FOREST FRAGMENTATION IN THE BRAZILIAN AMAZON: EVIDENCE FROM LAND REFORM SETTLEMENTS ALONG THE TRANSAMAZON HIGHWAY AND IN SOUTHERN PARÁ

by

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Abstract

The democratization of Brazil in 1985 brought hope and impetus for agrarian reform, especially after the proposal of a series of new settlement projects by many Presidents to expropriate and redistribute lands to the Brazil's landless. The landless poor, however, took this new state-sanctioned program into their own hands and started occupying lands to build land reform settlements. Social Movement Organizations (SMOs) that were established and working illegally gradually emerged and invaded large private landholdings near urban areas with a specific political agenda, while far rural landless people targeted unclaimed open public forest for land occupation to build spontaneous land reform settlements. Both types of land occupation actions constituted the Direct Action Land Reform (DALR). Recent literature has outlined the socio-economic circumstance that affected DALR, DALR settlement formation process and its implication to deforestation; however, no research considers forest fragmentation in these land reform settlements and its relationship with demographic factors. In order to fill this gap in the literature, this thesis first compared the temporal and spatial dynamics of deforestation fragment patterns in spontaneous DALR settlements around the municipality of Uruará along the Transamazon Highway, and in SMO-led DALR settlements in Southern Pará region using satellite imagery from 1986 to 2010 and three landscape metrics (patch mean area, area-weighted mean shape index and patch cohesion index). Metrics results were then respectively analyzed with selected field survey data to discover the impacts of demographic factors on forest fragmentation in DALR settlements. Results showed that SMO-led DALR settlements in Southern Pará primarily exhibited larger, more irregularly shaped and more physically connected deforestation fragments than spontaneous DALR settlements in the Uruará region over the whole

study period. Demographic factors that influenced forest fragmentation in DALR settlements included the number of people and children per household, family lot size, percentage of families receiving credit and the distance between the family lot and the nearest city. At last, constructive policy recommendations were provided based on research findings.

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Dedication

I would like to dedicate this thesis to my parents, Yinsheng Wang and Kehui Li, who raise me up, give me financial support during my studies, and teach me the importance of life and human standards. I would also like to dedicate my work to Zhouzhou He who always gives me love and spiritual support during the last two years.

CHAPTER 1 - INTRODUCTION

The inequitable distribution of land has been a major social issue in Brazil for centuries, which has created numerous land conflicts between the landless poor and large landowners. The end of the military regime and the democratization of Brazil in 1985 brought new hope to this country. In response to some violent civil conflicts in parts of the Brazilian Amazon, particularly in southern Pará State, many Presidents proposed agrarian reform actions through a series of new settlement projects, namely *Projetos de Assentamentos*, in order to bring peace to the landless poor and alter the uneven distribution of land holdings (Simmons *et al.*, 2010). One major approach was to expropriate and redistribute lands to the landless in the name of agrarian reform (Caldas, 2008; Simmons *et al.*, 2010), which made a significant shift from a previous state oriented colonization program in the 1970s to this state sanctioned settlement program (Sigaud, 2005; Simmons *et al.*, 2010). Unfortunately, the new settlement projects did not solve social conflicts and land concentration problems in Brazil at all (Caldas, 2008). Being tired of waiting for more concrete agrarian reform plans by the federal government, a number of motivated landless individuals took advantages of the land law and institutional resources made available by legislation, and initiated their own land reform actions (Caldas, 2008; Simmons *et al.*, 2010). One type of land reform actions was led by Social Movement Organizations (SMOs) that have gradually emerged since the mid-1980s (Caldas, 2008; Wolford, 2010). SMOs mobilized rural workers and landless farmers throughout Brazil and set out to occupy large private landholdings with a specifically designed political agenda, and to create land reform settlements for livelihood (De Janvry, Sadoulet, and Wolford, 2001; Siguad, 2005; Sigaud *et al*., 2008; Simmons *et al*., 2002; Simmons, 2005; Simmons *et al*., 2007a&b; Simmons *et al*., 2010; Caldas *et al*., 2010).

There also emerged another type of land reform actions in the Brazilian Amazon with no participation of SMOs but through a spontaneous process of occupying unclaimed open public forest land, or so called *terra devolutas*, by the rural landless people (Caldas, 2008; Simmons *et al.*, 2010). Both types of land occupation actions implemented by the landless poor in the Brazilian Amazon constituted was is known in the literature as Direct Action Land Reform (DALR)(Simmons et al. 2010), which has so far created more than 7,000 settlements for about 800,000 families throughout Brazil (MDA/INCRA, 2007). Settlements formed under a SMO leadership were therefore named SMO-led DALR settlements, while spontaneous DALR settlements referred to those formed by the rural landless people in a spontaneous way of land occupation in *terra devolutas* (Caldas, 2008; Simmons *et al*., 2010).

Concerns about the relationship between DALR settlement formation and forest loss have mounted over the past few years (Simmons, 2006; Caldas, 2008; Simmons *et al.*, 2010; Caldas *et al.*, 2010; Aldrich *et al.*, 2012). The formation of land reform settlements in the Brazilian Amazon has been considered as a new important driving force of deforestation, and its negative ecological effects in the landscape is most severe in the Amazon Rainforest (Fearnside, 2001b; Simmons *et al.*, 2010; Caldas *et al.*, 2010; Leite *et al.*, 2011). Deforestation rate increased dramatically after land reform settlements being officially recognized by the government, thus increasing forest fragmentation (Caldas, 2008; Caldas *et al.*, 2010). The pervasive forest fragmentation and edge effects, which are the most deleterious processes to the Amazon Rainforest, are caused by the rapid pace of deforestation (Gascon *et al.*, 2000; Murcia, 1995; Laurance, 1998; Skole and Tucker, 1993). In fact, the total area of fragmented rainforest and the remnants that are vulnerable to serious edge effects are much greater than the total deforested area (Skole and Tucker, 1993). Therefore, to some extent, the study of forest fragmentation issue in the Brazilian Amazon is more crucial than the study of deforestation problem itself.

The recent research has addressed DALR settlement formation process and its implication to land cover/land use change (Caldas, 2008; Simmons *et al.*, 2010; Caldas *et al.*, 2010). Pacheco (2008) examined the interactions among land reform, agrarian structures, and deforestation in the Brazilian Amazon. Caldas *et al.* (2010) related deforestation with contentious politics and institutional opportunities for the formation of spontaneous DALR settlements. Research also demonstrated that forest fragmentation in the Brazilian Amazon, especially detrimental edge effects from deforestation, not only had negative impacts on the local ecosystem, but also had profound influence on global climate change (Laurance *et al.*, 1997). The above mentioned literature, however, lacks the link between forest fragmentation and DALR settlements. The way demographic factors of smallholders in different types of DALR settlements influence forest fragmentation still remains unknown.

In order to fill this gap in the literature, this thesis research seeks to shed light on two important topics of forest fragmentation in DALR settlements in the state of Pará, which are: (a) to study the temporal and spatial dynamics of deforestation fragment patterns in different types of DALR settlements over the past two decades, and (b) to discover the effects of demographic factors and household characteristics of smallholders in different types of DALR settlements on deforestation fragment patterns. The municipality of Uruará along the Transamazon Highway in the state of Pará and Southern Pará are two study regions selected for this thesis. Due to the differences of environmental and socioeconomic characteristics between the Transamazon Highway region and Southern Pará (Leite *et al.*, 2011; Simmons *et al.*, 2010), settlers perform different deforestation habits in different types of DALR settlements, which will therefore result in distinctive patterns of deforestation fragments in the landscape. This research is to discover the distinctions.

The thesis is divided into 6 chapters. This first chapter gave an introduction of my thesis topics and their relevance to the literature. The next chapter will present a literature review around four topics related with this study: (1) how Brazilian government projects opened Amazônia and their influence on deforestation; (2) a summary of the causes of deforestation in the Brazilian Amazon; (3) DALR and the formation process of land reform settlements; and (4) forest fragmentation in the Brazilian Amazon and their ecological impacts. Based on the literature review, research questions and hypotheses will be proposed in the second part of Chapter 2. Chapter 3 will introduce study areas. Chapter 4 will describe research design that includes research methodology, data collection, and the selection of landscape metrics used for the spatial analysis of deforestation fragment patterns. Chapter 5 is a discussion about research results, including the dynamics of temporal and spatial patterns of deforestation fragments in DALR settlements, and the nonparametric statistics results obtained from Spearman's rank correlation analysis between landscape metrics results and demographic data collected in DALR settlements through field survey. The final chapter will be a presentation of conclusions.

CHAPTER 2 - LITERATURE REVIEW, RESEARCH QUESTIONS AND HYPOTHESES

In order to better understand the relevance of this thesis research, it is necessary to provide a detailed literature review about what has been achieved so far. This chapter is organized into five sections. The literature review will cover the first four sections and the last section will present the research questions and hypotheses. The first part of this review will discuss about how the Brazilian Amazon was opened by the government projects and their implications to deforestation. The second section will review main drivers of deforestation in the Brazilian Amazon and the roles of different agents in deforestation activities. The third part will present the formation process of DALR settlements and its relationship with deforestation. The last part deals with forest fragmentation in the Brazilian Amazon and its ecological impacts.

2.1 Opening the Brazilian Amazon

Prior to the 1960s, Amazônia was so basically intact that the access to the forest's interior was highly restricted (Kirby *et al.*, 2006). Unfortunately, a series of government projects broke the peace. The drive to settle Amazônia was a continuation of Brazilian governments' preemptive efforts to develop the interior and to bring modernity to this completely wild region. The construction of the Belém-Brasília Highway[1] that linked Amazônia to the south of the country during 1958 and 1960, and the opening of the Cuiabá-Porto Velho Highway connecting Mato Grosso with Rondônia in 1965 attracted millions of colonists to migrate into this region. Agricultural settlements and new cities, with their suites of infrastructures, sprang along the highway, which brought economic potential and development of the Brazilian Amazon in the late 1960s (Fearnside, 1984; Diegues, 1992). During this period, only a very small portion of forest was cleared by small farm households for livelihood.

After the mid-1970s, deforestation rapidly increased and it was mainly resulted from the large influx of colonists led by the federal colonization program (Moran, 1981). Overpopulation, poverty, and extreme inequality in land distribution in Northeastern Brazil were the immediate issues to be solved at that time, especially after the big drought in 1970 (Fearnside, 1984). In order to relieve extreme social pressures and prevent civil unrest, the Brazilian military government launched the National Integration Program (PIN) in 1970 to attract drought-affected victims in Northeastern Brazil to the colonization areas in Amazônia (Tavares *et al.*, 1972; Fearnside, 1984; Diegues, 1992). One solution was the construction of the Transamazon Highway (official designation BR-230) in 1972, which was intended to integrate the northeastern parts of Brazil with the rest of the country and transfer poor northeasterners to colonize along the highway (Fearnside, 1984). The advent of the PIN also led to the creation of a new government agency for colonization and land reform named the National Institute for Colonization and Agrarian Reform (INCRA), which is responsible for implementing the national policy of land reform (Caldas, 2008). It set out to colonize areas in Amazônia and establish colonization settlements through Integrated Colonization Projects (PICs) and Directed Settlement Projects (PADs) (Fearnside, 1984). The colonization of the Transamazon Highway was divided into three PICs: Marabá, Altamira and Itaituba (Fearnside, 1984). In order to stimulate economic growth, colonists received agricultural credit and technical assistance from the INCRA to produce a surplus that would be sold to the other parts of Brazil and even used for the exportation to other countries (Kleinpenning, 1979). Besides, the rapid occupation of Amazônia by Portuguese-speaking Brazilians was considered as the best defense against the potential invasion of foreigners (Kleinpenning, 1979). Therefore, economic benefits and strategic geopolitical considerations were the two main objectives of this state-led colonization program.

The military government's strategy was changed in the late 1970s. Its interest shifted from colonization settlements to a series of large scale development projects, namely the Polamazonia Plan (*Polos Agropecuarios e Agrominerais da Amazônia*) (Diegues, 1992; Simmons *et al.*, 2010). This Plan aimed to open up Amazônia for development, including encouraging and supporting mining and timber industry, constructions of new federal highways and the Tucuruí Dam, and especially the discovery of gold deposits. Consequently, this program attracted a large wave of spontaneous in-migration to the region (Simmons *et al.*, 2010). Deforestation rate was also dramatically accelerated because of extensive industrial activities, extending from areas held by small farmers to large private properties. Although some forest conservation areas were established to reduce the heavy negative environmental and ecological impacts, their role in minimizing deforestation was modest (Diegues, 1992; Fearnside, 2001a; Fearnside, 2005).

After the end of the military dictatorship and the democratization of Brazil in 1985, a series of new settlement projects were proposed by many presidents including President Cardoso that aimed to grant land rights to smallholders in order to establish a peaceful rural world through the effort of new agrarian reform actions (Pacheco, 2008; Simmons *et al.*, 2010). The actual effect, however, was so minimal that some motivated individuals took this agrarian reform into their hands and initiated their own land reform actions through large-scale land occupations (Caldas, 2008; Simmons *et al.*, 2010; Wolford, 2010). One way was to occupy unclaimed open public forest by rural landless people, which was referred to a spontaneous DALR. The other way was to invade and occupy large private landholdings under the leadership of a SMO. For illustration, the *Movimento dos Trabalhadores Rurais Sem Terra* (the Rural Landless Worker's Movement, or MST) was the most dynamic and well-organized SMO in Brazilian history that was established in the mid-1980s. According to the Federal Constitution and the Brazilian land law, a personal real property would be expropriated by the government if it is considered unproductive or not fulfilling its social function. The MST utilized the legislation to argue for the right to land property, and organized rural workers and landless farmers throughout Brazil to conduct land occupation actions with a specific political agenda (Wolford, 2010). If the occupation was successful, they evicted the landowner and then urged the federal government to expropriate and redistribute the occupied land to the landless poor in order to build a land reform settlement. This type of land reform action was considered as a SMO-led DALR (De Janvry, Sadoulet, and Wolford, 2001; Siguad, 2005; Sigaud *et al*., 2008; Simmons *et al*., 2002; Simmons, 2005; Simmons *et al*., 2007a&b; Simmons *et al*., 2010; Caldas *et al*., 2010). The formation of new DALR settlements through out the Brazilian Amazon has been detected as a new important contributor to deforestation in Amazônia in the past few years (Caldas, 2008; Simmons *et al.*, 2007b; Simmons *et al.*, 2010; Caldas *et al.*, 2010; Leite *et al.*, 2011).

2.2 Drivers of Deforestation in Amazônia

The first estimation of deforestation in Amazônia was made in the early 1970s, suggesting that little clearing of forest had taken place. Deforestation, however, increased rapidly after the mid-1970s (Fearnside, 1986; Diegues, 1992). The newly released data showed that since 1970, around 642,812 km^2 rainforest in the Brazilian Amazon has been destroyed, which is almost the same size as the French territory (640,294 km^2) (INPE, 2010). Although the deforestation rate has decreased dramatically since 2005 (from 31.5% in 2005 to 6.2% in 2010), the net value still keeps high (Figure 2.1).

There is a general consensus that deforestation in the Brazilian Amazon rainforest has been resulted from excessive human interferences rather than natural causes. Generally speaking, driving forces of deforestation in Amazônia since the 1970s can be summarized as three proximate causes and five underlying causes – Proximate causes include agricultural expansion, wood extraction and infrastructure extension; Underlying causes consist of economic development, political factors, technological change, cultural behaviors and demographic dynamics (Geist and Lambin, 2001; Mahar, 1979&1990; Diegues, 1992; Fearnside, 2005; Bauch *et al.*, 2009). These causes are mainly embodied and reflected in three agents who contribute most to deforestation in the Brazilian Amazon: commercial interests, cattle ranchers, and small farm households (Binswanger, 1991; Schmink and Wood, 1992; Roberts and Thanos, 2003; Walker, 2003; Margulis, 2004). Cattle ranching are undoubtedly the leading contributor to deforestation in the Brazilian Amazon (Sawyer, 1986; Fearnside, 1986; Downing *et al.*, 1992; Fearnside, 1993; Kaimowitz, 1996; Faminow, 1997; Mertens *et al.*, 2002; Ferraz *et al.*, 2005; Fearnside, 2005; Barreto *et al.*, 2006), which possesses nearly 80% of all cleared lands (Greenpeace Brazil, 2009). The relative impacts of smaller farmers versus large landholders on deforestation have been changing continuously with economic and demographic pressures (Fearnside, 2005). Pacheco (2009) compared deforestation in small farm households versus medium and large landowners, and found that smallholders contributed 70.9% while medium and large landowners only contributed 21.7%. The major land use of deforested areas for smallholders has been devoted to annual and perennial crops while a large portion of cleared lands in medium- and large-scale landholdings have been converted to pastures. For ranchers, the rate of forest conversion to pasture varies by landholder types: wealthier landholders deforest more land and at a more rapid proportional rate than poorer landholders. The rest of this section will discuss in detail about these three main agents of deforestation, which are commercial interests, cattle ranchers, and small farm households.

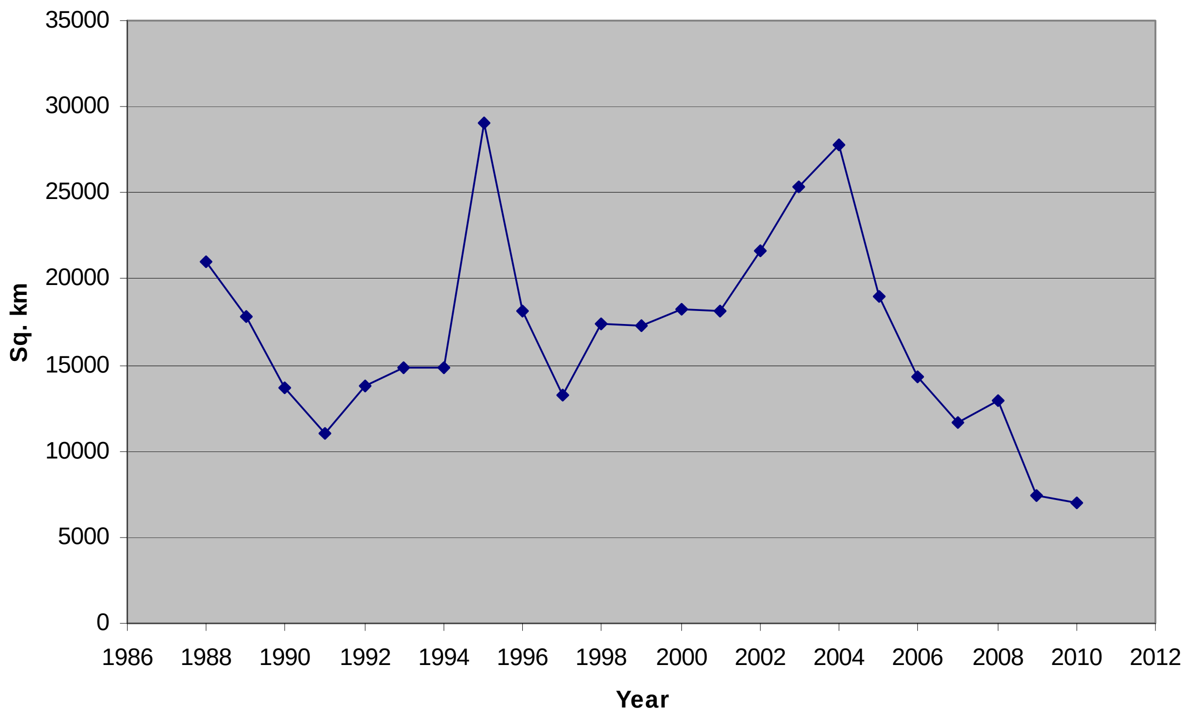

Figure 2.1 Annual deforestation area in the Brazilian Amazon since 1988 (Source: INPE, 2010)

2.2.1 Commercial Interests and Deforestation

Large capitalized agents, such as logging, mining, energy companies, large-scale cattle ranching, large commercial agriculture, accounted for the bulk of deforestation activity and expansion into frontier areas. The great impacts of cattle ranching on deforestation will be discussed in the next section. This section will only focus on large commercial agriculture and logging, which have been considered as two important contributors to deforestation in the Brazilian Amazon.

