LAND-USE AND LAND-COVER CHANGE IN THE CHAPARE REGION OF BOLIVIA.

Thesis submitted for the degree of

Doctor of Philosophy

at the University of Leicester

by

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March 2005

Abstract

Land-use and land-cover change in the Chapare region of Bolivia.

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This research examines the impacts of coca leaf cultivation (an ingredient for cocaine paste) on land-use and land-cover change (LULCC) in a colonised, humid-tropical forest area of central Bolivia. The socio-economic driving forces affecting the way farmers have utilised their land and the resulting effects on land-cover change are studied. Satellite imagery from 1975 to 2000, methods of participatory rural appraisal and socio-economic data has been combined to determine deforestation patterns, changes and the driving forces of LULCC.

Three communities were studied: Arequipa, dominated by coca production and alternative development crops; Bogotá, a cattle rearing community; and Caracas where fruit cultivation dominated. Three major periods were determined from a land-management synopsis in each community:

(i) pre-coca dominant, driven by weak national policies and economics, with high rates of deforestation;
(ii) coca-dominant, influenced by the international coca / cocaine economy, with the lowest rates of forest clearance; and
(iii) post coca-dominant, driven by strong international anti-narcotics policies, when forest clearance accelerated again.

The deforestation trajectories (rates) differ from published models and the variations are attributed to the rising dominance of coca being ascended by an enforced substitute economy. These driving forces have been conceptualised at local, national and international levels.

Specific fragmentation patterns developed because of the spatial arrangement of plots planned in the 1960s and the subsequent variations in land-use management strategies between, as well as, within individual plots over time. A five stage conceptual model has been constructed to represent forest fragmentation at the community level.

Overall, in the pursuit of global social gains, anti-narcotics policies caused rapid consumption of limited land resources and because of non-conservationist planning the connectivity between montane and humid tropical forests at the margins of a biodiversity hotspot is severely compromised - a message to planners and policymakers where conservation and development currently conflict in humid tropical regions.

Acknowledgements

The funding of the fieldwork made this study possible and I am grateful to Paul and Mary Slawson for their kindness and wishes to springboard young geographers in their careers. Through their generosity I would not have been able to rub shoulders with people of Bolivia, observe their culture, hardships, opinions and way of life. I would also like to thank the Royal Geographical Society (with the Institute of British Geographers) for their advice, adjudication and selection of my research project on behalf of Paul and Mary Slawson.

In Bolivia I must also thank the support of the BioAndes project staff from the Universidad Major de San Símon, Centro de Biodiversidad y Ginetica. In particular Felix Huanca Viraca for his companionship, patience, and lobbying to *sindicatos* and *campesino* farmers in the field. A special note is due here for the concern and worry that he expended as he responded to the *gringito's* gesticulations and grunts during a wicked stomach infection in the field. Thanks too for the hospitality and support of Ximena Velez-Liendo, Veronica and Daniel Mercado in Cochabamba, and of course the entertainment provided by their energetic son Ignacio and their three dogs.

Also a special mention to those farmers of Chapare who gave up a few hours of labouring to participate in this research. I will not name them as it is in their best interests to remain anonymous in a region where illicit coca cultivation is still practiced.

At the University of Leicester I must thank first, Professor Andrew C. Millington for his academic guidance through this study and as a comrade in the field and at conferences. Secondly, the postgraduate community and staff, for all their support, non-academic diversions down the pubs, clubs and on the sports field. Will we ever forget booting Physics out the Gilmore Lee cricket competition in the semis?!

AFP&R Delbray – weight 5lbs 7oz – minus 1lb for sweat.

Acronyms and abbreviations

AD	Alternative Development
AVHRR	Advanced Very High Resolution Radiometer
ATSR-2	Along Track Scanning Radiometer – 2
CA	Class area (landscape metric)
CONCADE	Counter-Narcotics Consolidation of Alternative Development Efforts
CORDEP	Cochabamba Regional Development Project
CRDP	Chapare Regional Development Project
DAI	Development Alternatives Incorporated
DEA	Drug Enforcement Agency
DMSP	Defense Meteorological Satellite Program
ED	Edge Density (landscape metric)
FAO	Food and Agriculture Organisation
FCC	False colour composite
FHV	Felix Huanca Viraca (field assistant)
GIS	Geographical Information System
GCP	Ground Control Points
GPS	Global Positioning System
IBTA	Bolivian Institute for Agricultural Technology
IDB	International Development Bank
IGBP	International Geosphere-Biosphere Programme
IGM	Instituto Geográphico Militar
IMF	International Monetary Fund
INE	Institute Nacional de Estadisticas
INC	Institute Nacional de Colonización
INPE	Brazillian National Space Research Institute
INRA	Institute Nacional de Reforma Agraria (Bolivia)
IRS	India Remote Sensing
ISODATA	Iterative Self Organising Data Analysis Technique
JERS-1	Japanese Earth Resources Satellite – 1
JRC	Joint Research Centre

Landsat MSS	Landsat Multi Spectral Scanner
Landsat TM	Landsat Thematic Mapper
Landsat ETM+	Landsat Enhanced Thematic Mapper Plus
LULCC	Land-Use and Land-Cover Change
MNN	Mean Nearest Neighbour (landscape metric)
MPS	Mean Patch Size (landscape metric)
MSI	Mean Shape Index (landscape metric)
NAS	Narcotics Affairs Section, US Government
NoP	Number of Patches (landscape metric)
NNSD	Nearest Neighbour Standard Deviation (landscape metric)
NNCV	Nearest Neighbour Co-Variance (landscape metric)
NGO	Non Governmental Organisation
PD	Patch density (landscape metric)
PDRA	Program of Alternative Development
PREADAC	Programe de Apoyo a la Estrategia de Desarrollo Alternativo en la Chapare
PRODES	Proyecto de Desarollo Chapare – Yungas
PSCV	Mean Patch Size Co-Variance (landscape metric)
PSSD	Mean Patch Size Standard Deviation (landscape metric)
RRA	Rapid Rural Appraisal
SPOT	Le Système Pour l'Observation de la Terre
(HRV)	Haute Résolution Visible
(VGT)	Vegetation
TEL	Total edge length (landscape metric)
TMF	Tropical Montane Forest
TREES	TRopical Ecosystem Environment observations by Satellite
UoL	University of Leicester
UMSS – CBG	University Major de San Símon – Centro de Biodiversidad y Genética
UNEP	United Nations Environment Program
USAID	United States Agency for International Development
US	United States
WB	World Bank
WRI	World Resources Institute

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Chapter 1

Introduction.

Chapter 1

Introduction

1.1 Introduction

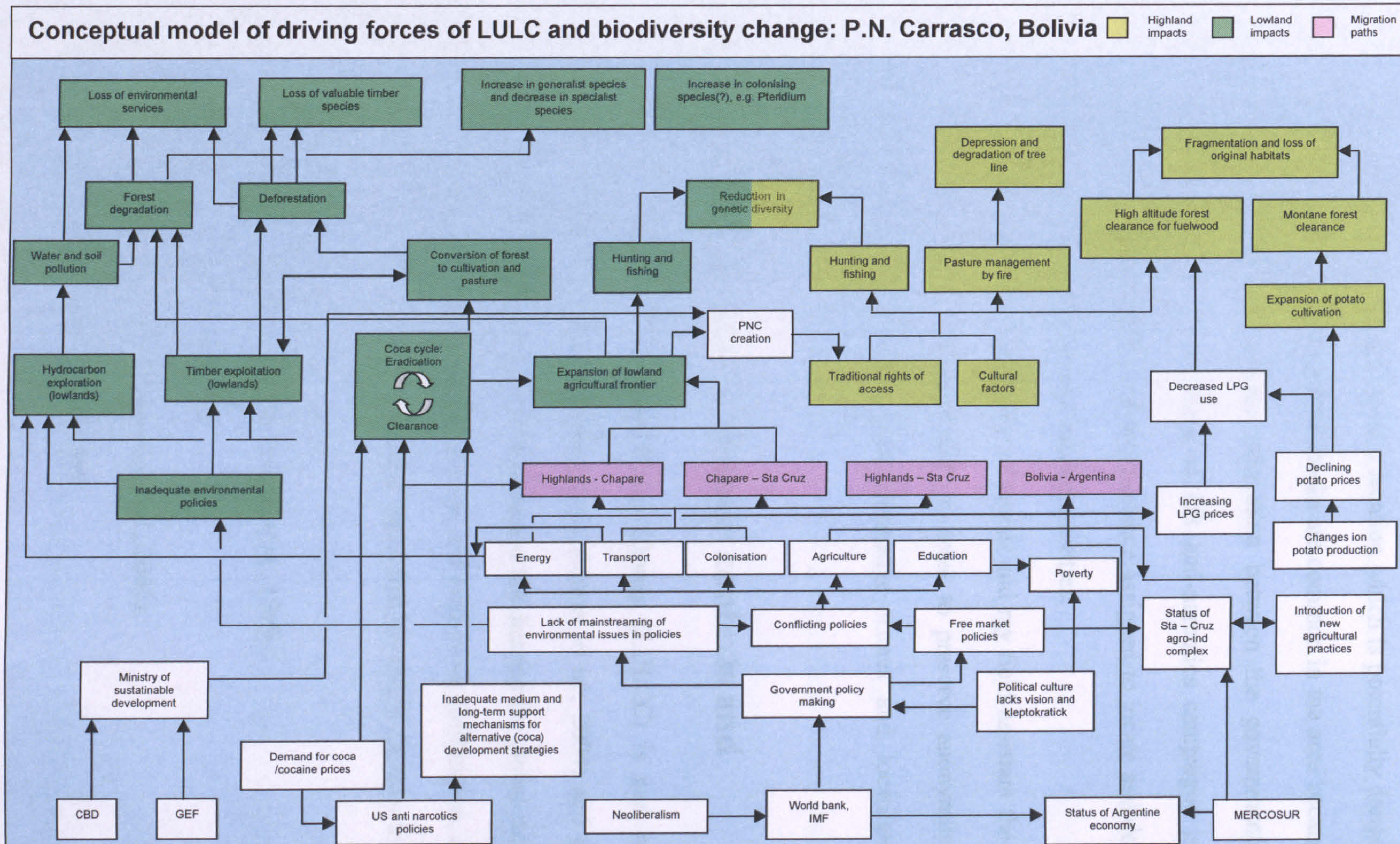
This thesis examines land-use and land-cover change in, and fragmentation of, a tropical rainforest in Bolivia in the heart of South America. The study area is occupied by agricultural colonists attracted as early as the 1940s by the potential to escape poverty in the Bolivian Andes. With aspirations of 'a better life in Chapare', forest has been cleared by farmers to make way for pasture and cultivation. The reality for many colonists today is mainly social hardship and limited economic benefit despite a boom period of coca leaf cultivation (an ingredient of cocaine paste) during the 1980s and 1990s.

This research studies the impacts that colonisation has had on the forest and investigates the factors that initiated and continue to drive the processes of land-use and land-cover change in Chapare. The research has involved the mapping of agricultural areas utilising satellite imagery, examined the development of forest fragmentation, engaged with farmers and farming communities, and linked the drivers of land-use and land-cover change through the contemporary and historical political economies of the area. Fieldwork took place in Bolivia during spring 2002 and autumn 2003. This research used qualitative and quantitative data at a range of different temporal and spatial scales using a multidisciplinary approach. The methodology therefore followed the research plan of the International Human Dimensions Programme – Land Use Cover Change (IHDP – LUCC) (Turner, 1995). Studies within this programme have since developed to tackle methodological issues and raise caveats for future LULCC research (Liverman *et al.*, 1998; Fox *et al.*, 2002; and Rindfuss *et al.*, 2004). The field studies were designed to engage with the farmers to verify the information processed from the satellite data and gather information from document archives and informants involved in agricultural activities in Chapare.

While in Bolivia I took part in the final BioAndes Project workshop[1] at the University Major de San Símon – Centro de Biodiversidad y Genética (UMSS-CBG) in Cochabamba. During the workshop I participated in the formulation and development of conceptual frameworks of driving forces threatening the loss of biodiversity in Andean National Parks. The framework developed for Parque Nacional Carrasco, Bolivia, is shown in Figure 1.1. The model shows how there are different threats to land-cover in the park from the highland and lowland regions that are driven by socio-economic and political factors at the local, national and international levels. The loss of biodiversity and change in land-cover at the local level is linked to policies created by the national governments. The national level is influenced by economies and policies at the international scale. The model shows that some international drivers relate directly to the local level. The main driver that directly links to international and local levels is the demand for, and the price of, cocaine which influences coca leaf cultivation in the area. Because of the global social consequences of the coca/cocaine trade the involvement of US government policies against narcotics have become focussed on the region. These policies are part of the coca cycle in which eradication forces and replanting of coca bushes convert mature forest to agriculture reducing the biodiversity in a protected area Parque Nacional Carrasco. I have adopted this framework and modified it (Chapter 6),

[1] The BioAndes project was an EU funded (ERBIC18CT980299) project which monitored and modelled the impacts of changing government policies on biodiversity conservation in the Andes and focused on the study of national parks in Argentina, Bolivia and Peru. The multidisciplinary project involved geographers, ecologists and social scientists in Europe and South America. The project ran from 1998 to 2002 and was co-ordinated from the University of Leicester. http://www.geog.le.ac.uk/research/BioAndes/index.html

Figure 1.1: The BioAndes conceptual model of driving forces of LULCC and biodiversity loss in Parque Nacional Carrasco, Bolivia.



to help analyse land-use and land-cover change to describe fragmentation of lowland humid forest in the communities I studied in detail.

The fieldwork has been carried out in a location which is potentially dangerous for white visitors. Demonstrations and road blocks are common in the area because of the fundamental disagreement over coca cultivation between the government and farmers (*campesinos*) and the involvement of US anti-narcotics campaigns in the region. There is also a highly visible military presence assigned to locate and destroy the coca plantations and to deter other coca related activities.

To avoid a compromise to the safety of myself and my field assistant the field visits to Chapare were brief and intense and, in order to preserve anonymity, the communities and farmers have been given alternative names and locations are deliberately vague.

1.2 Land-use and land-cover change: contexts and definitions

Research into Land-Use and Land-Cover Change (LULCC) is part of the understanding of human – environment interactions (Moran *et al.*, 2004) and global environmental change in the 1980s and 1990s increased the demand for global data sets on land-use and land-cover and changes in land-use and land-cover (Millington, 2005). Lambin *et al.* (2001) and Millington (2005) have stated that the major changes in land-cover are a concern for:

- global and regional climate modelling (Chase *et al.*, 1999);
- water budgeting (Chase *et al.*, 1999);
- global Biogeochemical Cycles (Houghton *et al.*, 2000);
- biodiversity studies (Sala *et al.*, 2000); and

- social and economic concerns in the arena of sustainable development (Vitousek *et al.*, 1997).

