate that they play an important role in maintaining interior habitat within the landscape.

MCAI results should be analyzed with caution, as any metric based on first-order statistics. Interesting results were found for MCAI of forest. In Anari, the average of core areas represent 12.5% of the forest class in 1988, but drops to 6.4% in 1998. In Machadinho, MCAI of forest represents just 4.1% of this class in 1988, but increases more than twofold to 8.8% in 1998 (Tables 37 and 40). The meaning of these results can be better interpreted in conjunction with the percentage of the landscape covered by forest (Table 28). Although deforestation is a concurrent process within both landscapes, the architectural design of Machadinho preserves more interior habitat, which relatively increases as the area of forests decrease. This is independent of the large patches of communal reserves and strictly related to the intricate design of Machadinho. Conversely, the initially lower fragmented patches of forest in Anari have a relatively higher percentage of interior habitats in earlier stages of colonization, which drops abruptly as the occupation process takes place.

Diversity metrics brought little new information about landscape pattern and process in Machadinho and Anari. Often criticized for not providing information on the actual composition of a landscape and its elements, these metrics were used solely as a summary about richness and evenness within the study area. Therefore, MSIDI results imply that Machadinho is a less diverse landscape or, in other words, has fewer classes per unit area than Anari. When excluding the reserves, the results for MSIDI in Machadinho are similar to those in Anari, indicating that the diversity within private properties is equivalent in both landscapes. Results for MSIEI suggest that the proportional distribution of area among classes in Machadinho is less equitable than in Anari or in Machadinho excluding reserves (Table 27). Also, MSIEI could be understood as the compliment of dominance (that is, evenness = 1 – dominance). Although diversity metrics do not convey any information about the contribution of each patch type to the final result, analysis of these metrics in conjunction with other metrics (e.g., PLAND) may provide a better perspective about the trends being analyzed. In this sense, lower values of MSIEI in Machadinho reflect a higher dominance of forest within this landscape. By the same token, the ascendant trend for MSIEI in all cases (Table 39) depict the process of deforestation toward landscapes with a more even distribution of patches among forest, succession, and production areas.

The last metric computed for this comparative study was the Interspersion and Juxtaposition Index (IJI). The classic and intuitive way of representing maximum interspersion is by a chessboard, where white cells are evenly distributed in relation to black cells. IJI results indicate that Machadinho's design leads to a more interspersed landscape than Anari's fishbone scheme. They also indicate that the highest interspersion during the period of analysis occurred in 1994 (Table 27). IJI results for forest and production areas follow a similar trend, with lower values in 1988 and 1998, and higher values in 1994. This possibly indicates a threshold in the trajectory of colonization and landscape transformation within the study area. On the other hand, values for succession areas show a decreasing trend in all cases, suggesting that these areas are becoming more isolated within the landscape (Tables 38 and 40). The impact of these spatial relationships to ecological processes is a promising subject for further studies. Particularly, it is important to follow the trends for forest and succession areas and understand the potential impact of patch location within the landscapes to processes such as vegetation recovery or degradation. For these studies, it will be relevant to consider that forest fragmentation in both settlements may affect the propagation of disturbances across the landscapes. For instance, a highly fragmented and interspersed forest, taken as a patch type within the landscape, may be less prone to total destruction by fire as a class in its entirety, although the fragments themselves are more susceptible. For other types of disturbances (logging, for example), larger patches of forest may show a higher resilience than several small fragments. These processes should be investigated and monitored for each landscape through time since they are affected by settlement design, as translated by the metrics discussed in this chapter.

### 5.5.2 - Unresolved Problems in Spatial Data Analysis

The search for quantitative methods to analyze and describe the structure of landscapes has become a high priority in landscape ecology (Turner and Gardner 1991, Wiens and Moss 1999). In addition, within a science still dominated by empirical approaches and case studies, the need of standardization is urgent. At least four potential methodological pitfalls should be addressed when analyzing spatial data: the boundary problem, the scale problem, the problem of modifiable units, and the problem of pattern (Burt and Barber 1996).

The boundary problem is related to the extent and location of the boundary of a study area, as well as the placement of the internal boundaries in an areal design (Wiens et al. 1985). The choice of boundaries is particularly important in landscape ecology, because the behavior of landscape metrics is affected by changes in spatial extent (Turner et al. *Effects* 1989). This was one of the first questions when designing the comparative analysis about landscape fragmentation processes in two distinct rural settlement designs in Rondônia. Which limits should be chosen? Where should the subsets be placed? Should the subsets have the same shape and extent? What will be the effects of boundary placement over landscape, class, and patch metrics?

One option was to choose subsets of exactly the same shape and extent. However, the settlements have completely different designs (Figure 6). Any shape would embrace more than the total area of the settlements or just a part of them. The landscape metrics calculated for these subsets would be strongly affected by segregation or integration problems, not allowing reasonable comparisons between the settlements as a whole. The other option was to digitize the geographic limits of each settlement and calculate the metrics in relation to their extent. Although the shape and extent of the subsets are different, comparative analyses become possible. The boundary problem in this case seems to be avoided, as the unit of analysis is the entire extent of the settlement, which is functionally circumscribed by administrative limits. Besides taking this option for the study, metrics with absolute values, such as number of patches or total area, were avoided to maintain consistency during the comparative approach.

The second problem when analyzing spatial data is related to the grain and is also called the scale problem or the areal aggregation problem (Cao and Lam 1997). In general, spatial aggregation tends to reduce the variation in spatial mosaics (Burt and Barber 1996). This is perhaps one of the most important issues in global change–related research, as scaling up and down is generally suggested (Curran 1989, National Research Council 1998). The qualitative and quantitative changes in measurements across spatial scales differ depending on how scale is defined. Therefore, measurements carried out at different scales may not be comparable. Also, the exact relationship varies across landscapes, creating difficulties in extrapolating from one region to another (Meentemeyer and Box 1987, Wiens 1989). Diversity metrics, for example, decrease linearly with increasing grain size, while dominance and contagion do not show a linear relationship. Rare classes are lost as grain becomes coarser and dispersed classes are lost more rapidly than clumped ones (Turner et al. *Effects* 1989).

Recognizing that landscape structure varies with scale, landscape ecologists have struggled for scale-invariant measures or indices (Withers and Meentemeyer 1999). The fractal dimension is the most commonly employed such measure. The range of spatial extent over which the fractal dimension is a constant is said to represent the 'scale' of the landscape, or the scale over which the landscape is 'self-similar' (Burrough 1981, Mandelbrot 1983). In other words, over that range of scales, landscape units display similar behavior, appear structurally similar, and are, presumably, affected by the same processes and controls. Other approaches, such as the square-pixel metric, have also been suggested for this purpose when dealing with raster data (Frohn 1998). An alternative measure for shape complexity is the lacunarity index, which is a multi-scaled method for determining the texture associated with patterns of spatial dispersion (e.g., landscape/habitat types or species locations) (Plotnick et al. 1993). Another approach is to identify the scale of discontinuity in landscape structure, or assess the variability or similarity between landscape types or patches. These measures include spatial autocorrelation (Legendre 1993), semivariograms (Curran 1988), and other geostatistical methods (Isaaks and Srivastava 1989, Rossi et al. 1992). A variety of complementary methods have also been developed. Fractal models of landscape patterns have been associated with neutral models of species co-occurrence (Milne 1992). Nested sampling designs have enabled the detection of a wide range of spatial structures, showing the relationships among nested spatial scales (Bellehumeur and Legendre 1998). Hierarchically structured maps have been suggested as a useful tool for studying landscape patterns at different scales (Lavorel et al. 1993). In sum, the need for a 'scale theory' has been defended frequently as an important methodological advance in spatial analysis (Raffy 1994).

For this research in Rondônia the scale problem was minimized using the same grain for both areas of study. The areas are adjacent and belong to the same classified Landsat TM scene. Therefore, comparisons between the areas were possible, as the agroecological processes under investigation (e.g., deforestation, secondary succession, and land conversion to pasture or agriculture) were studied using the same spatial resolution. Potential problems may arise if integration of spatial data produced at other scales is done (e.g., soil maps, topographic features, and so on). In this case, caution should be taken to keep away from biased estimations.

A third potential problem when dealing with spatial data is associated with modifiable units: results vary when areal units are progressively aggregated into fewer and larger units of analysis (Turner et al. *Effects* 1989). This may happen even when using the same grain and extent for the analysis. Burt and Barber (1996) explain how variance may or may not vary depending on the aggregation process. In general, smoothing techniques decrease variance and also increase autocorrelation (Bian 1997). However, the effects of using modified areal units are not always predictable. A rule of thumb to minimize the problem when aggregating data is to join zones with similar attributes (Bian and Butler 1999). This problem is typically recognized when classifying categorical data using hierarchical schemes such as Anderson's LULC system (Anderson et al.1976). Joining distinct classes must be done carefully to avoid an undesirable significant decrease in spatial variance. Important components to consider include the nature of the classification scheme itself, the process of classification output issues, and the phenomenon under investigation (Withers and Meentemeyer 1999).

For this research in Rondônia, image classification was done using the same parameters and spatial-spectral relations for both study areas. Just after obtaining the LULC map for the entire scene, the settlements were separated to run the landscape metrics. This method avoided incomparable approaches between the sites. Difficulties to discriminate some LULC types were solved by analysis of vegetation structure and spectral data, as discussed in Chapter 3. Aggregation of classes for the LULC analysis in Chapter 4 or for the classes used in this chapter was strictly based on functional aspects of each category within the classification system. Although the accuracy achieved using maximum likelihood algorithms was acceptable (Table 13), further approaches may improve the accuracy of LULC classifications for the study area. Spatial autocorrelation studies may support decisions about the classification system and the relationship of neighboring attributes within data elements (Legendre 1993). The use of semivariograms may help the detection of areas with higher chance of showing the modifiable areal unit problem (Curran 1988). Spatial-spectral algorithms may overcome the risk of joining very dissimilar categories (Kettig and Landgrebe 1976, Landgrebe 1980, Woodcock and Strahler 1987).

The pattern in spatial data is another problem for several methods of analysis. Many of them are incapable of assessing the type of pattern present in a spatial distribution (Burt and Barber 1996). Landscape ecologists have also attempted to address this fact when using landscape metrics. In this case, an extra effort has to be made to depict landscape configuration besides describing landscape composition (Li and Reynolds 1993). One way to address the problem is to use second-order statistics methods (e.g., Ripley's K, Moran's I, Geary's c, semivariance, among others). They allow the quantification of small-scale spatial pattern intensity (magnitude, degree) and scale (spatial extent). But, again, these methods were primarily implemented for point data, under the assumption of stationarity. A shortcut to analyze patch data using spatial statistics algorithms is through surface pattern methods, such as join-count spatial correlation coefficients, in which patch centroids can be analyzed with point-pattern methods (Fortin 1999). Perhaps, the landscape metrics more suitable to address pattern in patchy spatial data are contagion and interspersion indices. Contagion measures both patch type interspersion (i.e., the intermixing of units of different patch types) as well as patch dispersion (i.e., the spatial distribution of a patch type) (Li and Reynolds 1993). The interspersion index measures the extent to which patch types are interspersed (i.e., adjacent to each other). The interspersion index is not directly affected by the number, size, contiguity, or dispersion of patches *per se*, as the contagion index is (McGarigal and Marks 1995). Alternative metrics to quantify contagion have also been suggested (Frohn 1998).

For the research in Rondônia, besides the analysis of landscape composition within the two settlement designs, it was important to investigate the variation of spatial arrangement through space and time. Distinct land-use strategies and consequent land-cover spatial outcomes were depicted from this analysis. However, one of the main shortcomings of interspersion metrics, for example, is their capability of analyzing spatial pattern based only on relationships between neighboring zones. More complex spatial relationships involving distant patches are still not implemented.

Last but not least, studies have shown high correlation among particular landscape metrics (e.g., Hargis et al. 1998). Caution should be taken to look for complementary techniques when analyzing spatial data, avoiding redundancy when it is not required. Primarily, besides the constraints of operational limitations, the choice of metrics should be strictly related to the phenomena under investigation. This chapter intended to provide elements for discussion regarding landscape change in the Amazon through the use of quantitative methods of spatial analysis. The next chapter goes beyond the metrics to address the human dimensions of landscape change.

Table 25 - Recoding system of LULC classes for calculation of landscape metrics in Machadinho d'Oeste and Vale do Anari.

| **LULC CLASSES** | **RECODED CLASSES** |
|---|---|
| Forest | Forest |
| Advanced Secondary Succession | Secondary Succession |
| Initial Secondary Succession | |
| Pasture | Production |
| Agriculture | |
| Bareland | |
| Infrastructure | Others |
| Water | |

Table 26 - List of computed metrics for patches, classes, and landscapes in Machadinho d'Oeste and Vale do Anari

| METRICS TYPE | ACRONYM | METRICS |
|---|---|---|
| **Area metrics** | | |
| Patch | AREA | Area (ha) |
| Patch | PERIMETER | Perimeter (m) |
| Class | PLAND | Percentage of landscape (%) |
| Class/landscape | LPI | Largest patch index (%) |
| | | |
| **Patch density, patch size, and variability metrics** | | |
| Class/landscape | PD | Patch density (#/100ha) |
| Class/landscape | MPS | Mean patch size (ha) |
| Class/landscape | PSSD | Patch size standard deviation (ha) |
| Class/landscape | PSCV | Patch size coefficient of variation (%) |
| | | |
| **Edge metrics** | | |
| Class/landscape | ED | Edge density (m/ha) |
| | | |
| **Shape metrics** | | |
| Patch | SHAPE | Shape index |
| Patch | FRACT | Fractal dimension |
| Class/landscape | LSI | Landscape shape index |
| Class/landscape | AWMSI | Area-weighted mean shape index |
| | | |
| **Core area metrics** | | |
| Landscape | TCAI | Total core area index (%) |
| Class | MCAI | Mean core area index (%) |
| | | |
| **Diversity metrics** | | |
| Landscape | MSIDI | Modified Simpson's diversity index |
| Landscape | MSIEI | Modified Simpson's evenness index |
| | | |
| **Interspersion and juxtaposition metrics** | | |
| Class/landscape | IJI | Interspersion and juxtaposition index (%) |

Table 27 - Computed metrics for Machadinho d'Oeste and Vale do Anari landscapes in 1988, 1994, and 1998

| | MACHADINHO D'OESTE INCLUDING RESERVES | | | MACHADINHO D'OESTE EXCLUDING RESERVES | | | VALE DO ANARI | | |
|---|---|---|---|---|---|---|---|---|---|
| **Metrics** | **1988** | **1994** | **1998** | **1988** | **1994** | **1998** | **1988** | **1994** | **1998** |
| **LPI (%)** | 17.7 | 13.3 | 10.7 | 15.2 | 8.0 | 2.6 | 13.2 | 5.5 | 4.5 |
| **PD (#/100ha)** | 6.8 | 8.0 | 8.5 | 9.8 | 11.6 | 12.3 | 3.0 | 4.3 | 5.0 |
| **MPS (ha)** | 14.8 | 12.6 | 11.8 | 10.2 | 8.6 | 8.1 | 33.7 | 23.1 | 19.9 |
| **PSSD (ha)** | 582.8 | 371.6 | 285.7 | 299.7 | 127.5 | 72.3 | 436.3 | 258.5 | 181.2 |
| **PSCV (%)** | 3940.8 | 2960.7 | 2414.5 | 2937.8 | 1481.9 | 892.9 | 1295.7 | 1119.2 | 911.1 |
| **ED (m/ha)** | 24.5 | 36.3 | 43.6 | 34.7 | 51.4 | 61.0 | 20.4 | 34.2 | 44.3 |
| **LSI** | 31.9 | 47.4 | 56.8 | 37.6 | 55.7 | 66.1 | 19.0 | 31.8 | 41.3 |
| **AWMSI** | 6.8 | 5.2 | 4.7 | 6.8 | 4.3 | 3.4 | 3.4 | 4.2 | 4.2 |
| **TCAI (%)** | 76.3 | 64.2 | 56.2 | 64.9 | 48.2 | 38.1 | 77.8 | 62.5 | 50.8 |
| **MSIDI** | 0.24 | 0.50 | 0.72 | 0.34 | 0.72 | 0.99 | 0.27 | 0.64 | 0.93 |
| **MSIEI** | 0.17 | 0.36 | 0.52 | 0.25 | 0.52 | 0.71 | 0.19 | 0.46 | 0.67 |
| **IJI (%)** | 86.3 | 94.3 | 90.6 | 67.3 | 73.5 | 70.6 | 81.1 | 87.3 | 82.2 |

Table 28 - Percentage of landscape (PLAND) for each class in Machadinho d'Oeste and Vale do Anari in 1988, 1994, and 1998

| PLAND (%) | MACHADINHO D'OESTE INCLUDING RESERVES | | | MACHADINHO D'OESTE EXCLUDING RESERVES | | | VALE DO ANARI | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1988 | 1994 | 1998 | 1988 | 1994 | 1998 | 1988 | 1994 | 1998 |
| Forest | 88.4 | 76.0 | 65.7 | 83.4 | 65.8 | 51.1 | 86.8 | 68.5 | 52.9 |
| Succession | 1.6 | 8.4 | 13.5 | 2.3 | 11.9 | 19.0 | 1.5 | 7.9 | 16.9 |
| Production | 8.4 | 13.9 | 19.1 | 12.0 | 19.9 | 27.4 | 10.7 | 22.5 | 29.0 |
| Others | 1.6 | 1.7 | 1.8 | 2.2 | 2.4 | 2.5 | 1.0 | 1.0 | 1.1 |

Table 29 - Largest Patch Index (LPI) for each class in Machadinho d'Oeste and Vale do Anari in 1988, 1994, and 1998

| LPI (%) | MACHADINHO D'OESTE INCLUDING RESERVES | | | MACHADINHO D'OESTE EXCLUDING RESERVES | | | VALE DO ANARI | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1988 | 1994 | 1998 | 1988 | 1994 | 1998 | 1988 | 1994 | 1998 |
| Forest | 17.7 | 13.3 | 10.7 | 15.2 | 8.0 | 2.6 | 13.2 | 5.5 | 4.5 |
| Succession | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.2 | 0.1 | 0.1 | 0.3 |
| Production | 0.1 | 0.4 | 0.5 | 0.2 | 0.5 | 0.8 | 0.3 | 1.1 | 2.9 |
| Others | 0.2 | 0.3 | 0.3 | 0.3 | 0.4 | 0.4 | 0.2 | 0.2 | 0.2 |

Table 30 - Patch Density (PD) for each class in Machadinho d'Oeste and Vale do Anari in 1988, 1994, and 1998

| PD (#/100ha) | MACHADINHO D'OESTE INCLUDING RESERVES | | | MACHADINHO D'OESTE EXCLUDING RESERVES | | | VALE DO ANARI | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1988 | 1994 | 1998 | 1988 | 1994 | 1998 | 1988 | 1994 | 1998 |
| Forest | 0.28 | 0.35 | 0.39 | 0.46 | 0.61 | 0.78 | 0.16 | 0.31 | 0.42 |
| Succession | 0.79 | 2.02 | 2.27 | 1.14 | 2.90 | 3.19 | 0.63 | 1.81 | 2.05 |
| Production | 1.20 | 1.08 | 1.27 | 1.68 | 1.55 | 1.80 | 0.79 | 0.81 | 1.15 |
| Others | 4.50 | 4.52 | 4.52 | 6.53 | 6.57 | 6.57 | 1.39 | 1.41 | 1.41 |