2.2.1.1 Large Commercial Agriculture

Agricultural expansion into Amazônia and large-scale mechanized agricultural production has made Brazil one of the world's largest exporters of agricultural products, making this country a key player worldwide. There are a number of cash crops in the Brazilian Amazon such as coconuts, cocoa, coffee, sugarcane, tobacco, and palm oil. Soybean is the largest and most widely-grown cash crop, especially in the state of Mato Grosso, which is the largest soybean-producing state in Brazil (Margulis, 2004). Soy production is usually capital-intensive and large-scale, so it is not a smallholder subsistence crop (Bickel and Dros, 2003).

Agricultural use was considered unsuitable in central-western *cerrados* (a vast area of savanna-like grassland ecosystem) due to its poor soils. Soy varieties, however, have been adapted for tropical conditions by EMBRAPA (the Brazilian Enterprise for Agricultural Research, or the *Empresa Brasileira de Pesquisa Agropecuária*) since the early 1970s, permitting large agricultural exploitation and expansion in the *cerrado* (Bickel and Dros, 2003).

Some research suggested that much recent deforestation in the Brazilian Amazon was contributed by the expanding soybean farming. For illustration, Bickel and Dros (2003) argued that deforestation was closely related with soybean expansion and massive pesticide application in the *cerrado* and Southern Amazon Rainforest frontier. Fearnside (2005) criticized that the advance of soybean plantations, with its stimulus for massive government investment in infrastructure development, were expected to be the greatest threat to the Rainforest. Meanwhile, other research argued that soybean farming was not causing new deforestation, but expanding into areas previously occupied by pasture lands (Mueller, 2003; Brandao *et al.*, 2005). On the other hand, Arima *et al.* (2011) showed that soybean expansion in *cerrado* could indirectly cause deforestation in Amazônia, and most recent analyses suggested that deforestation has been driven by large scale of cattle ranching, rather than soybean farming (Barona *et al.*, 2010). In this context, analyses of census and survey data in Mato Grosso and Pará showed that soy cultivation might not have direct relationship with increasing deforestation in the Brazilian Amazon, but the problem was that it pushed cattle ranchers into the deep Rainforest, which indirectly caused further deforestation (Barona *et al*., 2010).

2.2.1.2 Logging

The increasing demand for cheap supplies of tropical timbers from both the Brazilian domestic market and the international market has made logging become another key contributor to deforestation in the Brazilian Amazon. In theory, logging in the Amazon is strictly controlled by laws in Brazil. Timber exploitation can only take place in designated areas by loggers with licenses. Nowadays, however, one of the greatest threats to the Amazon rainforest is illegal and destructive logging. The illegal timber trade represents a major factor in forest degradation. The Brazilian government itself estimated that nearly 80% of all timber produced in the Brazilian Amazon was illegal in origin (Greenpeace USA, 2004).

Research indicated that logging in the Amazon was closely related with road construction, which therefore increased forest fragmentation and resulted in edge effects (Fearnside, 2005; Broadbent *et al.*, 2008; Arima *et al.*, 2005). Logging firms built new roads on site in order to facilitate transportation of logs and to seek to exploit timber resources in deeper rainforest

(Arima *et al.*, 2005). Logging roads also made rainforest accessible to colonists, who exploited for fuelwood and temporary agricultural lands (Nepstad *et al.*, 1999; Arima *et al.*, 2005).

Logging roads aside, selective logging itself – where a limited number of valuable and marketable tree species were cut from a specific area – could not only cause ecological and biodiversity damages, but made rainforest vulnerable to soil erosion and forest fire (Asner *et al.*, 2005; Broadbent *et al.*, 2008). Research also showed that the logging process could result in an ecological damage in the Amazon rainforest of almost twice the volume of the trees being harvested (Veríssimo *et al.*, 1992).

2.2.2 Cattle Ranching and Deforestation

Brazil has the world's largest commercial cattle herd and has been the world's largest beef exporter since 2003 (Greenpeace Brazil, 2009). Research indicated that cattle ranching, which has been expanding continuously and inertially since the 1970s, has become the leading contributor to deforestation in the Brazilian Amazon (Sawyer, 1986; Fearnside, 1986; Downing *et al.*, 1992; Fearnside, 1993; Kaimowitz, 1996; Faminow, 1997; Mertens *et al.*, 2002; Ferraz *et al.*, 2005; Fearnside, 2005; Barreto *et al.*, 2006). A report given by the Greenpeace Brazil (2009) showed that from 1966 to 1975 only 38% of deforestation was due to cattle ranching; however, by 2009 almost 80% of cleared forest has been converted to pasture, occupying a total area around 214,000 square miles.

Five factors spurred cattle ranching in the Brazilian Amazon. First, cattle production has become a key driver of wealth accumulation for ranchers, and profit from beef cattle is a main income source that makes deforestation profitable. It is because cutting forest for pasture cultivation is the cheapest and most effective way to gain profit (Pacheco, 2009; Fearnside, 2005). Secondly, deforestation for pastures has become a main purpose of securing and maintaining a land title for colonists (Fearnside, 2005). Thirdly, the Brazilian *real* was devalued four times as the economy suffered hyperinflation in the early 1990s, which helped double the price of beef in *real* and stimulated beef production in Brazil (Aldrich *et al.*, 2006; Ewers *et al.*, 2008). Fourthly, constructions of roads made deep forest areas accessible for ranchers, and improvements of infrastructure and facilities provided much convenience and helped reduce the costs for shipping and packing beef products (Laurance *et al.*, 2002a; Aldrich *et al.*, 2006; Ewers *et al.*, 2008). Fifthly, ranchers utilized lands in Amazônia for land speculation purposes because they were very sensitive to economic changes such as interest rates, tax rates, land prices, inflation rates, and government subsidies for agricultural credit (Mahar, 1979; Diegues, 1992; Fearnside, 2005; Aldrich *et al.*, 2006). When prices of pasturelands exceeded forest land prices and when taxes on land and real interest rates were low, land speculation would be extremely attractive to ranchers because it was a good defense against inflation (Diegues, 1992; Fearnside, 2005).

2.2.3 Small Farm Households and Deforestation

Small farm households are identified as those small families of colonists or settlers who have been making family agricultural productions in Amazônia. Homma *et al.* (1995) mentioned that about 50% of deforestation in the Brazilian Amazon was made by smallholders at that time. Pacheco (2008) used land tenure information to reveal that deforested area in small holdings were proportionally greater than other types of holdings and a major portion of cleared forest in small holdings has been used to cultivate permanent and agricultural crops. Research indicated that the impact of small farm households on deforestation is due to household life cycle, shifting cultivation strategies, and financial incentives such as income and agriculture credit (Walker and Homma, 1996; McCracken *et al.,* 1999; Perz, 2001a & 2002; Walker, 2003; Caldas, 2008).

The successful constructions of two federal highways in the 1960s and the federal colonization projects (PIN) in the 1970s attracted a large wave of colonists to the Brazilian Amazon (Fearnside, 1984; Diegues, 1992; Tavares *et al.*, 1972). Young smallholders migrated to the Amazon frontier with their spouses and children. They established farms and subsisted on annual crops (such as rice, beans, corn and manioc) initially by clearing a small plot of primary forest because annual crops can be harvested soon after planting, which constitute a low-risk agricultural strategy (Walker and Homma, 1996). The soil fertility in the Amazon, however, declined rapidly with a frequently repeated farming strategy on a same plot of land, small farm households must periodically deforest more area in order to secure a basic subsistence. Therefore deforestation area increased rapidly after several years of colonization (Walker and Homma, 1996).

The labor/consumer ratio increased when colonists' children grew up and started to contribute to the household labor pool. Family crops gradually shifted from annual crops to perennial crops or tree crops (such as cocoa, coffee, coconuts and black peppers), which require substantial labor inputs in cultivation (Pichón, 1996). Households with fewer labors often shifted into pastures (Perz, 2001b; Pichón, 1996). No matter what kind of transition of farming strategies is, all types of land use change lead to more extensive deforestation (Walker *et al.*, 2000).

When children reached their adulthood, older parents sought to pass land on to children, and farmers might plant valuable trees on their lands for the sake of long-run production of timber. Therefore reforestation has been identified as the last stage of land use based on small farmers' household life cycle (Perz, 2001a). At this stage, children might stay in place and build on the family's property, or they might move to seek for another piece of land for occupation and start a new life cycle (Walker and Homma, 1996). In the latter case, new deforestation would occur beyond the forest frontier (Walker and Homma, 1996).

McCracken *et al.* (1999) summarized Walker and Homma's (1996) discussion about the relationships among smallholders' life cycle, land use change, and deforestation. They identify five stages of a household's life cycle. Stage I describes early colonists with their young children (duration of residence under five years) who primarily engage in cultivation of annual crops; stage II involves young parents with growing children, a duration of residence around five years, who have annuals, young perennials and newly formed pasture; stage III sees old parents with teenage children, a duration of residence around 10 years, a declining emphasis on annuals but emphases on perennials cattle ranching; in stage IV, duration of residence is around 15 years. Children begin to reach young adulthood, with ranching and perennials predominate; and in stage V, after 20 or more years, children may begin to leave, ranching activities and perennials production is high, reforestation can be found in old properties.

This thesis research only concerns about the impacts of smallholders on deforestation fragment patterns in terms of demographic factors and household characteristics.

2.3 Direct Action Land Reform and Deforestation

Besides these important drivers of deforestation in the Brazilian Amazon mentioned above, recently and sometimes contentious process of DALR settlement formation has been identified as a new important driving force of deforestation (Simmons *et al.*, 2007b; Caldas, 2008; Pacheco, 2009; Simmons *et al.*, 2010; Caldas *et al.*, 2010; Leite *et al.*, 2011; Aldrich *et al.*, 2012). The social and economic backgrounds of DALR have been introduced in the first chapter.

This section will only be focused on how DALR works and the impacts of DALR on deforestation.

2.3.1 The Constitution of DALR

Generally, DALR consists of two types of land occupation actions by the landless poor in the Brazilian Amazon. One type of land reform actions was under the leadership of a SMO, such as the MST, which was the most dynamic and well-organized SMO in Brazilian history (Caldas, 2008; Simmons *et al*., 2010; Wolford, 2010). Mobilization of the landless poor, land occupation, and the official recognition of land holdings after occupation were three main stages of a typical SMO-led DALR (Simmons *et al.*, 2010). The other type of DALR received no support from a SMO, but was through spontaneous land occupation in *terras devolutas* beyond the rainforest frontier by the rural landless people (Simmons *et al*., 2010).

DALR under a SMO leadership involved a coordinated set of actions designed to advance the political agenda as well as to obtain land for the creation of a land reform settlement (Simmons *et al.*, 2010). A large proportion of participants in a SMO were landless farmers or rural workers who came from urban or suburban areas (Wolford, 2010; Simmons *et al.*, 2010). A SMO typically selected large private landholdings for occupation, such as a latifundium[2] (Simmons *et al.*, 2010). Although SMOs could organize and achieve a land occupation quickly, official recognition of settlements by the government might take years to be accomplished, for the recent legislation has made this process more complicated (Simmons *et al.*, 2010).

Spontaneous land reform actions targeted unclaimed open public lands by the rural landless without too much political consciousness or forethought organization (Caldas, 2008; Simmons *et al.*, 2010; Caldas *et al.*, 2010). Spontaneous DALR did not have a political agenda like a SMO, but it was a process of agricultural expansion and smallholders' demographic life cycle involving mostly rural poor people attracted by the state-led colonization program in the 1960s and 1970s (Walker and Homma, 1996; Simmons *et al.*, 2010; Perz, 2001a; Perz and Walker, 2002; Walker *et al.*, 2002).

The main distinctions between spontaneous and SMO-led DALR were centered in:

1) Targeted property – spontaneous DALR targeted unclaimed open public lands, while SMO-led DALR was interested in large private properties (Caldas, 2008; Simmons *et al.*, 2010; Caldas *et al.*, 2010);

2) Government assistance – spontaneous DALR participants received little government assistance until a settlement was formed, but a SMO-led DALR was assisted by the government agency, such as the INCRA, from land occupation all the way to the official recognition (Simmons *et al.*, 2010);

3) Participants – most participants in spontaneous DALR came from distant poor rural areas in the rainforest, while SMO-led DALR intended to mobilize people in urban and suburban areas (Caldas, 2008; Simmons *et al.*, 2010).

There also existed a hybridized type of DALR settlements that were formed in a spontaneous way, but were later occupied and developed by a SMO under the assistance of the INCRA. Specifically, the formation process of a hybrid DALR settlement involved a wide variety of actors, such as the landless poor, radical leadership of a SMO, government officials from the INCRA, etc. Therefore, the constitution of this type of settlements exhibited elements from both SMO-led and spontaneous DALR (Simmons *et al.*, 2010; Caldas *et al*., 2010). This thesis research only concerns about forest fragmentation in spontaneous and SMO-led DALR settlements.

2.3.2 DALR Settlement Formation and Deforestation

Pacheco (2009) analyzed the impacts of land reform actions on deforestation at an aggregate scale based on official data from INPE, INCRA, and IBGE. Results showed that only 11.3% of the accumulated gross deforestation took place in land reform settlements, and the proportion of cleared forest area had slowly increased from 10.6% by 1997 to 14.3% by 2003. Deforestation was most obvious in SMO-led DALR settlements, but more than 85% of which took place before the settlements were built (Pacheco, 2009). Caldas *et al.* (2010) studied the relationship between the formation of spontaneous DALR settlements and deforestation based on satellite imagery and field survey data. Results revealed that deforestation in spontaneous DALR settlements increased slowly between 1986 and 1991, but it increased dramatically soon after the official recognition of a land reform settlement by INCRA. This was resulted from the improved infrastructure and agricultural expansion in a DALR settlement through credit support from the local government (Caldas *et al.*, 2010; Aldrich *et al.*, 2012).

Due to the distinctive social, economic and political backgrounds, settlers living in different types of DALR settlements may perform a wide variety of farming strategies and deforestation activities, causing different deforestation fragment patterns. When deforestation area becomes larger, forest patch size decreases. Isolated habitats destructed by forest fragmentation would make the population of wildlife species decline, which in turn reduces biodiversity in tropical rainforests (Harris, 1984).All the drivers of deforestation, such as ranching, mining, logging and road construction, can also become drivers of forest fragmentation in Amazônia (Fearnside, 1990; Laurance*et al.*, 2001a; Broadbent *et al.*, 2008; Perz*et al.*, 2008; Arima *et al.*, 2005). When forest is fragmented, human-ignited fires, logging, mining, road building, excessive hunting, fuelwood gathering, and livestock can penetrate into the forest remnants and cause more damages to fragmented forest (Schelhas and Greenberg, 1996; Laurance and Bierregaard, 1997; Curran *et al.*, 1999). The next section will review the negative impacts of forest fragmentation in Amazônia.

2.4 Impacts of Forest Fragmentation in Amazônia

In Amazônia, smaller, more irregular, and more isolated fragments tend to exhibit more negative ecological outcomes (Laurance and Bierregaard, 1997; Bierregaard *et al.*, 2001; Laurance *et al.*, 2002). Research also demonstrated that forest fragmentation in the Brazilian Amazon, especially detrimental edge effects from deforestation, not only has negative impacts on the local ecosystem, but also has profound influence on global environment and climate change (Laurance *et al.*, 1997). These negative impacts could be illustrated from three perspectives: an ecological perspective, a biomass perspective, and an edge effect perspective.

From an ecological perspective, forest fragmentation alters the biodiversity and biotic composition in the tropical rainforest (Bierregaard *et al.*, 1992; Lovejoy *et al.*, 1986). It can also change the ecological processes, such as nutrient cycling and pollination (Didham *et al.*, 1996; Klein, 1989; Harrison and Bruna, 1999). From a community scale, fragmentation can influence species population (Laurance *et al.*, 2001b) and alter the structure and dynamics of species community (Laurance, 2000; Laurance *et al.*, 2001b). From a biomass perspective, fragmentation can cause biomass collapse in rainforest (Laurance *et al.*, 1997). When biomass decomposes, it becomes a source of greenhouse gases, such as carbon dioxide (CO_2) and methane (CH_4). Such emission is considered as a main cause of global warming (Laurance *et al.*, 1997).

An increase in forest edge caused by fragmentation can result in many biotic changes and edge effects (Laurance and Bierregaard, 1997; Lovejoy *et al.*, 1986). Edge effects can extend from transition zones near the edge into the remnant interior. While the majority edge effects are considered to extend no further than 1km (Murcia, 1995), some may extend as far as 5–10 km into the forest (Curran *et al.*, 1999). Besides, one of the most striking edge effects is elevated rates of tree mortality and damage (Ferreira & Laurance 1997; Laurance *et al.*, 1998b). Research found that mortality rate is especially higher near forest edges than in remnant interiors (Laurance *et al.*, 2001c). The rise in tree mortality rate alters canopy-gap dynamics (Ferreira and Laurance, 1997; Laurance *et al.*, 1998b), which can further influence forest structure, composition, and diversity (Brokaw, 1985; Hubbell and Foster, 1986; Denslow, 1987). Fragment edges can also increase wind turbulence, which lead to windthrow and forest structural damage (Laurance, 1997). Fragments are very dry, especially along the fire-prone edges (Kapos, 1989), making fragments vulnerable to fires during droughts (Cochrane and Schulza, 1999; Cochrane *et al.*, 1999; Gascon *et al.*, 2000; Kauffman and Uhl, 1990; Nepstad *et al.*, 1999; Laurance *et al.*, 2001c).

Many factors can affect the appearance of forest fragmentation, such as road building and road networks (Arima *et al.*, 2005; Perz *et al.*, 2008). In the case of the Brazilian Amazon, studies have identified that the "fishbone" pattern of fragmentation along the Transamazon Highway is a consequence of road network (Perz *et al.*, 2008). In this context, the pattern is represented by elongated, irregularly-shaped strips of forest running between secondary roads[3], which run perpendicular to the Transamazon Highway. This pattern is a consequence of the early state-directed colonization program in the 1970s. The arrival of excess migrants led to the formation of many informal land settlements that extended the initial road network design and spatially propagated the fragmentation pattern. Later on, unfavorable biophysical conditions, state withdrawal, capital scarcity, and difficulties with perennial crops led to clearing of many small patches of forest, reinforcing the irregular fishbone fragmentation geometry (Perz *et al.*, 2008). Nowadays beyond the forest frontier, deforestation fragment patterns inside those newly formed DALR settlements along the Transamazon Highway and in Southern Pará are still unknown. This thesis research will analyze the deforestation fragment patterns and their relationship with demographic factors in different types of DALR settlements.