In this research I follow conventional definitions of land-cover and land-use: '*Land-cover* is the biophysical state of the earth's surface and immediate subsurface' (Turner *et al.*, 1995: p20). For example, the land surface may be grassland, forest or human construction (McConnel *et al.*, 2001). '*Land-use* involves both the manner in which the biophysical attributes of the land are manipulated and the intent underlying that manipulation - the purpose for which the land is used' (Turner *et al.*, 1995. p20). For example, grassland may be used for grazing and forest may be used for either an extractive purpose like logging or as a nature reserve.

Land-use is a result of a management decision(s) over an area of land and changes in management may result in a change in land-cover referred to as a trajectory of LULCC. A LULCC trajectory can either be a complete conversion of a land-cover, e.g. forest to pasture, or modification of a land-cover, such as the selective removal of trees in rainforests, and is a direct result of the manager (sometimes referred to as an agent). Behind a LULCC trajectory are the driving forces acting on an agent which have been categorised as underlying causes. Underlying causes can be the economic, policy and institutional, technological, cultural and demographic controls. These underlying causes operate at different spatial scales e.g., local, national and international (Geist *et al.*, 2001). The conceptual model illustrated in Figure 1.1, provides an example of the different geographical scales at which the underlying causes operate.

1.3 Study Area

1.3.1 Location

The study region is located in the centre of Bolivia below altitudes of 500 m.a.s.l. in Cochabamba Department between the cities of Cochbamba and Santa Cruz.

(Figure 1.2). The location, commonly known as Chapare, covers an area of approximately 6,000 km^2 and lies immediately to the north of the montane forests on a north-facing flank of the Andes (Figure 1.3). Most of the area was covered with various types of humid tropical forest until the 1970s but a majority of the forest has since been cleared for agriculture. The extent of this clearance is shown on a false colour composite (FCC) of a satellite image subscene acquired in 2000 (Figure 1.4).

Figure 1.2: The location of the study area in Bolivia.

Figure 1.3: Detail of the study area with places mentioned in the text.

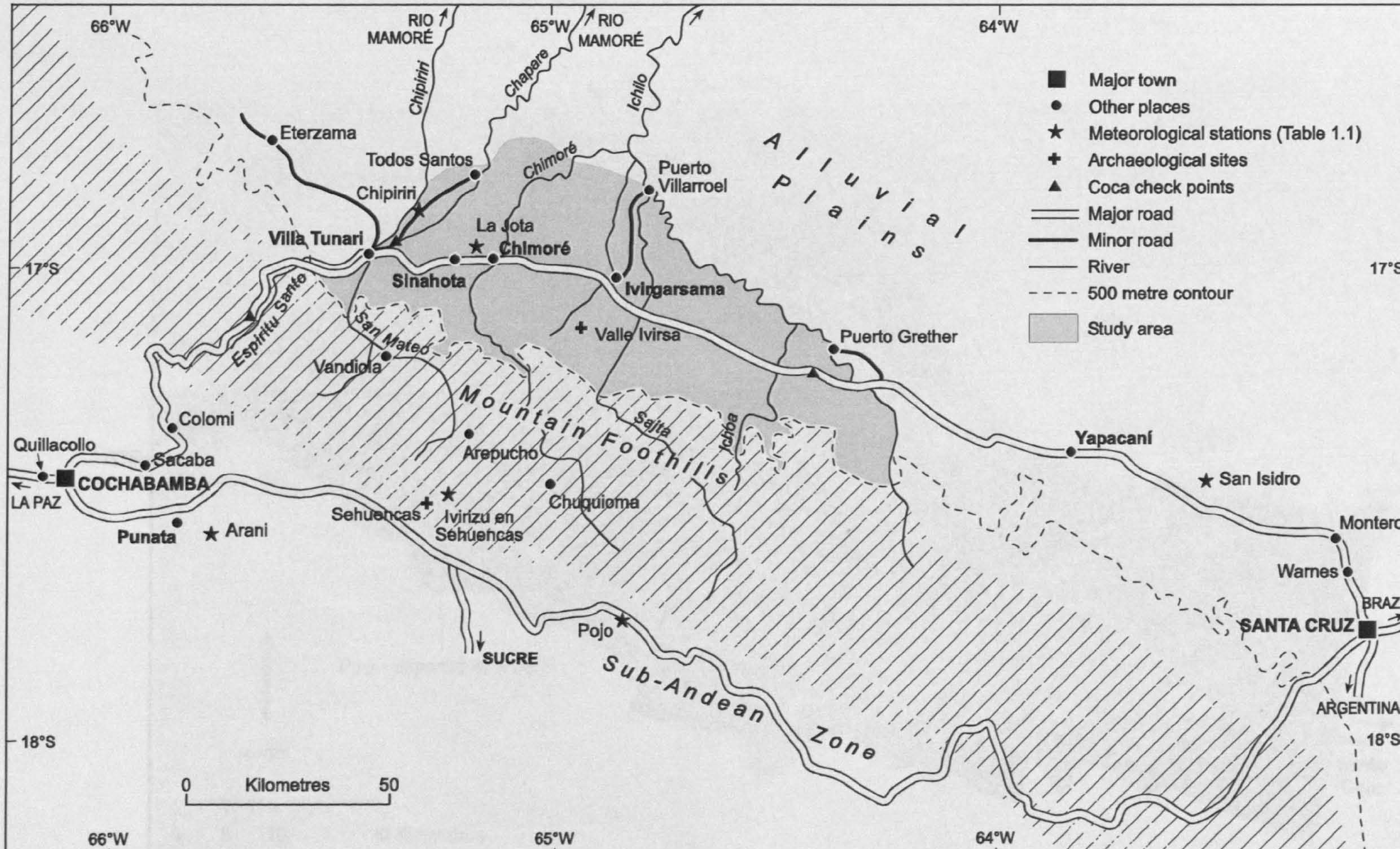
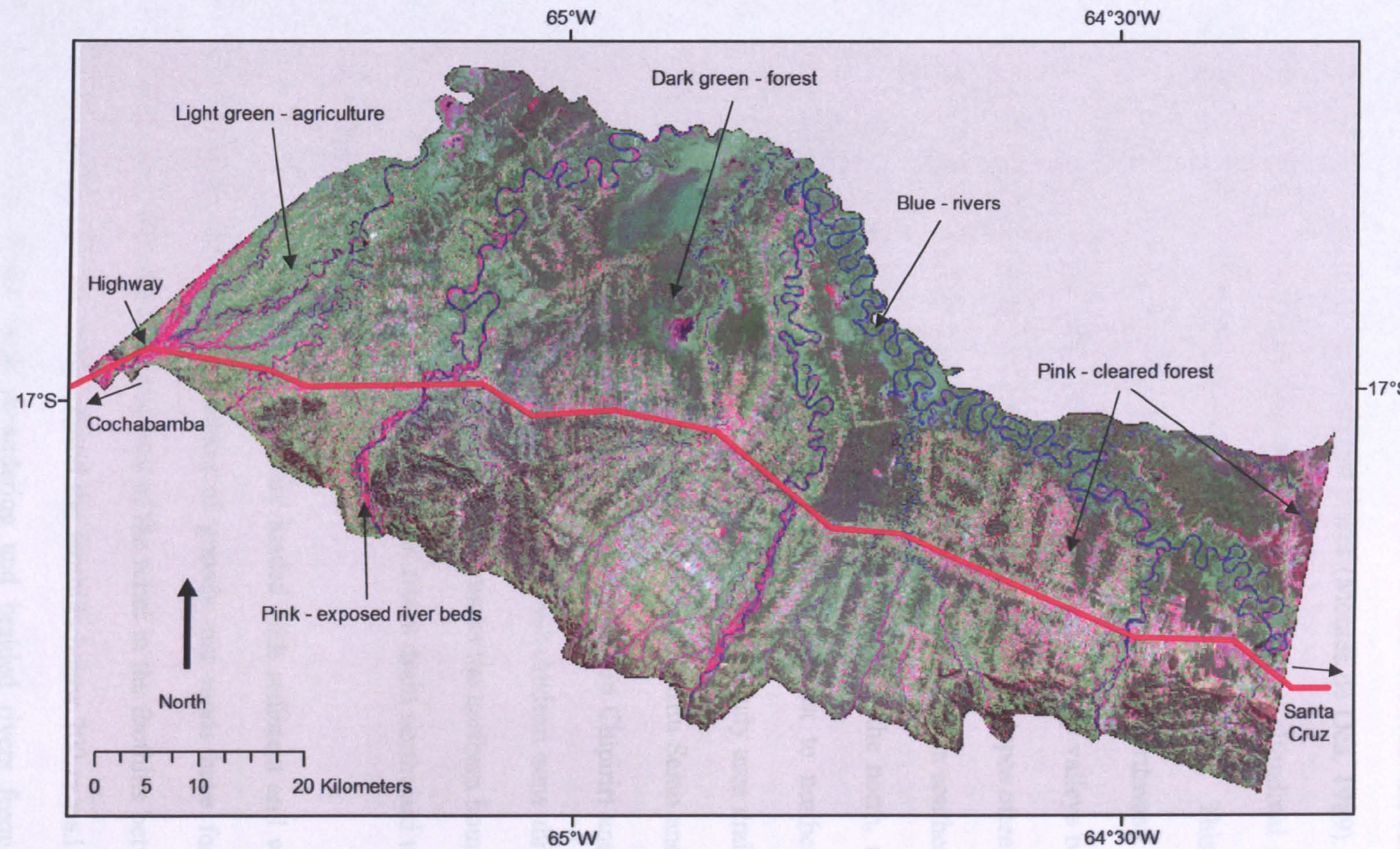


Figure 1.4: Landsat subscene inside the study area, the Cochabamba Santa Cruz highway is shown in red, the image is a False Colour Composite (FCC) bands 741. Path 232 Row 072 acquired on 14/07/2000.



1.3.1.1 Landscape

The landscape of the study region can be described in three sections: the sub-Andean zone; the mountain foothills; and alluvial plains (Montes de Oca, 1989). The sub-Andean zone is just to the south of the study sites and has an altitudinal range between approximately 400 and 4,000 m.a.s.l. over a distance of 60 km. This area consists of a series of ridges which trend from the southeast to the northwest. The ridges have an asymmetric structure and are divided by a series of deep valleys two or three kilometres wide and as much as 1,000 m deep. The south facing slopes often have vertical faces which oppose steep sloping north faces. The drainage flows southeast to northwest along the valleys but to reach the foothills and plains to the north, rivers occasionally drain perpendicular to the ridges – roughly southwest to northeast – through deeply dissected narrow canyons. The major rivers in the study area drain the sub-Andean zone into the alluvial plains (Figure 1.3). The Río Espiritu Santo and Río San Mateo join at Villa Tunari, but then split into tributaries of Río Chipiriri and Río Chapare. Río Chimoré, Río Sajta and Ichoa flow from the sub-Andean zone through the foothills into the east to west draining Río Ichilo which marks the northern boundary of the study area on the alluvial plain. Ultimately all the rivers drain northward to the Río Mamoré in the Department of Beni.

At the foot of the mountains these rivers are loaded with sediment and where they meet the flat alluvial plains the deposition of gravels and sands have formed alluvial fans. The alluvial fans make the majority of the relief in the foothills between 200 m.a.s.l and 400 m.a.s.l. To the north beyond the foothills below 200 m.a.s.l., are the alluvial plains, formed where large meandering and braided rivers frequently inundate and deposit sediment on their floodplains.

1.3.1.2 Precipitation and temperature

The area has most rain in the southern hemisphere summer (December to March) and least rain in the winter (June to September). High precipitation levels are a result of warm humid air from the northern Amazon plains being forced to ascend the Andes resulting in orographic rainfall. Annual amounts of precipitation from selected meteorological stations around Parque Nacional Carrassco are shown in Table 1.1. There are marked rainfall gradients from west to east, and north to south. O'Hanlon (2001) studied 56 meteorological stations within 100 km of Parque Nacional Carrasco and calculated that up to 500 m.a.s.l. there was a decrease in precipitation with elevation at the rate of 145 mm per 100 m and that above 900 m.a.s.l. the rate of decrease in precipitation was 100 mm per 100 m. There was also a decrease in precipitation from west to east of around 22 mm per km (O'Hanlon, 2001). Average annual temperatures are around 25°C, in the plains and 21°C in the mountain ranges. In the lowland area (below 400 m) the amplitude in diurnal temperature is low, around 5 °C (Casteñada *et al.*, 2002), however in the dry season cold fronts from the south can reduce this temperature markedly bringing in cold winds known as *suarzoes*. O'Hanlon (2001) estimated temperature changes around Parque Nacional Carrasco to be 7.6 °C per 100 m on north facing slopes and 6.9 °C per 100 m on south facing slopes. The temperature range is narrow, about 5 °C, but is increasingly wider at higher altitudes.

Table 1.1: Average precipitation at selected meteorological stations around Parque Nacional Carrasco. Sources: *O'Hanlon (2001); ** 20 year averages, Casteñada *et al.* (2002).

Station	Altitude (m.a.s.l.)	Annual Precipitation (mm)	Temp range (°C)	Latitude (degrees)	Longitude (degrees)
**Chipiriri	411	4,800	-	16° 55'	65° 19'
**La Jota	226	4,100	-	16° 58'	64° 57'
**San Isidro	327	2,050	-	17° 28'	63° 32'
*Ivirizu en Sehuencas	1,980	3,541	2.47	-	-
*Planta Corani	2,740	2,969	3.48	-	-
*Pojo	2,600	547	4.34	-	-
*Arani	2,740	454	4.7	-	-

1.3.1.3 Soils and vegetation

Soils in the Chapare region are alluvial, poorly drained, have a low pH of around 3-6 and are mainly Fluviosols and Cambisols (Jones, 1998). In the 1990s the soil units were further classified for agricultural purposes by Development Alternatives Incorporated (DAI) into sandy, loamy and clay and a GIS was used to map the spatial variation in physio-chemical variations in soil properties of Chapare (Ferrufino *et al.*, 2003).