Table 31 - Mean Patch Size (MPS) for each class in Machadinho d'Oeste and Vale do Anari in 1988, 1994, and 1998

| MPS (ha) | MACHADINHO D'OESTE INCLUDING RESERVES | | | MACHADINHO D'OESTE EXCLUDING RESERVES | | | VALE DO ANARI | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1988 | 1994 | 1998 | 1988 | 1994 | 1998 | 1988 | 1994 | 1998 |
| Forest | 319.0 | 219.1 | 167.4 | 182.1 | 107.8 | 65.7 | 556.4 | 224.9 | 126.7 |
| Succession | 2.0 | 4.2 | 5.9 | 2.0 | 4.1 | 5.9 | 2.4 | 4.4 | 8.3 |
| Production | 7.0 | 12.9 | 15.0 | 7.2 | 12.9 | 15.2 | 13.5 | 27.8 | 25.2 |
| Others | 0.4 | 0.4 | 0.4 | 0.3 | 0.4 | 0.4 | 0.7 | 0.7 | 0.8 |

Table 32 - Patch Size Standard Deviation (PSSD) for each class in Machadinho d'Oeste and Vale do Anari in 1988, 1994, and 1998

| PSSD (ha) | MACHADINHO D'OESTE INCLUDING RESERVES | | | MACHADINHO D'OESTE EXCLUDING RESERVES | | | VALE DO ANARI | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1988 | 1994 | 1998 | 1988 | 1994 | 1998 | 1988 | 1994 | 1998 |
| Forest | 2864 | 1768 | 1313 | 1375 | 543 | 268 | 1829 | 940 | 585 |
| Succession | 3.1 | 9.4 | 14.1 | 3.1 | 9.1 | 13.9 | 3.9 | 9.2 | 19.9 |
| Production | 17.4 | 38.5 | 51.6 | 17.5 | 38.5 | 52.1 | 35.3 | 92.8 | 117.1 |
| Others | 5.6 | 7.0 | 8.3 | 5.5 | 6.6 | 6.6 | 7.1 | 7.7 | 8.7 |

Table 33 - Patch Size Coefficient of Variation (PSCV) for each class in Machadinho d'Oeste and Vale do Anari in 1988, 1994, and 1998

| PSCV (%) | MACHADINHO D'OESTE INCLUDING RESERVES | | | MACHADINHO D'OESTE EXCLUDING RESERVES | | | VALE DO ANARI | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1988 | 1994 | 1998 | 1988 | 1994 | 1998 | 1988 | 1994 | 1998 |
| Forest | 897.8 | 806.8 | 784.2 | 755.1 | 503.6 | 407.6 | 328.7 | 417.8 | 462.1 |
| Succession | 151.3 | 226.1 | 236.7 | 152.7 | 220.8 | 233.6 | 167.4 | 210.1 | 240.8 |
| Production | 246.7 | 299.3 | 344.3 | 245.3 | 298.5 | 341.8 | 261.2 | 334.0 | 464.1 |
| Others | 1595 | 1877 | 2116 | 1619 | 1814 | 1726 | 1018 | 1038 | 1106 |

Table 34 - Edge Density (ED) for each class in Machadinho d'Oeste and Vale do Anari in 1988, 1994, and 1998

| ED (m/ha) | MACHADINHO D'OESTE INCLUDING RESERVES | | | MACHADINHO D'OESTE EXCLUDING RESERVES | | | VALE DO ANARI | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1988 | 1994 | 1998 | 1988 | 1994 | 1998 | 1988 | 1994 | 1998 |
| **Forest** | 16.8 | 20.9 | 22.1 | 26.3 | 31.8 | 32.5 | 14.1 | 19.7 | 21.6 |
| **Succession** | 5.0 | 20.1 | 27.8 | 7.2 | 28.6 | 39.0 | 4.2 | 18.3 | 29.9 |
| **Production** | 16.4 | 20.8 | 26.3 | 23.4 | 29.9 | 37.8 | 15.6 | 23.3 | 29.9 |
| **Others** | 10.7 | 10.8 | 11.0 | 15.4 | 15.5 | 15.8 | 7.0 | 7.0 | 7.2 |

Table 35 - Landscape Shape Index (LSI) for each class in Machadinho d'Oeste and Vale do Anari in 1988, 1994, and 1998

| LSI | MACHADINHO D'OESTE INCLUDING RESERVES | | | MACHADINHO D'OESTE EXCLUDING RESERVES | | | VALE DO ANARI | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1988 | 1994 | 1998 | 1988 | 1994 | 1998 | 1988 | 1994 | 1998 |
| **Forest** | 23.2 | 31.3 | 35.5 | 31.2 | 42.5 | 49.2 | 14.1 | 22.2 | 27.6 |
| **Succession** | 51.8 | 90.2 | 98.6 | 51.4 | 89.6 | 97.0 | 32.3 | 60.4 | 67.7 |
| **Production** | 73.9 | 72.9 | 78.6 | 73.1 | 72.5 | 78.1 | 44.4 | 45.8 | 51.7 |
| **Others** | 111.1 | 108.7 | 107.6 | 111.4 | 109.2 | 107.9 | 65.7 | 64.1 | 64.0 |

Table 36 - Area Weighted Mean Shape Index (AWMSI) for each class in Machadinho d'Oeste and Vale do Anari in 1988, 1994, and 1998

| AWMSI | MACHADINHO D'OESTE INCLUDING RESERVES | | | MACHADINHO D'OESTE EXCLUDING RESERVES | | | VALE DO ANARI | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1988 | 1994 | 1998 | 1988 | 1994 | 1998 | 1988 | 1994 | 1998 |
| Forest | 7.5 | 6.2 | 6.0 | 7.8 | 5.4 | 4.5 | 3.5 | 4.7 | 5.1 |
| Succession | 1.5 | 1.9 | 2.2 | 1.6 | 1.9 | 2.2 | 1.6 | 1.9 | 2.3 |
| Production | 2.6 | 3.1 | 3.2 | 2.6 | 3.1 | 3.2 | 2.9 | 3.7 | 3.8 |
| Others | 2.8 | 3.5 | 4.8 | 2.6 | 2.8 | 3.0 | 11.6 | 10.8 | 11.1 |

Table 37 - Mean Core Area Index (MCAI) for each class in Machadinho d'Oeste and Vale do Anari in 1988, 1994, and 1998

| MCAI (%) | MACHADINHO D'OESTE INCLUDING RESERVES | | | MACHADINHO D'OESTE EXCLUDING RESERVES | | | VALE DO ANARI | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1988 | 1994 | 1998 | 1988 | 1994 | 1998 | 1988 | 1994 | 1998 |
| Forest | 4.1 | 6.9 | 8.8 | 5.5 | 8.8 | 9.6 | 12.5 | 7.3 | 6.4 |
| Succession | 0.2 | 0.9 | 1.6 | 0.2 | 0.9 | 1.6 | 0.5 | 1.1 | 2.4 |
| Production | 1.8 | 3.5 | 3.9 | 1.8 | 3.5 | 3.9 | 3.6 | 5.9 | 5.1 |
| Others | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |

Table 38 - Interspersion and Juxtaposition Index (IJI) for each class in Machadinho d'Oeste and Vale do Anari in 1988, 1994, and 1998.

| IJI (%) | MACHADINHO D'OESTE INCLUDING RESERVES | | | MACHADINHO D'OESTE EXCLUDING RESERVES | | | VALE DO ANARI | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1988 | 1994 | 1998 | 1988 | 1994 | 1998 | 1988 | 1994 | 1998 |
| **Forest** | 87.4 | 93.6 | 86.7 | 69.3 | 74.1 | 69.0 | 76.6 | 83.8 | 78.2 |
| **Succession** | 89.4 | 87.7 | 85.4 | 71.1 | 69.8 | 67.9 | 83.4 | 78.2 | 74.2 |
| **Production** | 86.2 | 98.0 | 94.3 | 68.7 | 77.8 | 74.6 | 83.2 | 95.3 | 88.7 |
| **Others** | 79.7 | 95.6 | 93.1 | 63.3 | 75.7 | 73.3 | 76.2 | 81.9 | 78.8 |

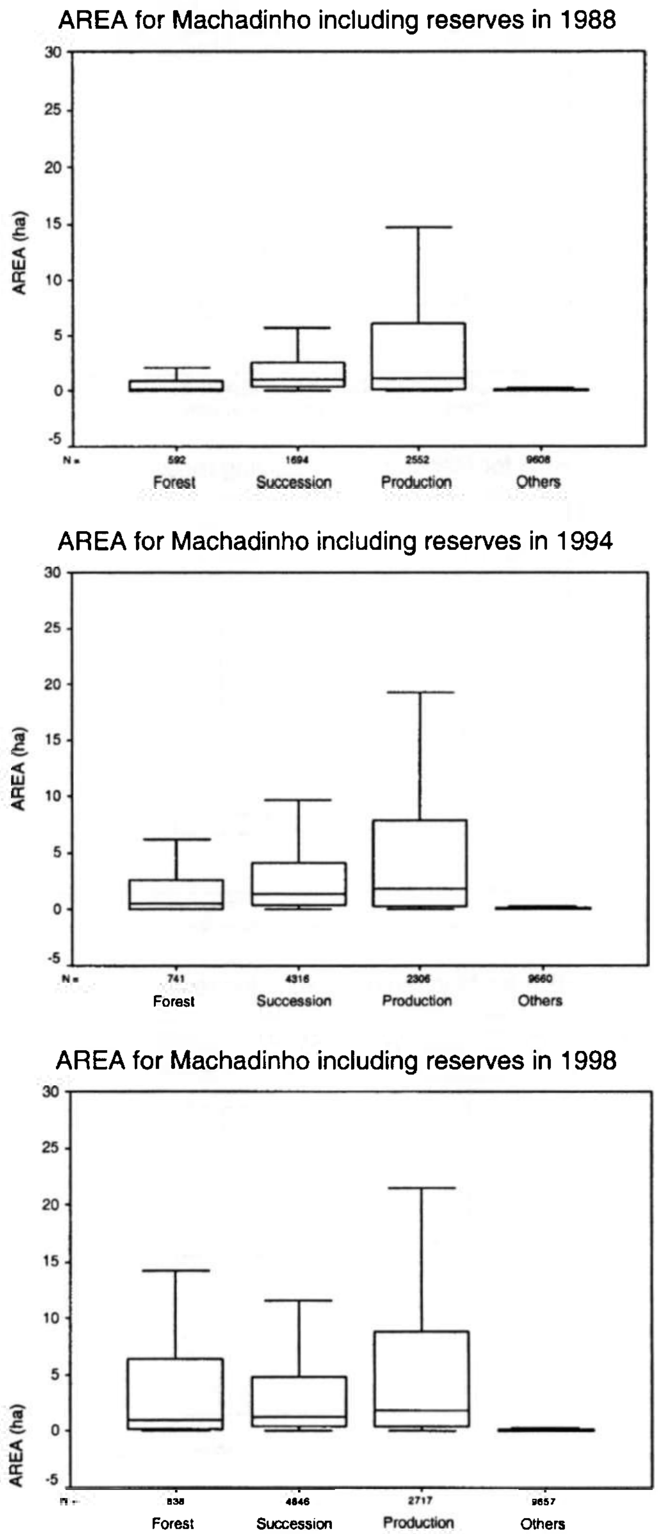


Figure 71 - Patch area distribution for Machadinho d'Oeste including reserves in 1988, 1994, and 1998

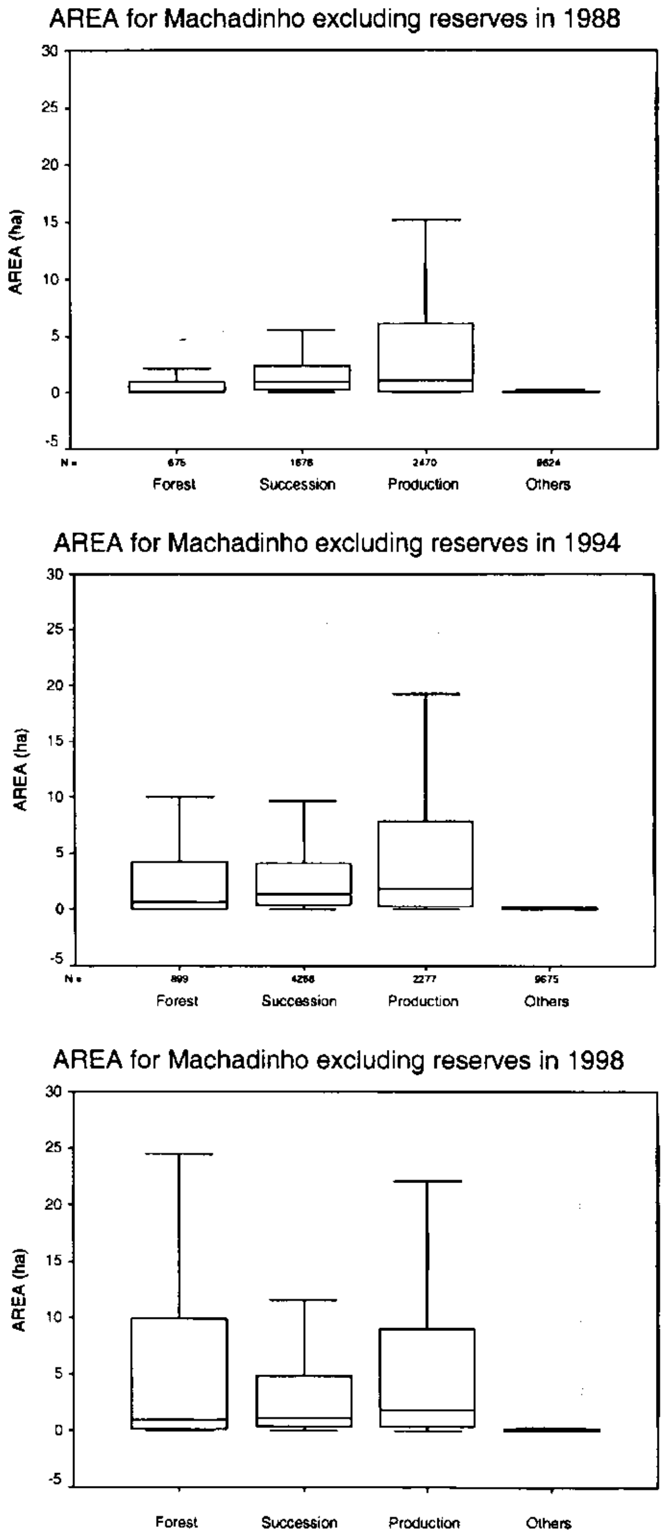


Figure 72 - Patch area distribution for Machadinho d'Oeste excluding reserves in 1988, 1994, and 1998