2.5 Research Questions and Hypotheses

Research has showed many evidences that deforestation activities have been accompanied all along with DALR settlement formation (Simmons *et al.*, 2007b; Caldas, 2008; Pacheco, 2009; Caldas *et al.*, 2010; Simmons *et al.*, 2010; Leite *et al.*, 2011). Nevertheless, the literature overlooked forest fragmentation issues in DALR settlements, especially the role of household's characteristics in forest fragmentation. In order to fill this gap in literature, this research will mainly address the following three research questions:

Question 1: Is there an initial fragmentation pattern in DALR settlements?

Hypothesis 1A: It is hypothesized that spontaneous DALR settlements will initially present small, irregular and disconnected patches of deforestation distributed randomly in the forest due to the fact that these settlements are located beyond the forest frontier.

Hypothesis 1B: It is hypothesized that in SMO-led DALR settlements in Southern Pará region, deforestation fragments will be initially characterized by larger, more regularly shaped and more physically connected patches of deforestation due to the fact that these settlements are located in the forest frontier, a region characterized by large landholdings.

Question 2: How did deforestation fragment patterns change spatially and temporally in DALR settlements?

Hypothesis 2A: In spontaneous DALR settlements, deforestation fragments would proliferate after the official recognition by the INCRA. Patches of deforestation would also become larger, more regularly shaped and more physically connected.

Hypothesis 2B: In SMO-led DALR settlements, deforestation fragments would also grow larger and become more regularly shaped and more connected over time and space.

Question 3: How did household characteristics of settlers influence deforestation fragment patterns?

Hypothesis 3A: Settlements with larger proportion of children and seniors[4] in a household would be expected to have more subsistence crops, thus deforestation fragments will be represented as smaller, more irregular and more disaggregate patches.

Hypothesis 3B: Settlements with larger proportion of adults would be expected to invest in more cash crops or cattle ranching for income. Consequently, it would show larger, more regularly shaped and more continuous fragments of deforestation in the landscape.

CHAPTER 3 - STUDY AREAS

This thesis research studies forest fragmentation in DALR settlements in two study regions in the state of Pará, which exhibit many different social and environmental characteristics, distinctive DALR actions and land reform settlement types (Tables 3.1 & 3.2). One region is the municipality of Uruará along the Transamazon Highway and the other is Southern Pará region (Figure 3.1). The specific pilot DALR settlements selected for this research are three spontaneous DALR settlements located along the Transamazon Highway around the municipality of Uruará: Rio Trairão, Rio de Peixe, and Uirapurú (Figure 3.1; Table 3.2), and three SMO-led DALR settlements in Southern Pará around the municipalities of Marabá, Parauapebas, and Eldorado dos Carajás, which are Alegria, Palmares Sul, and Santa Maria do Pontal (Figure 3.1; Table 3.2).

There are three reasons why the three selected spontaneous DALR settlements in the municipality of Uruará along the Transamazon Highway are the most appropriate study areas for an assessment of forest fragmentation patterns. First, they are typical spontaneous DALR settlements newly formed in the mid-1990s where used to be covered by public primary rainforest (Table 3.2). Secondly, smallholders are the most important social constitution of those settlements who have been performing mixed farming strategies including annuals, perennials, and an increasingly important role of cattle ranch (Perz, 2001a; Perz and Walker, 2002; Pacheco, 2008). Different farming systems have been considered to have different effects on forest fragmentation (Caldas, 2008). Thirdly, these three pilot settlements in the Uruará region have experienced dynamic frontier expansion and demographic life cycles (Perz, 2001a; Perz and

Walker, 2002; Walker *et al.*, 2002). Both of them are important factors that influence forest fragmentation in DALR settlements (Caldas, 2008).

There are also three reasons why Alegria, Palmares Sul, and Santa Maria do Pontal were selected from Southern Pará region for this research. First, they are three typical SMO-led DALR settlements newly formed in the late 1990s and early 2000s where used to be large private landholdings but were later occupied by SMOs (Table 3.2). Secondly, they have the same mixed farming systems as those three spontaneous DALR settlements, which make it possible to compare forest fragment patterns in different regions with the same farming systems. Thirdly, these three SMO-led DALR settlements have undergone dramatic sociopolitical and economic changes since the time of land occupation, which were considered to have different effects on forest fragmentation from spontaneous DALR settlements (Caldas, 2008). One goal of this research is to find out the differences.

Table 3.1 Environmental and social characteristics of two study regions.

Characteristics	Transamazon Highway Region	Southern Pará
Environmental characteristics		
Deforestation	Less	More
Land degradation	Less	More
Soil quality	Better	Worse
Social characteristics		
Conflict	Less	More
Type of land occupation	Open public land	Private property
Type of DALR process	Spontaneous DALR	SMO-led DALR
Proximity to urban centers	Farther	Closer
Origin of most settlers	Rural	Urban
Farming experience	More	Less
Family members nearby	More	Fewer

(Source: Leite *et al.*, 2011; Simmons *et al.*, 2010)

Table 3.2 Basic information of selected DALR settlements.

Settlement Name	Municipality	Type of DALR Tactic	Year INCRA recognized	Settlement capacity	Families settled
Rio do Peixe	Uruará	Spontaneous	10/25/1995	260	241
Rio Trairão	Uruará	Spontaneous	10/7/1997	170	160
Uirapurú	Uruará	Spontaneous	6/10/1997	262	252
Alegria	Marabá	SMO-led	12/9/1999	96	95
Palmares Sul	Parauapebas	SMO-led	12/31/2001	327	286
Santa Maria do Pontal	Eldorado dos Carajás	SMO-led	7/14/1997	115	67

(Source: Caldas, 2008; Simmons *et al.*, 2010)

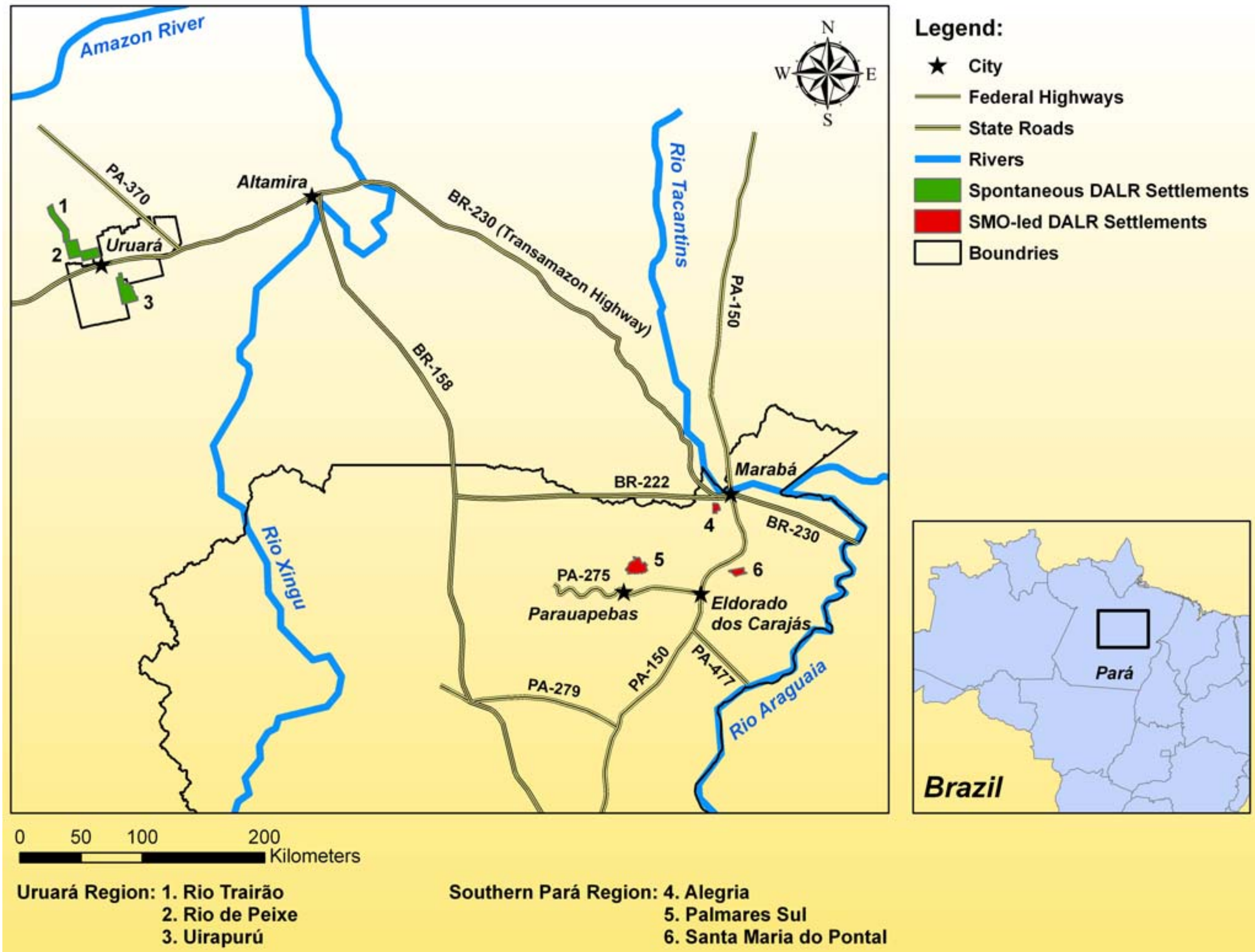

Figure 3.1 Map of study areas.

3.1 The Transamazon Highway Study Region: the Municipality of Uruará

The Transamazon Highway (official designation BR-230) was part of the National Integration Program (PIN) in the 1970s during the regime of the military government. It is a 5300 km-long highway built in 1972, which was intended to integrate northeastern parts of Brazil with the rest of the country and to transfer impoverished northeasterners to colonize along the highway (Fearnside, 1984; Tavares *et al.*, 1972; Fearnside, 1984; Diegues, 1992). The Transamazon Highway opened the capacious rainforest to the rest of the country and attracted large waves of colonization, development of its timber and mineral resources, and settlement building. In recent two decades, the open public rainforest lands along the Transamazon Highway have become vulnerable targets to land occupation for spontaneous DALR (Caldas, 2008; Simmons *et al.*, 2010; Caldas *et al.*, 2010). Occupations mainly took place in forest areas beyond existing settlements formed in the state-led colonization projects (Caldas, 2008).

Uruará is a municipality in the state of Pará in the middle of the Altamira-Itaituba road section of the Transamazon Highway 180 km west from Altamira. Uruará was part of the Altamira PIC (Integrated Colonization Project), one of the first official settlements in the Amazon (Arima *et al.*, 2005) created to resettle the poor landless from the Brazilian Northeast (Simmons, 2002; Moran, 1981; Perz and Walker, 2002). Uruará used to be recognized as an agrovillage, in which small farm households are the main actors (Pacheco, 2008). On May 5, 1988, the federal Law (No. 5.435) officially created the municipality of Uruará (Alonso and Castro, 2005).

Uruará experienced two main large waves of in-migration in its development history due to a combination of pull and push factors (Pacheco, 2008; Perz and Walker, 2002; Perz *et al.*, 2010). The first wave of in-migration appears in the early 1970s (IDESP, 1990). The military government demarcated 100-hectare lots for the old colonists to grow annual crops initially (Perz and Walker, 2002). It later diversified into perennials and pastures due to the household life cycles (Perz and Walker, 2002). The second wave of large in-migration occurred throughout the whole 1980s due to the stimulation of economic boom and raising prices of perennial crops (Perz *et al.*, 2010; Perz and Walker, 2002). The second migration wave raised the total population from over 11,000 in 1980 to about 25,000 in 1991 (IBGE, 1996). New census data show that by 2010 the population of Uruará municipality has reached 44,720 (Figure 3.2) (IBGE, 2010). The rapid population growth led to an increased land demand in this region, which was satisfied by spontaneous DALR settlement formation in the mid-1990s (Caldas, 2008). Land occupation took place beyond frontier forests and smallholders were the main force in DALR actions.

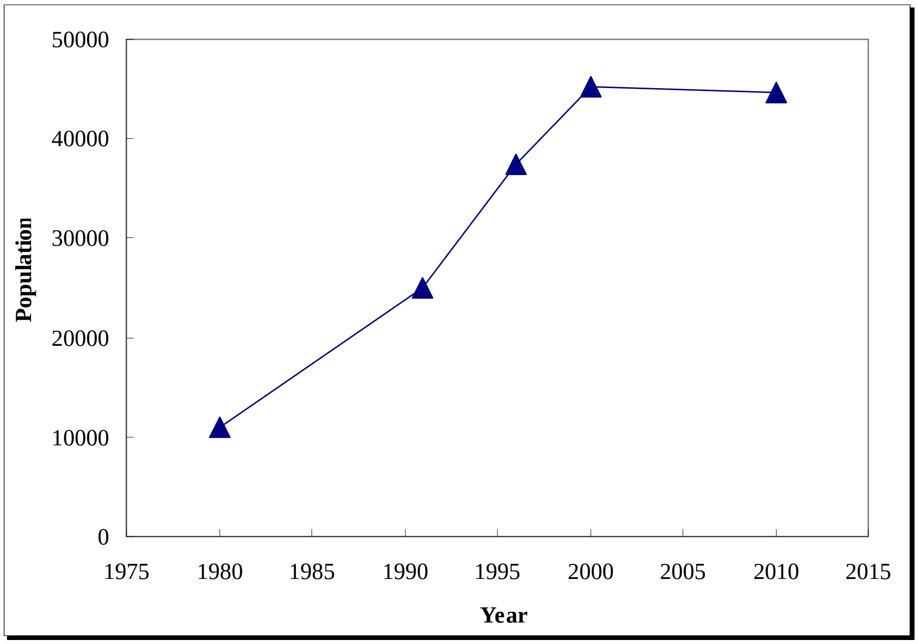

Figure 3.2 Population growth of the municipality of Uruará since 1980.

(Source: IBGE, 1996; IBGE, 1998; IBGE, 2004; IBGE, 2010)

Both small and large landholders were found in spontaneous DALR settlements around Uruará. Research showed that by 2002 smallholders possess 70.9 percent of land and they are responsible for 72.4 percent of the total deforestation, while medium and large landholders only possess 21.7 percent of land and only contribute 16.4 percent of deforestation (Table 3.3) (Pacheco, 2008). Besides, according the recent land-use data released by the INCRA and Pacheco (2008), old settlements occupy 35% of the whole municipality, new DALR settlements 10%, cattle ranchers 11%, and the rests are lands occupied by indigenous people, lands with overlapped rights, and federal lands (Pacheco, 2005). Household characteristics and land-use systems do not show a dramatic difference between old and new settlements (Pacheco, 2008). Although nowadays old settlements still occupy the dominant land share in the municipality of Uruará and most of the settlers are old colonists (Pacheco, 2008), this research will only be focused on newly formed spontaneous DALR settlements in this study region.

Table 3.3 Comparative assessment of landholders in the municipality of Uruará.

	Annual Deforestation (1991/92-2001/02)		Accumulated by 2001/02	
	Deforestation (1000 ha)	Contribution (%)	Land area (1000 ha)	Contribution (%)
Smallholders	9.7	72.4	163.8	70.9
Medium and large	2.2	16.4	50.1	21.7
Other areas	1.5	11.2	17.1	7.4
Total	13.4	100	230.9	100

(Source: Pacheco, 2008)

3.2 A Brief History of Spontaneous DALR Settlements under Study

Settlement Rio do Peixe was officially founded by the INCRA in October 25, 1995 (Table 3.2) through INCRA document #SR01/23 (Caldas, 2008), which has experienced two phases of occupation. The first occupation took place in 1981 within the boundary of *Gleba José de Souza* initiated by a group of squatters who decided to open trails to demarcate 40 lots with 100 ha for each (Brandão *et al.*, 1998). They tried to perform subsistence agriculture in order to assure legal rights to occupied lands (Brandão *et al.*, 1998). The second phase occurred in the early 1990s when new settlers occupied open public forest land for subsistence (Brandão *et al.*, 1998). Lacks of infrastructure, financial resources, and roads, however, made settlers to work in land parcels close to the Transamazon Highway. Besides, the uncertainty of obtaining a land title has made some settlers to sell their lots to the others (Caldas, 2008).

Settlement Rio Trairão was officially recognized by the INCRA in 1997 (Table 3.2), although the field survey and key informant interviews conducted by a group of researchers showed that there was a previous owner of this land before DALR settlement formation (Caldas, 2008). The same as Rio do Peixe, land occupation took place spontaneously in 1981 when squatters opened trails to demarcate lots (Caldas, 2008). The INCRA originally designed to settle 170 households in Rio Trairão with an area of 100 ha for each lot (Caldas, 2008). Due to the lack of infrastructure and the uncertainty of land title, however, some settlers abandoned their lands and only 160 families have been finally settled (Caldas, 2008).

Land occupation and settlement formation of Uirapurú is slightly different from the other two spontaneous DALR settlements. This land used to belong to a private company called Cotrijuí. During the period of occupation from 1981 to 1985, this company voluntarily abandoned its land because of some contradictory affairs with local aborigines, facilitating occupation by squatters (Caldas, 2008). Settlement formation of Uirapurú experienced three phases in history (Caldas, 2008). The first phase occurred in 1997 when the INCRA created 140 lots for families, which was a token of the official recognition of a DALR settlement formation. The second phase appeared in 2001 when 90 families were settled by the INCRA. The final phase emerged in 2004 when the INCRA settled another 35 families. The original planning was to settle 262 families in 18,900 ha of land, which slightly exceeded the holding capacity of this settlement; however, the current data showed that only 252 families have been finally arranged (Caldas, 2008).

3.3 An Introduction of Southern Pará Study Region.

The Southern Pará is a region that includes all of the municipalities that are geographically located south of the Transamazon Highway and east of the Xingu River in the state of Pará (Simmons *et al.*, 2007a).

Southern Pará has experienced dramatic economic, political, and social changes due to a series of federal colonization projects and wealthy reserve in natural resources in the last half century (Simmons *at al.*, 2007b). Abundantly endowed with natural resources and economic growth stimulated rapid in-migration population and industrial prosperity since the late 1950s (Schmink and Wood, 1992). The building of Belém-Brasilia Highway in 1956 and PA-150 state road in the 1970s opened this area to the rest of Brazil and made resources accessible, which consequently attracted large waves of colonists such as ranchers, loggers, and small farmers. Census data showed that the population increased more than nine fold between 1970 and 2000 (Table 3.4, Simmons *et al.*, 2007b). By 2000, 28 municipalities have been established in this region due to rapid population growth and infrastructure development, comparing with only two large municipalities in the 1950s and 1960s, which were Marabá and Conceição do Araguaia (Simmons *et al.*, 2007b). High concentration of population and large gap between the wealthy and the poor in Southern Pará brought social and economic impetus for land reform in the late 1990s and the early 2000s. Distinctively, most land reforms in this region are SMO-led DALR.