Before colonisation the alluvial plain was covered with Amazonian evergreen *terra-firme* rainforests inundated with pre-montane rainforest close to the sub-Andean region. The sub-Andean region still has a cover of different types of humid montane forests. The seasonal inundation in the alluvial plains means that there are several types of humid tropical forests and pre-montane forests which are similar to that described in Holdridge's (1967) classification (Jones, 1998). The structure of the forests is generally of multiple strata with a canopy punctuated by emergent trees around 25 to 35 metres high. The forests of the alluvial plains have lower plant diversity than the pre-montane forests because of periodic disturbance by seasonal flooding and shifting drainage patterns. Evidence for this is shown by shallow, wide-spaced levees, broad depressions and infilling ox-bow meanders. Tree species have tropical forest adaptations to seasonally flooded localities, with buttresses and respiratory aerial root systems. The understory vegetation is typically dense and around 15 to 17m high (Jones, 1998).

1.3.2 Historical context

1.3.2.1 Pre-colonial to the early 20th century

Archaeological evidence from Valle Ivirza and Sehuencas show evidence of contact between people in the highlands and lowlands around 1,100 to 400 B.C. (Pereira *et al.*, 2000). In the 15th Century the study area was inhabited by ethnic groups of hunter gatherers possibly trading feathers with coca from the highland peoples of the Andes (Walter Sanchez, UMSS, personal communication, 2002). From 1438 to 1532 the Inca Empire expanded and the Cochabamba Valleys were on the frontier of Tawantiasuya where there was an interest in protecting the coca plantations on the eastern slopes of highlands as the leaves were used for ceremonies and consumed by royalty (Meruvia, 2000). The Incas defended these limits from the Chiriguanos in the lowlands (Lazcano *et al.*, 2002). After the Spanish conquest of the Incas in 1532 the Spanish controlled the Andes and perceived the lowland peoples as barbaric and threatening to their control. Spanish interest in coca growing, which was situated around Arepucho and Chiquioma in the montane forest zone (now Carrasco National Park), probably worsened the situation through aggression and relations with the lowland groups deteriorated (Gordillo, 2002).

From the late 17th Century a series of Jesuit missions were founded in Beni (Figure 1.2) (Montenegro, 1990), ~200km to the north of the study area. However, moving foodstuffs to Beni from Cochabamba was difficult because no direct linkages existed because of the mountain ranges and forests in between. The only connection between Beni and the Andes was to travel south to Santa Cruz and then into the mountains of Chiquisaca then northwards through the mountains to Cochabamba (Figure 1.2). It was acknowledged that a more direct link would speed up trade between Cochabamba and Beni (Rodríguez, 1997). The Spanish Audencia encouraged the Jesuits to secure a passage between the two areas. In doing so the Jesuits would be responsible for creating settlements to 'domesticate' lowland ethnic groups (Larsson, 1998). In the 1780s Jesuits (Montenegro, 1990) and later the Fransciscanos (Osteria, 1999; Rodríguez, 1997) founded settlements known as *reduciones* of Yuracarés, the local indigenous group, with limited success. The Yuracarés could not be encouraged to settle in one location and often left to return to their hunter-gatherer existence. However, despite the failures the missionaries laid down the foundations for the difficult connections between Cochabamba and Beni using tracks, rivers and ports.

By the 1880s Beni had become a centre of economic attention because of the rubber boom. The market opportunities for the trading of maize and wheat from Cochabamba had great potential and a search for a reliable trade route once again became an important objective for entrepreneurs in Cochabamba. The failure of the entrepreneurs to do this led to the responsibility being taken on by the military, but in the late 1800s the military also had difficulties sustaining agricultural colonies close to present day Villa Tunari because of and lack of a workforce to farm products which also had weak markets. Eventually around 1920 a military colony which included European migrants established the 'Primera Colonía Nacional' at the port of Todos Santos. Shortly afterwards, in 1922, the Government of Bolivia (GoB) funded the construction of a road from Cochabamba to the principal colonies and river ports in Chapare and by the early 1940s it had reached San Antonio and Todos Santos (Figure 1.3). The lowland region was now far more accessible and highland migrants began to colonise along the roadside in the lowlands (Rodríguez, 1997).

1.3.2.2 Economic growth from the mid 20th century

The second half of the 20th Century has been characterised by three major political stages in Bolivia: 'The National Revolution' (1952 to 1963), 'The Counter Revolution' dominated by military governments (1964 to 1981) and 'Democracy' (1982 to present) (Morales, 2004). During this time Bolivian economic policies have varied. The period from 1952 to 1969 was dominated by policies to diversify products alongside import substitution. 1970 to 1979 saw a growing economy sustained by external borrowing leading to high debt accumulation. Between 1979 and 1985 a severe economic crisis set in and inflation reached up to 11,000% (Kaimowitz *et al.*, 1999). This was followed in 1985 by the implementation of neo-liberal policies as part of a structural adjustment programme employed by the Bolivian government (Pacheco 1998). Alongside these political and economic changes, Bolivia has been strongly supported by military and foreign aid, mainly lent by the USA, and driven by United States (US) government policies concerning communist subversion and anti-narcotics trafficking.

Following the agrarian reform in 1952, when the hacienda lands were re-distributed to the people, the government of Bolivia objectives were to diversify the nation's economic structure and substitute imports because the economy had been overly reliant on mineral exports. This was achieved by regulation of the internal market and control of the external market. The plan for the internal market was to consolidate mining and hydrocarbons and to expand agriculture in the tropical lowlands. The GoB needed external finances to implement these policies and the administration of US President Dwight Eisenhower willingly supplied this, and as a reciprocal gesture the GoB encouraged US oil investors and compensated tin companies that had been expropriated. In the early 1950s, following the visions of Plan Bohan which was set out in 1942 (de la Mesa, 1997), the first serious developments in a national road network improved internal connections between the major cities and the significant agricultural area of Santa Cruz, with a route across the highlands from Cochabamba to Santa Cruz. In 1956 more aid money was guaranteed by the IMF and US government, in return for adhering to the economic stabilisation plans. Further road infrastructure improvements figured in the Plan Decinal (1962-1971) which was funded by the Agency for International Development (AID) and Inter-Development Bank (IDB) (IF, 1973), to stimulate more migration from the altiplano and high valleys to the tropical lowlands.

These new developments included government sponsorship of settlement programs in Santa Cruz (Yapacaní), La Paz (Rio Alto Beni) and Cochabamba (Chapare) departments.

The strength of mineral and hydrocarbon exports weakened during the 1970s as the extraction and export of minerals was becoming economically unsustainable and the (then) known hydrocarbon reserves were decreasing. The government switched to public investment and external borrowing to sustain the hydrocarbon and mineral exports. In the early 1970s international financing for colonisation and investment in agriculture was reduced and investment concentrated on credit towards mechanisation of agriculture and infrastructure improvements. Priorities for infrastructure development in the early 1970s were directed away from the Cochabamba lowlands and by the end of the decade were concentrated on Santa Cruz and Beni, mainly to support the export of sugar and the transport of foodstuffs from the Santa Cruz region.

At the end of the 1970's an economic crisis set in. The macroeconomic factors that contributed to this were:

(i) a decrease in the capital from the mining sector;

(ii) a limited diversity of exports;

(iii) lower prices for the exports on the international markets;

(iv) an increase in interest rates on the nation's external debt and reductions in borrowing available on the international market; and

(v) a sudden fall in public investment that depended strongly on the value of exports and external finance (Pachecho, 1998).

The economic crisis led to the implementation of structural adjustment policies. The structural adjustment programme included the reduction of public employment, the most drastic cut being the laying off of 23,000 of 30,000 tin miners (exacerbated by a

50% decline in world tin prices during the 1980s). As well as the miners this also affected those whose livelihoods were underpinned by provisioning to the mining industry. Moreover, the effects of structural adjustment policies encouraged migration to cities and agricultural zones (particularly Chapare) and were compounded by drought and ecological degradation in the highland areas (Kaimowitz *et al.*, 1999). Structural adjustment policies led to the abandonment of programmes of colonisation. For example, in 1984 the Institute Nacional de Colonización (INC) was to select one million hectares in the lowlands for further colonisation but this never came to fruition. The remaining available resources of the INC were then used in land titling and contributing to coca substitution programs (Pachecho, 1998). Public investment between 1986 and 1994 was prioritised to develop 'corridors of exportation' in road development programs in order to connect Bolivia with trade on the Atlantic and Pacific seaboards of South America. Several road networks were developed and invested in around Santa Cruz, La Paz, Trinidad and in the Cochabamba lowlands. The final section of the east to west transport link across the country, the Chimoré to Yapacaní portion of the Cochabamba to Santa Cruz highway (Figure 1.3), was completed in 1988 with the aid of an IDB loan. As well as providing a faster link in comparison to the old highland road, access to more agricultural land was possible.

1.3.2.3 Chapare from the 1970s

Migration to the Chapare region increased the population from 9,750 to 350,000 between 1975 and 1989 (Lazcano 2002: Table 6) due to a number of push – pull factors (the population then began to decline in 1990 to 91,000). The push factors leading to migration (Section 1.3.2.2) were accompanied by pull factors in the lowlands. Alongside the colonisation program in Chapare, there were the financial rewards from coca leaf cultivation and processing of cocaine paste to supply the increasing world demand for cocaine (Painter *et al.*, 1991). Coca bush cultivation became the major activity in Chapare as migrants eased the poverty levels experienced on the highlands.

The increase in the supply of coca leaf (and other narcotics) had already attracted worldwide attention by the late 1970s, and source countries (e.g. Bolivia, Peru and Colombia) were expected to participate in the reduction of supply to avoid conditions attached to foreign lending. However, the blatant involvement of the administration of the Bolivian President Luis García Meza (July 1980 to August 1981) in cocaine trafficking put Bolivia in a weak negotiating position with international aid donors and eroded the power of future governments. Subsequently foreign loans were often granted on conditions regarding the reduction of coca cultivation and foreign governments (notably the USG) dictated certain policies relating to coca cultivation. Policy tools such as anti-coca laws and programs of crop substitution directly affected the management of farms in the Chapare region and form a key point in the discussion of LULCC in this area.

1.4 Research objectives

The research aims to investigate the socio-economic driving forces of LULCC that have acted or are acting on communities of farmers in Chapare and how farmers land management decisions have led to particular patterns of forest fragmentation. Within this overall aim there are seven specific research objectives.

1. **To analyse the political, social and economic history of Chapare from 1960.** This has involved the analysis of documentation and interviews with informants who were resident within and outside Chapare. The methods used for this research objective are considered in Chapter 4 (Sections 4.2 and 4.3), and described in Chapter 5 (Sections 5.2 to 5.4) and discussed in Chapter 6 (Sections 6.2 and 6.3).

2. **To conduct detailed surveys of farms and farmers' activities in 2002 decision-making processes in relation to LULCC.** The methods for this objective are introduced in Chapter 4 (Section 4.2) and the analysis described in Chapter 5.
3. **To map and monitor LULCC from 1975 to 2000 using repeat satellite imagery.** The methods for this research objective are described in Chapter 4 (Section 4.4.4.2) and the results are presented in Chapter 5 (Sections 5.2.1, 5.3.1 and 5.4.1).
4. **The measurement of forest fragmentation.** The methods for this research objective are found in Chapter 4 (Section 4.4.4) and the results are described in Chapter 5 (Sections 5.2.1, 5.3.1 and 5.4.1).
5. **Linking farm surveys, LULCC maps, measurements of forest fragmentation to understand how socio-economic drivers of LULCC lead to specific patterns of forest fragmentation in farming communities with different types of agriculture.** This research objective is considered in Chapters 6 and 7.
6. **To evaluate models of; (i) forest clearance patterns; and (ii) the development of a landscape fragmentation development model for LULCC Chapare.** The objective is considered in Chapters 6 (Section 6.6) and 7.
7. **To refine the conceptual model of LULCC for Parque Nacional Carrasco to explain LULCC in Chapare.** This research objective is considered in Chapters 6 and 7.

1.5 Thesis structure

This thesis has been structured to facilitate examination of the research objectives in Section 1.4. Chapter 1 has introduced pertinent historical, economic and scientific contexts of the study area. Chapter 2 reviews mapping and monitoring of tropical deforestation. This chapter includes the characteristics of deforestation on the global scale and looks at how researchers have explained the causes and patterns of deforestation from localised studies. The aim of Chapter 3 is to introduce the three communities where the land-use activities were studied in detail at the local level. The methodology described in Chapter 4 justifies the selection of the field sites, the farmers, the methods used for the community survey and how data was generated from satellite images to produce the clearance and fragmentation products. Chapter 5 describes the results of the data generated from the satellite images and the findings of the field work conducted in the three communities. In Chapters 6 and 7 the results are analysed and discussed. Chapter 6 explains the main LULCC trajectories and describes the proximate causes of clearance, rates of change and the underlying driving forces causing the LULCC. These results are compared to the time-dependent patterns that have been observed in farming communities elsewhere in South America. Chapter 7 describes the characteristics of fragmentation in the three study areas and then uses the driving forces (Chapter 6) with evidence of the local-scale community activities to explain the spatial and temporal patterns of forest fragmentation. These patterns are compared to predicted trends in landscape fragmentation. Chapter 8 summarises the main research findings and discusses what the study of Chapare has added to our understanding of LULCC.

Chapter 2

Mapping, monitoring and explaining humid tropical deforestation: a review

Chapter 2.

Mapping, Monitoring and Explaining Humid Tropical Deforestation: a review.

2.1 Introduction.

The following review will illustrate how mapping, monitoring and explanation of deforestation is truly multidisciplinary and involves the disciplines of remote sensing; environmental sciences including botany, ecology, soil science and physical geography; and social sciences e.g. economics, sociology, anthropology and human geography.

The chapter has three main parts. The first section describes the contemporary distribution of tropical forest loss. Estimates of forest loss, the way in which forest loss has been mapped, and the most frequently encountered spatial and temporal patterns of deforestation are considered. The second part considers explanations of tropical forest loss using theoretical analyses, economic models and meta analysis. The third part focuses on deforestation in South America with particular reference to colonisation areas.

2.2 Distribution of tropical forests.

There have been many recent estimates of global vegetation cover that incorporate the mapping of forests and tropical forests (e.g. Bryant *et al.*, 1997; Olsen *et al.*, 1998; 2001, DeFries *et al.*, 2000; Hansen *et al.*, 2000; Loveland *et al.*, 2000). The International Geosphere-Biosphere Programme (IGBP), for example, mapped the global extent of forests with AVHRR data at a 1km resolution. Thresholds were applied to the 1km data to determine the occurrence of forest i.e. 60% tree cover in a cell (Loveland *et al.*, 2000) (Figure 2.1). The Global Land-cover facility at the University of Maryland mapped percentage tree cover by merging datasets of vegetation characteristics and global land cover maps which are also derived from AVHRR (DeFries *et al.*, 2000; Hansen *et al.*, 2000) (Figure 2.2). The World Wildlife Fund classified forests according to species richness, species endemism, taxonomy, unusual ecological and evolutionary characteristics and keystone habitats. This map defined moist broadleaf, tropical broadleaf and conifer forests worldwide (Olson *et al.*, 1998) (Figure 2.3).