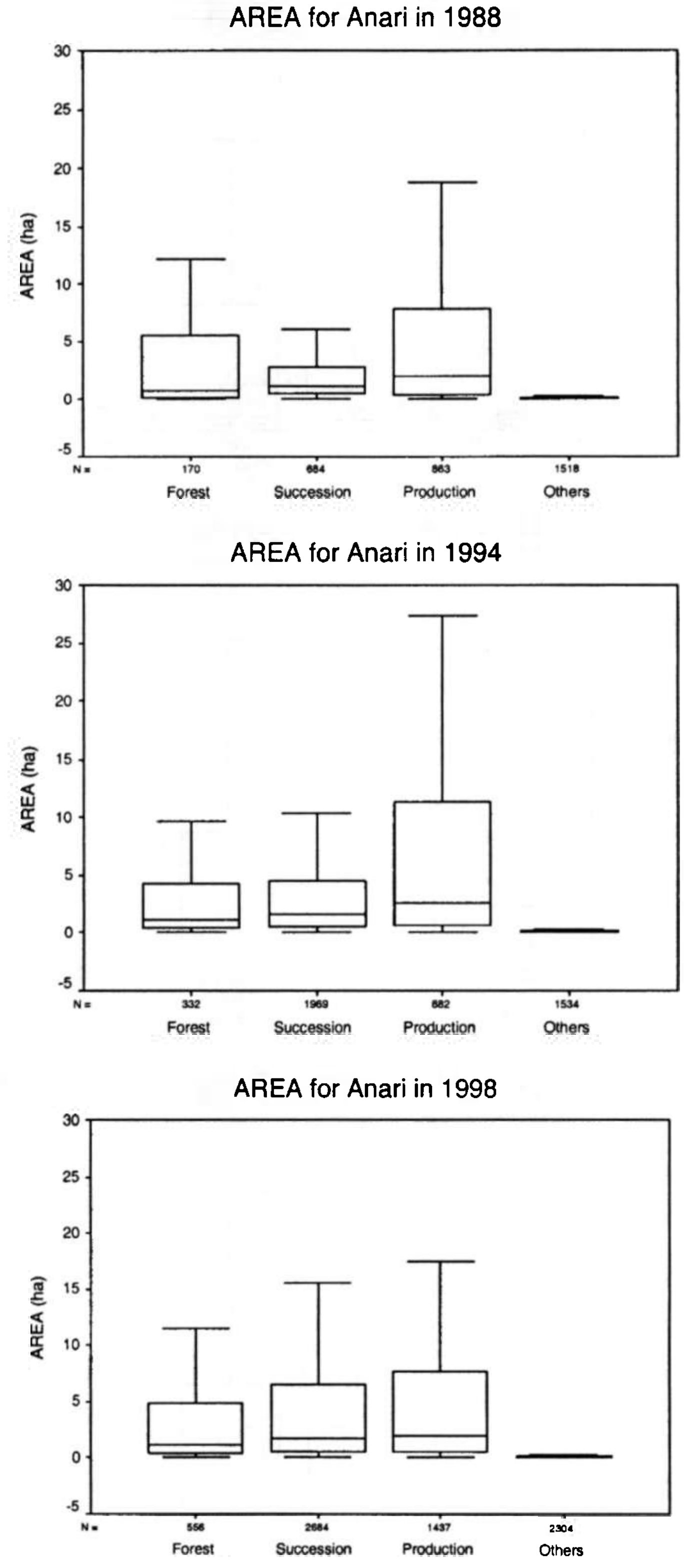


Figure 73 - Patch area distribution for Vale do Anari in 1988, 1994, and 1998

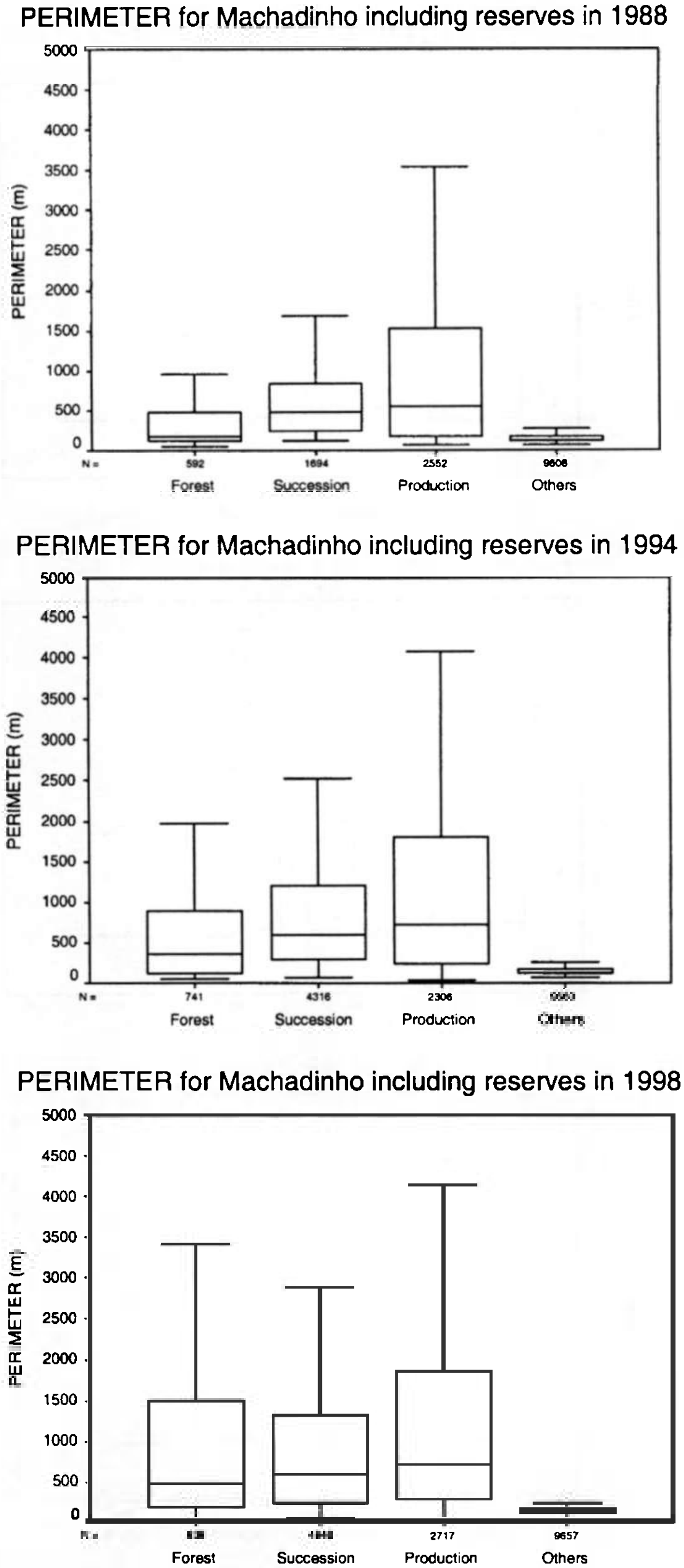


Figure 74 - Patch perimeter distribution for Machadinho d'Oeste including reserves in 1988, 1994, and 1998

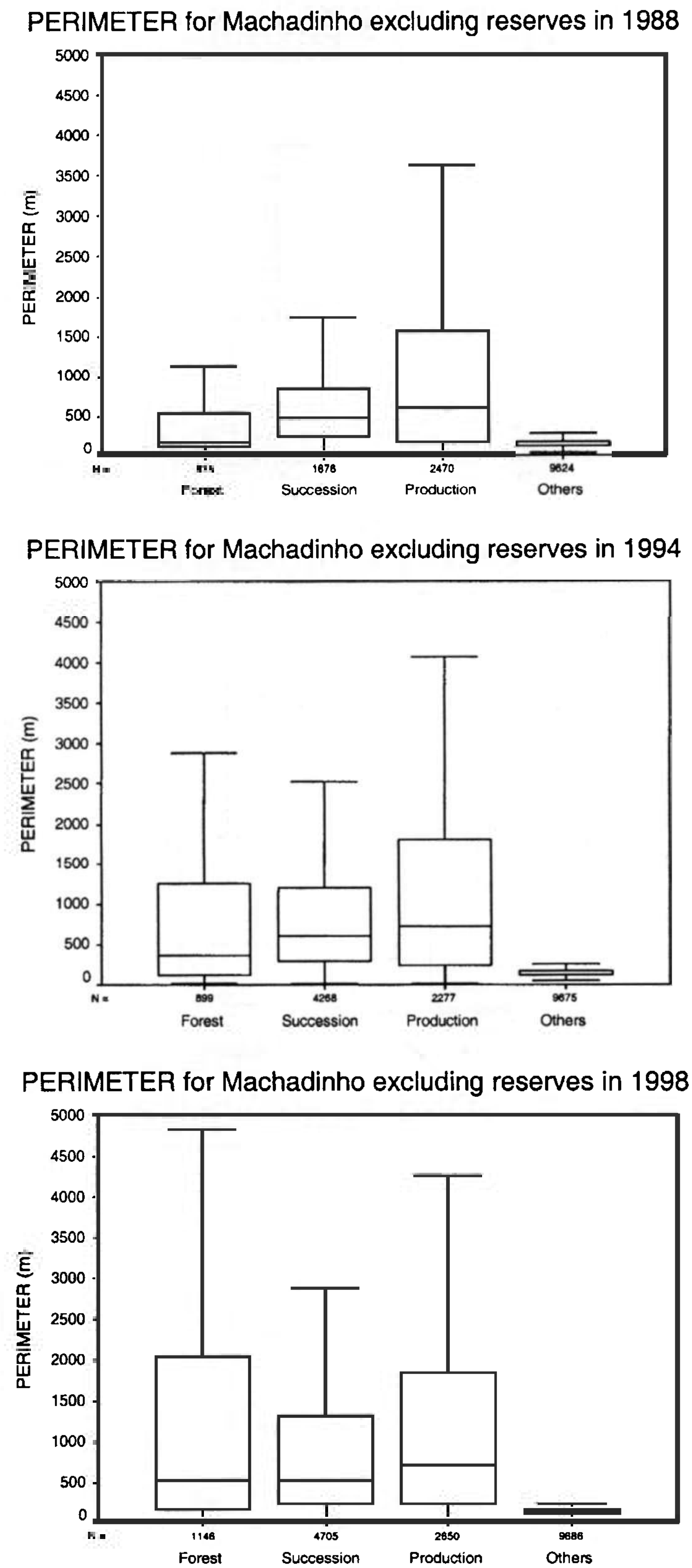


Figure 75 - Patch perimeter distribution for Machadinho d'Oeste excluding reserves in 1988, 1994, and 1998

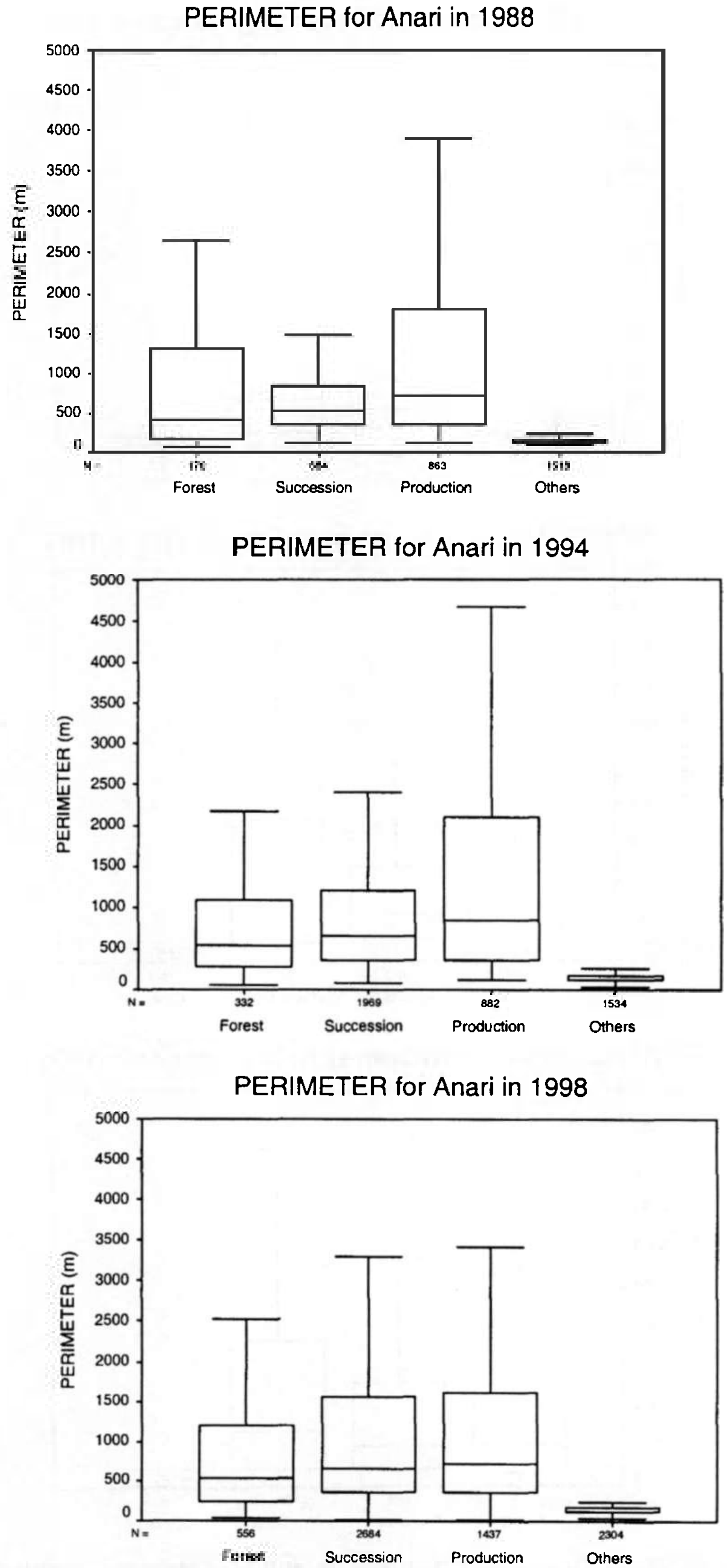


Figure 76 - Patch perimeter distribution for Vale do Anari in 1988, 1994, and 1998

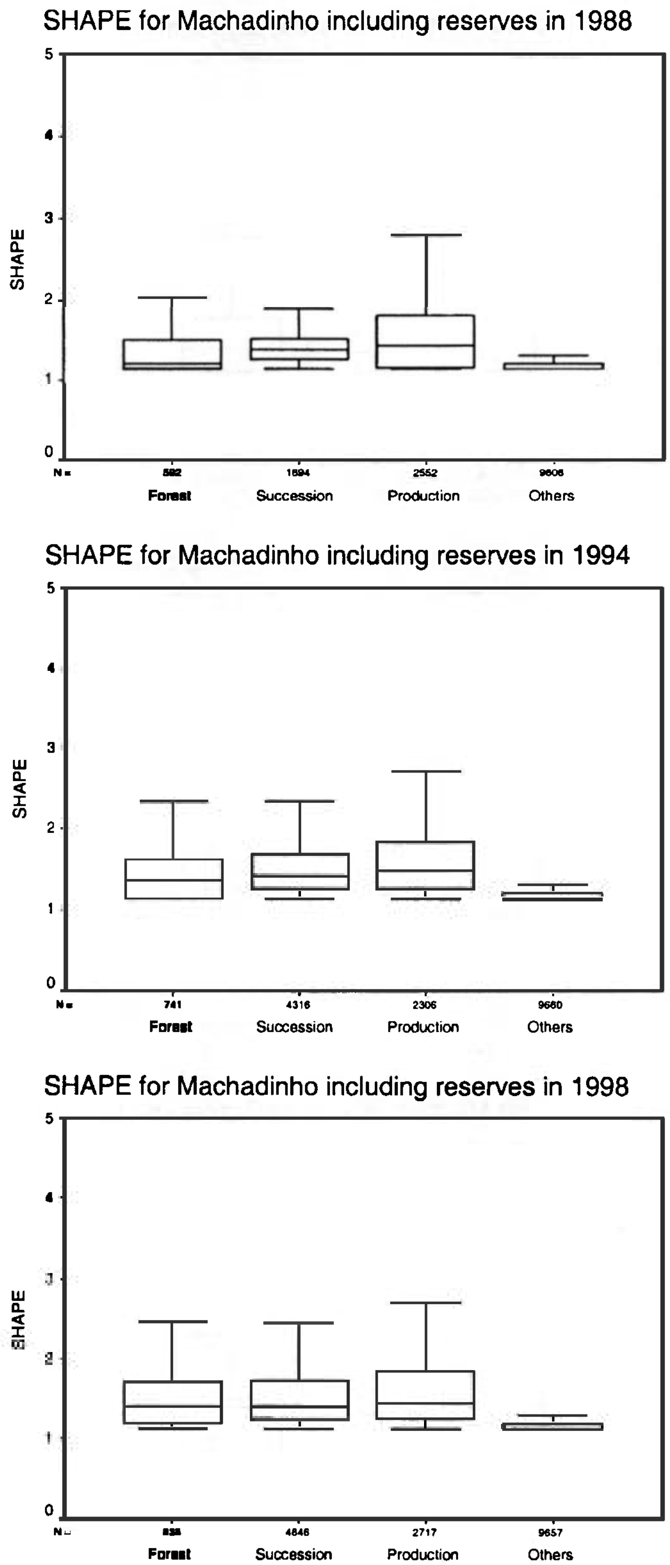


Figure 77 - Patch shape distribution for Machadinho d'Oeste including reserves in 1988, 1994, and 1998

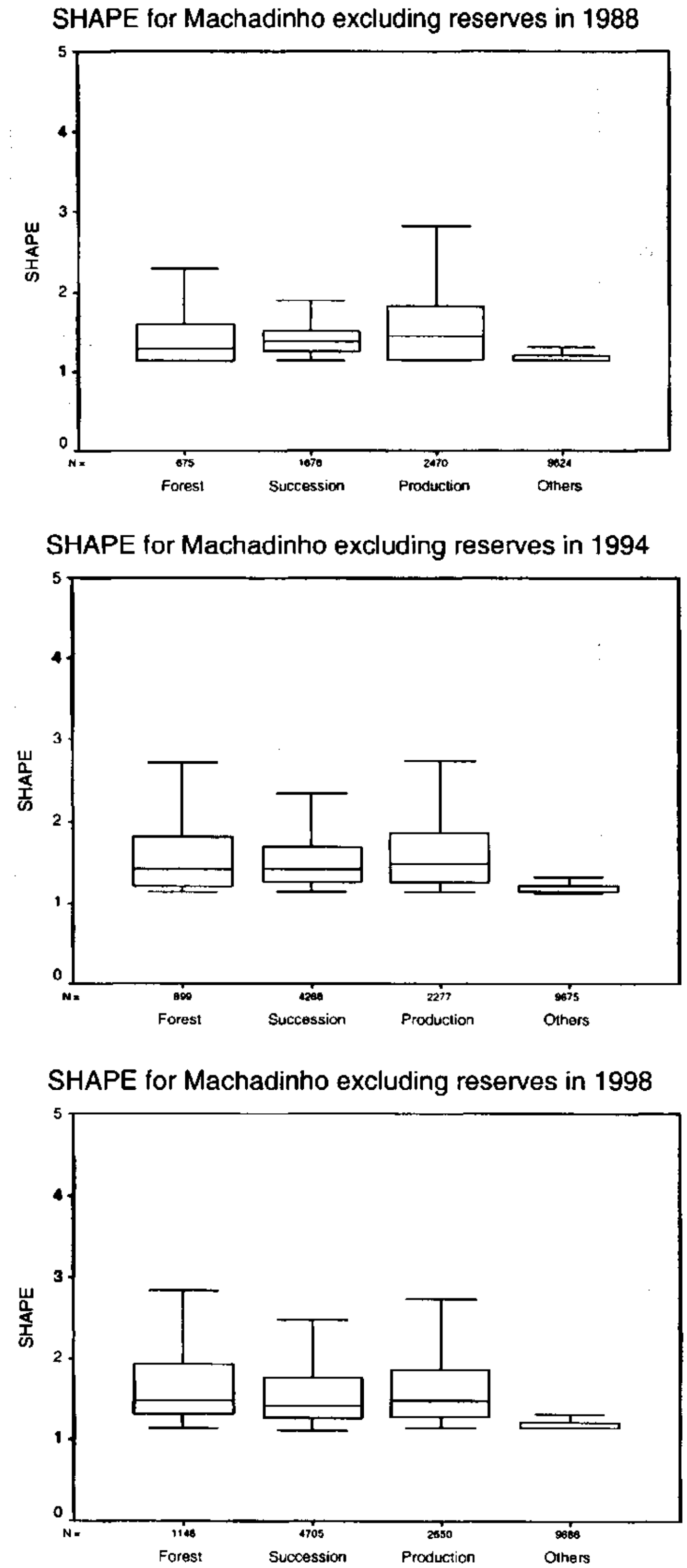


Figure 78 - Patch shape distribution for Machadinho d'Oeste excluding reserves in 1988, 1994, and 1998