Several riverside colonization settlements and large cattle ranches had been established long before DALR in Southern Pará. Those colonization settlements later became vulnerable targets of many smallholders and large interest groups for land occupation in DALR (Branford and Glock, 1985). By the 1980s, interest groups with different political influence constitute a mosaic of land claims in Southern Pará, which resulted in a dark period of contested land settlement involving rural violence such as assassinations and families displaced from their land claims (Schmink and Wood, 1992; Wagner de Almeida, 1995; Simmons *et al.*, 2007). These contentious issues led to two subsequent consequences: one was emergency land titling made by the state, which consequently only motivated further land occupations (Schmink and Wood, 1992), and the other consequence was widespread mobilization of smallholders and the landless in both rural and urban areas, supported by unions, churches and especially DALR SMOs, contesting large private landholdings (Branford and Rocha, 2002; Simmons *et al.*, 2007b). As a result, land occupations and DALR settlement formation, mostly led by SMOs, have proceeded in many parts of the Brazilian Amazon, and nowhere is more severe than the Southern Pará region (Simmons *et al.*, 2007b).

Table 3.4 Demographic features of Southern Pará.

Decade	Total population	Average increase rate (%)	Urban population	Percentage urban (%)	Population density (km^2)
1960	31,372	-	11,567	37	0.15
1970	80,170	16	24,984	31	0.38
1980	224,546	18	80,656	36	1.06
1990	575,669	16	320,112	56	2.71
2000	744,724	2.94	474,531	64	3.51

(Source: Simmons *et al.*, 2007)

CHAPTER 4 - RESEARCH DESIGN

In order to address the three research questions and to test the research hypotheses proposed at the end of Chapter 2, this thesis used several methods based upon remote sensing techniques, GIS spatial analysis, and nonparametric statistics. More specifically, this research applied satellite imagery and GIS techniques to uncover the temporal and spatial patterns of deforestation fragments in six selected land reform settlements in order to answer research questions 1 and 2. For research question 3, this study utilized the summary statistics of selected demographic data and Spearman's rank correlation analysis to test the actual effects of demographic factors on forest fragmentation in those DALR settlements. The first section of this chapter deals with satellite imagery selection and image processing procedures. The second part introduces three adapted landscape metrics utilized in GIS analysis of deforestation fragment patterns in DALR settlements. The third part explains Spearman's rank correlation analysis of landscape metrics and field survey data.

4.1 Satellite Imagery Selection and Image Processing

4.1.1 Satellite Imagery Selection

In order to identify the spatial and temporal dynamics of forest fragmentation patterns in DALR settlements, remote sensing data were utilized in this thesis research. Satellite imagery of two study regions was selected to reflect forest fragmentation situations at different time periods, which included the time before and after land occupation took place, and before and after the official recognition of a DALR settlement by the INCRA. Based on the availability and quality of satellite imagery of study areas, 24 scenes obtained by Landsat 5 TM (Thematic Mapper)

(Table 4.1) covering a 24-year period (1986, 1988, 1991, 1996, 2005, and 2010) were finally used. These images were obtained from the Landsat archives maintained by INPE (Instituto Nacional de Pesquisas Espaciais) and the USGS EROS (Earth Resources Observation and Science) Center.

The Landsat 5 TM sensor has seven bands with different spectral characteristics. This research only used Band 2 (a green band), Band 3 (a red band), and Band 4 (a near-infrared (NIR) band). In order to make a standard false-color composite, the red, green and blue layers were assigned with Band 4 (NIR), Band 3 (red), and Band 2 (green) respectively in *ERDAS IMAGINE* software (version 9.3). This false-color composite scheme could show clear boundaries between forest and non-forest areas because forest area appeared in shades of red, while deforestation area was light blue or grey in color. It is because vegetation has a high reflectance in the NIR region of the spectrum, but non-forest areas, such as roads, densely populated urban areas, and soils, have high reflectance in the visible light region (Jensen, 1996). After satellite imagery was selected, image pre-processing and processing procedures were then conducted.

Table 4.1 Characteristics of selected satellite imagery.

Study Region	Settlement Name	Path	Row
Transamazon Highway	Rio Trairão	227	62
	Rio de Peixe	227	62
	Uirapurú	226	63
Southern Pará	Alegria	223	64
	Palmares Sul	224	64
	Santa Maria do Pontal	223	64

4.1.2 Image Pre-processing

Prior to classification, all images were radiometrically, atmospherically, and geometrically corrected. Figure 4.1 shows detailed procedures.

In order to generate an image data set with compatible scenes that could be used to create optimal classification result, negative influence caused by atmospheric particles must be removed or greatly reduced (Song *et al.*, 2001; Lu *et al.*, 2010). Therefore radiometric and atmospheric corrections are the first two critical image processing steps to put multitemporal data on the same radiometric scale.

This research used a model developed by Chander and Markham (2003) to convert digital numbers (DNs) to radiance using the "Modelmaker" application:

$$L_\lambda = (L_{MAX_\lambda} - \frac{L_{MIN_\lambda}}{Q_{calMAX}}) \times Q_{cal} + L_{MIN_\lambda}$$

where L_λ is the spectral radiance at the sensor's aperture in $w/(m^2 \cdot sr \cdot \mu m)$ units, and Q_{cal} is the quantized calibrated pixel value in digital numbers (DNs). Then another model was built to convert radiance to reflectance corrected by Rayleigh scatter using the following formula:

$$R = \frac{\pi \times (L_\lambda - L_{Rayleigh}) \times r^2}{E_o \times \cos(\phi_S)}$$

where R is unitless surface reflectance, $L_{Rayleigh}$ is radiance owing to Rayleigh scatter, E_o is mean solar extraterrestrial irradiance, r is Earth-Sun distance in astronomical units, and ϕ_S is the Sun elevation angle in degrees (Paolini *et al.*, 2006). All input data were obtained from header files downloaded simultaneously with satellite images. By the end of this step, all original DNs have been converted to surface reflectance.

Images downloaded from the Internet may also have distortions in their geometry. These distortions can result from sensor characteristics (e.g. optical distortion and aircraft/satellite motion), viewing geometry (e.g. panoramic effect and earth curvature), platform motion (e.g. attitude changes and position variations), or target motion (e.g. earth rotation) (Jensen, 1996).

Therefore, correction of geometric errors is another prerequisite for satellite imagery analysis. Symptoms of geometric errors of satellite images used in this research mainly appear as random distortions, such as displacement of objects and occlusion of one image element by another. In order to correct these distortions, fifty ground control points (GCPs) were selected from each original image and their true coordinates were obtained from maps in Google Earth software. Using these GCPs, geometric correction was applied to all images with a second order polynomial approach. The accuracy of these corrections was considered acceptable only when the root-mean square (RMS) error was smaller than 0.5 pixels. All images were then georectified to the "WGS84 UTM Zone 21S" standard map projection.

4.1.3 Image Classification

All 24 satellite images were individually classified into three thematic classes using a hybrid unsupervised/supervised classification approach. The three pre-defined classes are forest area, deforested area and cloud. Unsupervised classification was performed first in order to determine the spectral class composition of each image, and to see how well the intended land cover classes can be defined from the image. After this step, supervised classification was then applied to classify the whole image into those three land cover types of interest.

The unsupervised classification method utilized an iterative procedure called ISODATA clustering algorithm. In general, this algorithm first uses the minimum spectral distance formula to generate initial cluster vectors. It then classifies each pixel to its closest cluster. In the third step the new cluster mean vectors are calculated based on all the pixels assigned to each cluster. The second and third steps are repeated until a maximum number of iterations have been performed or a convergence threshold has been reached (Jensen, 1996). In this thesis 10 maximum iterations and 0.95 convergence threshold were applied to classify the original image into 100 clusters using the ISODATA clustering algorithm. Then each cluster in the spectral signature file was highlighted with a bright color (e.g. bright red or bright yellow) and compared with the original image using the "Swipe" application in order to be identified as one pre-defined thematic class. For example, if pixels in one cluster mainly fall within the forest area in the original image, this cluster was therefore redefined as "forest area". All the clusters from the same thematic class were merged together until all three classes were finally identified. This new spectral signature file was saved and used as an input in the next supervised classification procedure.

The second step was a supervised classification using a parametric rule of maximum likelihood. It was performed to generate a final land-cover map with each pixel assigned to a class based on the new spectral signature. In this classification method, each pixel is judged as to the class to which it most probably belong based on the statistics (e.g. mean, variance, covariance, etc.) and a Bayesian Probability Function calculated from the inputs for classes established from training sites (Jensen, 1996).

Since this research only concerns about forest fragmentation within the boundaries of each DALR settlement, all six settlements under study were extracted from each classified satellite image using settlement shapefiles and the "Extract by Mask" geoprocessing tool in *ArcGIS* software (version 10.1). The final products were 36 classified satellite images of all DALR settlements for all study years (Figures 4.2 – 4.7).

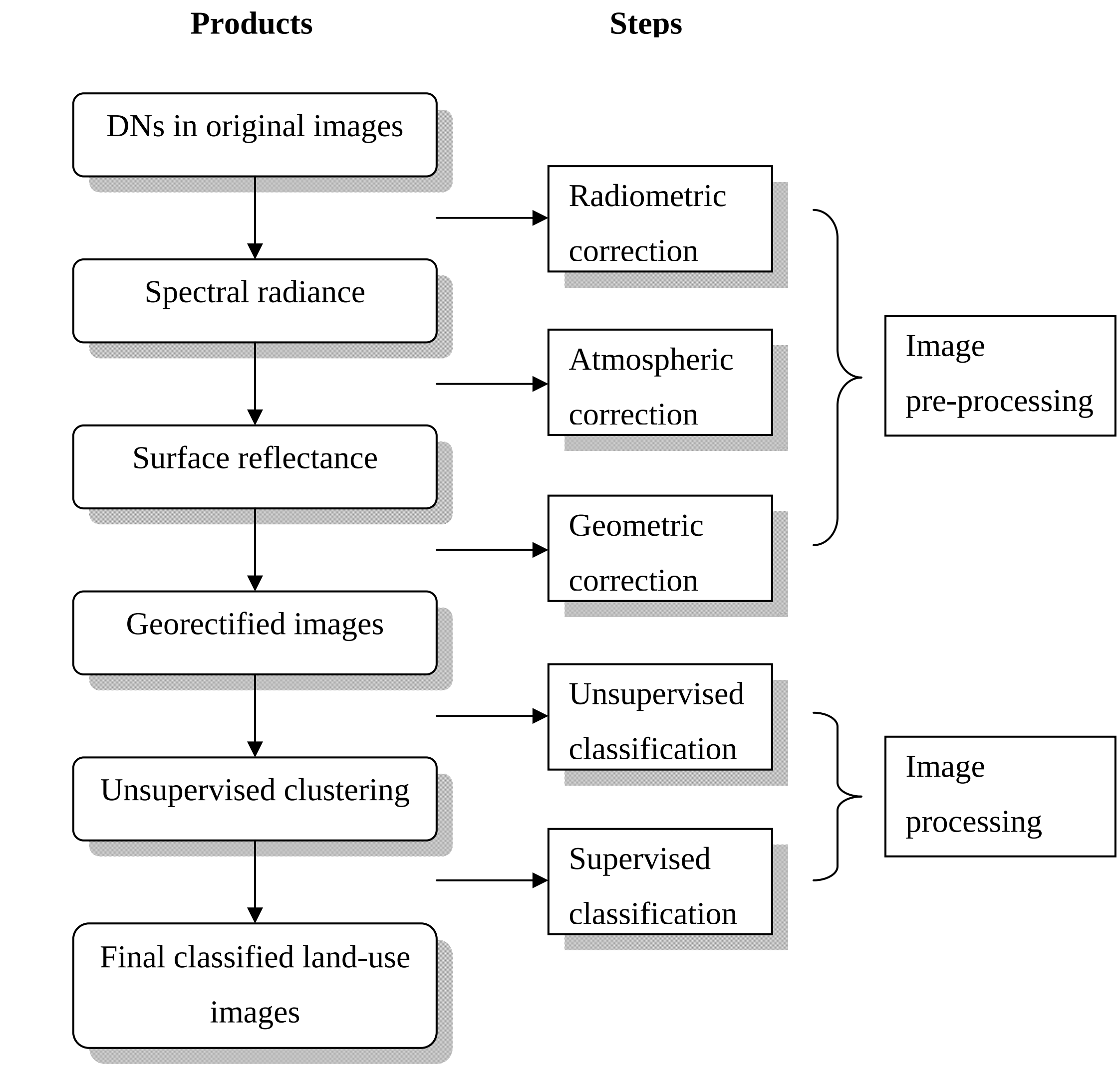

Figure 4.1 Procedures of satellite image pre-processing and processing.

4.2 The Analysis of Deforestation Fragment Patterns

In terms of interpreting the composition and complex spatial patterns in the distribution of resources in a landscape, landscape metric analysis is the most widely used method. Hundreds of landscape metrics have been developed to quantify categorical map patterns of the landscape within the designated landscape boundary. These metrics mainly fall within two big categories.

One is those metrics that quantify the composition of the map without reference to spatial attributes, and the other category includes those that quantify the spatial configuration of the map, requiring spatial information for their calculation (McGarigal and Marks, 1995; Gustafson, 1998). Landscape metrics have been widely utilized to study landscape fragmentation, but it has been found that most landscape metrics were highly correlated, such that contagion and edge density indices had a near-perfect inverse correspondence (McGarigal and McComb, 1995; Hargis *et al.*, 1998; Herzog *et al.*, 2001; Southworth *et al.*, 2002; Guirado *et al.*, 2007). Therefore, screening out appropriate landscape metrics is the foremost step for the spatial analysis of deforestation fragment patterns. This study selected the most suitable landscape metrics based on the following two rules:

(1) Target landscape metrics should not be correlated with each other;

(2) The dynamics of deforestation fragment patterns in DALR settlements discussed in this thesis include temporal and spatial changes of the size, shape and physical connectedness of deforestation fragments. Therefore, target landscape metrics should reflect all these three properties of deforestation fragment patterns.

Three adapted landscape metrics were finally selected based on the two requirements: Patch Mean Area (*PMA*), Area Weighted Mean Shape Index (*AWMSI*), and Patch Cohesion Index (*PCI*).

1) Patch Mean Area (*PMA*) – This metric was used to quantify the mean area of deforestation patches in each DALR settlement at a specific year. It is formulated as:

$$PMA = \frac{\sum_{i=1}^{n} a_i}{n} \left(\frac{1}{10,000}\right)$$

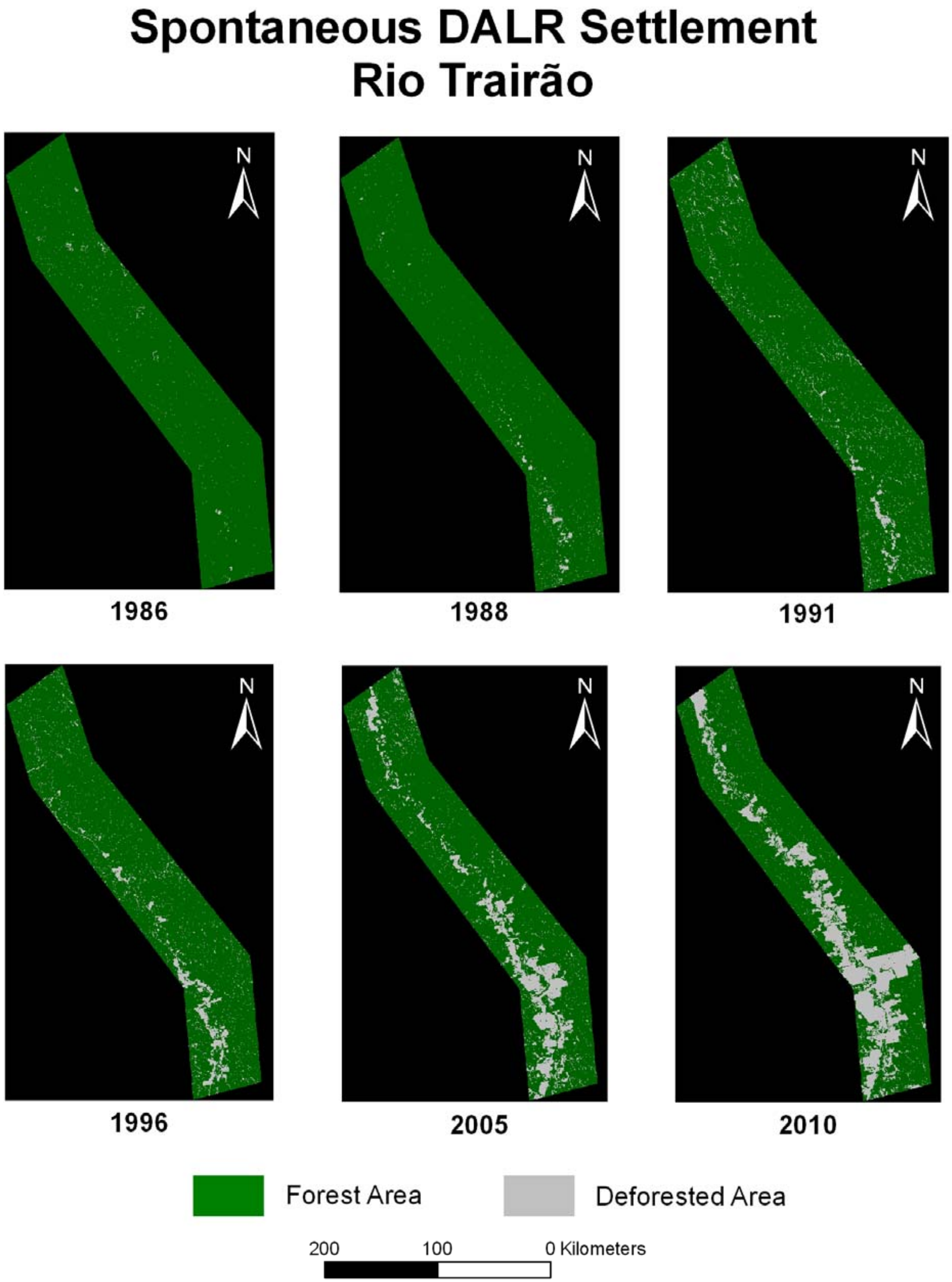

Figure 4.2 Classified satellite images of DALR settlement Rio Trairão.