In terms of actual areas, the WRI survey provided an estimate of forest cover and classified different cover types (WRI, 1988). The WRI estimated that 49% of the land surface between the Tropics of Cancer and Capricorn was covered by forest. This comprised 12 million km^2 of closed forest, 7.34 million km^2 of open woodland, 4.1 million km^2 of fallow forests and 0.115 million km^2 of tropical forest plantations. The locations of humid tropical rainforests are mainly found in three distinct regions, Latin America and the Caribbean (40,000 km^2), Central and West Africa (18,000 km^2) and South and South East Asia, including Australia and the Pacific islands (25,000 km^2) (Reading *et al.*, 1995).

Bryant *et al.* (1997) made the distinction between frontier forests (those defined as being relatively undisturbed) and non-frontier forests (which include secondary forest and plantations) and produced forest threat maps. Figures 2.4 to 2.6 show the distribution of threatened frontier forests in the tropical areas of Latin America and the Caribbean, Western and Central Africa and SE Asia and Australia. As well as showing the human impacts on the forest, these maps provide information on the locations where habitat and species loss are threatened because of total clearance and / or forest fragmentation, areas where ecosystem services would be impacted upon, and where there are dangers of losing indigenous tribal peoples.

Figure 2.1: Global extent of forests IGBP (Loveland *et al.*, 2000). Source: www.wri.org.

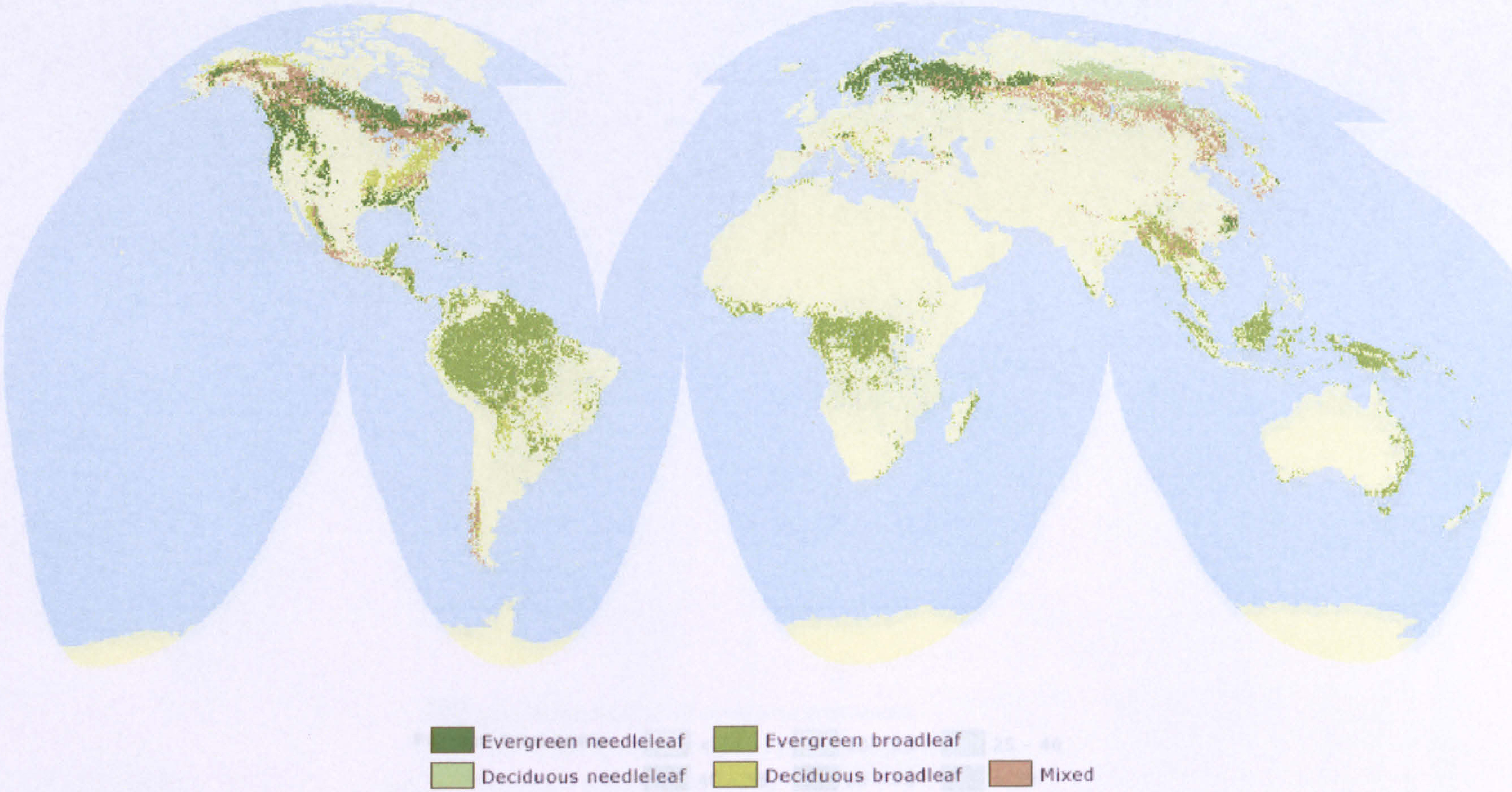


Figure 2.2: Global tree cover (DeFries *et al.*, 2000). Source: www.wri.org.

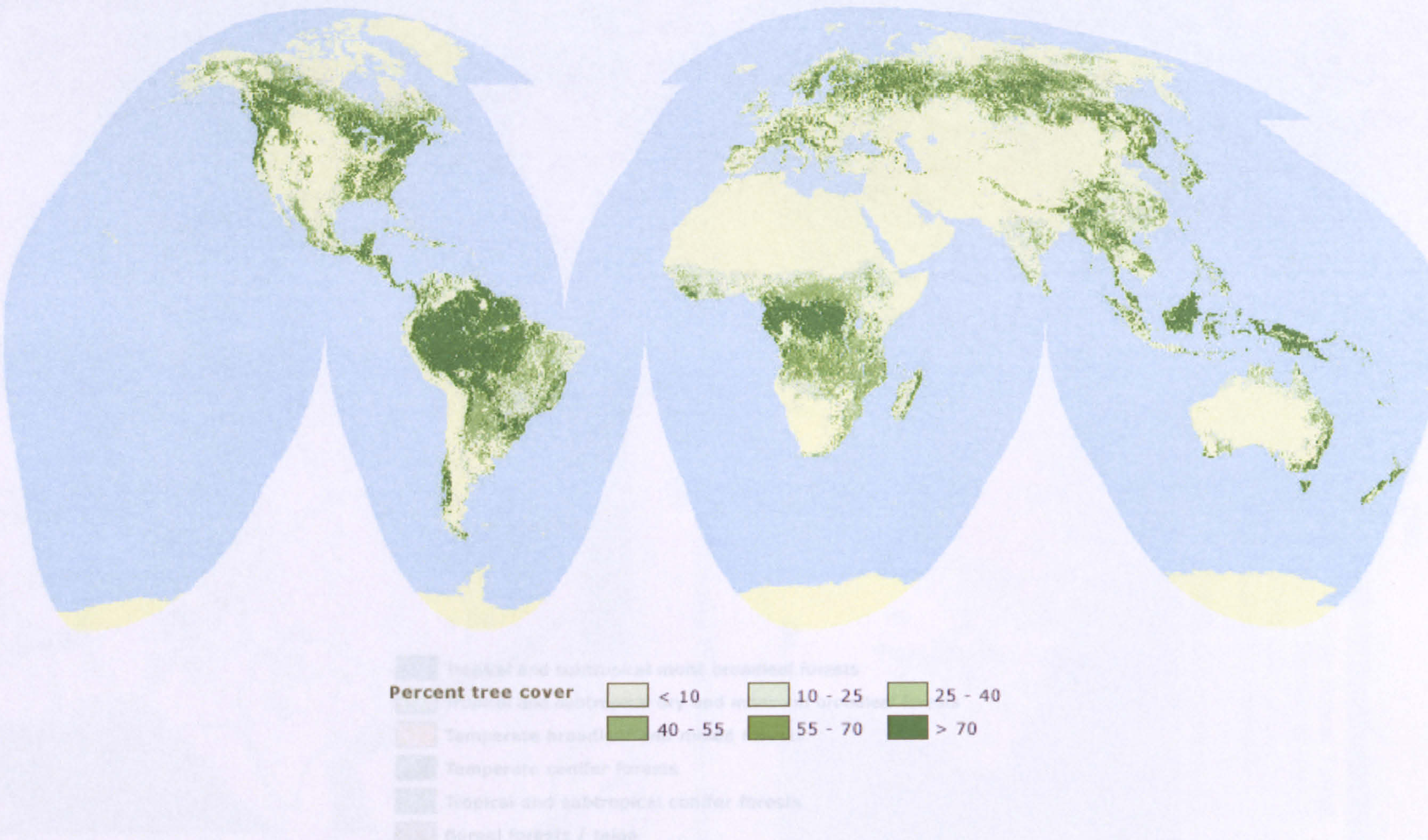


Figure 2.3: Global 200 forest ecoregions (Olson *et al.*, 1998). Source: www.wri.org.

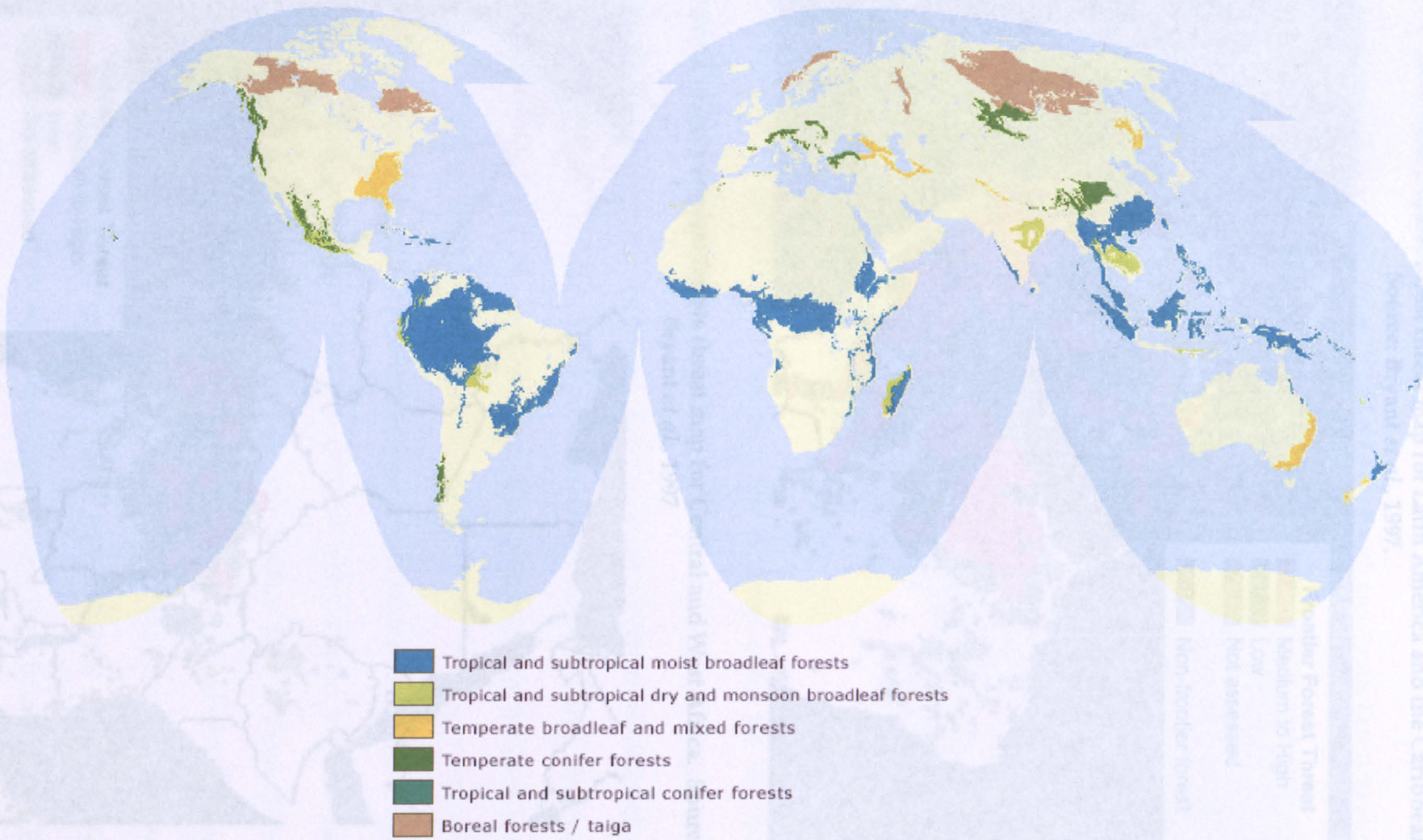


Figure 2.4: Humid tropical forest threat map for Latin America and the Caribbean. Source: Bryant *et al.*, 1997.