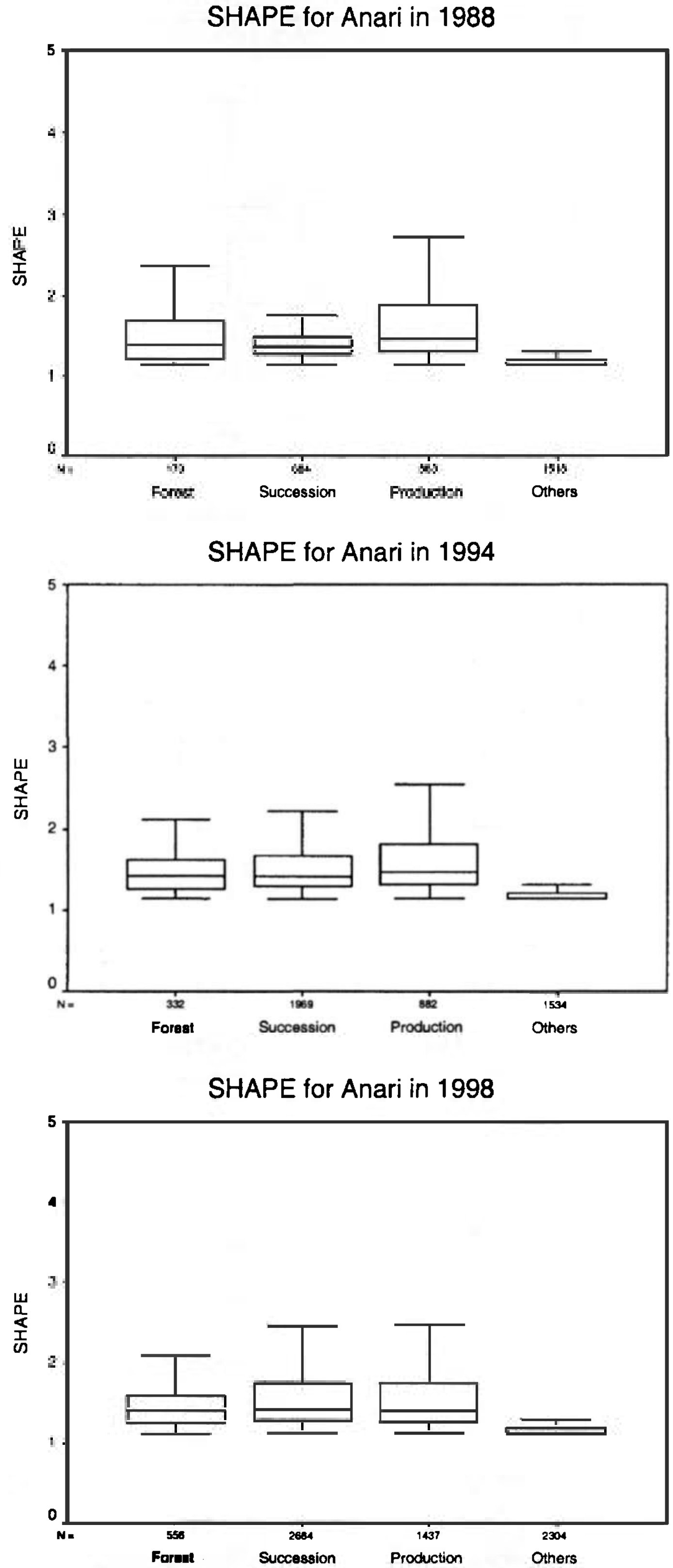


Figure 79 - Patch shape distribution for Vale do Anari in 1988, 1994, and 1998

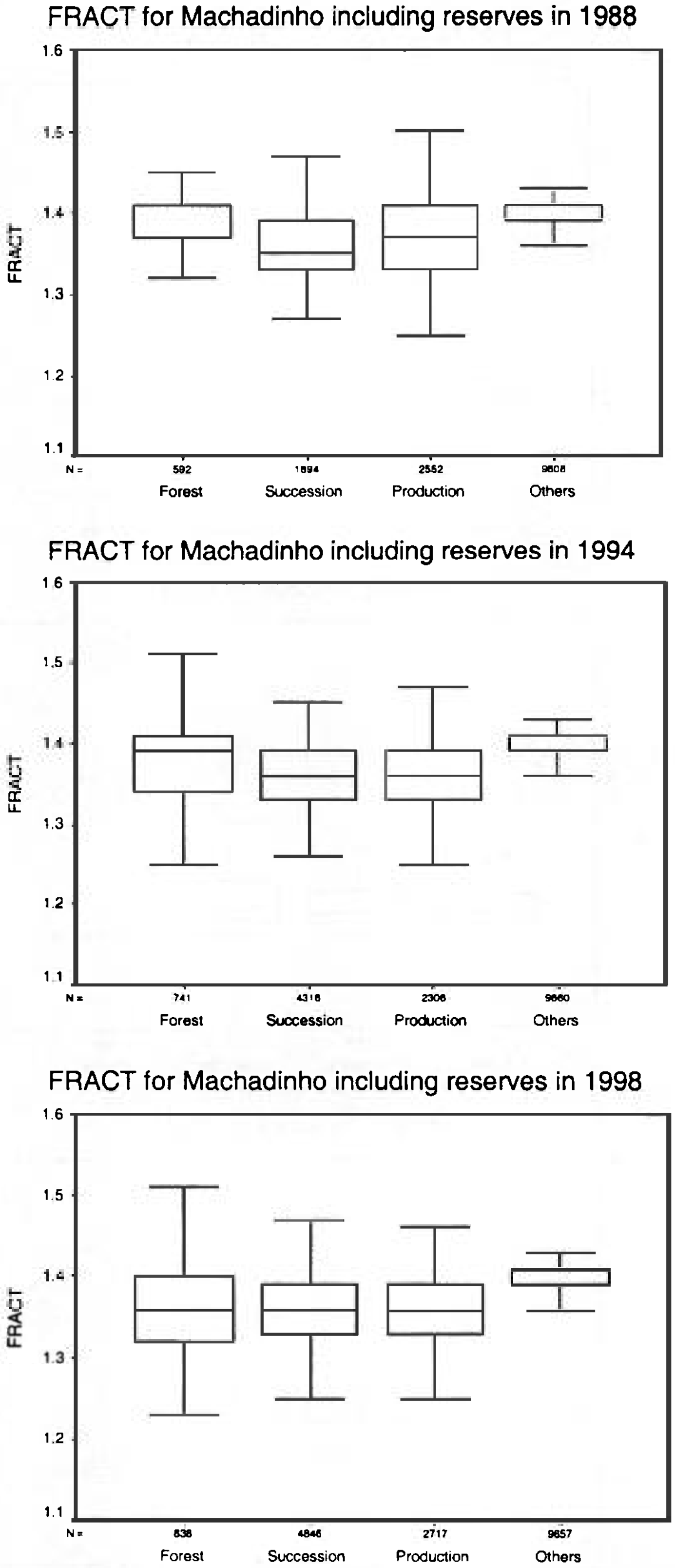


Figure 80 - Patch fractal dimension distribution for Machadinho d'Oeste including reserves in 1988, 1994, and 1998

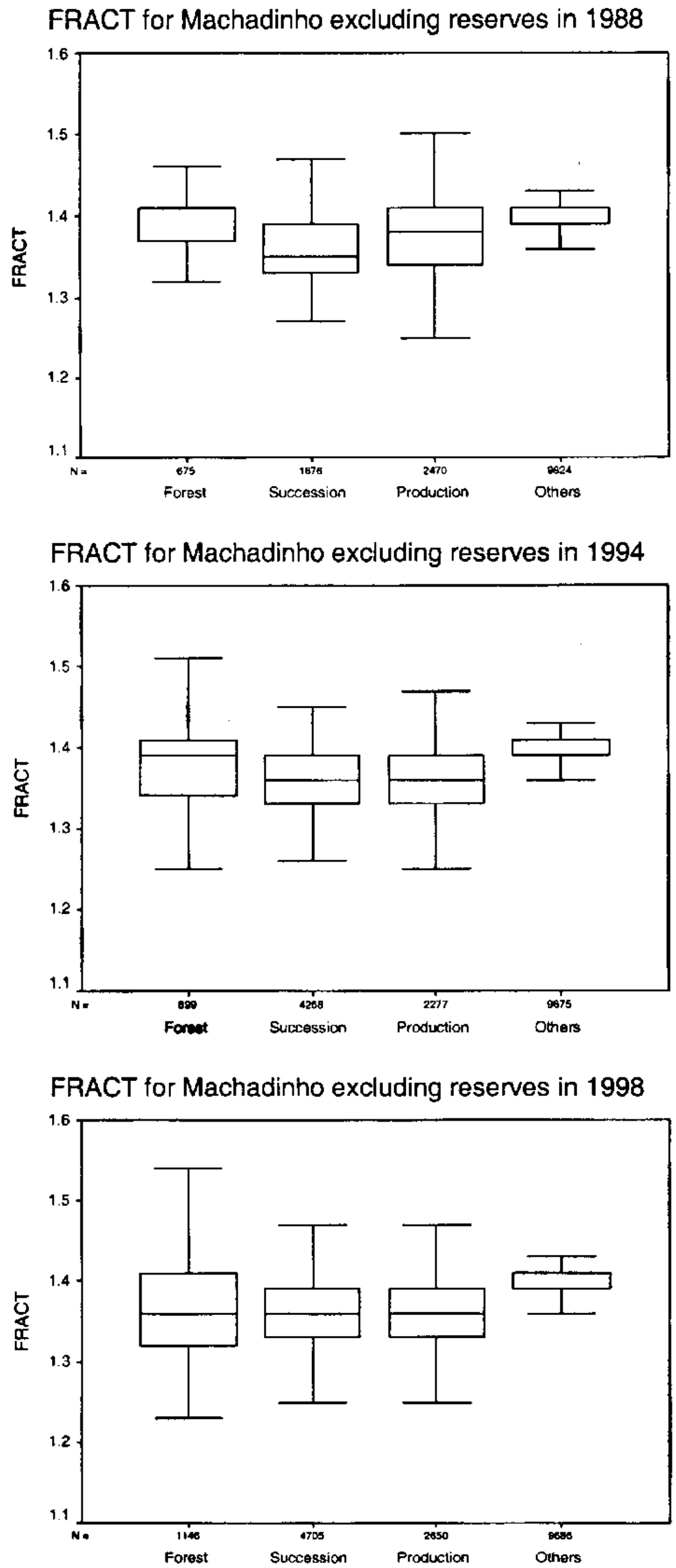


Figure 81 - Patch fractal dimension distribution for Machadinho d'Oeste excluding reserves in 1988, 1994, and 1998

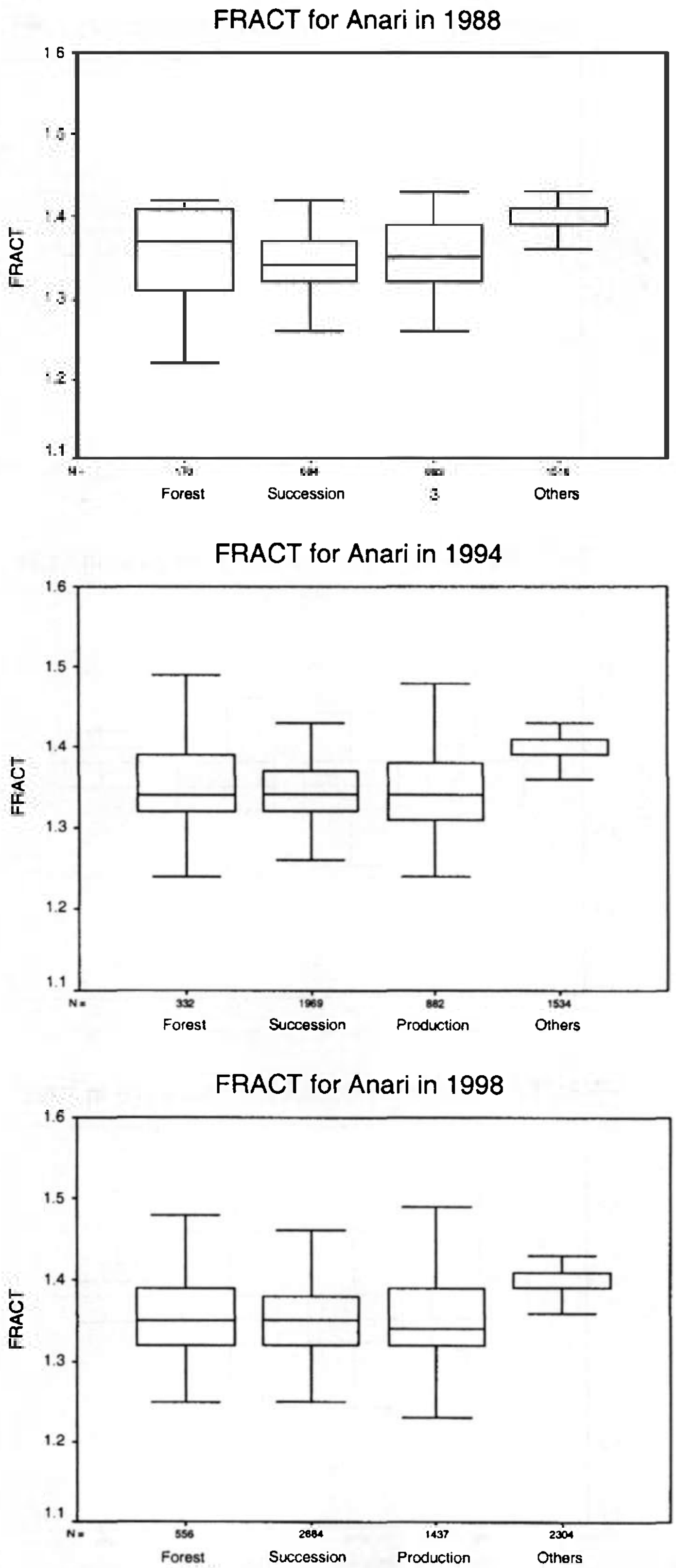


Figure 82 - Patch fractal dimension distribution for Vale do Anari in 1988, 1994, and 1998

Table 39 - Trends found for landscape metrics in Machadinho d'Oeste and Vale do Anari between 1988 and 1998

| | MACHADINHO D'OESTE INCLUDING RESERVES | MACHADINHO D'OESTE EXCLUDING RESERVES | VALE DO ANARI |
|---|---|---|---|
| **Metrics** | **1988-1998** | **1988-1998** | **1988-1998** |
| **LPI (%)** | - | -- | -- |
| **PD (#/100ha)** | + | + | + |
| **MPS (ha)** | - | - | - |
| **PSSD (ha)** | -- | -- | -- |
| **PSCV (%)** | - | -- | - |
| **ED (m/ha)** | + | + | ++ |
| **LSI** | + | + | ++ |
| **AWMSI** | - | -- | + |
| **TCAI (%)** | - | - | - |
| **MSIDI** | ++ | ++ | ++ |
| **MSIEI** | ++ | ++ | ++ |
| **IJI (%)** | + | + | + |

Legend: - = decrease less than twofold

-- = decrease more than twofold

o = equal

\+ = increase less than twofold

++ = increase more than twofold

Table 40 - Trends found for class metrics in Machadinho d'Oeste and Vale do Anari between 1988 and 1998

| | MACHADINHO D'OESTE INCLUDING RESERVES | | | | MACHADINHO D'OESTE EXCLUDING RESERVES | | | | VALE DO ANARI | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Metrics** | **F** | **S** | **P** | **O** | **F** | **S** | **P** | **O** | **F** | **S** | **P** | **O** |
| **PLAND (%)** | - | ++ | ++ | + | - | ++ | ++ | + | - | ++ | ++ | + |
| **LPI (%)** | - | ++ | ++ | + | -- | ++ | ++ | + | -- | ++ | ++ | + |
| **PD (#/100ha)** | + | ++ | + | + | + | ++ | + | + | ++ | ++ | + | + |
| **MPS (ha)** | - | ++ | ++ | o | -- | ++ | ++ | + | -- | ++ | + | + |
| **PSSD (ha)** | -- | ++ | ++ | + | -- | ++ | ++ | + | -- | ++ | ++ | + |
| **PSCV (%)** | - | + | + | + | - | + | + | + | + | + | + | + |
| **ED (m/ha)** | + | ++ | + | + | + | ++ | + | + | + | ++ | + | + |
| **LSI** | + | + | + | + | + | + | + | + | + | ++ | + | - |
| **AWMSI** | - | + | + | + | - | + | + | + | + | + | + | - |
| **MCAI (%)** | ++ | ++ | ++ | o | + | ++ | ++ | o | - | ++ | + | o |
| **IJI (%)** | - | - | + | + | - | - | + | + | + | - | + | + |

Legend: F (Forest), S (Succession), P (Production), O (Others), - (decrease less than twofold), -- (decrease more than twofold), o (equal), + (increase less than twofold), ++ (increase more than twofold)

# APPENDIX 2

## FORMULAS USED FOR THE COMPUTATION OF METRICS FOR LANDSCAPES, CLASSES, AND PATCHES IN MACHADINHO D'OESTE AND VALE DO ANARI (McGarigal and Marks 1995)

| Term | Definition |
|---|---|
| $E'$ | Total length (m) of edge in landscape; includes entire landscape boundary and background edge segments regardless of whether they represent true edge |
| $e_{ik}$ | Total length (m) of edge in landscape between patch types (classes) i and k; includes landscape boundary segments representing tree edge only involving patch type i |
| $e'_{ik}$ | Total length (m) of edge in landscape between patch types (classes) i and k; includes all landscape boundary and background edge segments involving patch type i, regardless of whether they represent true edge |
| $e''_{ik}$ | Total length (m) of edge in landscape between patch types (classes) i and k; includes the entire landscape boundary and background edge segments, regardless of whether they represent true edge |
| $N$ | Total number of patches in the landscape, excluding any background patches |
| $n = n_i$ | Number of patches in the landscape of patch type (class) i |
| $n_{ij}^{c}$ | Number of disjunct core areas in patch ij based on specified buffer width (m) |
| $m$ | Number of patch types (classes) present in the landscape, excluding the landscape border if present |
| $m'$ | Number of patch types (classes) present in the landscape, including the landscape border if present |
| $m_{max}$ | Maximum number of patch types (classes) present in a landscape |
| $g_{ik}$ | Number of adjacencies (joins) between pixels of patch types (classes) i and k |
| $P_i$ | Proportion of the landscape occupied by patch type (class) i |

| Term | Definition |
|---|---|
| Subscripts: | |
| $i$ | 1, ... , m or m′ patch types (classes) |
| $j$ | 1, ... , n patches |
| $k$ | 1, ... , m or m′ patch types (classes) |
| Symbols: | |
| $A$ | Total landscape area ($m^2$) |
| $a_{ij}$ | Area ($m^2$) of patch ij |
| $a_{ijs}$ | Area ($m^2$) of patch ijs within specified neighborhood (m) of patch ij |
| $a_{ij}^c$ | Core area ($m^2$) of patch ij based on specified buffer width (m) |
| $a_{ijq}^c$ | Area ($m^2$) of disjunct core area q in patch ij based on specified buffer width (m) |
| $p_{ij}$ | Perimeter (m) of patch ij |
| $p_{ijk}$ | Length (m) of edge of patch ij adjacent to patch type (class) k |
| $E$ | Total length (m) of edge in landscape; includes landscape boundary and background edge segments if the user decides to treat boundary and background as edge; otherwise, only boundary segments representing true edge are included |

## METRICS USED FOR LANDSCAPES

- LARGEST PATCH INDEX: percentage of landscape accounted for by largest patch

$$LPI = \frac{\max_{j=1}^{n}(a_{ij})}{A}(100)$$

Units: Percent.

Range: $0 < LPI \leq 100$.

- PATCH DENSITY: number of patches per 100 ha for a landscape

$$PD = \frac{N}{A}(10{,}000)(100)$$

Units: Number per 100 hectares.

Range: PD > 0, without limit.

- MEAN PATCH SIZE: average patch size for a landscape

$$MPS = \frac{A}{N}\left(\frac{1}{10{,}000}\right)$$

Units: Hectares.

Range: MPS > 0, without limit.

- PATCH SIZE STANDARD DEVIATION: population standard deviation for patch sizes of a landscape

$$PSSD = \sqrt{\frac{\sum_{i=1}^{m}\sum_{j=1}^{n}\left[a_{ij} - \left(\frac{A}{N}\right)\right]^2}{N}}\left(\frac{1}{10{,}000}\right)$$

Units: Hectares.

Range: PSSD ≥ 0, without limit.

- PATCH SIZE COEFFICIENT OF VARIATION: population coefficient of variation in patch size relative to the mean patch size for a landscape

$$PSCV = \frac{PSSD}{MPS}(100)$$

Units: Percent.

Range: PSCV ≥ 0, without limit.

- EDGE DENSITY: length of edge per hectare for a landscape

$$ED = \frac{E}{A}(10{,}000)$$

Units: Meters per hectare.

Range: ED ≥ 0, without limit.

- LANDSCAPE SHAPE INDEX: ratio of sum of edge lengths to total area for a landscape measured against a circle standard

$$LSI = \frac{E'}{2\sqrt{\pi \circ A}}$$

Units: None.