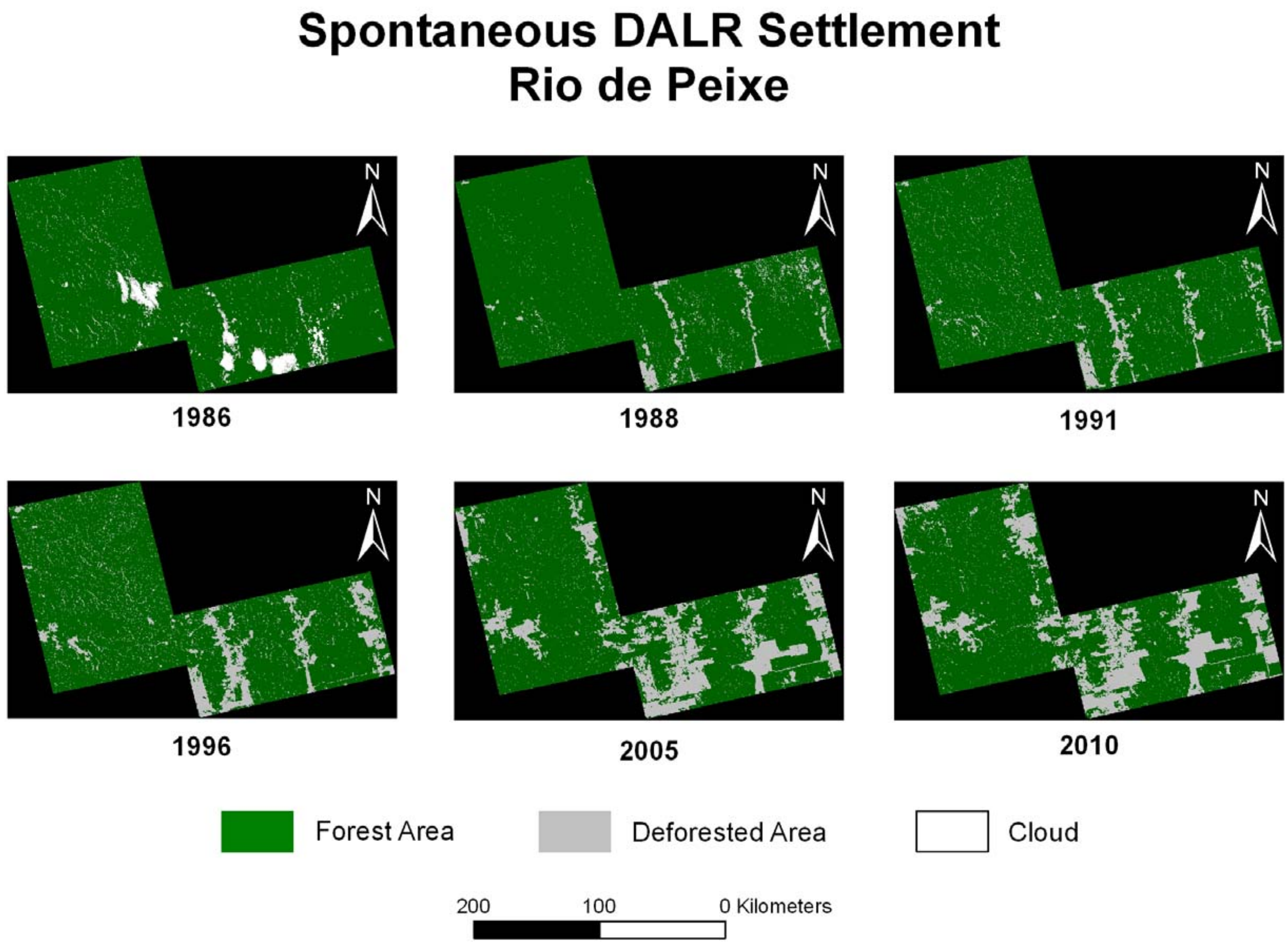

Figure 4.3 Classified satellite images of DALR settlement Rio de Peixe.

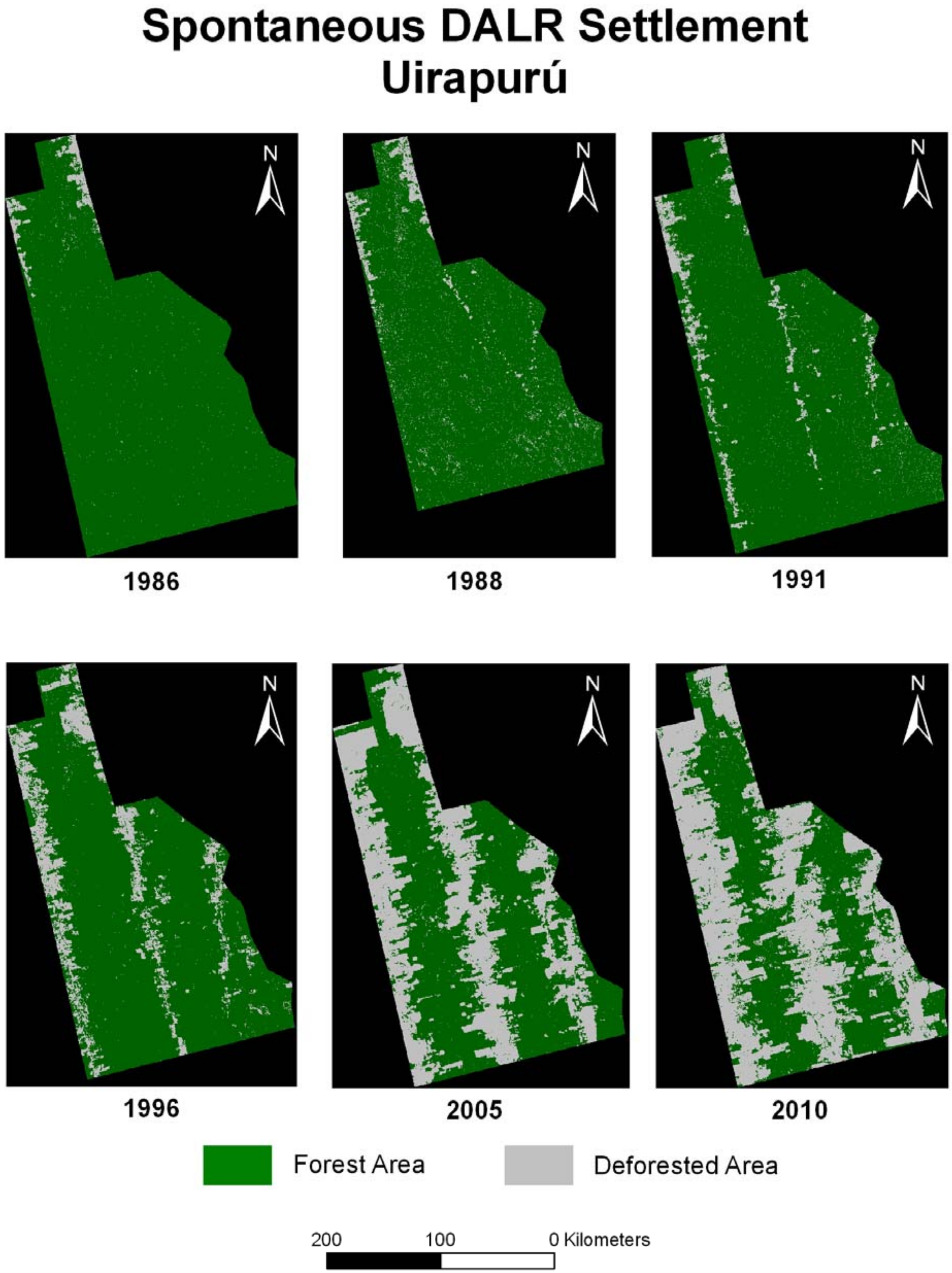

Figure 4.4 Classified satellite images of DALR settlement Uirapurú.

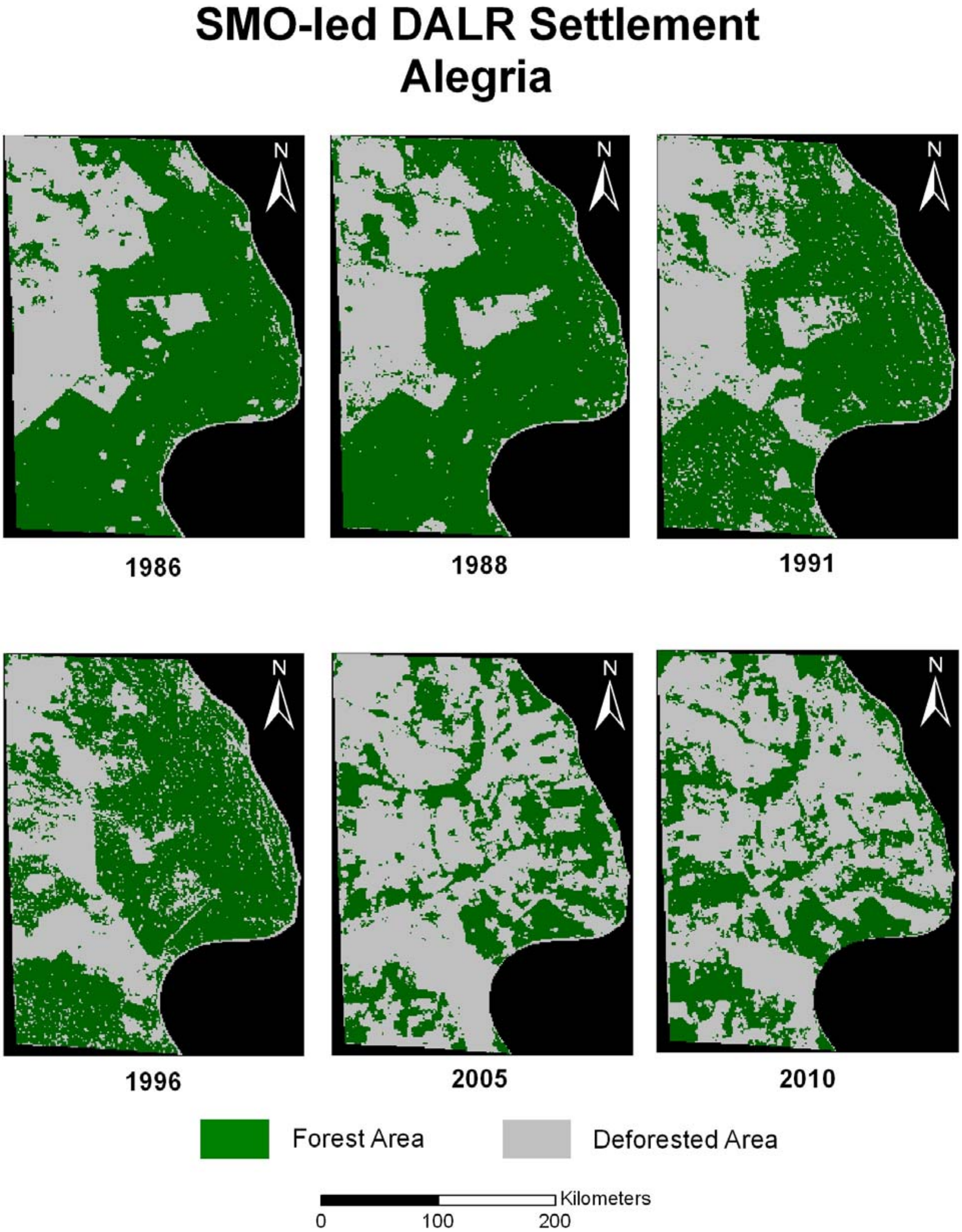

Figure 4.5 Classified satellite images of DALR settlement Alegria.

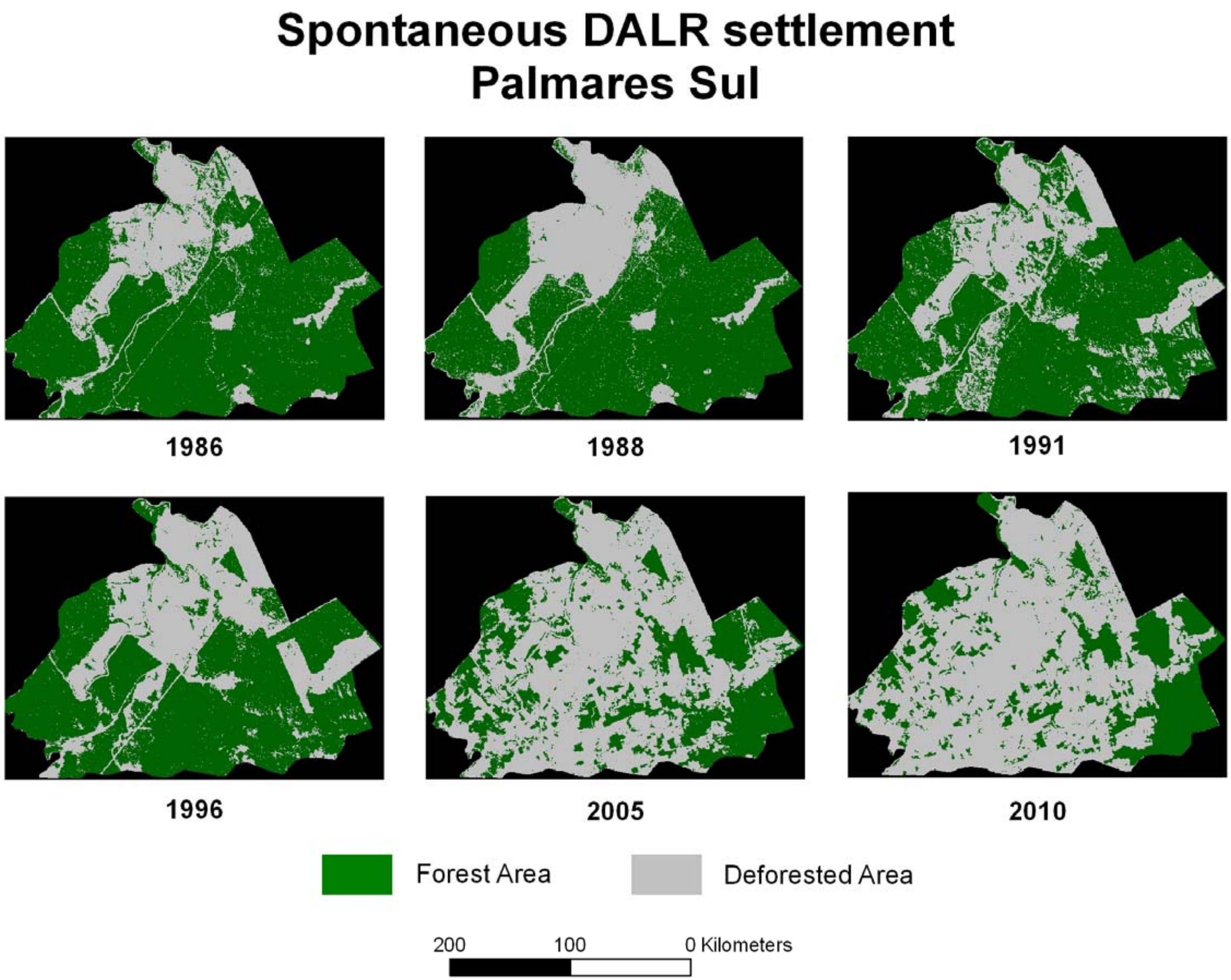

Figure 4.6 Classified satellite images of DALR settlement Palmares Sul.

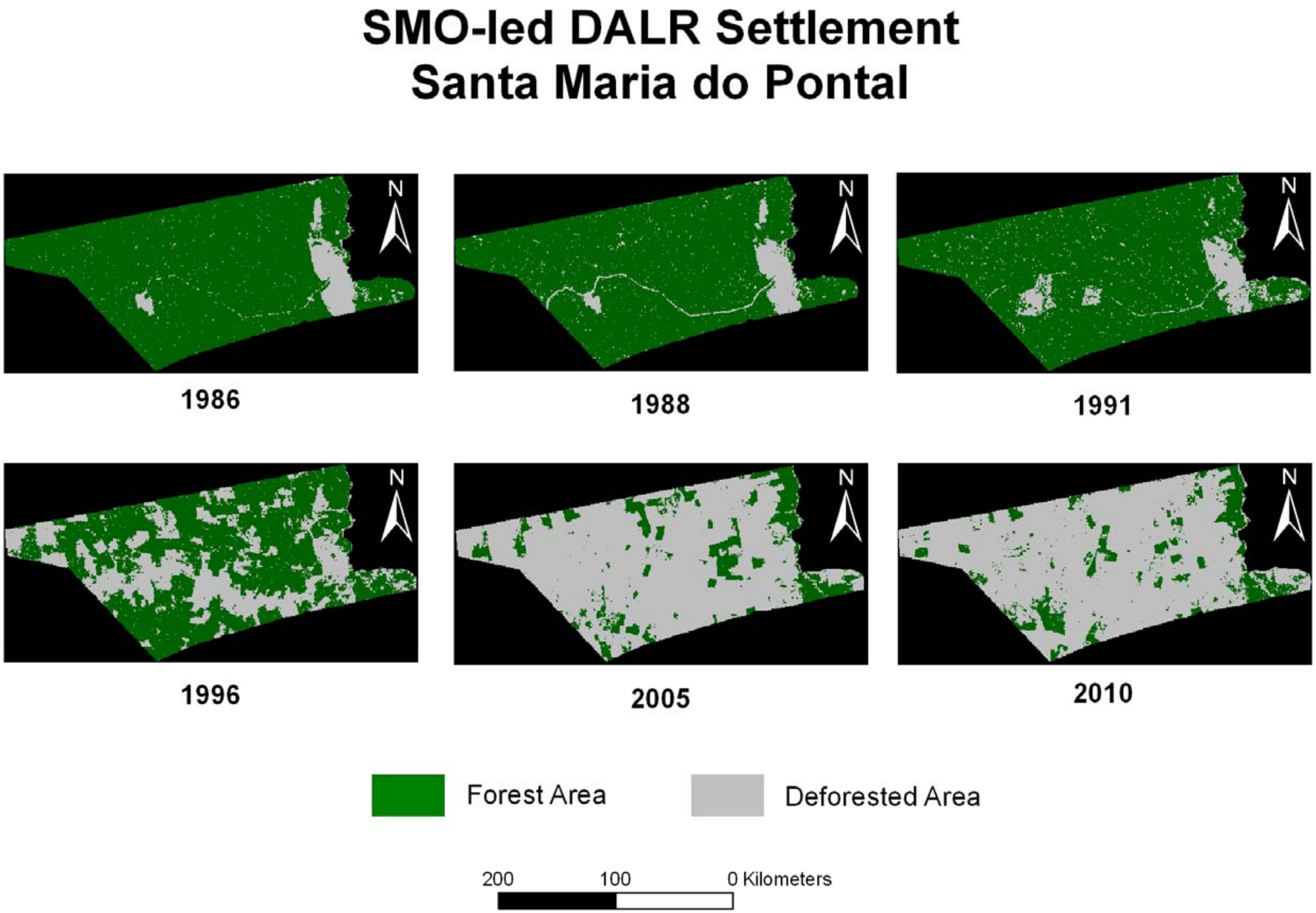

Figure 4.7 Classified satellite images of DALR settlement Santa Maria do Pontal.

where *n* is the total number of deforestation patches, and a_i is the area of deforestation patch *i* in square meters. The unit of *PMA* is hectares (McGarigal *et al.*, 2002). The *PMA* metric is going to increase over time as most deforestation patches in the landscape of a DALR settlement become bigger, and vice versa.

2) Area Weighted Mean Shape Index (*AWMSI*) – This is a landscape shape index used to quantify the average perimeter-to-area ratio for a landscape of a DALR settlement, weighted by the size of its deforestation patches. Its formula is given as:

$$AWMSI = \sum_{i=1}^{n}\left[\left(\frac{0.25p_i}{\sqrt{a_i}}\right)\left(\frac{a_i}{\sum_{i=1}^{n} a_i}\right)\right]$$

where *n* is the number of deforestation patches in the landscape, a_i is the area of deforestation patch *i* in square meters, p_i is the perimeter of deforestation patch *i* in meters. *AWMSI* is unitless and has values greater or equal to 1 (McGarigal *et al.*, 2002). *AWMSI* equals 1 when all deforestation patches in the landscape are perfect squares. It increases without limit as the shape of deforestation patches becomes more and more irregular.