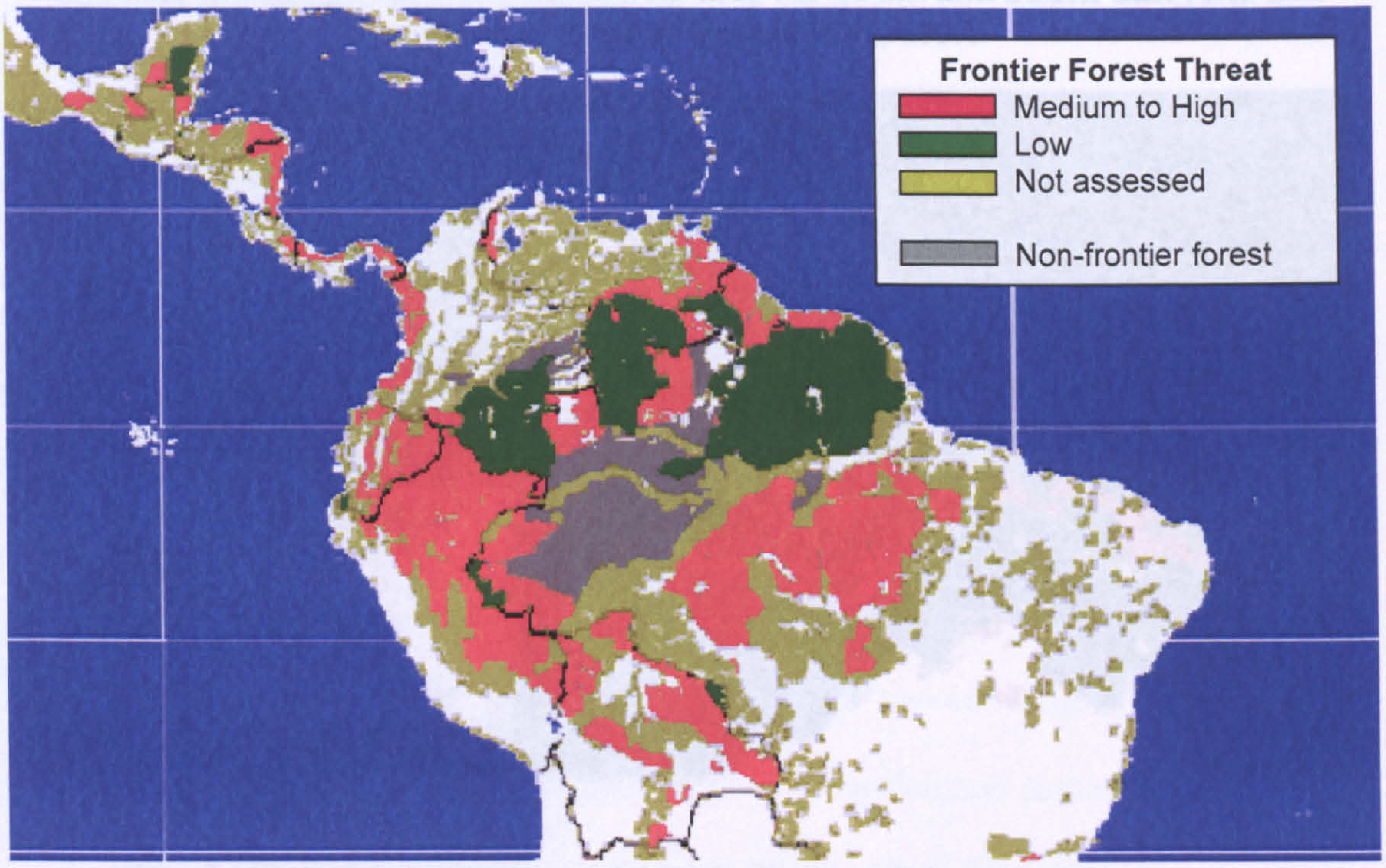


Figure 2.5: Humid tropical forests threat map for Central and West Africa. Source: Bryant *et al.*, 1997

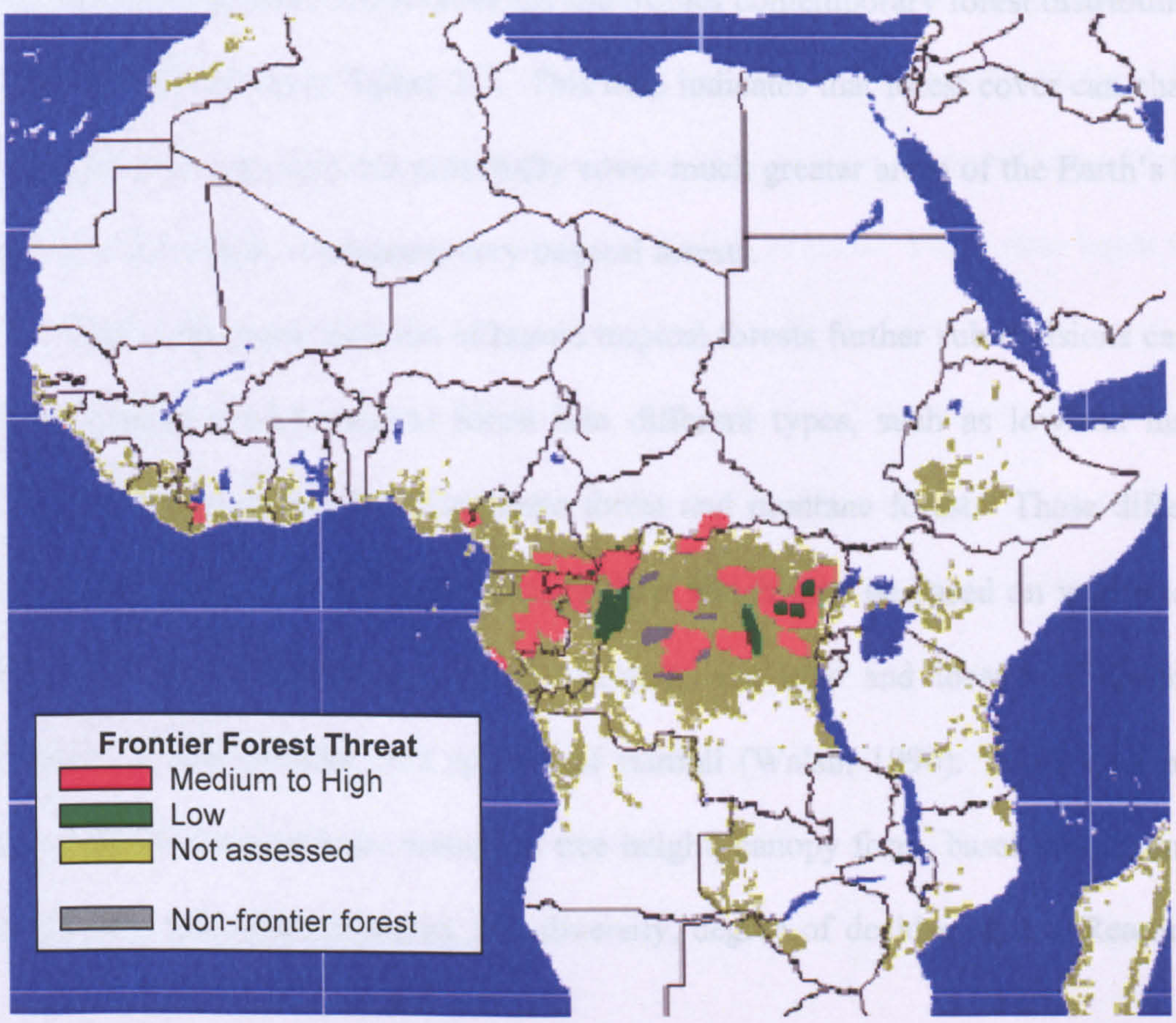
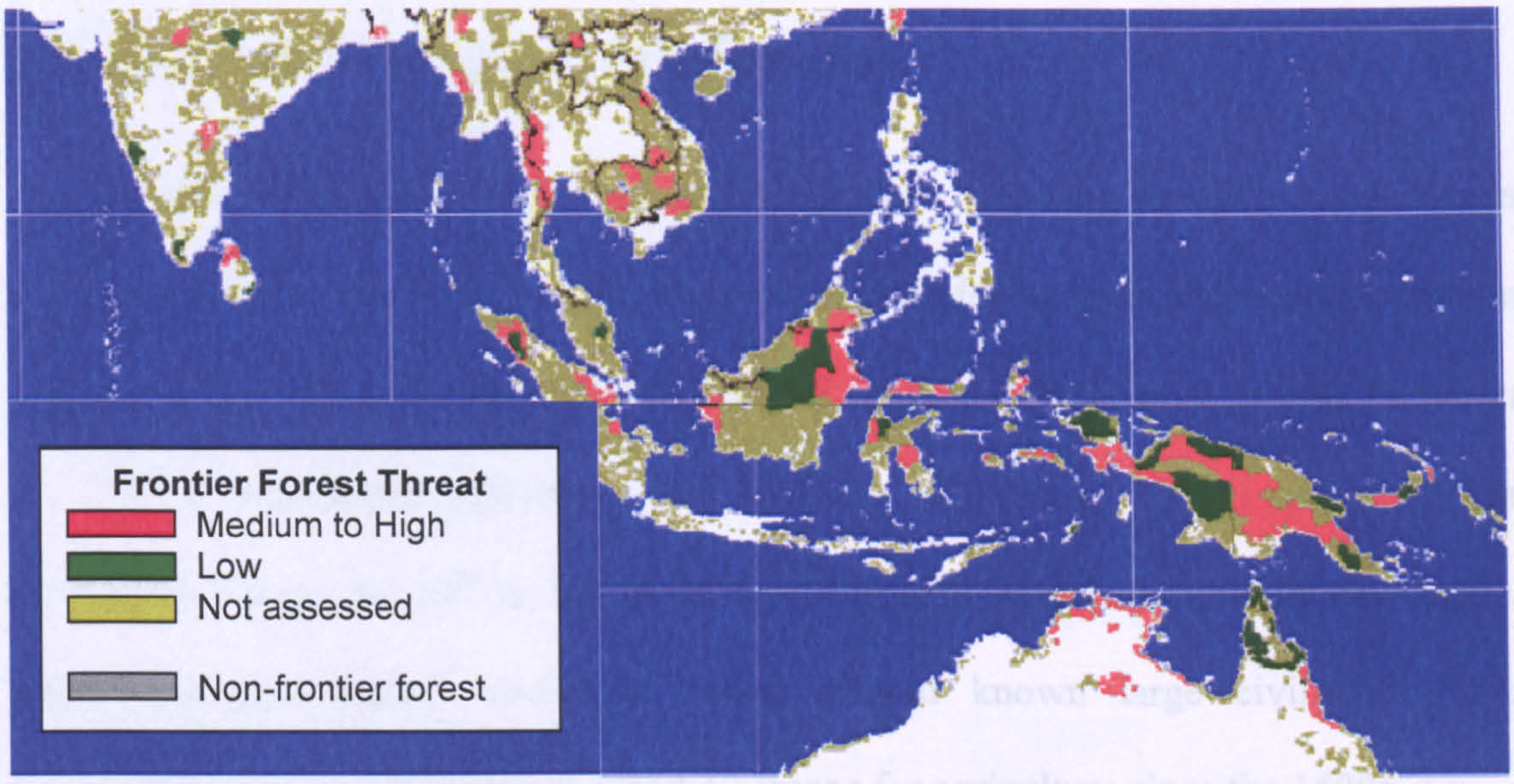


Figure 2.6: Humid tropical forests threat map for South and South-East Asia and Australia. Source: Bryant *et al.*, 1997.



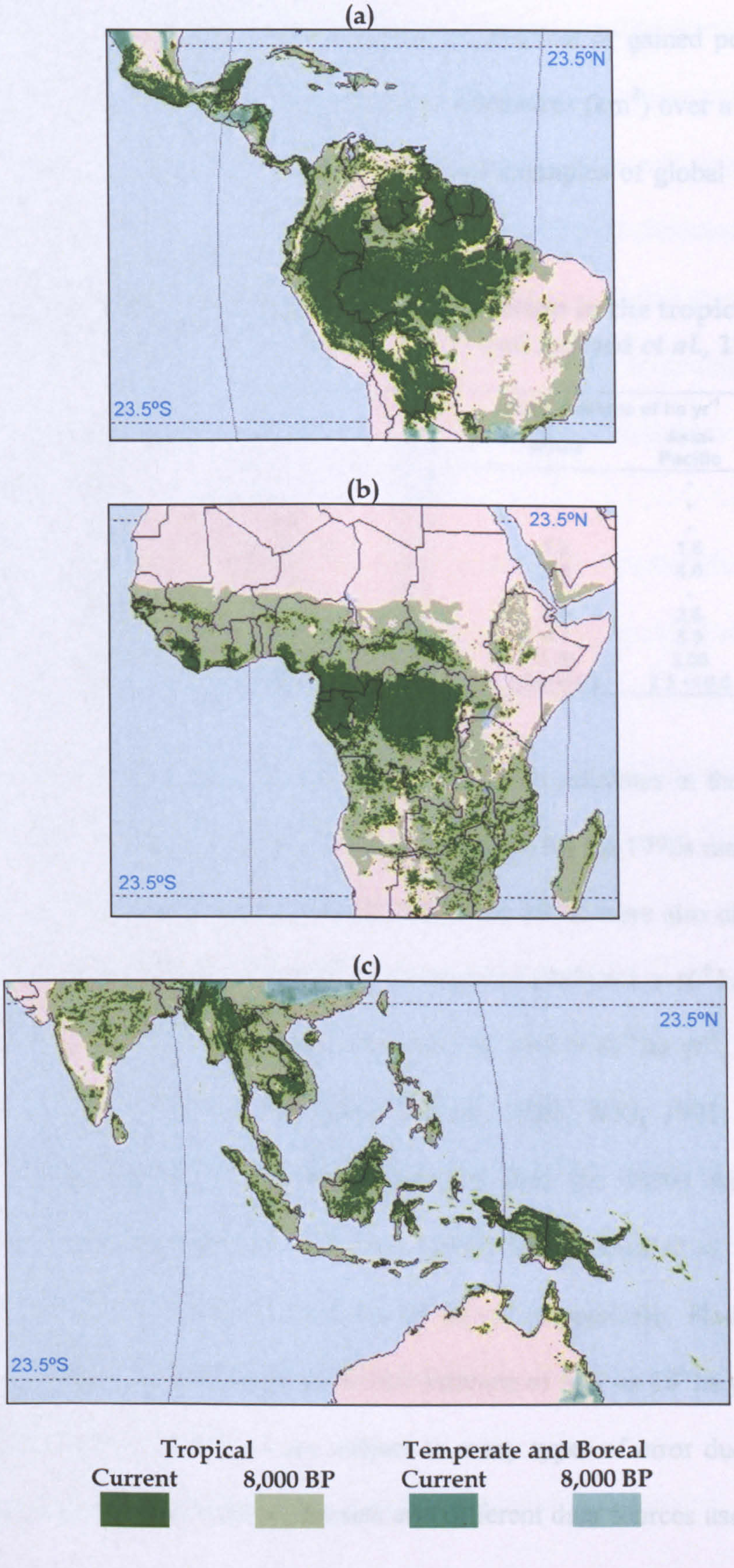
All of these estimates are of recent limits of forest cover but the World Conservation Monitoring Centre compiled a map of forest cover 8,000 years before present and compared the forest cover for the tropics contemporary forest distributions; the estimates are shown in Figure 2.7. This map indicates that forest cover can change significantly over time and can potentially cover much greater areas of the Earth's land surface than the extent of contemporary tropical forests.