Range: LSI ≥ 1, without limit.

- AREA-WEIGHTED MEAN SHAPE INDEX: average perimeter-to-area ratio for a landscape, weighted by the size of its patches

$$AWMSI = \sum_{i=1}^{m}\sum_{j=1}^{n}\left[\left(\frac{p_{ij}}{2\sqrt{\pi \circ a_{ij}}}\right)\left(\frac{a_{ij}}{A}\right)\right]$$

Units: None.

Range: AWMSI ≥ 1, without limit.

- TOTAL CORE AREA INDEX: core area defined by specified edge distance from the patch perimeter for the entire landscape as a percentage of total landscape area

$$TCAI = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n} a_{ij}^{c}}{A}(100)$$

Units: Percent.

Range: 0 ≤ TCAI < 100.

- MODIFIED SIMPSON'S DIVERSITY INDEX: proportional abundance of each patch type within the landscape

$$MSIDI = -\ln \sum_{i=1}^{m} P_i^2$$

Units: None.

Range: MSIDI ≥ 0.

- MODIFIED SIMPSON'S EVENNESS INDEX: measurement of the distribution of area among patch types within the landscape

$$MSIEI = \frac{-\ln \sum_{i=1}^{m} P_i^2}{\ln m}$$

Units: None.

Range: 0 ≤ MSIEI ≤ 1.

- INTERSPERSION AND JUXTAPOSITION INDEX: observed interspersion divided by maximum interspersion for the patch types in a landscape

$$IJI = \frac{-\sum_{i=1}^{m'} \sum_{k=i+1}^{m'} \left[\left(\frac{e_{ik}}{E}\right) \circ \ln\left(\frac{e_{ik}}{E}\right)\right]}{\ln(\frac{1}{2}[m'(m'-1)])} (100)$$

Units: Percent.

Range: 0 < IJI ≤ 100.

## METRICS USED FOR CLASSES

- PERCENTAGE OF LANDSCAPE: percentage of landscape accounted for a class

$$\%LAND = P_i = \frac{\sum_{j=1}^{n} a_{ij}}{A}(100)$$

Units: Percent.

Range: 0 < %LAND ≤ 100.

- LARGEST PATCH INDEX: percentage of class accounted for by largest patch

$$LPI = \frac{\max_{j=1}^{n}(a_{ij})}{A}(100)$$

Units: Percent.

Range: 0 < LPI ≤ 100.

- PATCH DENSITY: number of patches per 100 ha for a class

$$PD = \frac{n_i}{A}(10{,}000)(100)$$

Units: Number per 100 hectares.

Range: PD > 0, without limit.

- MEAN PATCH SIZE: average patch size for a class

$$MPS = \frac{\sum_{j=1}^{n} a_{ij}}{n_i}\left(\frac{1}{10{,}000}\right)$$

Units: Hectares.

Range: MPS > 0, without limit.

- PATCH SIZE STANDARD DEVIATION: population standard deviation for patch sizes of a class

$$PSSD = \sqrt{\frac{\sum_{j=1}^{n}\left[a_{ij} - \left(\frac{\sum_{j=1}^{n} a_{ij}}{n_i}\right)\right]^2}{n_i}}\left(\frac{1}{10{,}000}\right)$$

Units: Hectares.

Range: PSSD ≥ 0, without limit.

- PATCH SIZE COEFFICIENT OF VARIATION: population coefficient of variation in patch size relative to the mean patch size for a class

$$PSCV = \frac{PSSD}{MPS}(100)$$

Units: Percent.

Range: PSCV ≥ 0, without limit.

- EDGE DENSITY: length of edge per hectare for a class

$$ED = \frac{\sum_{k=1}^{m'} e_{ik}}{A}(10{,}000)$$

Units: Meters per hectare.

Range: ED ≥ 0, without limit.

- LANDSCAPE SHAPE INDEX: ratio of sum of edge lengths to total area for a class measured against a circle standard

$$LSI = \frac{\sum_{k=1}^{m} e_{ik}^{''}}{2\sqrt{\pi} \circ A}$$

Units: None.

Range: LSI ≥ 1, without limit.

- AREA-WEIGHTED MEAN SHAPE INDEX: average perimeter-to-area ratio for a class, weighted by the size of its patches

$$AWMSI = \sum_{j=1}^{n} \left[ \left( \frac{p_{ij}}{2\sqrt{\pi} \circ a_{ij}} \right) \left( \frac{a_{ij}}{\sum_{j=1}^{n} a_{ij}} \right) \right]$$

Units: None.

Range: AWMSI ≥ 1, without limit.

- MEAN CORE AREA INDEX: average of core areas defined by specified edge distance from the patch perimeter for the entire class as a percentage of total class area

$$MCAI = \frac{\sum_{j=1}^{n} \left( \frac{a_{ij}^{c}}{a_{ij}} \right)}{n_i} (100)$$

Units: Percent.

Range: 0 ≤ MCAI < 100.

- INTERSPERSION AND JUXTAPOSITION INDEX: observed interspersion divided by maximum interspersion for patches in a class

$$IJI = \frac{-\sum_{k=1}^{m'} \left[ \left( \frac{e_{ik}}{\sum_{k=1}^{m'} e_{ik}} \right) \ln \left( \frac{e_{ik}}{\sum_{k=1}^{m'} e_{ik}} \right) \right]}{\ln (m' - 1)} (100)$$

Units: Percent.

Range: $0 < IJI \leq 100$.

## METRICS USED FOR PATCHES

- AREA: area of the patch in hectares

Vector

$$AREA = a_{ij} \left( \frac{1}{10{,}000} \right)$$

Units: Hectares.

Range: AREA > 0, without limit.

- PERIMETER: perimeter of the patch, including any internal holes in the patch

Vector

$$PERIM = p_{ij}$$

Units: Meters.

Range: PERIM > 0, without limit.

- SHAPE INDEX: ratio of sum of edge lengths to total area for a patch, measured against a circle standard

$$SHAPE = \frac{p_{ij}}{2\sqrt{\pi \circ a_{ij}}}$$

Units: None.

Range: SHAPE ≥ 1, without limit.

- FRACTAL DIMENSION: degree of complexity of patches based on a perimeter-to-area ratio

$$FRACT = \frac{2 \ln p_{ij}}{\ln a_{ij}}$$

Units: None.

Range: 1 ≤ FRACT ≤ 2.

# CHAPTER 6

# BEYOND THE METRICS: HUMAN DIMENSIONS OF LANDSCAPE CHANGE

*'Dormia produtor, acordava associado'*

## 6.1 - UNDERSTANDING THE HUMAN DIMENSIONS OF LANDSCAPE CHANGE

In modern human history, the loss of forest cover has been a persistent phenomenon. Civilizations have systematically 'cleared' extensive areas previously covered by forests as a way to occupy their territories (FAO 1999). Many causes, consequences, and responses to these processes have been suggested, depending on the culture and environment under analysis. In the tropics, where the trend of deforestation remains consistent, the subject has stimulated violent discussions (Whitmore 1998).

B. Turner et al. (1993) have proposed four categories of driving forces affecting LULC change: variables that affect demand, variables that determine the intensity of land use, variables that reflect access to resources, and variables that create incentives. Others have emphasized specific aspects related to these categories, such as environmental conditions and accessibility, macroeconomic changes, cultural characteristics influencing patterns of colonization and development, economic aspects (i.e. demand and value of timber and non-timber forest products), tenure security, institutional arrangements, among others (Angelsen 1995, Kaimowitz et al. 1999, Mertens et al. 2000). As a counterpart of the process, afforestation dynamics (i.e., the return of forest cover to lands previously deforested) have also been noted (Moran et al. 1996). The ever-increasing information about LULC processes has helped to draw a better picture about past dynamics and future scenarios within forest environments. The attractive subject has been the focus of several research initiatives (Skole et al. 1994, Turner et al. 1994, B. Turner et al. 1995, National Research Council 1998).

Landscape change in the Brazilian Amazon has been associated with land occupation in agroecological frontiers (Moran and Brondizio 1998, Woods and Skole 1998). Facing the biocomplexity of those lands and the adversity of living there, local communities and migrants to the region have used different strategies to cope with the needs of production and subsistence (Uhl and Subler 1988, Hecht and Cockburn 1990). The subject has attracted a great deal of attention, not because it is a new phenomenon but because important environmental and socioeconomic outcomes are linked to this discussion (Schmink and Wood 1992).

Several causes of deforestation have been discussed for the Amazon region (Fearnside 1989a, Southgate et al. 1991, Moran 1993b, Painter and Durham 1995, Pfaff 1999). In particular, ultimate and proximate causes have been analyzed as variables defining the structure of incentives toward land-use decisions. The latter gives rise to or controls the proximate causes, which have direct effect on decision-making situations regarding the use of natural resources (Turner et al. 1990). Development strategies and socioeconomic dynamics due to geopolitical reasons, population migration, line credits, and tax incentives have been indicated as general ultimate forces driving LULC change within the region (Fearnside 1987, Binswanger 1991). The conversion of forests to pasture seems to be a general outcome in both small and large properties (Hecht 1993, Walker et al. 2000).

Institutional arrangements and rules-in-use among local social actors may function as proximate causes defining opportunities and constraints to individuals in regard to the use of environmental resources (FAO 1999, Gibson et al. 2000). A broad way to define 'institutions' is through a 'set of formal and informal rules and norms that shape interactions of humans with others and nature' (Agarwal and Gibson 1999). Institutional factors can influence incentives toward land-use decisions through the implementation of a system of rules or through the rearrangement of rules. The former are given starting (or turning) points that strongly define (or redefine) the social and biophysical context in which land-use decisions take place. They shape incentives to users by delineating the initial boundaries for decision-making processes. The latter are dynamic changes in social and biophysical context that continuously modify the structure of incentives toward the use of natural resources according to each user group.

A major challenge in understanding this double-sided trajectory is to depict how multi-tiered rules affect individual decisions regarding landscape transformation (Moran et al. 1998, Leach et al. 1999). For instance, while the initial establishment of rules, such as the land-titling system, the architectural design of settlements, the access to infrastructure, and rules for the use of natural resources may define land access, other rules shaped during the process of colonization and development may affect the type of use (or lack of use) by each user group. As a result, the diversity of situations involving multiple actors, biophysical features, and rules leads to a mosaic of land-use trajectories and landscape patterns.

In the Brazilian Amazon and particularly in Rondônia, government-sponsored projects of rural settlement represent an illustrative example of how institutions can trigger a complex landscape-change process. These rural settlements have been implemented through a pre-defined institutional design, which includes initial rules affecting the path to land-use decisions. Despite their primary goal of providing land for small farmers, the establishment of settlements typically brings along a complex social structure including multiple actors, such as loggers, extractivists, and cattle ranchers. As the initial institutional design is adjusted to local realities, new incentives and constraints arise, creating distinct patterns of interaction and variation in land-use decisions. As a result, landscape-change processes vary according to the combination of user groups involved and the ruling system in use. On the other hand, the environmental context including the architectural design in which actors interact defines resources to be used or limits factors with which to cope.

Chapters 4 and 5 discussed the outcomes of colonization processes in Machadinho and Anari regarding LULC dynamics and landscape change. This chapter analyzes factors interfering in these processes from an institutional perspective with focus on how different architectural and institutional designs have produced distinct outcomes in Rondônia. The itinerary includes a discussion of ultimate driving forces and proximate causes of landscape change. Not always is the interrelation between causes and outcomes direct or easily identifiable. However, a hierarchical approach helps to understand the intricate mosaic of interactions between people and environment. In particular, as a study of 'human-altered landscapes,' the chapter explores national-to-local level factors affecting the study areas, the historical role of people causing landscape disturbances, and the differences and similarities between the two settlements under investigation.

Most of this chapter is based on extensive fieldwork and interviews with local individuals in both Machadinho and Anari urban and rural areas. More than one hundred people were interviewed during 6 weeks in 1999 and 4 weeks in 2000. The interviewees included farmers, loggers, rubber tappers, politicians (e.g., mayors, cabinet staff, city councilors), the catholic priest, evangelic ministers, governmental and non-governmental heads, local leaders, and individuals in general.

## 6.2 - THE STRUCTURE OF RULES AND INCENTIVES AFFECTING LAND USE IN MACHADINHO AND ANARI

The occupation of the Brazilian Amazon is taking place through several mechanisms, including governmental and private programs, and spontaneous colonization. In all cases, local population growth occurs, mainly through migration during the settlements' implementation phase. Different levels of land-use decision making are involved. International, national, regional, and local incentives, rules, and policies affect the process, the environmental outcomes, as well as the socioeconomic conditions present in that portion of the country of relatively difficult access. Attributes of the local community and biophysical attributes of landscapes set the scenarios for individual decisions. Figure 83 illustrates a multi-tiered framework to address factors affecting landscape change. The approach is based on the Institution Analysis and Development framework (Ostrom 1997), where actors within an action arena interact and adapt according to environmental attributes, community attributes, and rules-in-use. From the operational standpoint, the analysis of these processes within the research in Rondônia was derived from a multi-temporal and multi-spatial approach about the study area and its actors (Figure 84).

The first step was the choice of boundaries. As stated in Ostrom et al. (1994), it is not easy to distinguish where one situation ends and the next one begins. However, for analytical purposes it is essential to define boundaries in space and time in order to focus on specific events. This chapter, as the rest of the dissertation, focuses on the settlements of Machadinho and Anari, considering their administrative boundaries as implemented by INCRA. The time frame went back to the early 1980s to ensure a broader context about processes and patterns of interactions occurring within the study area.

Figure 85 illustrates a sequence of events occurring at national, regional, and local contexts during Machadinho and Anari implementation and consolidation phases. These events affected the action arena and the actors' decision-making processes through time, leading to social and environmental outcomes. For the purpose of this analysis, the so-called actors (i.e., loggers and settlers in Anari, and loggers, settlers, and rubber tappers in Machadinho) are the direct agents of landscape change. They take actions concerning the land, clearing areas, managing natural resources, and developing production systems.

Figure 86 illustrates the main actions taken by settlers, rubber tappers, and loggers on private properties and communal reserves in Machadinho and Anari.

Settlers had access to land through elimination and classification criteria based on socioeconomic assets and carried out by INCRA. The process of choice of property lots was somewhat chaotic and sometimes involved corruption. Conflict resolution between new settlers and previous occupants of the land (*posseiros*) was in general mediated by INCRA, but often involved violence. The action of *grileiros* also caused problems for settlers. They often took over the land from weakened households. The situation involved persuasion (i.e., convincing illiterate settlers that they did not have the right to use the lot) or violence (i.e., expelling families of settlers under threat of murder). In the early 1980s, the general picture in Machadinho and Anari included families of settlers from south and southeast Brazil coping with their environmental and social opportunities and constraints in searching for a better life at an Amazonian agroecological frontier.

Rubber tappers have lived in the study area since the late 1800s. They are mostly descendants of northeastern migrants to Rondônia during the rubber boom. The saga of rubber tappers in the Amazon has been extensively described and will not be discussed in detail here. One of the most important changes in their function as social actors occurred recently with the creation of extractive reserves throughout the Amazon (Allegretti 1989, Miranda et al. 1990, Anderson 1992). Specifically, they have played a central role in Machadinho, where extractive reserves were included within the settlement design. The right to use natural resources within the reserves is restricted to rubber tappers. They also had the opportunity to apply for property lots. In fact, some reserves have rubber tappers living in the reserves' surroundings. In this case, the distinction between these two groups of actors (i.e., settlers and rubber tappers) is somewhat interrelated. Besides this specific situation, they inhabit the reserves and make their living through a subsistence economy.

Loggers represent another important group of actors at rural settlements in Amazônia (Browder 1986, Almeida and Uhl 1995). They often exploit timber resources in all phases of a settlement according to the availability of economic species and rules of access to forests. Illegal operations are frequent, mainly during early stages of land occupation. Loggers extract timber from unclaimed lands without permission, but also from claimed lands through invasion or accords with local governmental organizations, settlers, and, more recently, rubber tappers. The action of loggers has been often necessary to provide access for the settlers to their lots through road building. Also, loggers have cleared initial portions of the lot where settlers develop their production systems. The interactions between settlers and loggers have been often based on opportunistic actions by the latter, which quickly exploit the most valuable species without concern for environmental or social impacts. Recently, efforts have been made by the Brazilian government and IBAMA to set up clear policies for timber extraction in the Amazon, mainly through the release of legal permissions consonant with management plans. However, these initiatives are far from being effectively enforced.

Processes of landscape transformation caused by human occupation in Machadinho and Anari are discussed throughout this dissertation. In order to provide a better understanding about the trajectories of each colonization project, the following sections describe historical aspects associated with their implementation and the structure of rules and incentives for each actor taking direct actions over the landscape and its environmental resources.

### 6.2.1 - Anari: A 'Rapid Settlement Project'

The implementation phase of Anari started between 1980 and 1982. The settlement was part of a cooperative program between the federal agency INCRA and the State government of Rondônia with the goal of settling 16,000 families. The strategy was called 'rapid settlement project' (*projeto de assentamento rápido*), and carried out as an emergency plan. The program succeeded in settling 12,315 households in approximately 800,000 ha in 11 tracts throughout Rondônia (Rondônia 1996d). INCRA was responsible for carring out part of the implementation phase (including land demarcation and distribution) and the emancipation phase, when land titles were issued. The State government was supposed to provide basic infrastructure and maintenance services. Thus, INCRA delivered the settlements with just the main dirt road and partially opened feeder trails to provide access to the lots.

Anari was the largest settlement within the 'rapid project' strategy, encompassing an area of 1,246 $km^2$. Approximately 2,000 families were settled in lots of 50 ha each (Rondônia 1996d). Anari maintained the blueprint of a fishbone-like design, with a main road crossing the settlement and secondary feeder roads crossing perpendicularly every four kilometers from the main village (Figures 5 and 6). However, since the State government failed to fulfill its commitment to improve the road network, the poorly opened feeder trails provided difficult access to the parcels. The lack of an improved road system created an extra burden to settlers, who had to open the way to their properties. By that time, families were settled at their lots without water, electricity, roads, or assistance for beginning their life at the frontier. The main village had only a few houses and no available infrastructure.

Another infrastructure problem that narrowed the options regarding the use of rural properties in Anari by settlers was the lack of a center with basic services. Improvements to the village and to the main road took place only with the implementation of the Machadinho settlement project years later (1982-1984). Health problems, such as malaria strongly affected the labor force available in the area during the early stages of the settlement (Rondônia 1996b). Land abandonment was frequent, creating opportunities for speculators to aggregate underused lots by clearing them and converting the land to pasture. Although showing an increasing trend during the last five years, the population of Anari after twenty years of colonization consisted of 7,713 inhabitants, 76% of them still living in the rural area (Table 41) (IBGE 2000a).

Besides all the constraints on the establishment of properties, land use was also limited by federal legislation, in which 50% of the parcel was to be kept intact as private forest reserves. In addition, settlers were restrained from bank loans due to lack of information within their settlement, difficult access to the closest urban centers where banks were located (i.e., about 80 km of poorly maintained dirt roads), and lack of political organizations that could mediate the negotiation. At the time, a different scenario was taking place in Machadinho.