3) Patch cohesion index (*PCI*) – This is a connectivity metric used to measure the physical connectedness of deforestation patches in the landscape of a DALR settlement. Its formula is written as:

$$PCI = \left[1 - \frac{\sum_{i=1}^{n} p_i}{\sum_{i=1}^{n} p_i\sqrt{a_i}}\right]\left[1 - \frac{1}{\sqrt{A}}\right]^{-1}(100)$$

where *n* is the number of deforestation patches, a_i is the area of deforestation patch *i* in square meters, p_i is the perimeter of deforestation patch *i* in meters, and *A* is the total landscape area in square meters. *PCI* is a percentage quantity so its range limit is between 0 and 100% (McGarigal *et al.*, 2002). In this research, *PCI* approaches 0 as the deforestation class in the landscape become increasingly subdivided and patches are less physically connected. *PCI* increases as the deforestation patches become more clumped or aggregated in its distribution, hence, more physically connected.

All the computations of landscape metrics can be realized in the landscape pattern recognition software *FRAGSTATS* (version 3.3) (McGarigal *et al.*, 2002). It is a free software developed by a group of researchers from the Landscape Ecology Lab at the University of Massachusetts in 1995. This software can perform calculations for all landscape metrics at a landscape, class, or a patch level. In order to analyze deforestation fragment patterns in land reform settlements, metrics were computed at a class level (deforestation class) in this research. All classified satellite images were converted into ASCII format before being processed. Computation results were saved as a text file for a later nonparametric statistical analysis.

4.3 Field Survey Data Collection and Correlation Analysis

4.3.1 Field Survey Data Collection

Another goal of this thesis was to understand the actual impacts of demographic factors of smallholders on deforestation fragment patterns in different types of DALR settlements. In order to accomplish this task, I made use of field survey data gathered in 2006 in two study regions by a group of scholars from Michigan State University. This survey, which assembled information from 751 small farm households in two states of the Brazilian Amazon region, was administered in 26 DALR settlements. Interviewees included key informants from the INCRA, government officials, community and union leaders, and settlement residents. But this research only used demographic data obtained from small farm households in six DALR settlements in the state of Pará under study. The number of households that were interviewed in each DALR settlement is listed in Table 4.2.

Four categories of field survey data are considered to have potential impacts on deforestation and forest fragmentation in DALR settlements: lot information (e.g. lot size, distance from the lot to the nearest city), family information (e.g. length of residence, percentage of families holding a land document or receiving credit), household composition (e.g. number of children, number of seniors, number of adult men), and agricultural characteristics (e.g. area of annual and perennial crops, and area of pasture) (Caldas, 2008; Caldas *et al.*, 2010). All the information of demographic factors listed in Table 4.3 was extracted from the field survey database and was used to study its effect on forest fragmentation in DALR settlements. More specifically, this study first computed the average values for each data entry (Table 4.3) based on the household survey results obtained from each DALR settlement (See Table B.1 – B.4 in Appendix B for detail.). Since this field survey was undertaken in 2006, results of landscape metrics for the year 2005 (Table A.1 – A.3 in Appendix A) were used. They were analyzed respectively with all the averages of demographic data of each corresponding DALR settlement using a nonparametric statistical method to discover the relationship between demographic factors and forest fragmentation patterns in DALR settlements.

4.3.2 Correlation Analysis of Landscape Metrics and Field Survey Data

In order to detect the effects of demographic factors on forest fragmentation in DALR settlements, a statistical analysis between landscape metrics and field survey data was performed. Multivariate regression analysis is one of the most popular statistical techniques used

Table 4.2 Number of households being interviewed in each DALR settlement.

Study Region	Settlement Name	# households being interviewed
Transamazon Highway	Rio Trairão	28
	Rio de Peixe	37
	Uirapurú	65
Southern Pará	Alegria	22
	Palmares Sul	30
	Santa Maria do Pontal	23

to explore the relationship between a series of independent variables and the dependent variable. This technique, however, is not suitable here because this research uses field survey data and landscape metrics obtained from only six DALR settlements. Due to the restrictions of such a small sample size, a correlation analysis was considered as the most suitable method. More specifically, this research used Spearman's rank correlation analysis, or Spearman's rho (ρ), to analyze the monotonic relationship between the results of three adapted landscape metrics and the average values of selected field survey data from the corresponding DALR settlement. There were three reasons why Spearman's rho was applied to conduct the correlation analysis. First, the Spearman's rank correlation can be applied to ordinal variables. Secondly, it is less sensitive to bias and robust to outliers. Thirdly, it does not require data to be metrically scaled or of normality assumption. Therefore, Spearman's rho is the most suitable nonparametric statistical technique for this research. A full report of Spearman's rank correlation coefficients is presented in Table C.1 in Appendix C.

A Spearman's rho varies from -1 to +1. A zero value indicates no correlation between two variables. A positive rho demonstrates that there is a positive relationship between two variables: one increases when the other increases, and vice versa. If it is negative it means that two selected variables are negatively correlated: one increases when the other decreases, and vice versa.

Table 4.3 Selected field survey data to be used in the analyses.

Data type	Data Entry
Lot information	Lot size (ha)
	Distance to the nearest city (km)
Family information	Length of residence (year)
	Percentage of families holding a land document (%)
	Percentage of families having difficulty in lot demarcation (%)
	Percentage of families receiving credit (%)
	Percentage of families receiving technical assistance (%)
Agricultural characteristics	Area of annual crops per family (ha)
	Area of perennial crops per family (ha)
	Area of pasture per family (ha)
	Percentage of families raising cattle (%)
Household composition	Number of person per household
	Number of children (<15) per household
	Number of seniors (>65) per household
	Number of adult men per household
	Number of adult labors[4] per household

CHAPTER 5 - RESULTS AND DISCUSSIONS

In the previous chapter, the research methodology was developed to study forest fragmentation in DALR settlements and to discover the effects of demographic features and household characteristics on deforestation fragment patterns. This chapter will first present the results of landscape metrics derived from *FRAGSTATS* software to explain the spatial and temporal dynamics of deforestation fragment patterns in different types of land reform settlements. Then the nonparametric statistical results of Spearman's rank correlation analysis between demographic data and landscape metrics results will be discussed.

5.1 Spatial and Temporal Dynamics of Deforestation Fragment Patterns

One objective of this research was to study forest fragmentation patterns in different types of DALR settlements. In order to realize this goal, deforestation patches in each DALR settlement for each study year were analyzed in *FRAGSTATS* software using three adapted landscape metrics *PMA*, *AWMSI*, and *PCI* based on classified satellite images of each DALR settlement. Figures 5.1 – 5.3 are graphs made from three landscape metrics results respectively. Detailed calculated landscape metrics results are presented in Tables A.1 – A.3 in Appendix A.

In this research, the *PMA* index was used to quantify the mean area of deforestation patches in each DALR settlement (Figure 5.1). In the year of 1986, which was the time before land occupation occurred in the state of Pará, all DALR settlements had very small deforestation patches with an overall average of 1.2842 ha. SMO-led DALR settlements, however, had larger deforestation patch size than spontaneous DALR settlements on average at the beginning (2.3056 ha for SMO-led DALR settlements and 0.2628 ha for spontaneous ones). It was because before land reform took place, most parts of SMO-led DALR settlements used to be large cattle ranches or commercial croplands, which were satisfied by relatively larger areas of deforestation plots, owned by private landholders, while over 95% of the area in spontaneous DALR settlements were originally covered by unclaimed primary forest (Pacheco, 2008; Caldas, 2008; Simmons *et al.*, 2010; Caldas *et al.*, 2010). Besides, most settlers in a spontaneous DALR settlement were from distant rural areas (Table 3.1). They lacked initial capital to deforest and to invest in their crops, thus only a small plot of primary forest was cleared in order to grow subsistence crops to support the whole family (Caldas, 2008; Caldas *et al.*, 2010).

During 1988 to 1991, which was the period when land occupation took place, the area of deforestation patches slowly increased at a constant average rate of about 0.1 ha per year. The gap of deforestation patch mean area between two types of land reform settlements gradually became more and more distinctive starting in 1996, which was the time soon after settlements were officially recognized by the INCRA. *PMA* rocketed from 4.5228 ha in 1996 to 34.0092 ha in 2010 for SMO-led DALR settlements on average, while for spontaneous DALR settlements *PMA* only increased from 1.8022 ha to 5.6964 ha in 2010 on average. The gap was 2.7206 in 1996, but it reached at 28.3128 ha in 2010. This finding gives supportive evidence to the literature that land reform settlement formation and official recognition of these settlements did dramatically increase deforestation in the Brazilian Amazon (Simmons et al., 2007b; Caldas, 2008; Simmons *et al.*, 2010; Caldas *et al.*, 2010). Generally speaking, SMO-led DALR settlements had constantly larger deforestation patch area than spontaneous DALR settlements over the whole study period. A possible explanation is that family lots in spontaneous DALR settlements were not as fully demarcated as those in SMO-led DALR settlements, and fewer families in a spontaneous DALR settlement received credits to invest in their crops after official

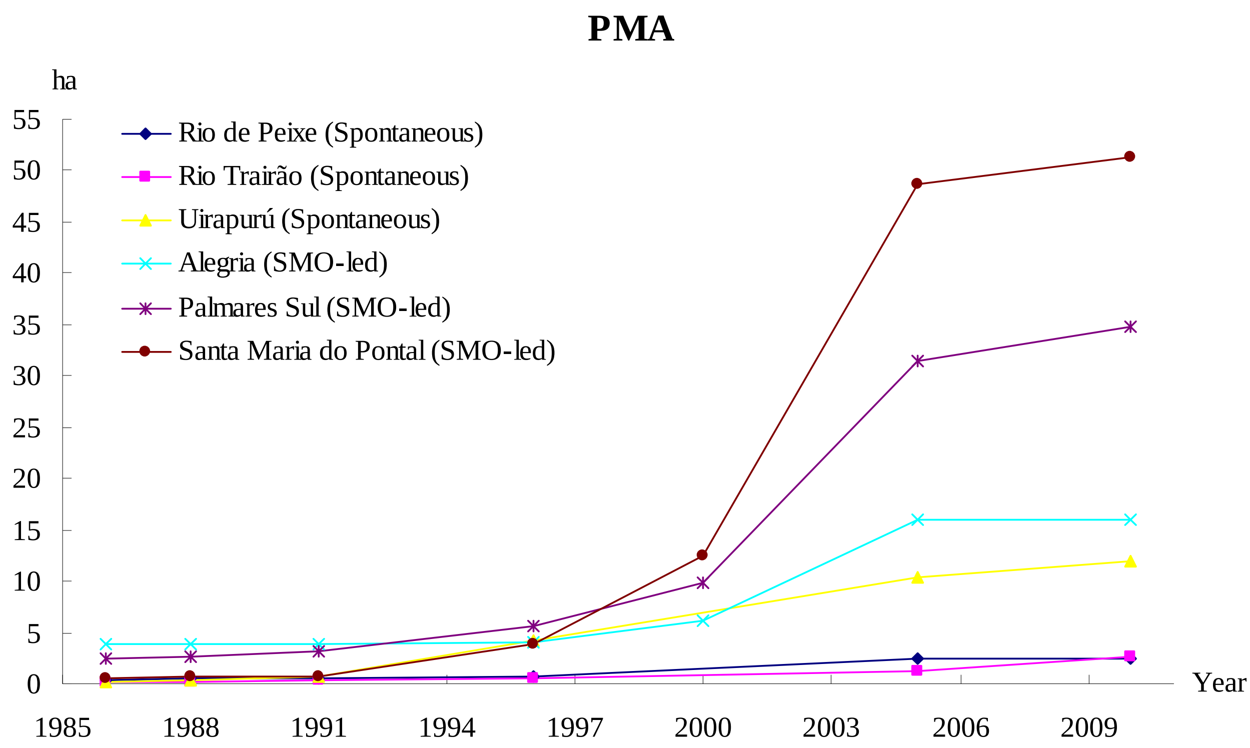

Figure 5.1 Patch Mean Area (*PMA*)

recognition by the INCRA (Table B.2 in Appendix B). Under this situation, settlers would never be willing to clear a large area of forest at the risk of their land being confiscated by the government (Caldas, 2008).

Another topic of this research was to find out how the shape of deforestation patches in different types of DALR settlements changed during the study period, which can be realized using the *AWMSI* index (Figure 5.2). The increasing trend of *AWMSI* values demonstrates that the shape of deforestation fragments in all DALR settlements became more and more irregular over time. For SMO-led DALR settlements, deforestation patches were constantly more irregular than spontaneous land reform settlements except Santa Maria do Pontal. *AWMSI* values for Alegria and Palmares Sul rocketed between 1996 and 2005, which was the same time when settlements were formed and officially recognized. This trend is not very distinct for Santa Maria do Pontal whose deforestation patches changed very slowly over the whole study period. For spontaneous DALR settlements, between 1986 and 1988 deforestation patches were almost square-shaped according to their low *AWMSI* values (an average of 2.36). Patches gradually became more irregular over time with their *AWMSI* values increasing slowly.

The evidence suggests two reasons why deforestation fragments in SMO-led DALR settlements became more and more irregular over time. First, most settlers in SMO-led DALR settlements came from urban or suburban areas (Caldas, 2008; Simmons *et al.*, 2010). Different land holders might perform different farming systems, including annuals, perennials, and pastures. The promiscuous land use strategy would therefore lead to a more irregular mosaic of deforestation fragments. Secondly, settlers in SMO-led DALR settlements had less farming experience (Table 3.1) or received less technical assistance (Table B.2 in Appendix B). Besides, Southern Pará has a land degradation problem and bad soil quality (Table 3.1). Settlers had little knowledge to battle against these issues so they had to change their farming strategies periodically according to the availability of land and overall soil quality, which would therefore decrease the regularity of deforestation patches.

It is noteworthy that the change in magnitude of deforestation patch shapes in spontaneous DALR settlements was overall much more prominent than SMO-led DALR settlements based on their starting and ending values. For illustration, in 2010, the shape index value of deforestation patches for Rio Trairão is almost 7-times greater than that in 1986. This dramatic change was, however, not detected in SMO-led DALR settlements. This could be explained using household life cycle theory. Young settlers brought their sons and daughters to this new piece of land and subsisted on annual crops initially (such as rice, beans, corn, and

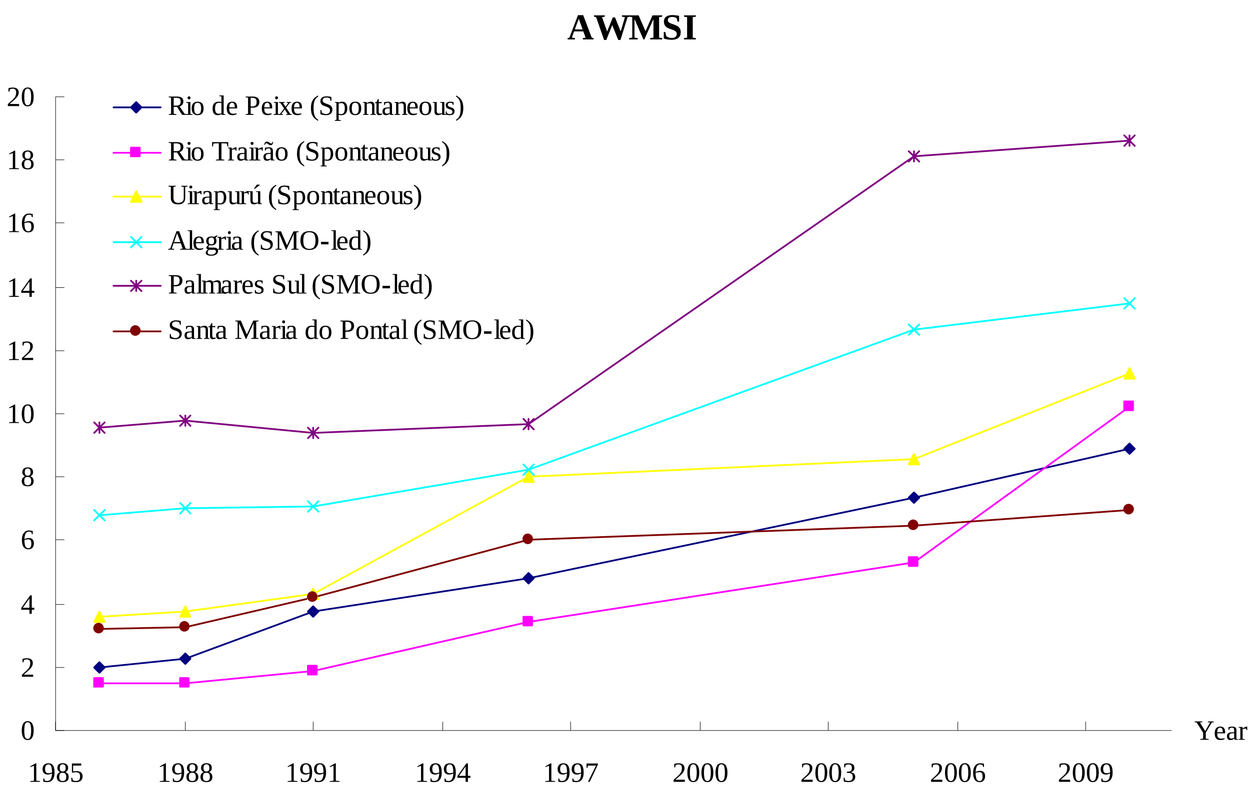

Figure 5.2 Area Weighted Mean Shape Index (*AWMSI*)

manioc) by clearing a small plot of primary forest because annual crops can be harvested soon after planting, which constitutes a low-risk agricultural strategy (Walker and Homma, 1996). Most of these plots were regularly-shaped (almost squares) seen from satellite images. After their children grew up, family crops started to shift from annuals to perennials or even tree crops (such as cocoa, coffee, coconuts and black peppers), which require substantial labor inputs in cultivation (Pichón, 1996). Households with fewer laborers often shifted into pastures (Perz, 2001b; Pichón, 1996). No matter what kind of transition of farming strategy occurred, all types of land use change would lead to extensive deforestation, which would further result in a mosaic of more and more irregularly-shaped plots (Walker *et al.*, 2000); however, currently there is no evidence in the literature indicating that SMO-led DALR settlements also experienced the same household life cycle because their settlers had relatively shorter length of residence than those in spontaneous DALR settlements (Table B.1 in Appendix B). It is not only the reason why deforestation patch shapes became more and more irregular in spontaneous DALR settlements over time, but also the reason why this shape change was more dramatic than SMO-led DALR settlements.

In this research it is also important to understand how spatial arrangement of deforestation fragments changed over time. Therefore, a *PCI* index was utilized to quantify the physical connectedness of deforestation patches in a DALR settlement. Figure 5.3 shows the research result. The constantly high index values for SMO-led DALR settlement indicate that they have exhibited much more aggregated deforestation fragments since the beginning of the study period, and it was especially obvious for settlements Alegria and Palmares Sul. The reason here is very straightforward. SMOs targeted private landholdings that were formerly large cattle ranches or commercial agricultural lands (Pacheco, 2008; Caldas, 2008; Simmons *et al.*, 2010). The level of deforestation activities was originally high in these SMO-led land reform settlements and these deforestation patches were always larger in size and more physically connected in their spatial distribution. Since deforestation activities became more severe and more intensive after land occupation, patches would therefore continuously become more aggregated over time in SMO-led DALR settlements.

During the year of 1986 to 1991, which was the period before land occupation occurred, a huge gap in index values between spontaneous and SMO-led DALR settlements could be easily detected (see Figure 5.3), especially for 1986 (more than 26% of difference on average).