Within the major division of humid tropical forests further sub-divisions can be made to classify humid tropical forest into different types, such as lowland humid forest, premontane forest, lower montane forest and montane forest. These different types can have monsoon and ever-wet variations which may be based on vegetation – climate associations (Holdridge, 1967), wetness, soil type and location (Whitmore, 1990) and / or the duration and amount of rainfall (Walsh, 1996). Each type has a common set of characteristics related to tree height, canopy form, basal area, numbers of species per unit area (richness), tree diversity, degree of deciduousness (Reading *et* *al.*, 1995; Whitmore, 1998) and environmental parameters such as flooding (Pires *et al.*, 1985).

2.3 The loss of tropical rainforests.

Deforestation is not a new process. It has been occurring slowly in limited areas for thousands of years. For example, there is evidence for large settled societies with an agricultural base like the Maya in Mexico (Ooi Jin Bee, 1983; Furley, 1998; Turner *et al.*, 2001); subsistence agriculture in Amazonia (Denevan, 2001); and a Khmer civilisation during the 10th to 12th centuries at Angkor, Cambodia (Whitmore, 1998). Recent palaeoecological studies in areas without known large civilisations are beginning to uncover evidence of forest clearance for agriculture since the 1500s, e.g. Teluk Banten, Indonesia (Van der Kaars *et al.*, 2004). Maloney (1988) also considers a number of examples of pre-historic use of the rainforest. Multiple data sources have been used to produce historic data bases of global land-cover Ranmankutty *et al.* (1999) and similarly the HYDE database Goldewijk (2000). The data bases contain time slices of geo-referenced areas of crops and pasture since 1700, and have been produced for the Post Global Changes Project, part of the IHDP-LUCC project. These data bases were combined with palaeoecological data to produce the Biome 300 data base at 0.5° resolution. Despite the early exploitation of forests during European colonisation, the Biome 300 products show that deforestation (or land conversion) began to accelerate exponentially since the mid 18th century (Millington, 2005), becoming much faster and more widespread particularly from 1945 onwards (Park, 1992). However there are regional differences in tropical deforestation between Latin America, SE Asia and Africa which relate to different land-use histories (Lambin *et al.*, 2003)

Figure 2.7: The extent of original forest 8,000 yrs B.P., and remaining forest in the tropics (a) Latin America and the Caribbean, (b) Central and West Africa, and (c) SE Asia and Australia. Source: www.unep-wcmc.org.



2.3.1 Global and continental loss of tropical forests.

Estimates of forest loss at global, continental and national scales vary considerably. Forest change is usually reported as area lost or gained per year, or in rates of loss, with units of hectares (ha) or square kilometres (km^2) over a defined time period, normally per annum (yr^{-1}). Table 2.1 shows examples of global deforestation rates since the mid 1970s.

Table 2.1: Selected estimates of rates of deforestation in the tropics. Sources: Downton, 1994**; Grainger, 1993**, 1996*** and Achard *et al.*, 1998*, 2002.**

Source	Date	Period	Total, millions of ha yr^{-1} Global	Africa	Asia-Pacific	Latin America
Sommner**	1976	1970s	11-15	-	-	-
Myers**	1980	1970s	7.5-20	-	-	-
Lanley****	1982	1975 to 1980	11.3	-	-	-
Grainger**	1983	1976 to 1980	6.1	1.2	1.6	3.3
Myers**	1989	Late 1980's	14.2	1.6	4.6	7.7
WRI****	1991	1980s	16.4	-	-	-
FAO**	1992	1980s	12.2	3.0	2.6	6.6
FAO***	1993	1981 to 1990	15.4	4.1	3.9	7.4
FAO*	1997	1990 to 1995	11.90	3.70	3.06	5.15
Achard *et al.*	2002	1990 to 1997	5.8 +/-1.4	0.85 +/-0.3	2.5 +/-0.8	2.5 +/-1.4

Sommer (1976) produced worldwide deforestation estimates in the early 1970s of 11-15 x 10^6 ha yr^{-1} whereas Myers' (1980) calculations for the 1970s ranged from 7.5 to 20 x 10^6 ha yr^{-1}. Estimates for the second half of the 1970s were also different, from Lanley's (1982) rate of 11.3 x 10^6 ha yr^{-1} to Grainger's (1983) 6.1 x 10^6 ha yr^{-1}. In the 1980s estimates of deforestation ranged from 12.2 to 15.4 x 10^6 ha yr^{-1}, but there are differences in the time periods considered (Myers, 1989; WRI, 1991; FAO, 1992; 1993). The inconsistency in estimates continued into the 1990s with yet more discrepancies in estimates between the FAO (1997) and Achard *et al.* (2002), who estimated rates of 11.9 x 10^6 ha yr^{-1} and 5.8 x 10^6 ha yr^{-1} respectively. However Achard *et al.* (2002) do report the possible error in their estimate of +/-1.4x 10^6 ha yr^{-1}.

The estimates in Table 2.1 are subject to many types of error due to different methods of data collection between data sets and different data sources used. Downton

(1995) noted that, Sommer's (1976) estimate of forest loss for the FAO was derived from government sources of only thirteen countries. The estimate of Lanley (1982), also for the FAO, included 76 countries and used Landsat satellite data and Synthetic Aperture Radar for 31 of those countries. Myers (1989) used literature and information from professionals, governments and non-government sources and used the social, political and economic trends of individual countries to predict deforestation rates in 1989 for the closed canopy forests. The FAO (1993) GIS accounted for the variations within separate countries and calculated rates of forest change beginning in 1981 for 644 sub units of 90 countries and that twenty four of these countries had multiple satellite image dates.

A summary of the common sources of errors has been compiled from Soussan *et al.* (1992); Skole (1994); Downton (1995); Reading *et al.* (1995) and include:

(i) variations in the geographical areas covered;

(ii) variations in the definitions of vegetation types between different countries;

(iii) the definition of deforestation which can fall anywhere between clear felling and selective logging;

(iv) the incorrect use of inventories compiled for a specific purpose;

(v) the concentration of inventories on commercial timber forests, thereby leading to an undervaluation of non-commercial forests or forest land;

(vi) estimates are not always specific to the type of forest and may group humid tropical forests with all forest in countries covering a number of climate zones (e.g. China or Mexico);

(vii) the withholding of data by commercial enterprise and governments for strategic purposes; and,

(viii) variations in the methods used to calculate and predict deforestation.

Poor definitions of forest zones in the 1990 FAO assessment exacerbate the errors outlined above (Grainger, 1996; Mather *et al.*, 2000). These problems are still apparent in the FAO 2000 assessment and to compound the inconsistencies, the baseline definition of forest was changed making the FAO 2000 assessment and earlier assessments incomparable (Matthews, 2001).

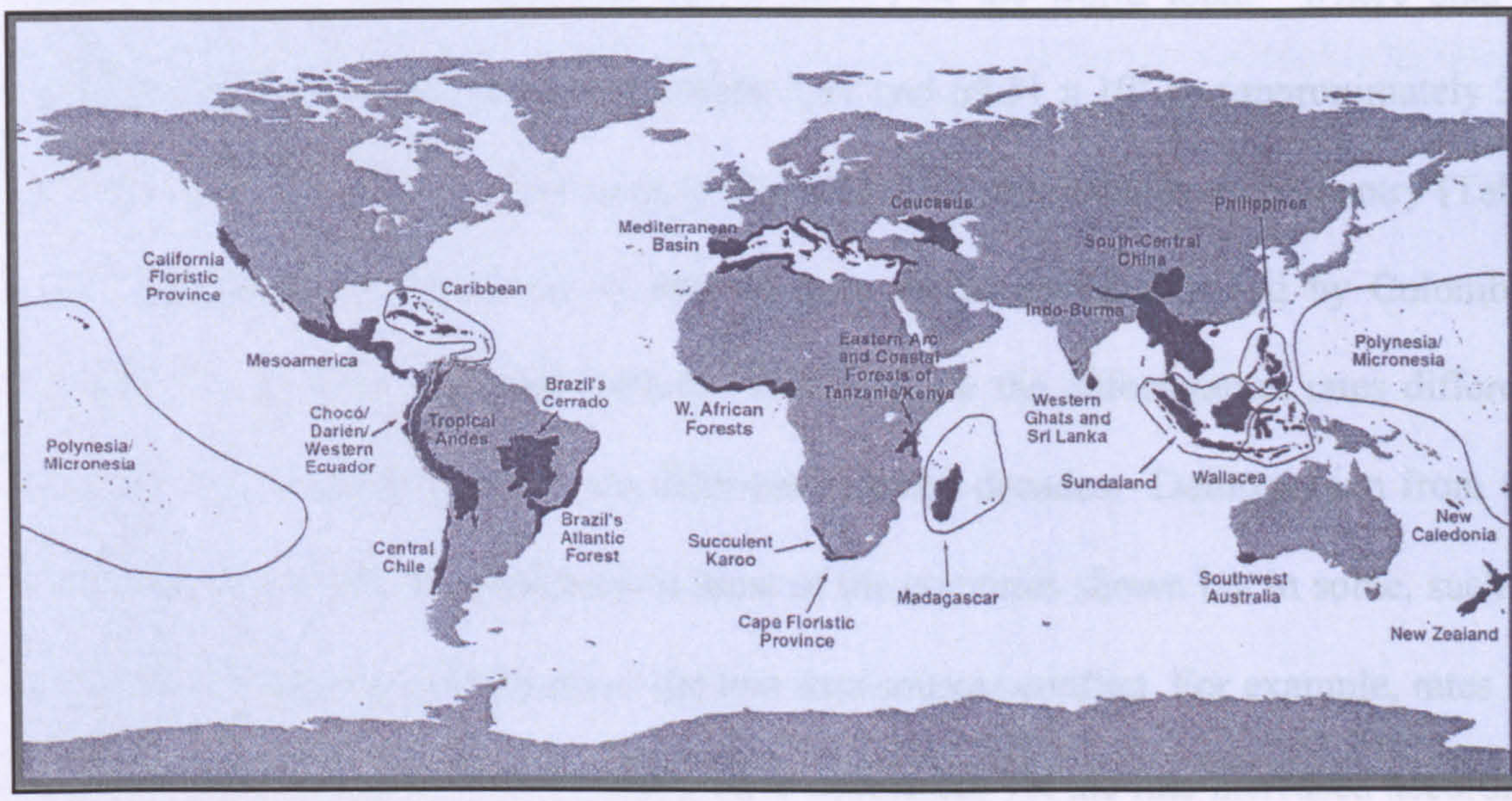
Grainger (1993) and Downton (1995) noted that the increased use of satellite-based monitoring should provide a key tool for tropical deforestation measurements in the future. But, even with the inclusion of satellite data, estimation problems were still evident. Downton (1995) illustrates this problem by comparing three estimates of total deforestation in 1988 in the Legal Brazilian Amazon by the Brazilian National Space Research Institute (INPE) (Fearnside, 1993), the World Bank (WB) (Mahar, 1989) and INPA (Fearnside, 1990). The estimates were 37.5 x 10^6 ha, 60.0 x 10^6 ha and 25.0 x 10^6 ha respectively. Downton (1995) also reported differences in deforestation rates between 1978 and 1988 of 2.2 x 10^6 ha yr^{-1} from automated interpretation of Landsat data at INPE (Fernside, 1993) and 1.52 x 10^6 ha yr^{-1} from manual interpretation of Landsat data (Skole *et al.*, 1993) covering the legal Brazilian Amazon.

Despite the errors between different estimates it was clear that forest loss was variable through time and could actually decrease as well as increase. For example, the FAO reported a fall in rates of forest loss from 15.4 x 10^6 ha yr^{-1} (Table 2.1) in the 1980s (FAO, 1982) to 12.7 x 10^6 ha yr^{-1} for 1990 to 1995 (FAO, 1997). However, Angelsen *et al.* (1999), argue whether this reduction was real because of the new definitions of forest used and the better data sources. More recent measures of deforestation agree that the FAO estimates are high (Achard *et al.*, 2002, DeFreis *et al.*, 2002). But even so the estimates calculated by Achard *et al.* (2002) and DeFries *et al.*

(2002) are different for different continents and the errors reported are in different locations (Skole *et al.*, 2004).

Myers (1993) identified the occurrence of 14 major pockets of deforestation globally and referred to them as deforestation 'fronts', or 'hotspots' where forests were threatened. This was first increased to 24 biodiversity hotspots and 3 wilderness areas (Mittermeier *et al.*, 1998) to focus conservation priorities; and then increased to 25 hotspots of biodiversity (Myers *et al.*, 2000) according to their degrees of endemism, overall species richness and threats to habitat loss (Figure 2.8). Conservationists, land-use planners, forestry experts and policymakers could use this to construct preventative measures of biodiversity loss and work towards building an understanding of processes consuming tropical forests (Myers *et al.*, 2000).

Figure 2.8: The 25 hotspots of biodiversity. Source: Myers *et al.* (2000).



2.3.2 Forest loss in South America.

2.3.2.1 Contemporary loss.

Latin America contains approximately half the tropical rainforests of the world so it is no surprise that a number of key studies related to deforestation of humid tropical forests have been located here. National statistics of forest loss through the 1970s and 1980s in selected South American countries are shown in Table 2.2.