### 6.2.2 - Machadinho: A Better Design for Settlement Projects in the Amazon?

Machadinho was implemented between 1982 and 1984 by INCRA as part of a broader development project funded by the World Bank (POLONOROESTE). The original settlement had an area of 2,090 $km^2$ with 2,934 plots designated for landless small farmers. Despite a similar demand to accommodate migrants in Rondônia, the settlement project (*projeto de assentamento - PA*) Machadinho, along with two other projects — Cujubim and Urupá — represented an alternative design for rural development, which was meant to overcome past failures (Fearnside 1986, 1989).

As part of this endeavor, Machadinho was a settlement project gifted with distinct architectural and institutional designs in comparison to former initiatives throughout the Amazon. Property lots were defined according to watershed topographic features. The road network was constructed along the ridges, facilitating its maintenance and allowing water access to almost all settlers by including a stream in the rear of the property. The topography-oriented design was combined with an alternative institutional design related to forest reserves (Figure 6). The settlement included 16 communal reserves of different sizes, which encompassed 33% of the total settlement area (685 $km^2$) with right-of-use to rubber tappers (Table 16). The reserves were created to achieve ecological, economic, and social goals. Ecologically, larger forest areas could be preserved under lower levels of fragmentation. Economically, by ensuring forest preservation within the communal reserves, settlers would be allowed to use the full extent of their properties with no legal constraint.[4] Socially, the rubber tappers who had lived in 90 extractive locations (*colocações*) distributed throughout the settlement would have their livelihood ensured by the communal reserves.

In addition, settlers counted on a privileged treatment in terms of infrastructure, including gravel roads throughout the rural area. INCRA built 725 km of road network in Machadinho, divided into four hierarchical levels: 11 km of four main roads (access roads), 105 km of feeder roads level 1 (collect roads), 314 km of feeder roads level 2 (feeder roads), and 295 km of feeder roads level 3 (penetration roads). These figures represent the best-served road structure of all regular settlement projects in Rondônia up to this date in both gross and per area of road footage.[5] INCRA also provided basic services such as one school, one health center, electric and water pipe systems, and an airport (59 ha) within the 2,000 ha urban center. In the rural area, 10 secondary villages (953 ha), 44 schools, 547 houses, 60 wells, and 5 health centers were built (Miranda and Mattos 1993). Agencies related to agriculture and environmental activities were set in the area to provide technical assistance to the farmers (e.g., INCRA, EMATER, EMBRAPA, CEPLAC, IDARON, IBAMA, SEDAM). In particular, the extension agency EMATER supported the creation of associations in different tracts throughout the settlement.

The institutional arrangement derived from Machadinho's design led to the existence of three major groups as direct agents of landscape transformation (i.e., settlers,

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[4] This rule was not supported by federal legislation and recently has been questioned.

[5] Other special settlement projects — directed settlement projects and integrated colonization projects — were similarly served with larger road infrastructure, but following the fishbone scheme (Rondônia 1996d).

rubber tappers, and loggers). The settler population came mostly from the States of Paraná and Minas Gerais and encompassed 2,934 immigrant households. They occupied 67% of the area (1,415 $km^2$) in private lots of about 44 ha. The outcomes in terms of LULC change at the properties were described in Chapter 4.

The communal reserves house a total of 401 individuals. The reserves are property of the State with the residents having the right-of-use. They are organized in a local rubber tapper association, which is linked to state and federal councils. Their income is centered on the production and commercialization of raw rubber and based on subsistence economy (i.e., slash-and-burn agriculture, forestry, game, and, more recently, small coffee plantations). In 1995, the reserves were decreed State Extractive Reserves, allowing communities to make their own management plans, which may include sustainable logging operations. Just one reserve has a different status with use restricted to the State (*Floresta de Rendimento*) (Olmos et al. 1999).

As mentioned before, loggers also play an important role in modifying forest structure and in clearing forests in Machadinho. Chapter 2 briefly describes the production systems associated with settlers, rubber tappers, and loggers. The sections below discuss the incentives and constraints for each group affecting landscape within the study area.

## 6.3 - ACTORS AND RESOURCES: THE UNDERLYING PROCESSES OF LANDSCAPE CHANGE

Anari and Machadinho represent two radically different cases of settlement design strategy in the Amazon. In spite of biophysical and historical similarities, their implementation differs due to the political context in which each settlement was conceived. As discussed earlier, the population growth in the 1980s due to rural and urban development in Rondônia created a demand for new colonization projects in order to settle the landless population coming mostly from southern and southeastern Brazil. On the other hand, the constant critique of settlement projects in the Brazilian Amazon created a need to implement a more socially and ecologically consonant model of colonization.

It was between these two political pressures — demand to settle landless migrants and demand for a more sustainable settlement model — that Anari and Machadinho were conceived. As an effort to ameliorate social problems resulting from waves of migration, Anari was part of an emergency initiative led by INCRA and the State government of Rondônia. According to this joint program, INCRA would demarcate and distribute 50 ha lots with their respective land titles. The State government would assume the responsibility of providing basic infrastructure and institutional support. Two years later, INCRA and international donors teamed up to establish Machadinho as part of a pilot initiative to create a settlement model that would lower social and ecological impacts. The agreement, in this case, established that INCRA would provide all infrastructure and institutional support during the project implementation through financial support from the World Bank. While the State government failed to accomplish its commitment in Anari, Machadinho was implemented as planned.

As a result of the distinct institutional and architectural scenarios, social development following the implementation phase took different paths in each settlement. From a pristine situation when the region was mostly forested to the current mosaic of LULC patches, the human footprint has established new landscape patterns in the last twenty years. Different processes of forest clearing and land use are outcomes of both the settlement architectural design and the distinct institutional arrangements within the settlements. The implementation strategy, when a set of rules was defined during the initial phase of the settlements, and the consolidation phase, when systems of rules were rearranged due to internal and external pressures, were key components in the complex process driving local populations to make land-use decisions that are reflected in the current landscape patterns.

### 6.3.1 - Implementation Phase

The initial architectural and institutional design in which a settlement is conceived defines opportunities and constraints toward land-use decisions at households and communities. Such land-use decisions reflect directly in the land cover. Settlement designs in the Amazonian frontier are a case in point. Often, the implementation of settlements has taken place through government-sponsored projects based on blueprint fishbone road networks, occupied by migrants claiming rights to land through forest clearing. Among several negative social and ecological consequences, this settlement implementation strategy has produced high deforestation rates to ensure land occupation, frequently followed by land aggregation for cattle ranching after abandonment by smallholders (Hecht 1993). Moreover, social conflicts have also been reported between newcomers and local populations, such as indigenous residents (Schmink and Wood 1992), *caboclos* (Moran 1981), and rubber tappers (Allegretti and Schwartzman 1986).

Anari and Machadinho are extreme examples of how implementation design can influence LULC change within a rural development project. Anari illustrates the classic blueprint settlement model carried out in the Amazon Basin and particularly in Rondônia. Machadinho illustrates how settlement implementation can incorporate ecological (topography-based), economic (infrastructure), and social (accountability to local populations) attributes that have usually been overlooked in other development projects.

In regard to ecological accountability, orthogonal road networks often create unequal access to fertile soil, relatively flat terrain, and sources of water (McCracken et al. 1999). In Machadinho, the property grid design based on topography has produced major implications in the efficiency of land-use systems and landscape outcomes. First, forest reserves were defined in steeper areas where farming production is more difficult. Private lots were laid out in less rugged terrain in such a way that most lots have access to at least one stream. In this sense, water access is relatively equal compared to fishbone designs, in which straight lines do not take topography or watershed boundaries into account. Although streams in Machadinho are usually placed in the back of the property, which may create some limitations to water access, the distribution of this resource among landowners is far more effective than in Anari. As a result, in Anari few settlers have been granted lots served by water springs and flatter areas, while many received lots with hilly terrain and no water access.

Interestingly enough, the accountability for ecological features in the settlement design of Machadinho has not affected the decision of settlers to clear forest, at least in terms of the percentage of the property. As mentioned in Chapter 4, landowners from both settlements have cleared an average of 54% of their lots to date (Tables 19 and 22). According to Brondizio et al. (in press), the behavior of groups of settlers (cohorts) in frontier lands can be predicted and often is affected by the time of arrival. Cohorts of settlers tend to produce similar outcomes in terms of forest clearing. This pattern seems to be reproduced in the study area. However, as also pointed out in Chapter 4, the area cleared per property is higher in Anari because the lot is generally larger and the settlement was implemented two years earlier than Machadinho. Perhaps, the major differences in terms of LULC change in Anari and Machadinho are related to decisions regarding production systems. Anari settlers have produced a higher rate of forest conversion to pasture than in Machadinho (Table 14). Moreover, it seems that better water access as well as less rugged terrain in most lots improved the efficiency of agricultural systems in Machadinho. This is corroborated by productivity indices measured by the Brazilian government (IBGE 2000b). As a result, settlers have had less incentive to convert forest to pasture.

In regard to infrastructure, the topography-sensitive road network in Machadinho contrasts with the fishbone-like road network in Anari. Besides accounting for relief variability, Machadinho roads were well established in three hierarchical levels, reaching the most remote lots. In addition, the road network allocation along the ridges has lowered the maintenance costs when compared to the fishbone design. Orthogonal roads crossing the drainage system perpendicularly demand bridge building and higher levels of erosion control, which is often neglected in the region. As seasonality is an important variable affecting trafficability, many settlers remain isolated during the wet months. The relative high transportation cost also influences smallholders to choose pasture over cash cropping in Anari. Besides the fact that ranchers can drive cattle herds even on poorly maintained dirt roads, ranching is an easier activity to manage whenever market access and incentives toward agricultural activities are unstable. Two other important aspects of infrastructure provision in Machadinho are related to the allocation of an urban center with many facilities and the strong presence of governmental agencies accelerating rural development. This has helped smallholders to have access to credit lines (banks), social organization (associations), technical information (extensionists), health aids (health centers), and general market goods.

Finally, social sensitivity toward forest dwellers was a major institutional novelty in the settlement design of Machadinho. In general, settlement projects carried out by the Brazilian government have focused solely on migrant settlers. However, the existence of a more heterogeneous group of actors regarding land-use interests can lead to different patterns of interaction depending on the social context. For example, the interaction between loggers and settlers in frontiers where road access is poor follows a singular pattern. In this case, loggers usually take advantage of the situation and extract timber cheaply from private lots in exchange for providing machinery and labor to open roads and trails for the landowners. Anari was more vulnerable to this process due to the need of improving the road network.

Another intricate interaction occurs between local populations and migrant settlers. While landowners were allowed to clear only 50% of their lots in other settlements (regardless of the lot size), Machadinho settlers were allowed to clear 100% of their lands as a result of the creation of communal reserves within the settlement. By the same token, rubber tappers could choose to stay in their area or to receive a private lot in the reserve surroundings. The establishment of forest reserves produced positive ecological outcomes in Machadinho. The reserves helped to maintain larger forest patches spatially spread throughout the landscape as opposed to smaller and fragmented forest remnants within the fishbone-like settlements. The consolidation process that followed the implementation phase led to other changes that further affected each actor regarding land-use decisions and landscape transformation.

### 6.3.2 - Consolidation Phase

The previous section discussed how the implementation phase of Machadinho and Anari defined the initial social and ecological arena where local decisions were taken. In addition to initial incentives, internal variations emerged according to different social assets among actors. Smallholders turned into subsistence cultivators, perennial crop cultivators, and cattle ranchers according to different portfolios of production systems, as illustrated by Table 4. The co-existence of loggers and rubber tappers in Machadinho complete the social mosaic that is directly reflected on the landscape. However, the landscape outcome differed within the settlements as they are related to how the structure provided in the implementation phase affected the institutional changes carried out during the consolidation phase. The variation in land-use decisions is related to both external and internal changes. Figure 85 includes a general overview of events affecting the consolidation of Machadinho and Anari. For example, Machadinho was emancipated in 1988, while Anari became a municipality only in 1995. Recently, new settlements have been established in both municipalities, a process that still occurs in a dynamic fashion. Although some social and economic links still remain, the two municipalities have increasingly taken independent economic and political paths. In addition, land tenure system, product prices, and provision of bank loans have changed in the last decade, each affecting differently the three main actors in the region.

In regard to settlers, the initial rule providing alienation rights to the lots was promptly violated. According to INCRA, settlers hold right-of-use during the first five years, receiving the title if land use is demonstrated. However, turnover in parcel ownership took place informally right after the parcels were allocated to settlers. Land aggregation for cattle ranching was the expected consequence, as in other settlement projects within the Brazilian Amazon. The results on LULC suggest that this process was more prominent in Anari. The maintenance of larger areas in crops rather than pasture in Machadinho is related not only to original design but also to how settlers responded to bank loans. The support of EMATER, combined with relatively organized associations in Machadinho have supported smallholders to continue cash cropping along with other activities in their farming system as opposed to Anari, where the lack of institutional support and infrastructure encouraged pasture conversion.

The large number of associations does not mean that effective social organization is occurring. The variation of individual interests and the increasing level of internal conflicts among members have weakened the sense of association, formerly promoted by governmental initiatives as well as religious efforts (particularly by the Catholic Church). Thus, the growing number of associations in recent years has been mainly due to incentives to create legal entities to apply for bank loans. Following loan approval, the organizations are left purposeless and weakened. An alternative form of organization that has emerged in the region combining both political strength to claim rights and the economic goal of marketing achievements is the cooperative located in Machadinho. With more than 200 members, it is the strongest association within the settlements.

Regardless the weak political strength of local associations in the region, the more expressive presence of such organizations in Machadinho is an important social capital that has helped settlers to be more resilient to external influences such as product prices, bank loans, and land conflict issues. In Anari, some initiatives are taking place, as EMATER and IDARON have also installed offices in town. An important trend to follow is the trajectory in coffee cultivation, as most of these associations are improving the production of coffee seedlings and stimulating the use of new technologies such as agricultural mechanization and irrigation. In Machadinho, a research project analyzing the role of associations in LULC change is currently under way (Sydenstricker-Neto 2000).

As land-use strategies have been changing rapidly in the region, a major challenge for the maintenance of forest stands within the private lots in Machadinho exists. Recently, IBAMA has disclosed a claim that the 100% deforestation permission in Machadinho parcels was mistakenly taken and has no legal value. In other words, despite the implementation of communal forest reserves within the settlement, settlers should follow similar restrictions in their lots as in other Amazonian areas. Therefore, INCRA agents have erroneously passed an informal permission that was not considered detrimental twenty years ago. International and national concerns toward monitoring deforestation in the Brazilian Amazon and the recently decreed Land Zoning for the State of Rondônia have faced this institutional misunderstanding by enforcing the 50% forested area rule in Machadinho.

Other trends have influenced land use in terms of labor force, technology, access to bank loans, and new market demands. In regard to labor force, during the earlier years of settlement, the average family size in Machadinho was approximately five people with three members of working age. Family labor constituted the main source of agricultural labor, while contracted labor was rare (Miranda and Mattos 1993). More recent studies have shown that families now frequently contract labor outside the household, employing an annual average of five temporary and two permanent workers per family (Miranda et al. 1997). In regard to technology, mechanization, irrigation techniques, as well as weeding machines have recently enabled households to cultivate larger areas. The release of small bank loans has allowed settlers to more easily have access to those technological innovations. As a result, while forest clearing in both settlements at the property level has reached an average of approximately 54% after fifteen years of occupation, only now do settlers feel the weight of this land-use restriction. It is still unclear how the combination of these new internal and external changes will fit with the fact that the 50% forest reserve rule that had been lifted until recently will suddenly be effective. Recent discussions are taking place in congress for a new Forestry Code, in which the percentage of land to be preserved could be even higher. However, it is questionable if these rules will be successfully enforced.

While settlers face new trends in land-use restrictions, rubber tappers in Machadinho face new opportunities regarding the management of natural resources. Perhaps, the major flaw of the Machadinho design as far as rubber tappers activities are concerned, was posing the burden of forest conservation on them while economic support to use forest resource was scarce. Rubber tappers were granted a large area of 685 $km^2$ where only 401 individuals live. Those who chose to leave the reserve and receive a private lot are accused of taking advantage of both figures (private lots and communal reserves). Yet, a major problem posed to those living at communal reserves was the limited use of land for subsistence and lack of economic activity, while some companies illegally carried out logging operations. Rubber tapping has become increasingly uneconomic and the lack of alternatives has created incentives for residents to search for other activities. Only recently, when these forests were decreed State Extractive Reserves, rubber tappers were enabled to formulate their own forest management strategy with support of agencies and grassroots organizations to use the forest for commercial purpose, including sustainable logging (Olmos et al. 1999). As a result, incentives to monitor poaching by illegal logging activities have increased. In addition, rubber tappers have been provided with infrastructure to patrol the area. The outcome of this new institutional turn is too recent to be evaluated. Within the following years, land cover within the communal reserves, where landscape change was practically null during the last twenty years, will probably reflect in different landscape patterns. Whether this change will affect the ecological stability of the landscape depends on the ability of rubber tappers to develop a coherent management plan and a monitoring system to keep up with the system.

The development of forest management plans by rubber tappers has been relatively isolated from settlers' activities. Yet, loggers have been affected by rubber tappers' decisions. The ability of rubber tappers to manage their own reserves is not only essential in providing social justice to these local populations who have been deprived from economic alternatives, but they have also helped to halt the illegal activities of several logging companies. In addition, new rules of timbering included in the National Forestry Code have required management plans for every logging activity. Although the enforcement of these rules is still not effective, there is a chance are for better use of forest resources if surveillance operations are carried out within the settlements. Despite the restrictions regarding forest reserves, logging has represented an important part of the economy in Machadinho, where a new industrial area is being established to house several logging companies. In addition, the implementation of other settlement projects has opened new frontiers to logging activity within the municipality. Therefore, while communal reserves may be maintained by rubber tappers' management plans, a better institutional strategy is still to be found that will ensure forest protection from illegal logging in other areas close by.