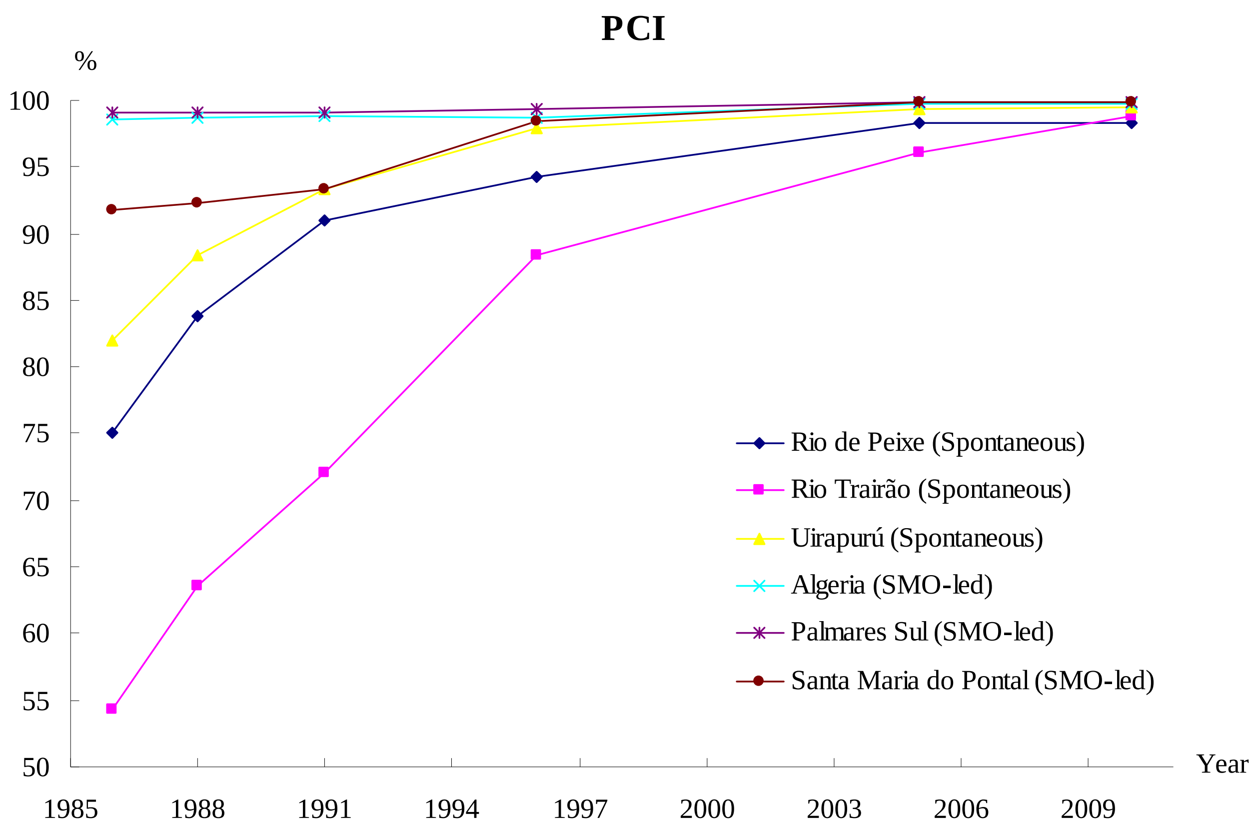

Figure 5.3 Patch Cohesion Index (*PCI*)

Initially, deforestation patches in all spontaneous DALR settlements were widely dispersed and subdivided in their distribution. They gradually became more and more physically connected as evidence by their index values increasing monotonically over time. This huge gap exists because settlers in spontaneous DALR settlements lacked initial capital or credit to invest in their crops since most of them were from poor rural areas (Table 3.1) (Caldas, 2008; Simmons *et al.*, 2010; Caldas *et al.*, 2010). Fragments would therefore be small in size and dispersed in distribution, hence, less physically connected in space. After settlement formation, especially after settlements were officially recognized by the INCRA, a growing number of settlers received credits from the government to expand agricultural lands and to invest in infrastructures, such as road building.

Deforestation fragments in settlements would therefore become gradually physically connected by roads. The graph in Figure 5.3 shows that at the end, all DALR settlements had almost completely connected deforestation fragments with an asymptote approaching the percolation threshold of almost 100% cohesion. This is because, according to the survey data (Table B.3 in Appendix B), an average of 80.3% of families in SMO-led DALR settlements and 77.8% of families in spontaneous DALR settlements were raising cattle in 2006. The aggregation of deforestation fragments finally reached its maximum level since pasture became the dominate land-use type in all DALR settlements (Table B.3 in Appendix B).

All in all, it can be concluded from the above results of landscape metrics that:

i) SMO-led DALR settlements always had greater mean deforestation patch area than spontaneous DALR settlements;

ii) Generally, deforestation fragments in SMO-led DALR settlements were more irregular in shape than those in spontaneous DALR settlements;

iii) Deforestation patches in SMO-led DALR settlements were constantly more physically connected and aggregated in space than spontaneous DALR settlements.

5.2 Spearman's Rank Correlation Analysis

Another ultimate goal of this research was to discover the impacts of demographic factors and household characteristics on forest fragmentation. To achieve this goal, I utilized a nonparametric statistical technique of Spearman's rho to study the correlation between the results of three adapted landscape metrics *PMA*, *AWMSI*, and *PCI* for the year of 2005 (Tables A.1 – A.3) and the average values of selected field survey data (Tables B.1 – B.3). More specifically, the result of each landscape metric for the year of 2005 was analyzed using Spearman's correlation analysis with all the average values of selected field survey data. The null hypothesis was that there was no correlation between landscape metrics results and the field survey data. In other words, the deforestation fragment patterns and demographic factors were independent of each other. The significance level used in this nonparametric analysis was 0.1 (or 90% confidence interval). Here in this chapter only Spearman's rho with a *p*-value less than 0.1 will be reported (see Tables 5.1 – 5.3). Coefficients with one superscript star are at a significance level of 0.10, while two superscript stars indicate a significance level of 0.05. A full statistical report can be found in Table C.1 in Appendix C.

It could be first generalized from the statistic result that the family lot size is consistently negatively correlated with all three metrics results and they are statistically significant (p-value < 0.05) (Tables 5.1 – 5.3). It indicates that the larger the family lot size is, the smaller, more regularly shaped and less physically connected deforestation fragments will be in a DALR settlement. Larger family lot size could be typically found in a spontaneous DALR settlement and it is over twice the lot size of a SMO-led DALR settlement (Table B.1). The family lot size might be related with the population density and land availability in a land reform settlement. The fact was that the Uruará region had much smaller population density and spontaneous DALR targeted unclaimed public rainforest, while in Southern Pará region settlements were more concentrated around urban areas with fewer lands available (Caldas, 2008). Easier access to the open public forest lands but smaller population density in the Uruará region resulted in larger family lot size. Although settlers in a spontaneous DALR settlement had larger lot size, they did not have as much credit as those families in a SMO-led DALR settlement do to invest in infrastructure development such as road building, or agricultural expansion such as planting market-oriented large crops and pasture (Table B.2). Resulting deforestation fragments would therefore be smaller in size, more regular in shape, and less physically connected in spatial distribution in spontaneous DALR settlements in the Uruará region.

The number of children per household is also negatively correlated with all landscape metrics results (Tables 5.1 – 5.3). This result indicates that if a settlement has a larger number of children per household on average, it would have smaller, more regularly shaped and less physically connected deforestation patches, and vice versa. This finding is also consistent with my hypothesis. Table B.4 shows that spontaneous DALR settlements had more children per household, but a smaller labor/consumer ratio than SMO-led DALR settlements on average. Household life cycle was the foremost cause of deforestation activities and land-use transitions in a spontaneous DALR settlement (Walker and Homma, 1996; McCracken *et al.,* 1999; Perz, 2001a & 2002; Walker, 2003; Caldas *et al.*, 2007). Families with a larger number of children but a smaller labor/consumer ratio would be more willing to live on subsistence fields, such as annual crops or some common perennial crops, in order to maintain the household (Walker and Homma, 1996). These crops were mostly smaller in size, more regular in shape and less physically connected in spatial distribution.

The total number of persons per household also shows a negative relationship with *PMA* and *PCI* (Tables 5.1 & 5.3), which means that if a settlement has more family members per household the deforestation patches would be smaller and less physically connected, and vice versa. The reason here is similar to that stated above. Although spontaneous DALR settlements had a relatively larger number of persons per household, its labor/consumer ratio is much lower than SMO-led DALR settlements. This means that families from a spontaneous DALR settlement consisted of more consumers than laborers working in the field. Therefore subsistence crops, which exhibit smaller in size and less physically connected in space, were the dominant land-use for those families; however, no statistically significant correlation was found between the number of persons per household and *AWMSI* metrics result.

Percentage of families receiving credit is positively correlated with both *PMA* and *PCI*, with a *p*-value at a 0.5 significant level (Tables 5.1 & 5.3). In other words, if a larger proportion of families in a settlement receives credit from the government, deforestation fragments would be larger and more physically connected, and vice versa. Credit and fiscal incentives given by many government agencies have been pointed out as a primary driver of deforestation in some parts of the Amazon (Pfaff, 1999; Andersen et al., 2002). Credit received by DALR families was mainly used for infrastructure improvement and agricultural expansion, especially for pasture formation (Caldas, 2008; Walker *et al.*, 2000), thus increasing deforestation and fragmentation in a settlement. Moreover, developed infrastructure, such as road building, would make deforestation fragments become more physically connected in space. Expanded agriculture, such as cultivating large commercial fields and planting more pasture, would also cause more deforestation, thus increasing the overall area of deforestation fragments; however, this demographic feature didn't show a strong effect on the shape of deforestation patches in a land reform settlement.

The average distance between each family lot and the nearest city has strong negative correlations with *AWMSI* (*p*-value<0.01) and *PCI* (*p*-value <0.05) results (Tables 5.2 & 5.3). This result demonstrates that if family lots in a DALR settlement are further away from the nearest city, deforestation patches would be more regularly shaped and less physically connected, and vice versa. Spontaneous DALR settlements were generally further away from the urban area than SMO-led DALR settlements (Table B.1) because spontaneous DALR targeted unclaimed open public rainforest beyond the frontier for land occupation, while SMO-led DALR targeted large private landholdings closer to the urban area (Caldas, 2008; Simmons *et al.*, 2010). Due to the high transportation cost and lack of infrastructure, settlers living far away from the urban area would like to grow more subsistence crops for self-sufficiency instead of cultivating large scale market-oriented agricultural crops or growing pasture (Caldas, 2008). Although nowadays a growing number of families in spontaneous DALR settlements have been involved in raising cattle and planting pasture, annual and perennial crops still account for about 50% of total land-use, while in SMO-led DALR settlements pasture has along been the dominant land-use strategy (Table B.3). Deforestation fragments would therefore become more regularly shaped and less physically connected in spontaneous DALR settlements; however, the correlation between this demographic feature and deforestation patch mean area was not statistically significant.

To conclude, the above nonparametric statistic results of Spearman's rank correlation analysis between calculated landscape metrics results and demographic data revealed that:

1) DALR settlements with a larger number of children per household and larger family lot size would mainly exhibit smaller, more regularly shaped and less physically connected deforestation fragments, and vice versa;

2) It would appear smaller and less physically connected deforestation fragments in a DALR settlement that has larger number of people per family, and vice versa;

3) DALR settlements with greater percentage of families receiving credit show larger and more physically connected deforestation patches, and vice versa;

4) DALR settlements further away from the urban areas present more regularly shaped and less physically connected deforestation patches, and vice versa.

Table 5.1 Spearman's rho of *PMA* result and its correlated field survey data

	Lot size	Percentage of families receiving credit	# persons per household	# children per household
PMA	-0.8286**	0.7714*	-0.8286**	-0.7714*
p-value	0.0416	0.0724	0.0416	0.0724

Table 5.2 Spearman's rho of *AWMSI* result and its correlated field survey data

	Distance to the nearest city	Lot size	# children per household
AWMSI	-0.9429**	-0.8286**	-0.7714*
p-value	0.0048	0.0416	0.0724

Table 5.3 Spearman's rho of *PCI* result and its correlated field survey data

	Distance to the nearest city	Lot size	Percentage of families receiving credit	# persons per household	# children per household
PCI	-0.8286**	-0.9429**	0.8286**	-0.7714*	-0.8857**
p-value	0.0416	0.0048	0.0416	0.0724	0.0188

CHAPTER 6 - CONCLUSIONS

DALR settlement formation through a series of settlement projects proposed by the federal government in the name of agrarian reform has been identified as a new significant contributor to deforestation in the Brazilian Amazon, which has been affecting the most vulnerable parts of the Amazon Rainforest for almost two decades (Simmons *et al.*, 2007b; Caldas, 2008; Simmons *et al.*, 2010; Caldas *et al.*, 2010; Aldrich *et al.*, 2012). This thesis makes a new contribution to our cognition of the relationship between DALR settlement formation and deforestation from a forest fragmentation perspective. More specifically, two main objectives of this thesis research were to contrast the dynamics of spatial and temporal patterns of deforestation fragments in two different types of DALR settlements, and to discover the impacts of demographic factors and household characteristics of smallholders on deforestation fragment patterns. Three spontaneous DALR settlements (Rio Trairão, Rio de Peixe, and Uirapurú) around the municipality of Uruará along the Transamazon Highway and three SMO-led DALR settlements (Alegria, Palmares Sul, and Santa Maria do Pontal) in Southern Pará were selected as study areas. In order to realize the two goals, I integrated knowledge and techniques from remote sensing, GIS spatial analysis, and nonparametric statistics of field survey data. More specifically, satellite images of study areas were first processed and classified using a binary classification scheme (forest and deforestation area) in *ERDAS IMAGINE* software. Then the deforestation class of each classified image was analyzed in *FRAGSTATS* software using three adapted landscape metrics *PMA*, *AWMSI*, and *PCI* to uncover the deforestation fragment patterns in DALR settlements. Landscape metrics results for 2005 and the average values of selected demographic data collected in six target DALR settlements in 2006 were finally analyzed using

Spearman's rank correlation analysis in *STATA SE* software to test the effects of settlers' demographic factors on deforestation fragment patterns in DALR settlements.

At the end of Chapter 2, three research questions and two hypotheses for each research question regarding two types of DALR settlements were proposed. In this conclusion chapter, I will first answer these questions and verify all hypotheses respectively based on research results. Two policy recommendations will be provided for each type of DALR settlement later regarding reforestation, credit support, infrastructure improvement, and agricultural training.

The first research question asked about the initial pattern of deforestation fragments in two different types of DALR settlements. Hypothesis 1A stated that spontaneous DALR settlements around the municipality of Uruará would present small, irregularly shaped and disconnected deforestation patches distributed randomly in the forest initially. Hypothesis 1B asserted that SMO-led DALR settlements would have larger, regularly shaped and contiguous deforestation patches at the beginning.

Hypotheses 1A and 1B were both partially consistent with the final research results. The metrics results indicated that spontaneous DALR settlements generally exhibit smaller and less physically connected deforestation fragments than SMO-led DALR settlements in 1986 before land occupation took place (Figures 5.1 & 5.3, Tables A.1 & A.3). SMO-led DALR targeted large private landholdings for occupation that were previously cattle ranches or large commercial agriculture land, while spontaneous DALR aimed at unclaimed open public land, especially primary forest beyond the frontier, to build land reform settlements (Simmons *et al.*, 2007b; Caldas, 2008). Therefore, deforestation fragments in SMO-led DALR settlements were larger in area and more physically connected in spatial distribution before land occupation.

Nevertheless, what contradicts the first two hypotheses is that results showed that deforestation fragments in SMO-led DALR settlements were more irregularly shaped than spontaneous DALR settlements before land occupation (Figure 5.2 & Table A.2). Actually, before land occupation, deforestation in spontaneous DALR settlements around Uruará was mostly accomplished by old colonists who arrived at this region through the Transamazon Highway in the early 1980s (Perz and Walker, 2002; Perz *et al.*, 2010). By given initially low levels of capital and little farm experience, old colonists mainly cultivated annual crops for subsistence, generating small and regularly-shaped deforestation patches (Walker and Homma, 1996; Caldas *et al.*, 2007). The Southern Pará region, however, was developed under the military government's projects in the 1980s, which mainly exhibited a mosaic of cattle ranches, market-oriented large commercial agriculture, and timber extraction fields (Simmons *et al.*, 2007b; Caldas, 2008). Therefore, the shape of deforestation patches was more irregular than spontaneous DALR settlements.

The second question concerned about the spatial and temporal dynamics of deforestation fragment patterns in two types of DALR settlements. It was hypothesized that in both spontaneous and SMO-led DALR settlements deforestation patches would become larger, more regularly shaped and more physically connected over time, but the change in magnitude of deforestation patches in SMO-led DALR settlements would be much greater than those in spontaneous DALR settlements.

The *PMA* metric result (Figure 5.1 & Table A.1) indicated that the deforestation patch mean area increased dramatically in SMO-led DALR settlements since settlement formation in the early 1990s, but only a slight change was found in spontaneous DALR settlements. It was because many factors have been detected to cause deforestation expansion in Southern Pará region since land occupation. SMO-led DALR settlements were much closer to urban areas (Table B.1) and had worse soil quality with more severe land degradation issues (Simmons *et al.*, 2010; Leite *et al.*, 2011). Besides, a higher percentage of families lots had been demarcated by the INCRA and more families received credit to invest in agricultural expansion and infrastructure improvement (Table B.2). Though in spontaneous DALR settlements, deforestation was mainly resulted from demographic life cycle and income incentives (Walker and Homma, 1996; Caldas, 2008). The expansion of deforestation would therefore be much faster in SMO-led DALR settlements. This finding is consistent with my hypothesis.

Deforestation patches also became more and more aggregated and physically connected over time, which is also in accordance with my hypothesis (Figure 5.3 & Table A.3); however, this change in magnitude was subtle in SMO-led DALR settlements in Southern Pará except Santa Maria do Pontal, but much sharper in spontaneous DALR settlements. This big contrast was because, before land occupation, deforestation patches had been almost physically connected in SMO-led DALR settlements. For spontaneous DALR settlements, deforestation fragments were dispersed in the landscape with little connectedness at the beginning. They gradually became more and more physically connected with each other due to the improved infrastructure by means of road construction (Caldas, 2008). Road construction facilitated settlers to sell their agricultural products in the nearest market, thus brought them more income. Settlers would in turn invest more in perennial crops or pasture land, which was satisfied by increasing deforestation and, therefore, more physically connected fragments.