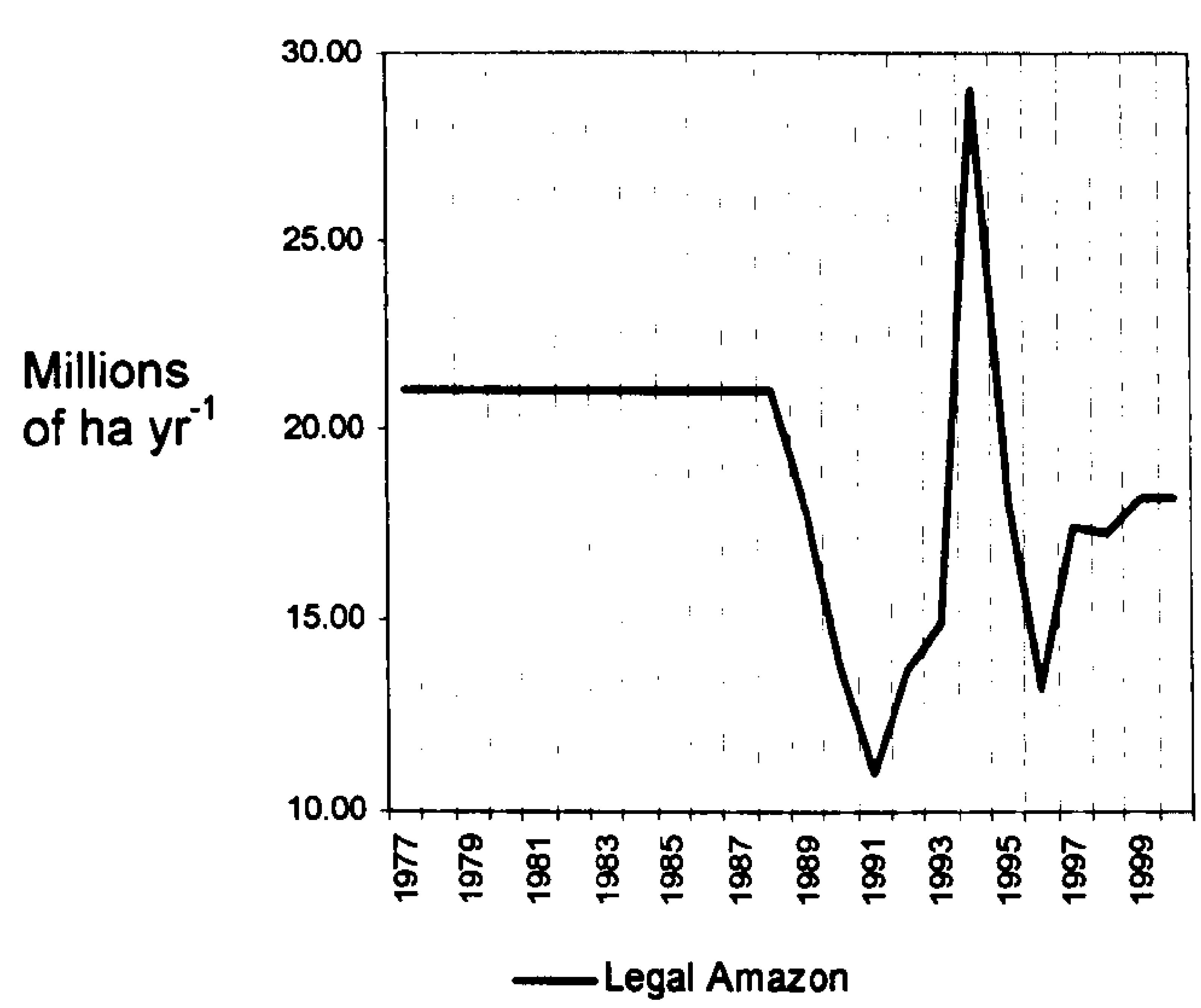
Table 2.2: Deforestation rates for selected South American countries for the 1970s (FAO/UNEP) and 1980s (Myers, 1989; WRI, 1990). Sources: **Skole *et al.* (1993); *Skole (1994).

Country	Total forest area (ha x10^6)	% world total	FAO/UNEP (ha yr^{-1} x 10^6)	Myers (ha yr^{-1} x 10^6)	WRI (ha yr^{-1} x 10^6)
			1970s	1980s	1980s
Brazil*	356.28	30.7	1.36	5.0	8.0
Peru*	69.31	6	0.245	0.35	0.27
Colombia*	46.4	4	0.8	0.65	0.82
Bolivia*	44.01	3.8	0.065	0.15	0.087
Venezuela*	31.87	2.7	0.125	0.15	0.125
Ecuador**	-	-	0.3	0.3	0.34
Guyanas**	-	-	0.004	0.05	0.005
Paraguay**	-	-	0.16	-	0.19

Data in Table 2.2 shows that most of the tropical forest in South America is in Brazil (356.28 x 10^6 ha) and that this is 30.7% of the world total. Where data is available the other countries have between 3.87 and 69.31 x 10^6 ha (approximately 2.7 to 6 % of the world total). The rates of forest loss are not equal in each country (Table 2.2). The highest rates of forest loss by area are in Brazil followed by Colombia, Ecuador, Peru, Venezuela and Bolivia. Not only are the deforestation rates different between the countries but they are different between decades. Deforestation from the 1970s into the 1980s has increased in most of the countries shown but in some, such as Colombia, Venezuela and Ecuador, the two data sources conflict. For example, rates for Colombia, according to Myers (1989), have decreased, yet the rate increased according to the WRI (1990). As with the global estimates of deforestation there are variations in the methodologies used to calculate these data nevertheless what is certain is that deforestation rates do vary between individual countries.

The accuracies of estimates of forest loss are often determined by the interval between the time points considered. Koop *et al.* (2001) discuss the problems of extrapolating deforestation estimates between two time points. Such an analysis can result in a continuous rate of deforestation over a number of years or the rate may remain implausibly constant over long periods of time. Their solution was to categorise deforestation according to the degree of the deforestation in the country. This is well illustrated by INPE's continuous monitoring of the Brazilian Legal Amazon[1]. Initially INPE made estimates of forest clearance in the late 1970s (Tardin *et al.*, 1980) and continuous estimates were made from 1988 (INPE, 2002). The latter estimates showed that inter-annual variations in forest loss can be significant. An average value for the 10 year period showed a constant loss of forest of 2.105 x 10^{-6} ha yr^{-1} (Figure 2.9). From January 1988, when INPE began monitoring deforestation on an annual basis year on year variations in the forest area cleared were revealed (Figure 2.9).

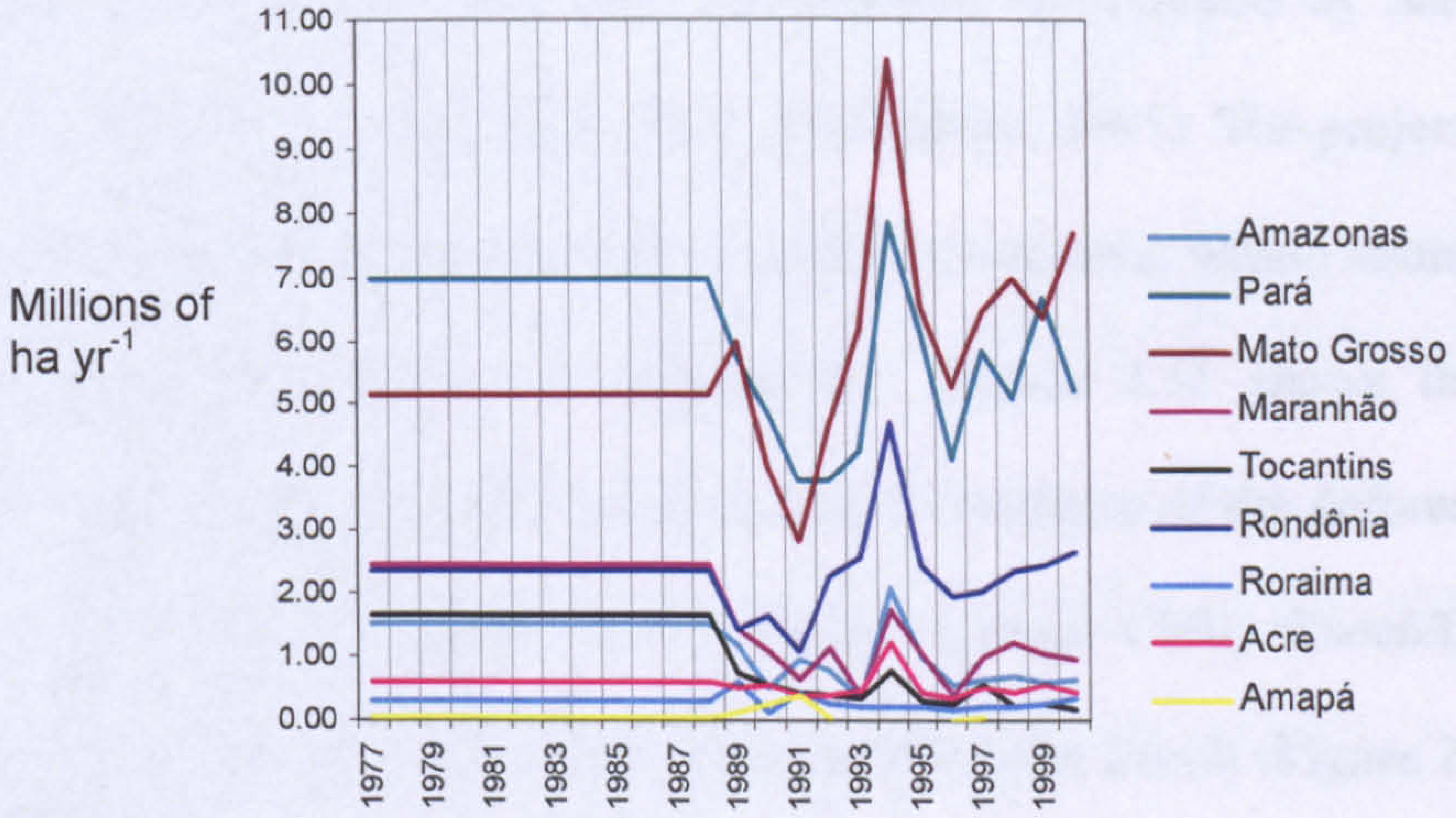
Figure 2.9: Annual loss of forest in the Legal Amazon. After the decadal calculation of 1978 - 1988, forest loss was calculated annually. Source: INPE (2002).



[1] The Legal Amazon of Brazil is defined by law to include the states of Acre, Amapá, Amazonas, Pará, Rondônia, Roraima, Mato Grosso, Maranhão, and Tocantins [Fundãcao Instituto Brasileiro de Geografia e Estatística (IBGE) 1991].
Source: http://www-eosdis.ornl.gov/LBA/guides/lba_legamazon.html

Forest loss decreased to a low of 1.11 x 10^{-6} ha yr^{-1} in 1990/1 but by 1994 it had almost tripled to 2.90 x 10^{-6} ha yr^{-1}, after which it dipped to 13.23 x 10^{-6} ha yr^{-1} in 1996/97. The rate of forest loss was approximately 1.7 x 10^{-6} ha yr^{-1} by the late 1990s. The rate of forest loss also varies between individual states (Figure 2.10). Figure 2.10 shows that in each individual state the actual rates of forest loss are different. This demonstrates that the overall rate of forest loss is not spread evenly across the Legal Amazon. However there are some common trends between the states, generally the rates decreased in the early 1990s, although the minimum rates did not always coincide in the same year between all the states, and some states saw slight increases in some years.

Figure 2.10: Annual loss of forest for individual states in the Legal Amazon. After the decadal calculation for 1978 - 1988, forest loss was calculated annually. Source: INPE (2002).

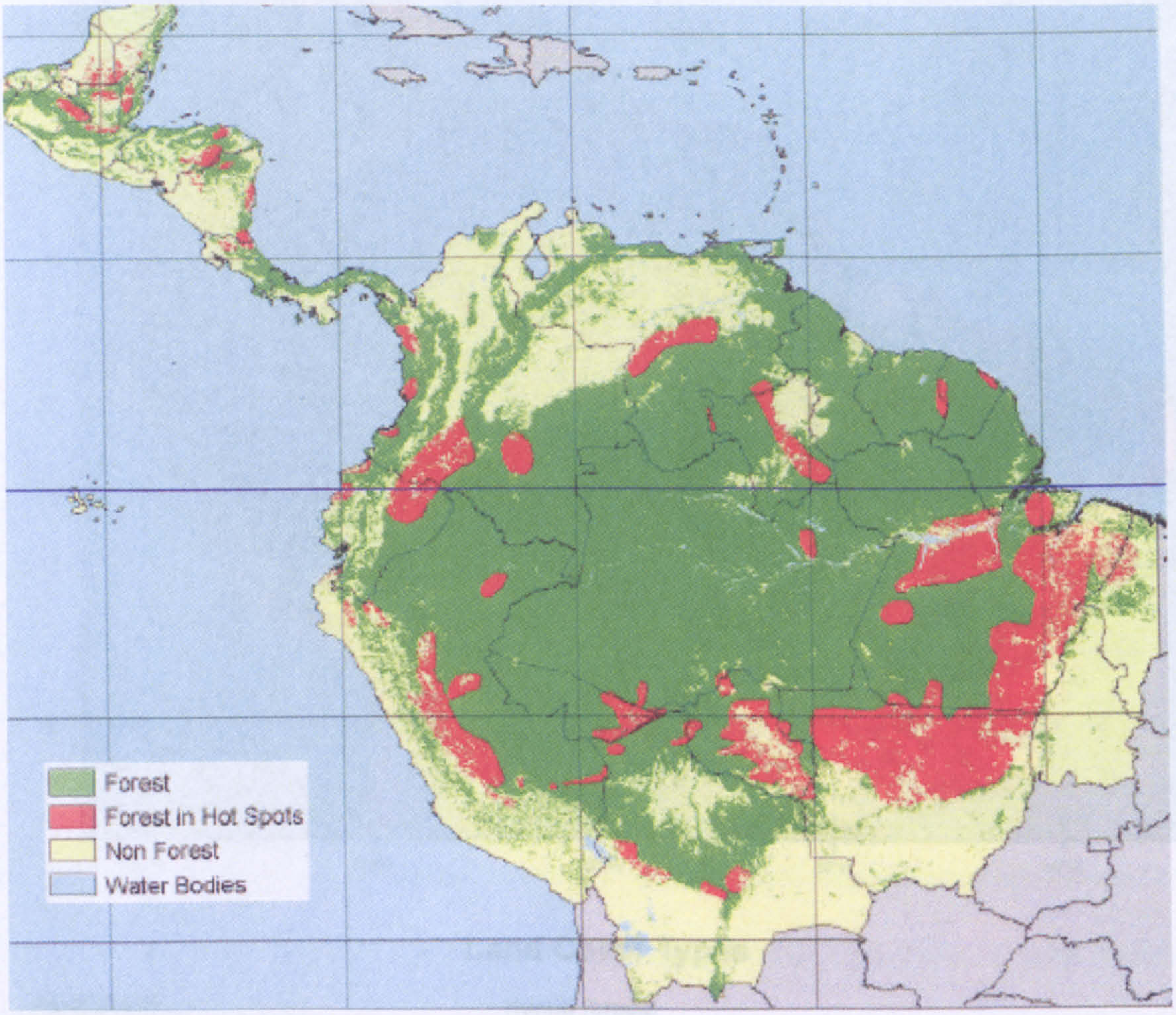


By 1994 there was a notable increase in rates in virtually all the states followed by a decrease in rates from 1994 to 1996. From 1996, in most states, there has been a general increase in rates to 2000, in Mato Grosso, Pará, Rondônia, Roraima and Acre, the 2000 rates of forest loss are as high as or almost as high as the 1977 to 1986 values, but in 2000 in the other states the rates of forest loss are actually lower than the 1977 to

1986 levels. These findings are significant because annual calculations of forest loss have not been replicated for other countries in South America and, more importantly, the INPE data shows the spatial variation of forest loss across the Legal Amazon (Wood, 2002). Moreover, forest loss is confined to localised pockets or regions which do not necessarily confine themselves to state limits. An agricultural frontier has advanced northwards from the eastern, southeastern and western margins of the Legal Amazon through Pará, Tocantins, Mato Grosso, Rondônia and Acre and has created what has now been referred to as the 'arc of deforestation'. Advancing deforestation along highways has also been evident and this is related to roads developed under federal development programmes such as the Transamazon Highway in Pará (Alves, 2002).