## 6.4 - TOWARD BETTER INTERACTIONS AMONG ACTORS IN THE FRONTIER

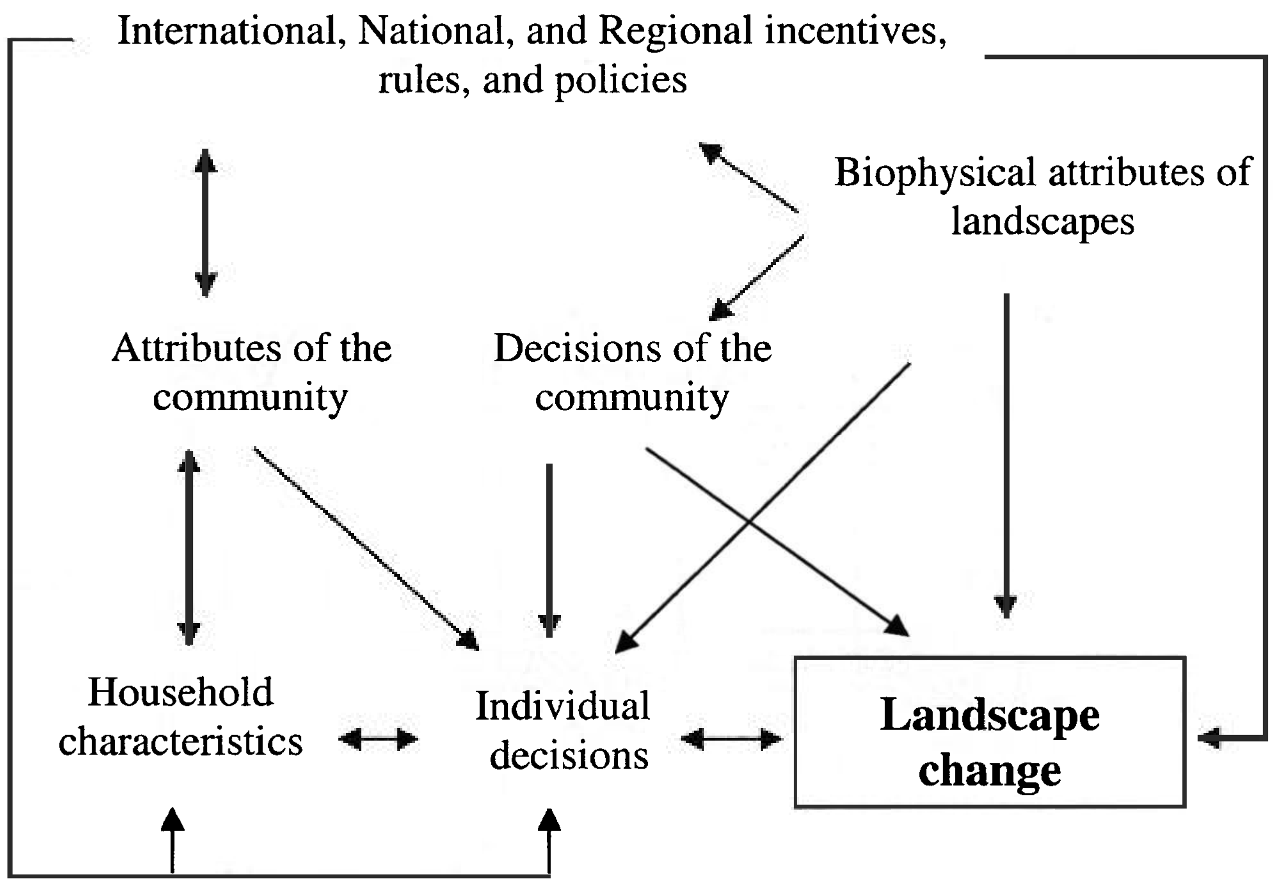
Identifying the human dimensions of landscape change in Machadinho and Anari is as complex as comparing the effects of different settlement architectural designs in land-use decision making processes. This double-sided puzzle underlies multiple sections of this dissertation, but it is in this chapter that a more institutional-based analysis was carried out. The rationale behind this approach is that addressing the human dimensions of ecological processes within the settlements' landscapes allows a better understanding not only about local people's social trajectories, but also about interrelated causes, consequences, and outcomes of LULC change.

Land-use decisions in the study area are influenced by two major sets of events. The scenario has a starting point (establishment event) when initial rules delineate the structure of incentives to the actors. In Machadinho and Anari, the establishment of different architectural and institutional designs during the settlement implementation phase defined distinct opportunities and constraints for settlers, rubber tappers, and loggers. The second set of events took place as dynamic changes, affecting the structure of incentives toward land use and resource management. In the study area, land tenure arrangement, bank loans mediated by associations and governmental organizations, and the establishment of communal extractive reserves, represent major events affecting LULC dynamics and landscape change.

While some institutional arrangements have taken place in order to adjust land-use activity to an ecologically and socially sound plan, many other institutional changes have created incentives for uncontrolled use of resources. Changes have taken place at different tiers of actions (e.g., technology and labor force at the household level, bank loans, land tenure, forest-use rules at the group level, and policies and infrastructure at the regional level). Each factor has synergistic effects on the landscape and depends on the pace and intensity of change that reflect land-cover outcomes. In this sense, recent trends are important. While some land-cover changes have been related to institutional and architectural design through incentives for land-use activities to date, many changes are only beginning to take place.

Following these trends may bring new elements to the understanding of the important role of interactions among actors during the implementation and consolidation phases of settlements in Rondônia. Moreover, as rural development, LULC change, urbanization, and social class differentiation take place, it is important to watch for possible conflicts among actors and how they are mediated. In particular, actions causing or increasing forest fragmentation and environmental degradation should be followed with attention.

This discussion highlights the importance of the management of common-pool resources (Ostrom 1990, Hardin 1998). Recent integrative works have advocated the need of governance over resources by local people (i.e., institutions-centered approaches) rather than focusing on community-centered approaches (Agrawal and Gibson 1999). The communal reserves in Machadinho are exemplary. In Chapter 4, multi-temporal LULC assessments have shown that forest cover within these reserves has not decreased. This has happened not only because of the reserves per se, but because of their management by rubber tappers organized in associations and with clear strategies regarding their rights over these lands. Perhaps, the answer for a more sustainable environmental outcome in rural Amazonian areas depends on more sustainable interactions among actors using natural resources.




Source: adapted from Ostrom (1997)

Figure 83 - Hierarchical approach defining landscape change in Machadinho d'Oeste and Vale do Anari

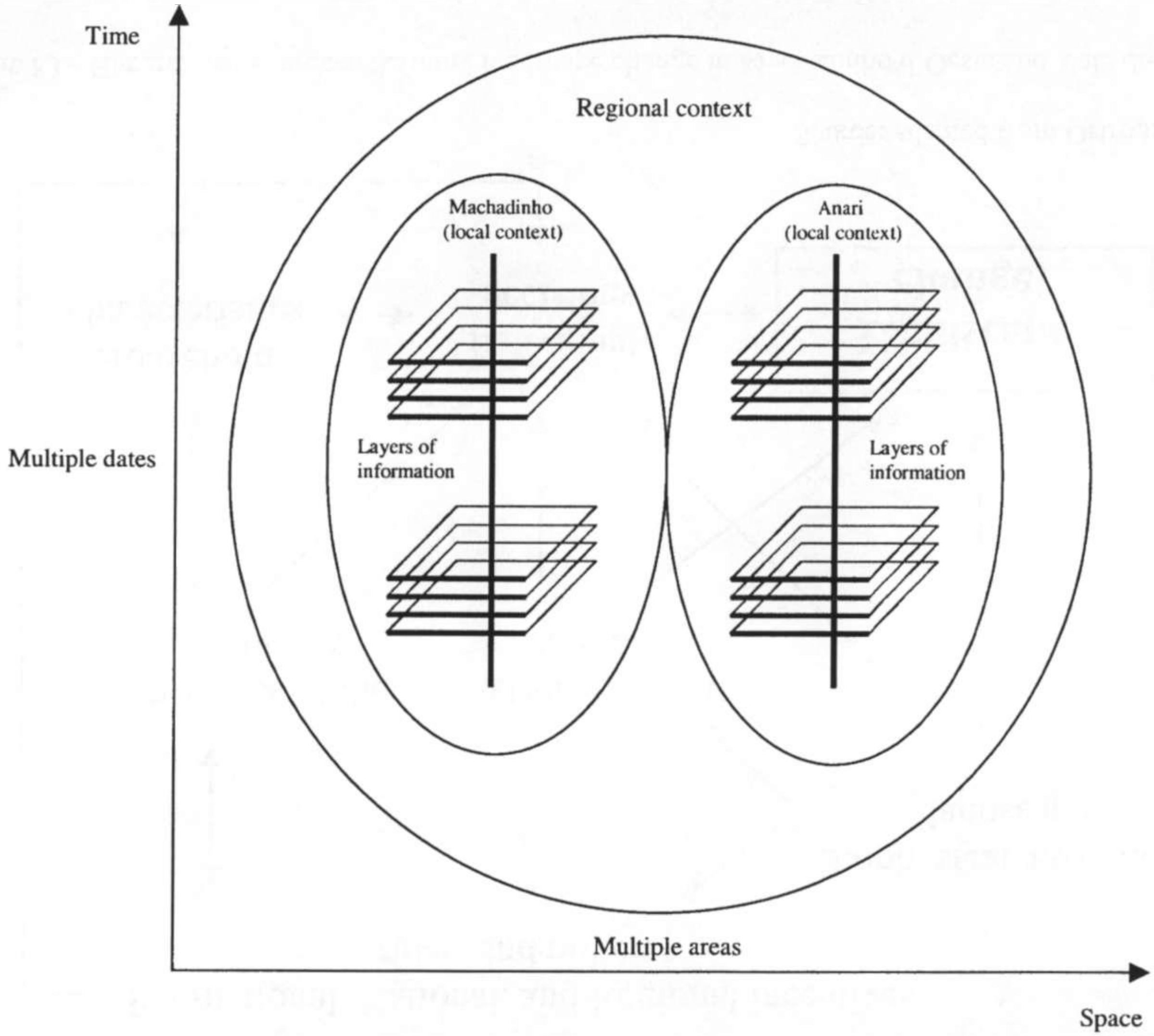
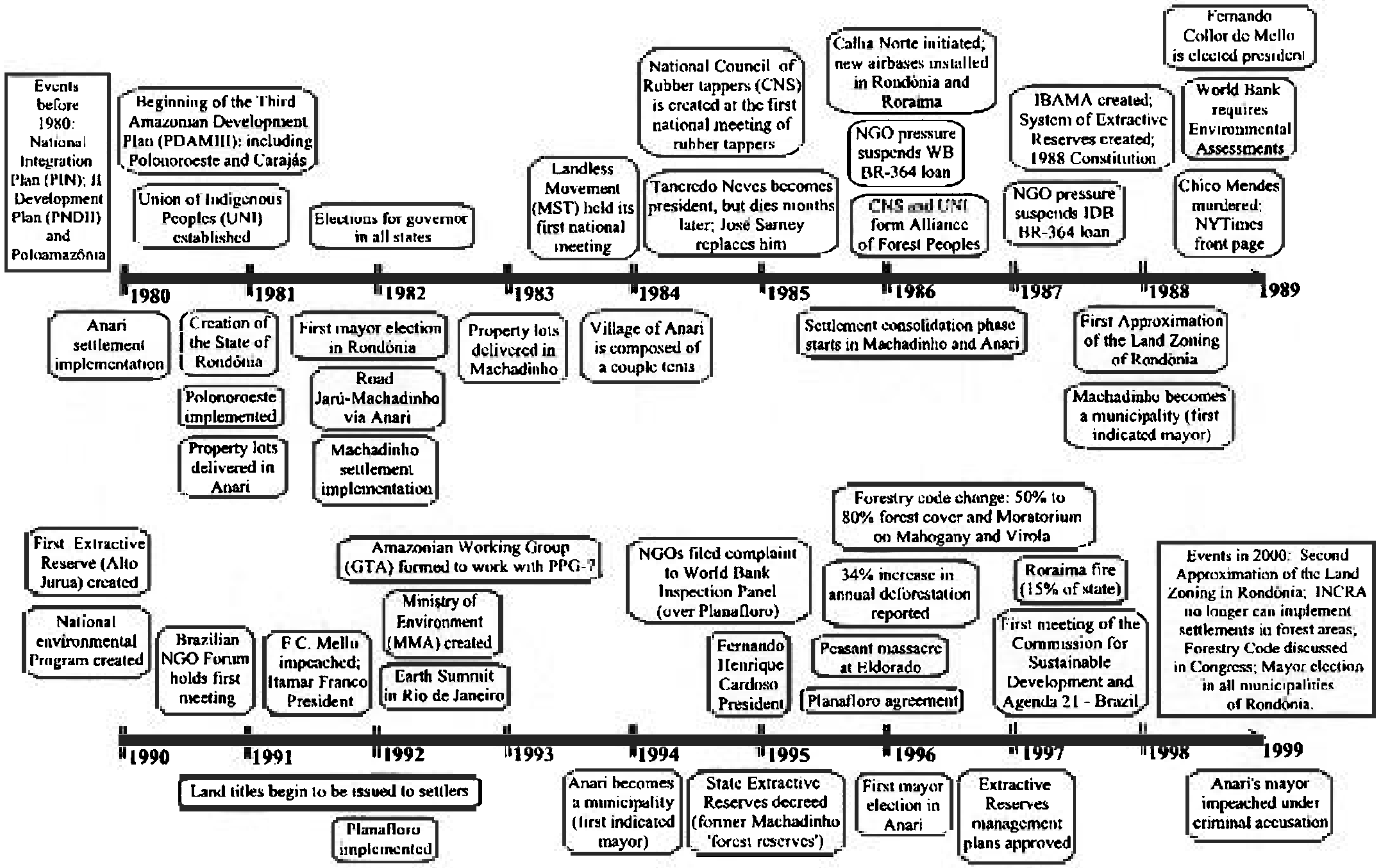



Figure 84 - Conceptual approach for analyses of the human dimensions of landscape change




* Items above the timelines refer to general events; items below the timelines refer to local events. Source: adapted from Domask (1998).

Figure 85 - Timeline of selected events affecting Machadinho d'Oeste and Vale do Anari.

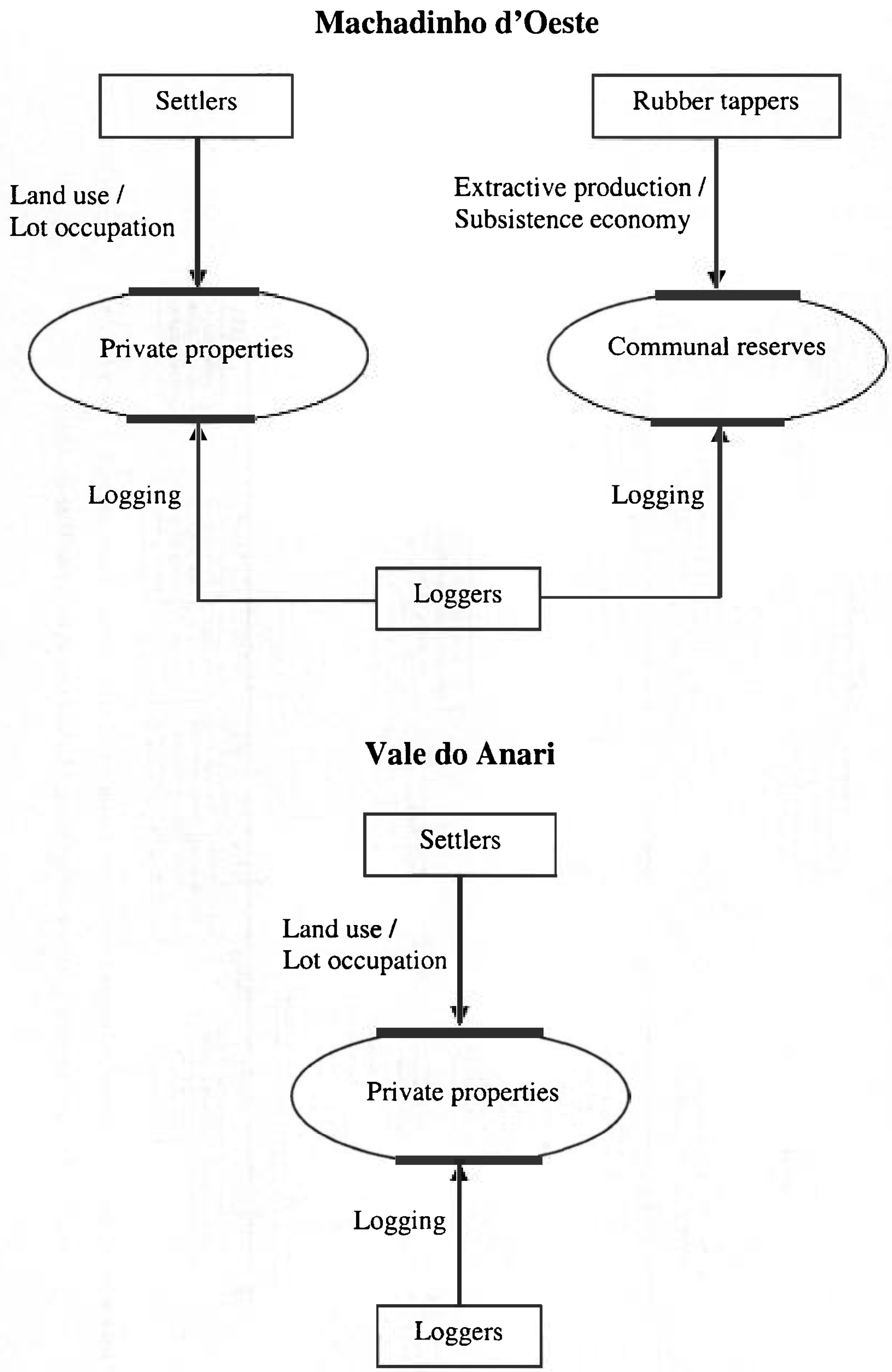



Figure 86 - Actors and actions in Machadinho d'Oeste and Vale do Anari

Table 41 - Population in Machadinho d'Oeste and Vale do Anari

| MUNICIPALITIES | POPULATION | | | | | | ANNUAL CHANGE RATE (%) |
|---|---|---|---|---|---|---|---|
| | 8/1/1996 | 8/1/2000 | | | | | |
| | | Total | Male | Female | Urban | Rural | |
| Machadinho d'Oeste | 23,095 | 22,717 | 12,235 | 10,482 | 10,962 | 11,755 | -0.41 |
| Vale do Anari | 5,854 | 7,713 | 4,222 | 3,491 | 1,832 | 5,881 | 7.14 |

Source: IBGE (2000a)

# CHAPTER 7

# CONCLUDING REMARKS

*'Eu vô num vim'*

## 7.1 - THIS DISSERTATION IN THE CONTEXT OF LANDSCAPE ECOLOGY

The current effort to develop a more integrative scientific vision addressing the complex interactions between people and the environment has been carried out by a combination of environmental and social sciences (Wilson 1998, Berkes and Folke 2000, Haberl et al. 2001). Scientists are building a new approach capable of addressing a variety of questions that examines multiple temporal and spatial scales (Dyson 1998, Gibson et al. 2000). Human ecology is among the antecedents of this initiative (Richerson 1977, Moran and Herrera 1984, Kormondy and Brown 1998). Historical ecology is a recent example of such a multi-dimensional approach (Crumley 1994, Roberts 1996). Other fields, such as ecological economics, promise to address sustainability of ecosystems and economic systems (Funtowicz and Ravetz 1991, Costanza et al. 1993). Completing this scenario, landscape ecology emerges as the science of 'human-altered land mosaics' (Naveh and Lieberman 1994, Forman 1997).

Landscape ecology has developed scientific bases for land and landscape management, conservation, development, and reclamation, overstepping the classical bioecological sciences and including the realm of human-centered fields of knowledge (Wiens and Moss 1999). Since its early years, landscape ecology has been cited as an 'emerging branch of human ecosystem science' (Bertrand 1978, Naveh 1982). However, as every emerging science, while the theoretical foundations have been built, there is still a lack of methodological procedures and standardization in research (M. Turner et al. 1995, Dale 2001). This makes the study of the human dimensions of landscape change a challenge (Baerwald 1991). Only recently has this 'linkage' been addressed in a systematic fashion, mainly through studies about the relationship between LULC and social metabolism (Nassauer 1999, Haberl et al. 2001).