Regarding the temporal dynamic of deforestation patch shapes, the result is controversial to my hypothesis. Deforestation patches in both spontaneous and SMO-led DALR settlements became more and more irregularly shaped over time, with no indication showing that they would be regular afterwards (Figure 5.2 & Table A.2). The fragments in SMO-led DALR settlements were more irregular over the whole study period with an exception of Santa Maria do Pontal, but the change in magnitude was much greater in spontaneous DALR settlements. Irregularly shaped deforestation fragments were mainly caused by a mosaic of mixed land-use strategies. In Southern Pará, some previously deforested landholdings were converted to annual or perennial crops by settlers, while a large proportion of land was still used as pasture for cattle ranching (Table B.3). Therefore, the fragments were initially irregular in a SMO-led DALR settlement. In addition, Southern Pará was notorious for its poor soil quality and land degradation problems. Settlers got agricultural assistance from the local INCRA and performed a mixed farming system in order to keep crops productive. Otherwise, they just left crops as fallow to increase secondary growth or to renew soil fertility (Walker *et al.*, 2002). The increasingly mixed land-use strategies would therefore result in more and more irregularly shaped deforestation patches. The same as Southern Pará, settlers in spontaneous DALR settlements around Uruará also exhibited increasingly mixed cultivation strategies due to the demographic life cycle. At an earlier stage of the demographic life cycle, settlers subsisted on annual crops (Walker and Homma, 1996; Caldas *et al.*, 2007), which were characterized by small in size and regular in shape. As settlers' children grew up, the labor/consumer ratio of a household increased, and the demographic life cycle reached a higher stage. The cultivation strategy gradually shifted from annual crops to the perennials or pasture, which resulted in larger and more irregularly shaped deforestation fragments. It is also the reason why the change in magnitude of deforestation patch shapes in spontaneous DALR settlements was greater than SMO-led DALR settlements.

The last question concerned about the impacts of demographic factors and household characteristics of smallholders on deforestation fragment patterns. Hypothesis 3A proposed that

DALR settlements with larger proportions of children and elderly people in a family would have smaller, more irregular and more disaggregated patches. Hypothesis 3B depicted that land reform settlements with larger proportions of adults and men would create larger, more regularly shaped and more physically connected deforestation fragments in the landscape.

According to the result of Spearman's rank correlation analysis (Tables 5.1 –5.3), although the number of people and children per household did show a strong impact on deforestation fragment patterns, no other household characteristic showed statistically significant effect. Instead, deforestation fragment patterns were more correlated with some other demographic factors, such as the distance from the lot to the nearest city, family lot size, and the percentage of families receiving credit. More specifically, first, a DALR settlement with larger number of children per household would exhibit smaller, more regularly shaped, and less physically connected deforestation patches. This was because a family with larger number of children was at an early stage of the demographic life cycle. Those families had a small labor/consumer ratio and lacked agriculture credit to invest in their crops. They basically lived on subsistence crops that required less credit or labor investment (Walker and Homma, 1996). These crops were smaller in size, more regular in shape, and less physically connected in spatial distribution. This reason could also be used to explain the research finding that DALR settlements with larger numbers of people would create smaller and less physically connected deforestation patches.

Secondly, smaller, more regularly shaped and less physically connected deforestation fragments could be found in settlements with larger family lot size (Tables 5.1 –5.3). Family lot size varies a lot for two study regions. On average, spontaneous DALR settlements around Uruará had more than twice the size of a family lot in SMO-led DALR settlements in Southern

Pará (Table B.1). It has been considered that family lot size is not the only factor that influenced deforestation fragment patterns. The size of family lot is related with the population density and land availability: the Uruará region had smaller population density, and new spontaneous DALR settlements were formed in unclaimed open public forest area, while in Southern Pará settlements were more concentrated around urban areas with less land available for land reform (Caldas, 2008). More land availability but less population density in Uruará resulted in larger family lot size; however, settlers in those spontaneous DALR settlements were lack of credit support (Table B.2). Even though they had larger lot size, they did not have enough credit to invest in infrastructural development or agricultural expansion. Therefore demographic life cycle was the foremost causation of deforestation activities and land-use transitions in a spontaneous land reform settlement.

Thirdly, settlements with a greater proportion of families receiving credit would have larger and more physically connected deforestation fragments. This was because it brought more fiscal incentives to those families who received credit from government agencies, and they were more willing to invest the credit in both infrastructural development, such as road building, and agricultural expansion, such as cultivating more perennial crops, tree crops and pasture (Caldas *et al.*, 2007; Caldas, 2008). Deforestation fragments would therefore became larger in size and more physically connected in spatial distribution.

Finally, the greater the average distance between family lots and the nearest city was, the more regular and less physically connected deforestation fragments would appear. Due to the high transportation cost, families living far from the urban area (mostly spontaneous DALR settlements in the Uruará region, see Table B.1) would like to grow more subsistence crops for self-sufficiency instead of cultivating market-oriented agriculture or pasture (Caldas, 2008). This can also be verified using information in Table B.3. Settlers in spontaneous DALR settlements were cultivating larger areas of both annual and perennial crops, which indicated a medium stage of the demographic life cycle. Deforestation fragments would therefore appear more regularly shaped but less physically connected than SMO-led DALR settlements.

Based on the above research findings and conclusions, policy recommendations for each type of DALR settlement regarding reforestation, credit support, infrastructure construction, and agricultural training could be proposed.

First, both government agencies (e.g. the INCRA) and non-governmental organizations (NGOs) should provide more agricultural training and technical support to settlers living in SMO-led DALR settlements. The summary statistics of the field survey data show that, on average, only 17.55% and 31.45% of settlers from SMO-led DALR settlements received agricultural training and technical assistance respectively (Table B.2). The severe loss of forest for agricultural production and pasture (Table B.3) after settlement formation was partially resulted from land degradation and poor soil quality in the Southern Pará region (Simmons *et al.*, 2010; Leite *et al.*, 2011). Therefore, as this thesis recommends, providing more knowledge of agricultural training and technical support would probably help settlers in Southern Pará with land degradation problem and make their fields more efficient and productive, which could be considered as an alternative feasible solution to the severe forest loss in SMO-led DALR settlements.

Secondly, for settlers living in spontaneous DALR settlements, it would be wiser for local syndicates and the INCRA to increase credit lines and to accelerate infrastructure improvement. In 2006, only 60.15% of the families received credit, comparing with almost 80% for SMO-led DALR settlements (Table B.2). Although settlers have been living there relatively longer (Table B.2), 24.52% of families still have difficulties in lot demarcation. Besides, the lack of infrastructure resulted in higher transportation cost and lower productivity (Caldas, 2008). Therefore, more credit support and a thorough infrastructure would ideally help improve the economic environment in spontaneous DALR settlements and enhance the quality of life.

Due to the restriction of such a small sample size in this thesis research, only a nonparametric technique of Spearman’s rank correlation analysis and a 0.1 significance level were used to test the relationship between demographic factors and deforestation fragment patterns of DALR settlements, which made the results and conclusions unpersuasive and inconclusive. In the future, research would like to extend the study regions to other neighboring states and increase the sample size of target DALR settlements. Demographic data of corresponding settlements and landscape metrics results would be analyzed using ordinary least squares (OLS) method and multivariate regression model.

Notes

1. The Belém-Brasília Highway was the first federal highway in Brazil (official designation BR-010) connecting Amazônia and the south. It was built between 1957 and 1960 and was improved for year-round traffic later in 1964 (Fearnside, 1984). The total length of the highway is 1,950 km, passing through the Federal District and four states.

2. Latifundium in Brazil is large piece of private land area or property possessed by a landowner.

3. Secondary roads are unofficial roads that were built by colonists and loggers in order to attract people to the deep Amazon Rainforest via primary roads ("official" roads, such as the Transamazon Highway) by state policies, market conditions, or other factors (Perz *et al.*, 2008).

4. Although the United Nations Convention on the Rights of the Child defines a child as "a human being below age of 18 years" (United Nations, 1989), based on the results of field surveys and interviews with local settlers in DALR settlements, most old settlers' descendants start to join family farm work at 15 years old, which could be considered as a contribution to regional land-use and land-cover change. In the same way, most elderly dependents in DALR settlements no longer participate in farm work at 65 years old. Therefore in this thesis, I define a 'child' as people aged 14 (inclusive) or younger, define a 'senior' as people aged 65 (inclusive) or older, and define an "adult labor" as people who aged between 15 and 64 years old.

5. If a is the total area of deforestation class (in terms of number of cells) and n is the side of the largest integer square smaller than a (denoted $\mathrm{int}\left(\sqrt{a}\right)$) and $m = a - n^2$, then the minimum perimeter of deforestation class will take one of the three forms (McGarigal *et al.*, 2002):

i) $\min e_i = 4n$, when $m = 0$, or

ii) $\min e_i = 4n + 2$, when $n^2 < a < n(1 + n)$, or

iii) $\min e_i = 4n + 4$, when $a > n(1 + n)$.

If A is the landscape area, including all internal background (in terms of number of cells), B is the number of cells on the boundary of the landscape, Z is the total perimeter of landscape boundary given in number of cell surfaces, and P_i is the proportion of the landscape comprised of deforestation class, then the maximum perimeter of deforestation class will take one of the three forms (McGarigal *et al.*, 2002):

i) $\max e_i = 4a$, when $P_i \leq 0.5$

ii) $\max e_i = 3A - 2a$, when A is given; $0.5 < P_i \leq (0.5A + 0.5B) / A$, or

iii) $\max e_i = 3A - 2a + 3$, when A is odd; $0.5 < P_i \leq (0.5A + 0.5B) / A$, or

iv) $\max e_i = Z + 4(A - a)$, when $P_i > (0.5A + 0.5B) / A$.

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Appendix A - Detailed Calculated Results of Three Landscape Metrics

Tables A.1 – A.3 below are detailed calculated results of three adapted landscape metrics (*PMA*, *AWMSI*, and *PCI*) derived from *FRAGSTATS* software based on classified satellite images.

Table A.1 Calculated results of *PMA* index (unit: ha).

Landscape metric	***PMA***					
DALR type	Spontaneous			SMO-led		
Settlement name	Rio de Peixe	Rio Trairão	Uirapurú	Alegria	Palmares Sul	Santa Maria do Pontal
1986	0.3952	0.1704	0.2227	3.8334	2.4869	0.5966
1988	0.5020	0.2387	0.3783	3.8366	2.5584	0.6781
1991	0.5478	0.3169	0.7642	3.8761	3.1447	0.7285
1996	0.7229	0.4499	4.2338	4.0004	5.6873	3.8806
2005	2.5104	1.2958	10.3186	16.0001	31.4643	48.7545
2010	2.5284	2.6155	11.9454	16.0019	34.7614	51.2644

Table A.2 Calculated results of *AWMSI* index (unitless).

Landscape metric	***AWMSI***					
DALR type	Spontaneous			SMO-led		
Settlement name	Rio de Peixe	Rio Trairão	Uirapurú	Alegria	Palmares Sul	Santa Maria do Pontal
1986	2.0163	1.4773	3.5765	6.7995	9.5846	3.2075
1988	2.2757	1.4764	3.7545	7.0009	9.7679	3.2456
1991	3.7517	1.8886	4.3082	7.0468	9.4143	4.2056
1996	4.8233	3.4082	7.9913	8.2331	9.6440	6.0438
2005	7.3568	5.3249	8.5644	12.6416	18.1456	6.4567
2010	8.9156	10.2399	11.2923	13.4536	18.6050	6.9799

Table A.3 Calculated results of *PCI* index (unit: %).

Landscape metric	***PCI***					
DALR type	Spontaneous			SMO-led		
Settlement name	Rio de Peixe	Rio Trairão	Uirapurú	Alegria	Palmares Sul	Santa Maria do Pontal
1986	75.1158	54.2576	82.0301	98.6141	99.0690	91.8195
1988	83.8680	63.5934	88.4273	98.6653	99.0822	92.2787
1991	91.0527	72.0110	93.3061	98.7720	99.0897	93.2792
1996	94.2913	88.4250	97.8580	98.7531	99.3704	98.4183
2005	98.3436	96.1425	99.3785	99.7341	99.8983	99.8758
2010	98.2422	98.8557	99.5175	99.7586	99.9297	99.8718

Appendix B - Summary Statistics of Selected Field Survey Data

Tables B.1 – B.5 below show the summary statistics of selected field survey data used in this research.

Table B.1 Summary statistics of family lot information.

Name	DALR Type	Distance to the nearest city (km)	Lot size (ha)
Alegria	SMO-led	22.63	39.25
Palmares II	SMO-led	12.98	29.40
Santa Maria do Pontal	SMO-led	29.26	60.52
AVERAGE		**21.62**	**43.06**
Std. Dev.		**8.19**	**15.91**
Rio do Peixe	Spontaneous	30.85	92.79
Rio Trairão	Spontaneous	56.69	110.00
Uirapurú	Spontaneous	27.41	87.62
AVERAGE		**38.32**	**96.80**
Std. Dev.		**16.00**	**11.72**

Table B.2 Summary statistics of family information.

Name	DALR Type	Length of residence (year)	Percentage of families holding a land document (%)	Percentage of families having difficulty in lot demarcation (%)
Alegria	SMO-led	6.95	18.18	18.18
Palmares II	SMO-led	10.98	16.67	30.00
Santa Maria do Pontal	SMO-led	9.30	30.43	4.35
AVERAGE		**9.08**	**21.76**	**17.51**
Std. Dev.		**2.02**	**7.55**	**12.84**
Rio do Peixe	Spontaneous	12.40	65.71	28.57
Rio Trairão	Spontaneous	10.25	25.00	25.00
Uirapurú	Spontaneous	12.02	78.46	20.00
AVERAGE		**11.56**	**56.39**	**24.52**
Std. Dev.		**1.15**	**27.92**	**4.30**

Table B.2 Summary statistics of family information (continued).

Name	DALR Type	Percentage of families receiving credit	Percentage of families receiving technical assistance
Alegria	SMO-led	68.18	50.00
Palmares II	SMO-led	96.67	40.00
Santa Maria do Pontal	SMO-led	73.91	4.35
AVERAGE		**79.59**	**31.45**
Std. Dev.		**15.07**	**24.00**
Rio do Peixe	Spontaneous	71.43	45.71
Rio Trairão	Spontaneous	42.86	35.71
Uirapurú	Spontaneous	66.15	41.54
AVERAGE		**60.15**	**40.99**
Std. Dev.		**15.20**	**5.02**

Table B.3 Summary statistics of agriculture information.

Name	DALR Type	Area of annuals per family (ha)	Area of perennials per family (ha)	Area of pasture per family (ha)	Percentage of families raising cattle (%)
Alegria	SMO-led	3.13	1.54	14.45	77.27
Palmares II	SMO-led	5.11	2.91	10.86	76.67
Santa Maria do Pontal	SMO-led	1.33	3.66	23.52	86.96
AVERAGE		**3.19**	**2.70**	**16.28**	**80.30**
Std. Dev.		**1.89**	**1.08**	**6.52**	**5.78**
Rio do Peixe	Spontaneous	2.46	14.41	18.55	74.29
Rio Trairão	Spontaneous	5.24	2.09	15.04	71.43
Uirapurú	Spontaneous	5.77	15.71	15.97	87.69
AVERAGE		**4.49**	**10.74**	**16.52**	**77.80**
Std. Dev.		**1.78**	**7.52**	**1.82**	**8.68**

Table B.4 Summary statistics of household composition.

Name	DALR Type	# persons per household	# children per household	# seniors per household	# adult men per household	# adult labors per household	Labor/consumer Ratio*
Alegria	SMO-led	4.43	1.26	0.35	1.48	2.83	0.64
Palmares II	SMO-led	4.32	1.19	0.16	1.77	2.97	0.69
Santa Maria do Pontal	SMO-led	4.04	1.32	0.14	1.25	2.57	0.64
AVERAGE		**4.26**	**1.26**	**0.22**	**1.50**	**2.79**	**0.65**
Std. Dev.		**0.20**	**0.07**	**0.12**	**0.26**	**0.20**	**0.029**
Rio do Peixe	Spontaneous	4.36	1.50	0.16	1.75	2.68	0.61
Rio Trairão	Spontaneous	5.04	1.85	0.04	1.81	3.15	0.62
Uirapurú	Spontaneous	4.64	1.72	0.12	1.71	2.80	0.60
AVERAGE		**4.68**	**1.69**	**0.11**	**1.76**	**2.88**	**0.61**
Std. Dev.		**0.34**	**0.18**	**0.06**	**0.05**	**0.24**	**0.011**

*The labor/consumer ratio was calculated using the number of adult labors divided by the total number of persons.

Appendix C - Report of Spearman's Rank Correlation Analysis

In Chapter 5, only Spearman's rank correlation coefficients with a *p*-value less than 0.1 were reported (a significance level of 0.10). Table C.1 below shows the full report of this nonparametric statistical analysis derived from *STATA* software. Coefficients with one superscript star are at a significance level of 0.10, and coefficients with two superscript stars are at a significance level of 0.05. Numbers in parentheses are *p*-values.

Table C.1 A full report of Spearman's rank correlation coefficients.

Variable name[†]	*PMA*	*AWMSI*	*PCI*
city_distance	-0.6571 (0.1562)	-0.9429[**] (0.0048)	-0.8286[**] (0.0416)
lot_size	-0.8286[**] (0.0416)	-0.8286[**] (0.0416)	-0.9429[**] (0.0048)
residence_length	-0.4286 (0.3965)	0.0286 (0.9572)	-0.3143 (0.5441)
%document	-0.3143 (0.5441)	-0.4286 (0.3965)	-0.4857 (0.3287)
%demarcation	-0.3714 (0.4685)	0.3143 (0.5441)	-0.0857 (0.8717)
%credit	0.7714[*] (0.0724)	0.4857 (0.3287)	0.8286[**] (0.0416)
%tech_support	-0.2571 (0.6228)	0.5429 (0.2657)	-0.1429 (0.7872)
annuals	-0.4857 (0.3287)	0.1429 (0.7872)	-0.3143 (0.5441)
perennials	-0.0286 (0.9572)	-0.0857 (0.8717)	-0.0857 (0.8717)

Table C.1 A full report of Spearman's rank correlation coefficients (continued).

	PMA	*AWMSI*	*PCI*
pasture	0.0286 (0.9572)	-0.6571 (0.1562)	-0.2571 (0.6228)
cattle	0.6000 (0.2080)	0.3143 (0.5441)	0.4857 (0.3287)
#persons	-0.8286** (0.0416)	-0.2571 (0.6228)	-0.7714* (0.0724)
#children	-0.7714* (0.0724)	-0.7714* (0.0724)	-0.8857** (0.0188)
#seniors	0.4058 (0.4247)	0.6957 (0.1248)	0.4928 (0.3206)
#adult_men	-0.6571 (0.1562)	-0.0857 0.8717	-0.4286 (0.3965)
#adult_labor	-0.4286 (0.3965)	0.1429 (0.7872)	-0.2000 (0.7040)

† The corresponding demographic features and household characteristics of each variable name used in Spearman's rank correlation analysis:

- city_distance: the distance between each family lot to the nearest city
- lot_size: family lot size;
- residence_length: the length of family residence in a DALR settlement;
- %document: the percentage of families in a DALR settlement holding a land document;
- %demarcation: the percentage of families in a DALR settlement having difficulty in lot demarcation;
- %credit: the percentage of families in a DALR settlement receiving credit from the government;
- %tech_support: the percentage of families in a DALR settlement receiving technical assistance from the government;
- annuals: the area of annual crops for each family;
- perennials: the area of perennial crops for each family;
- pasture: the area of pasture land for each family;
- cattle: the percentage of families in a DALR settlement raising cattle;
- #persons: the number of persons per household;
- #children: the number of children (aged 0-14) per household;
- #seniors: the number of seniors (aged 65+) per household;
- #adult_men: the number of adult men (all females aged 14-64) per household;
- #adult_labor: the number of adult labors (aged 15-64) per household.