Recent scientific priorities for research include the study of processes across time, space, and culture (Turner et al. 1990, Stern et al. 1992, Kates 1994, Arrow et al. 1995, Vitousek et al. 1997). LULC issues are at the core of this perspective, due to their intricate dynamics and its consequences in landscape structure and function (B. Turner et al. 1995, Lambin 1997, Turner 1997). In the Brazilian Amazon, this is particularly relevant because landscape transformation and forest fragmentation are occurring throughout the region (Skole and Tucker 1993, Skole et al. 1994, Laurance et al. 1997, Alves 1999). In this sense, the comparative study carried out by this dissertation offered a singular opportunity for the discussion of the human dimensions of landscape pattern and process. The rationale behind this initiative is that landscape ecology and social sciences can 'meet in the middle,' providing a meso-level integration between local and regional processes (McConnell and Moran 2001). Landscape characterizations allow a not-too-broad and not-too-fine perspective regarding transitions within Amazonian colonization settlements. As knowledge about these processes increases through studies at several scales and approaches, there is growing agreement on the need to investigate culture and context, before testing general hypotheses about human-induced ecological outcomes (Lambim 1997, Kaimowitz and Angelsen 1998).

This dissertation focuses on processes of LULC dynamics and landscape change within two distinct settlement designs in Rondônia, Brazilian Amazon. One settlement, Anari, reflects the lack of ecological and social accountability in its design, so land-use processes are related solely to aspects of how settlers can individually overcome land access and product flow constraints. The other settlement, Machadinho, represents an attempt to account – if only, partially – for ecological and social features within the system, so land use is related to how access to services and resources are filtered by different actors. The combination of privately based decisions for the properties with community-based decisions for the reserves clearly indicates that this architectural and institutional design can produce positive social and environmental outcomes in Amazonian settlements. The section below discusses the hypotheses defined in Chapter 1 based on the distinctions and similarities among the settlements (Table 42), and the main findings described throughout the dissertation (Table 43).

## 7.2 - HYPOTHESES REVISITED

### Hypothesis 1

The fishbone settlement design of Anari leads to faster deforestation than Machadinho's architecture based on topographic features and including communal forest reserves.

As stated, Hypothesis 1 should be accepted. In fact, Machadinho had 15% more forest cover than Anari after 15 years of colonization. However, an accurate evaluation of this hypothesis depends on two main points. First, it is necessary to evaluate whether or not the fishbone settlement design in itself leads to faster deforestation than an architecture based on topographic features. Second, it is important to understand the role of the communal reserves in maintaining higher levels of forest cover in Machadinho. The first assertion is not necessarily true per se. The results indicate that it is not the fishbone design itself that is leading to faster deforestation, but the absence of communal forest reserves in Anari. Moreover, the results presented in Chapter 4 and summarized in Table 43 emphasize that the percentage of forest cover is similar between the settlements if the Machadinho reserves are excluded from the analysis. Analyses at the property level confirmed that the area deforested per property per year is the same in both settlements if averaged for the period since their implementation. However, the rate of deforestation in Anari was lower before 1988 and higher between 1994 and 1998, indicating different cycles of clearing within each settlement. As important as the amount of deforestation is the findings that pasture conversion is more prominent in the fishbone settlement (correlation between forest and pasture of –0.6 in 1998, while in Machadinho the correlation was –0.4, both significant at $p<0.01$). The causes for this trend were discussed in Chapter 6 and include lack of assistance, lack of credit for agricultural production, and the precarious road infrastructure found in Anari.

**Hypothesis 2**

Landscape fragmentation is higher in the fishbone settlement of Anari.

The striking differences in the architectural design of Machadinho and Anari suggested that the LULC spatial patterns are also different. This was first indicated by the results obtained for buffers along roads and confirmed by the analysis of landscape structure. Again, the relationship between settlement architectural design and landscape fragmentation is more complex than Hypothesis 2 states. Taking the settlement as a whole (i.e., including the communal reserves in the analysis), Machadinho's landscape is less fragmented, more complex, and more interspersed than Anari after 15 years of colonization. This was indicated by selected metrics in Chapter 5. However, the temporal factor should not be neglected. Results on the mean patch size of forest, for example, showed that Anari was less fragmented at earlier stages of its implementation. As soon as colonization and deforestation processes took place, the maintenance of forest cover within the reserves produced a less fragmented landscape in Machadinho. If Machadinho had no communal reserves, Hypothesis 2 should be rejected. Selected landscape structure metrics indicated that the design based on topography would lead to more fragmentation if it did not include large patches of preserved forest. On the contrary, if taking into account the actual configuration of the entire settlements (i.e., Machadinho with its reserves), Hypothesis 2 should be accepted. In addition to fragmentation, shape complexity, and interspersion, another important finding depicted by landscape metrics must be highlighted. That is, Machadinho's forest patches have on average more core area in relation to the total area of forest within the settlement, including or excluding the communal reserves in the analyses (Table 37). In this case, the design based on topography plays an important role in maintaining or increasing forest interior habitat relative to the entire landscape area, lowering the impact of forest fragmentation on the occurrence and distribution of organisms.

**Hypothesis 3**

Institutional arrangements accounting for different social actors and allowing governance over natural resources to local actors in Machadinho produce positive environmental and social outcomes.

This hypothesis should be accepted for the study area. The accountability to different actors has created opportunities for interactions with positive outcomes. Whenever these interactions are not accounted for in governmental settlement plans, chances for conflict increase. In Machadinho, this problem has been attenuated due to the implementation of communal forest reserves with right-of-use for rubber tappers. The reserves bring about another key issue in rural development projects in the Amazon, that is the compatibility of their use by local population with private lots occupied by smallholders. This higher heterogeneity of actors within the community in Machadinho fostered less conflictive situations, as distinct groups were granted with distinct land ownership regimes. In addition, the better infrastructure and the incentives for the establishment of associations in Machadinho have created mechanisms toward better and clearer interactions among actors. For instance, the enforcement of environmental laws regarding logging operations has been greatly ameliorated by the action of rubber tappers, who patrol the reserves' boundaries and denounce any invasion.

In sum, the architectural and institutional design of Machadinho has created a set of structural features that define different options of land use for the existing actors in the rural area (i.e., settlers, rubber tappers, and loggers). On the other hand, the lack of a design accounting for ecological and social heterogeneity in Anari led to higher deforestation at the settlement level, more isolated settlers, and marginalized rubber tappers.

## 7.3 - SIGNIFICANCE AND IMPLICATIONS OF THIS STUDY

Although it is appealing to compare LULC dynamics and landscape change through space and time at regional or cross-national levels, caution should be taken when suggesting scenarios. The easiest way to carry out these broad generalizations is to assume that similar processes produce similar outcomes everywhere. However, when dealing with the complex relationships between people and the environment, different environmental outcomes may result from similar socioeconomic dynamics, and distinct socioeconomic dynamics may produce similar environmental outcomes. This dissertation followed an alternative path. It addresses the trajectories of distinct settlements in Rondônia in a comparative fashion as a basis for other studies willing to contribute to the Amazonian debate regarding colonization processes within the Amazon. As far as multi-disciplinary research is concerned, the methods used were appropriate and sufficient to answer the questions and test the hypotheses listed in Chapter 1.

The benefit of this project to ongoing research at EMBRAPA and Indiana University was clear. Both organizations have carried out research related to the topics discussed in this dissertation, facilitating cooperation. The rationale behind these initiatives follows the priorities of a new research agenda on coupling of environmental and social sciences, and based on multi-level and multi-disciplinary tasks. Thus, studying biophysical and socioeconomic processes that lead to landscape variability and change in the Amazon provides important information to calibrate regional- and global-scale simulation models. Besides the elaboration of a methodological strategy based on multi-disciplinary integration for the study of colonization trajectories in the Amazon, the results of this dissertation contribute with further work using new sensors and processing techniques to improve the classification of different types of forests, stages of secondary succession, pasture, crops, and infrastructure. Achieving more accurate information on these distinct LULC categories represents a crucial step to inform ongoing research linked to enterprises such as refining global carbon modeling and LULC spatial-temporal analyses. Moreover, the use of selected landscape metrics proved to be useful when looking for indicators of landscape structure and change in the region. Last but not least, the study of the human dimensions of environmental change provided a critical assessment of driving forces leading to landscape transformation in the study area.

Four major implications of this dissertation can be identified. The first implication relates to studies on landscape characterization and modeling. The integration of vegetation structure and spectral data to inform LULC classifications and landscape structure characterizations is a robust approach applicable to other Amazonian study areas (Batistella and Brondizio 2001). In addition, comparing different designs of settlements adds to the literature available for areas of fishbone colonization. Modeling efforts such as the Dynamic Ecological Land Tenure Analysis (DELTA) (Dale et al. 1993, *Modeling* 1994) and agent-based simulations (Evans et al. 2001, Lim et al. in press) could be extended to simulate settlement patterns, LULC dynamics, and carbon release in distinct landscape structures through time, providing a broader approach to the heterogeneity of situations present in the Brazilian Amazon. The behavior of landscape metrics for settlement characterization and monitoring in areas of tropical rain forest can also be evaluated from a multi-temporal analysis and comparative approach such as used in this dissertation. From these evaluations, numerous applications can be derived, particularly those focusing on conservation and management of resources in colonization areas.

A second implication of this dissertation refers to the primary spatial entity within the complex mosaic encompassed by colonization areas in the Amazon and particularly in Rondônia: the rural property. Work based on household research indicates that the outcomes in terms of landscape structure are greatly affected by land-use decisions taken by landowners (Netting 1993; Pichón 1992, 1993; Bilsborrow and Hogan 1996). Attempting a generalization about the process, the World Bank (1992) tried to define a general trajectory followed by colonists in the frontier. The so-called 'peasant pioneer cycle' described how farmers had little choice when coping with environmental constraints and subsistence needs, which was consistently translated into deforestation, pasture conversion, land degradation, or secondary succession. Pichón (1997) offered a broader concept about farm-level characterizations, calling attention to 'household's demographic and socioeconomic circumstances, as well as the local and national policy and institutional context' that define the range of land-use options in the Amazonian frontier. The contribution of this dissertation to this debate comes from the possibility of tracking LULC dynamics at the property level through the integration of spatial data. The use of multi-temporal remote sensing analyses and georeferenced property grids provides accurate information about clearing cycles, land-use patterns, vegetation regrowth, and other phenomena related to farm management. When integrated with in-depth household data through relational databases, these sets of data allow powerful descriptions and predictions for a better understanding of colonization trajectories in the Amazon.

From the landscape to the farm, the dynamic character of land occupation in the region requires a multi-level framework that address both the environmental and the community attributes to understand the structure of incentives facing actors in a situation, what choices are most likely to be made, and how these choices tend to produce particular patterns or outcomes. This framework has been developed and applied in a number of studies (Ostrom et al. 1994, Ostrom 1997, Moran et al. 1998). As a comparative case study in the Amazon, this dissertation can inform the creation of robust institutions in the frontier that are resistant enough to cope with the dynamic processes of colonization but resilient enough to adapt to local and regional circumstances and context.

Finally, the policy implications of this work in Rondônia are controversial. Based on the findings of Chapters 4, 5, and 6, one could argue that the architectural design of rural settlements in the Amazon does not affect the pace of deforestation at the property level, so it is not relevant. Others would rely on other ecological indicators to defend settlement designs based on topographic features. Others would highlight the importance of communal reserves with right-of-use to local actors and the structure of incentives in producing better environmental and social outcomes, and conclude that the colonization model of Machadinho should be replicated throughout the Amazon. This debate is crucial for further initiatives regarding settlement implementation. The important point here is to realize that there is no magic formula applicable to all ecological and socioeconomic contexts within the region. Development and conservation strategies can be informed by the results of this comparative work in Rondônia, but regional dynamics and local context should be taken into account to avoid political failures. The path for a reasonable conceptual approach explaining the heterogeneous processes of colonization in the Amazon is far from achieved. Future studies that extend the reach of this dissertation are suggested in the next section.

## 7.4 - OPPORTUNITIES FOR FURTHER STUDIES

It is almost a truism that research answers a couple of questions and raises dozens of new questions. The findings presented in Chapters 3, 4, 5, and 6 are answers to the questions listed in Chapter 1. On the other hand, following the multi-disciplinary approach used in this dissertation, further studies will be necessary to uncover other socioecological processes affecting the trajectories of landscape transformation. These studies should include, for example, the integration of household data with multi-temporal LULC assessments to achieve a finer understanding of settlers' decisions regarding land use. This approach could focus on specific processes, such as agricultural intensification within properties or land aggregation by cattle ranchers. By the same token, detailed studies about the performance of rubber tappers and their decisions regarding the management of reserves should be carried out. A number of specific issues should be addressed in the near future. In particular, attention should be given to the role of associations in facilitating access to resources and new technologies (e.g., mechanization and irrigation for settlers and commercial logging for rubber tappers). Some initiatives have already started in Machadinho, where data from households and communal reserves are available (Miranda et al. 1997, Sydenstricker-Neto 2000). For Anari, the enterprise is more complex, as no data are available at the same level of detail.

Another approach would be to extend the comparative analysis between Machadinho and Anari all the way to their municipal boundaries. New settlements have been implemented within these municipalities, creating a complex mosaic of properties in different stages of development. Integration of household data for the study of settlements and census data for the study of municipalities encompassing the settlements could provide a better understanding about the multi-tiered processes occurring in areas of relatively recent colonization. Going beyond the two adjacent areas (i.e., Machadinho and Anari), comparisons with other settlements within the Amazon should also be carried out. Two promising comparisons are foreseen: the fishbone design along the Transamazon Highway (Pará) and the radial scheme of Humaitá (Acre). Upon completion of these comparative studies, modeling techniques could enhance the description and prediction of colonization trajectories in the Amazon. A useful approach could be to simulate the creation of reserves within the fishbone design and investigate their effect regarding landscape structure within the settlements.

A third study should focus on the interactions among actors within the study area. For example, loggers interact with both settlers and rubber tappers, exploiting their lands in an opportunistic fashion or through management plans for logging operations, as recently enforced by the government. The interaction between rubber tappers and settlers in Machadinho is also important. It is common to hear settlers concerned about the amount of land decreed as reserves. They say they have been trapped when INCRA assured them they could use 100% of their properties because the communal reserves would play the role of forest conservation. Recently, national and regional discussions about forest management and a new Forestry Code have required the enforcement of environmental laws despite previous agreements. Understanding how the different actors organize themselves and interact with others within the action arena may provide insights about future scenarios.

Recent trends should be monitored and understood in order to answer the following questions related to both the private properties and the communal reserves.

- What is the future of the communal reserves in Machadinho?
- Will rubber tappers manage the reserves in a sustainable way?
- Will loggers and rubber tappers interact for their mutual benefit?
- Knowing that forest cover is already reduced to 51% of the total area of private properties on average, will settlers need more land for production?
- How will they cope with the environmental laws enforcing conservation of 50% or even 80% of forests within rural properties?
- Will settlers look for more intensified production systems?
- How will these dynamics continue in Machadinho and Anari?

These questions should be addressed in a multi-disciplinary fashion, with social sciences and environmental sciences helping to identify driving forces affecting LULC dynamics and landscape change. In this sense, various initiatives are appropriate and have already being tested. Some promising procedures include:

- Increasing temporal resolution (i.e., other satellite image dates) to have a better control over LULC dynamics
- Testing new sensors to scale the analysis down and up (e.g., IKONOS and MODIS)
- Testing new geoprocessing techniques to improve the accuracy of LULC classifications (e.g., linear mixture models, multivariate analysis, spatial-spectral classifiers)

- Increasing the use of ancillary data for the study of landscape structure and change (e.g., topography, soils, and institutions)
- Testing selected indicators and metrics of landscape structure for other study areas and research contexts
- Integrating landscape and household data for a better understanding of processes affecting LULC dynamics and landscape change
- Increasing fieldwork efforts to gather data on recent trends regarding actors' land-use decisions

I plan to join research teams in Brazil to search for answers to these new questions. In this sense, I intend to participate in national and international efforts to better understand LULC dynamics and landscape change in high priority areas such as the Amazon. This personal goal is embedded in a scenario where the 'frontier' concept tends to be surpassed as new development trends take place in this region of myths and challenges. Hopefully, this dissertation and other initiatives will build frameworks that address the wide array of colonization trajectories within the region and contribute to better social and environmental outcomes in a land still searching for its destiny.

Table 42 - Distinctions and similarities between Machadinho d'Oeste and Vale do Anari

| SETTLEMENTS | | MACHADINHO D'OESTE | VALE DO ANARI |
|---|---|---|---|
| **Distinctions** | **Architectural design** | Area of 2,090 $km^2$ | Area of 1,246 $km^2$ |
| | | Topography oriented with patches of forest communal reserves | Fishbone without patches of forest communal reserves |
| | | Property size ~ 44 ha | Property size ~ 50 ha |
| | | Properties with more equitable access to fertile soil, relatively flat terrain, and sources of water | Properties with unequal access to fertile soil, relatively flat terrain, and sources of water |
| | **Institutional design** | Private properties (67%) and forest communal reserves (33%) | Private properties (100%) |
| | | Good infrastructure | Fair infrastructure |
| | | Governmental assistance | Lack of governmental assistance |
| | | Incentives for the creation of associations | Lack of incentives for the creation of associations |
| | | Actors: settlers, loggers, and rubber tappers | Actors: settlers and loggers |
| **Similarities** | | Biophysical features within the settlements' landscapes (e.g., climate, topography, soils, original vegetation) | |
| | | Settlement age (both settlements were implemented in the early 1980s) | |
| | | Assets among colonists (settlers were selected following the same eliminatory and classificatory criteria) | |

Table 43 - Selected findings of this dissertation.

| SETTLEMENTS | | MACHADINHO D'OESTE | VALE DO ANARI |
|---|---|---|---|
| Findings | Vegetation structure | 3 stages of secondary succession distinguished using vegetation structure data | |
| | | 2 stages of secondary succession distinguished using LANDSAT TM data | |
| | LULC | 66% of forest cover in 1998 (51% if excluding reserves) | 51% of forest cover in 1998 |
| | | 44% of forest within the 800-meter buffers along roads in 1998 | 25% of forest within the 800-meter buffers along roads in 1998 |
| | | 1.35 ha deforested per year per property | 1.35 ha deforested per year per property |
| | | 13% of pasture within properties in 1998 | 16% of pasture within properties in 1998 |
| | | Correlation of forest and pasture of –0.434 in 1998 (p<0.01) | Correlation of forest and pasture of –0.626 in 1998 (p<0.01) |
| | Landscape structure | Lower forest fragmentation | Higher forest fragmentation |
| | | Greater shape complexity | Lower shape complexity |
| | | Higher interspersion between patch types | Lower interspersion between patch types |
| | Institutions | Importance of associations since implementation | Associations are more recent |
| | | Better interactions among actors | Poor interactions among actors |

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