Hotspots of actual forest depletion have been mapped by the Joint Research Centre's (JRC) TRopical Ecosystem Environment observations by Satellite (TREES) project (Achard *et al.*, 1994, 1998, 2002; Malingreau, 1995). The project identified and marked distinct pockets of deforestation within continents, within countries as well as across political boundaries and ecosystems. Figure 2.11 shows the locations of deforestation hotspots in South America. The coincidence of the deforestation hotspots (Figure 2.11) with five biodiversity hotspots, Central Chile, Chocó/Darién Western Ecuador, Tropical Andes, Brazil's Cerrado and Atlantic Forest (Figure 2.8) is alarming. For example, the arc of deforestation in Brazil borders the evergreen forest in Brazil's Cerrado biodiversity hotspot, and several deforestation hotspots are located in and around the Tropical Andes biodiversity hotspot. There are also deforestation hotspots occurring in small pockets, some of which cross political boundaries. More recently the GLC2000 map (Eva *et al.*, 2004) shows the encroachment of land-cover classed as agriculture into the tropical forests (Figure 2.12).

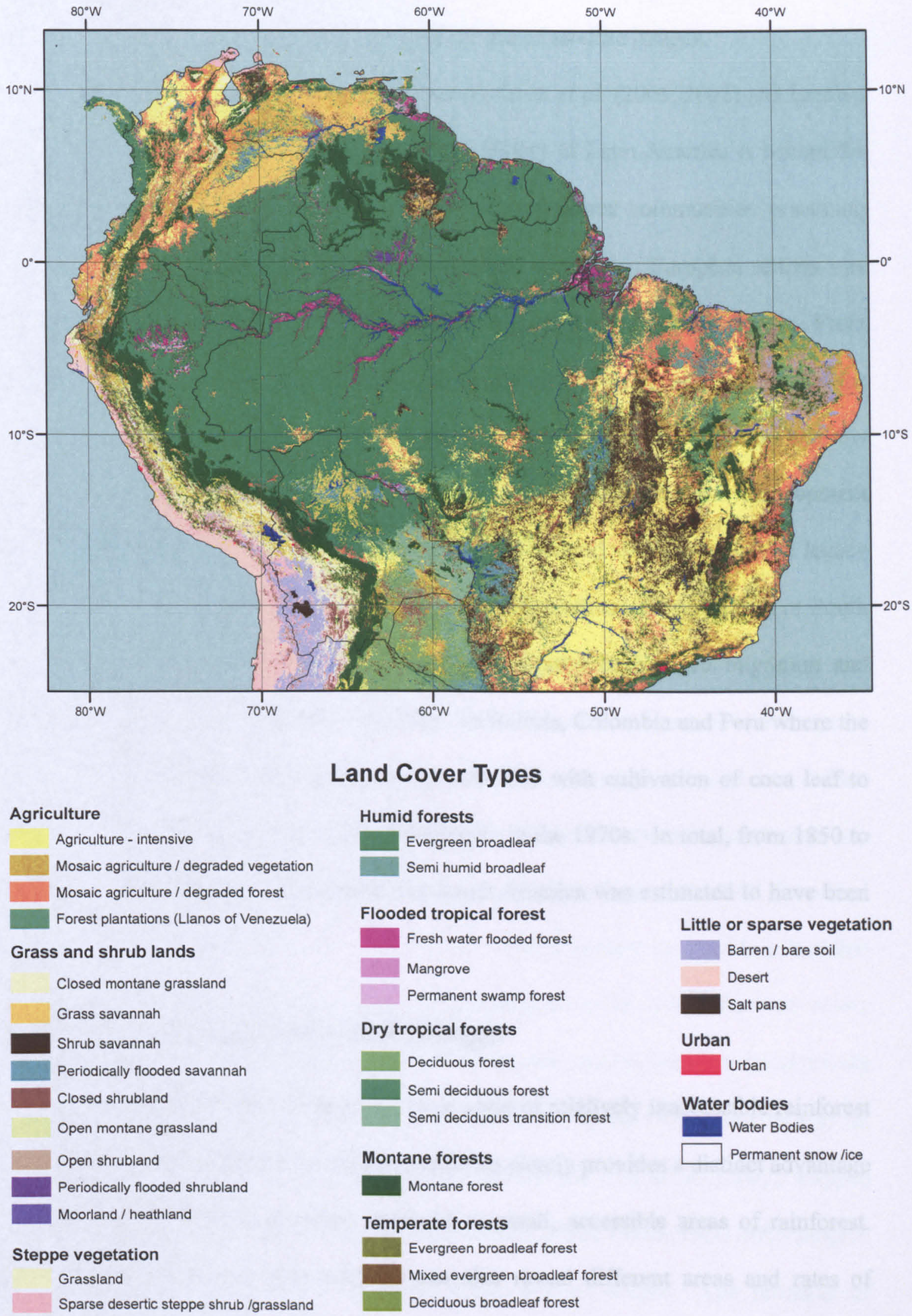
Figure 2.11: TREES deforestation hotspots for South America. Hotspots are outlined in red and light green represents dense evergreen forest. Source: Achard *et al.* (1998).



2.3.2.2 Historical loss.

Houghton *et al.* (1991) made an historical (1850 to 1985) estimate of tropical deforestation in Latin America. They justified 1850 as the start date, as this is the time when human perturbations of carbon dioxide are acknowledged to have begun. Due to the uncertainties about the extent of tropical forest in the FAO world forest inventories from 1945, Houghton *et al.* (1991) derived land-cover change by using data on activities related to land-cover types that would encroach onto tropical forests, e.g. agricultural areas and grazing areas. The latter being inferred from cattle stock populations. It was clear that tropical forests were diminishing as the results indicated that 28% of forests had been lost since 1850; although it was noted that a lack of information on shifting

Figure 2.12: Global land-cover map 2000. Source: Eva et al., 2004



cultivation within the tropical forests may have added a significant error to the data. After 1975 such errors were resolved through the use of satellite images.

Using 78 case studies from Latin America, Giest *et al.* (2001, 2002) and Lambin (2003) consider that the environmental land-use history of Latin America is behind the contemporary processes of deforestation. While indigenous communities practicing slash-and-burn had a relatively low impact on the forests that of European settlers was probably greater from around 1600, when settlers began to extract exotic timber. From the 19th to mid 20th Century the rubber trade was facilitated by steam shipping and the establishment of cities in the new world. However rubber and nut extraction had low impacts on the forest cover. From the beginning of the 1960s national development plans initiated frontier colonisation often orientated around cattle ranching, a legacy dating back to the era of Spanish and Portuguese colonisation. Governments of South America interested in national development and security encouraged migration and colonisation in the Amazon during the 1960s. In Bolivia, Colombia and Peru where the climatic variables were suited deforestation coincided with cultivation of coca leaf to supply the boom in the cocaine trade which began in the 1970s. In total, from 1850 to the 1980s one third of the tropical forest in South America was estimated to have been cleared.

2.3.3 Mapping forest cover and change.

The regular synoptic coverage of large areas of relatively inaccessible rainforest provided by sensors mounted on satellite platforms clearly provides a distinct advantage over field surveys which are often restricted to small, accessible areas of rainforest. Deforestation monitoring with satellites can also reveal different areas and rates of forest loss within the same political unit in situations where there is more than one deforestation 'frontier', whereas government-derived (or advised) estimates of deforestation are often aggregated within a political unit.

Satellite imagery can be processed to give products which provide both quantitative measures and qualitative evidence of forest loss. Jeanjean *et al.* (1997) have described land-cover mapping as a static approach to forest monitoring. Land-cover mapping usually involves creating a composite of images to make a single land-cover map using imagery from, ideally, the same year, to map the land-cover for a single 'time slice'.

The sources of remote sensing data can be optical, thermal or microwave (the last two will not be discussed in great detail as radar and thermal data have not been used in this research). Many sensors have been used to monitor tropical forest loss but in the optical and reflective infrared wavelengths the sensors commonly used are ATSR, ATSR-2, AVHRR, IRS-LISS, Landsat MSS, TM, ETM+, MODIS, SPOT -HRV and VEGETATION. All sensors are constrained by their spatial, spectral and temporal resolutions. AVHRR provides daily coverage, with a wide angle of view, but suffers from low pixel resolution (1.1km^2 at nadir). Therefore it tends to be used to create continental and global data sets (Eidenshenk *et al.*, 1994, DeFreis *et al.,* 1995, Loveland *et al.*, 2000). AVHRR data were used by the TREES project to provide a baseline assessment of global deforestation hotspots (Malingreau *et al.,* 1995, Archard *et al.,* 1998) and led to a revised determination of deforestation rates in humid tropical forests (Archard *et al.*, 2002). At the continental scale, Stone *et al.* (1994) and Eva *et al.* (2004) mapped South America, Steibig *et al.* (2003) and Giri *et al.* (2003) mapped South East Asia, and Cabral (2003) mapped Southern Africa for the GLC 2000 project, which includes tropical forest areas using SPOT 4-VGT images. The potential of MODIS for land-cover mapping has been examined by Freidl *et al.* (2002). Examples of land-cover mapping in tropical forest regions using a range of sensors for smaller scales include SE Asia (Achard *et al.*, 1995), Central Africa (Mayaux *et al.*, 2000), Marajo Island, Brazil (Brondizio *et al.*, 1996) and Langkawi Island, Malaysia (Baban *et al.*, 2001). Landsat and SPOT sensors tend to be used for local case studies (e.g. McCracken *et al.*, 1999; Naughton-Treves, 2004; Vina 2004) because of the high cost of obtaining imagery to cover large areas alongside the low rate of image acquisition required to cover the same area in the same year (Goward *et al.*, 2001). Nevertheless there have been efforts to use higher spatial resolution imagery on sub-continental scales. For example, the NASA Pathfinder Humid tropical deforestation project[2] has acquired imagery covering approximately 75% of the world's tropical forests to produce deforestation maps at decadal time intervals for the early 1970s, mid-1980s and mid-1990s (Chomontowski *et al.*, 1994). Their archives cover Africa, South East Asia and the Amazon Basin including the countries in the Pan Amazon i.e. Bolivia, Peru, Ecuador, Colombia, Venezuela, Guyana, Surinam and French Guiana.

By monitoring the same area at different times using repeat composite images it is possible to observe and calculate the rates and spatial patterns of forest clearance in specific locations where deforestation has occurred. Jeanjean *et al.* (1997) described this type of mapping as a dynamic approach to forest monitoring. In essence monitoring the Earth's surface at different times can be described as land-cover change mapping and can be defined as the comparison of a multiple of images representing the same area in different years. Detection of land-cover change in tropical forests can be analysed by a number of image processing techniques e.g. univariate image differencing, image regression, image ratios, vegetation index differencing (commonly using NDVI), principal components analysis, post classification comparisons, direct

2 NASA Landsat Pathfinder Humid Tropical Deforestation Project, Geography Department, University of Maryland, College Park MD

multi-date classification, change vector analysis and background subtraction (Singh, 1989). More recently spectral mixture analysis, artificial neural networks and combining other data with remote sensing in a GIS have been added to the suite of change detection methods (Lu *et al.*, 2004). Change in global tropical forests on a global scale was first assessed by Malingreau *et al.* (1989) with AVHRR GAC data. Subsequent continental and regional scale studies have included SE Asia (Achard *et al.*, 1995), the Amazon basin (Skole *et al.*, 1993), West Africa (Lambin *et al.*, 1994; Ehrlich *et al.*, 1997), the Sub-Saharan Africa (Lambin *et al.*, 1997; Borak *et al.*, 2000) and Central Africa (Eva *et al.*, 1998; Mayaux *et al.*, 2000). These studies have used coarse spatial resolution data, AVHRR and / or ATSR and ATSR-2, to cover vast areas and are often calibrated using land-cover derived information from finer spatial resolution data, e.g. Landsat TM (Mayaux *et al.*, 1995).

The high cost of medium resolution imagery (considered as falling between 10m and 30m) has forced researchers and practitioners to make estimates of deforestation by either using coarse resolution data sets, which can overestimate deforestation by up to 50% (Skole *et al.*, 1993) because land-cover types are aggregated in a pixel producing inaccurate estimates of clearance, or random sampling of areas of deforestation with smaller scenes of high resolution data (e.g. Malingraeu *et al.*, 1988, 1989). As a solution to the aggregation of coarse resolution data, Mayaux *et al.* (1995) built in a correction function for the AVHRR data set they used by integrating fragmentation patterns from classifications of selected Landsat scenes. They improved estimates of tropical forest land cover types by 25.5%. The land cover estimates were further improved by 35% by adding a non-linear function to estimate forest fragmentation and spatial aggregation. The improvements included AVHRR brightness value to substitute for a fragmentation index and improve the interpretation of mixed pixels (Mayaux *et al.*, 1997). However, random sampling does not account for much of the deforestation which is concentrated in hotspots as these have a high probability of being excluded by random sampling methods, unless the sampling procedure includes a high proportion of the area to be measured (Tucker *et al.*, 2000). They found that to achieve a deforestation estimate within +/- 20% of the actual loss 90% of the time, 37 from 40, 55 from 61 and 37 from 45 scenes were required for Bolivia, Colombia and Peru respectively. Lambin *et al.* (1997) designed a funnel method to detect deforestation hot spots from broad spatial scales of analysis to enable them to concentrate analyses on a limited number of areas. They found they could only approximate hot spot locations due the lack or poor quality of the data on processes which drive deforestation processes at the local scale (e.g. population dynamics and poor coverage of sensors that monitor fire activity).

2.3.4 Patterns of forest clearance.

With optical, thermal and microwave sensors, observation and identification of of forest/non-forest boundaries is possible. The variation between broad forest and non-forest classes create both irregular and regular spatial and temporal patterns in the landscape. These patterns can be described qualitatively and quantitatively.

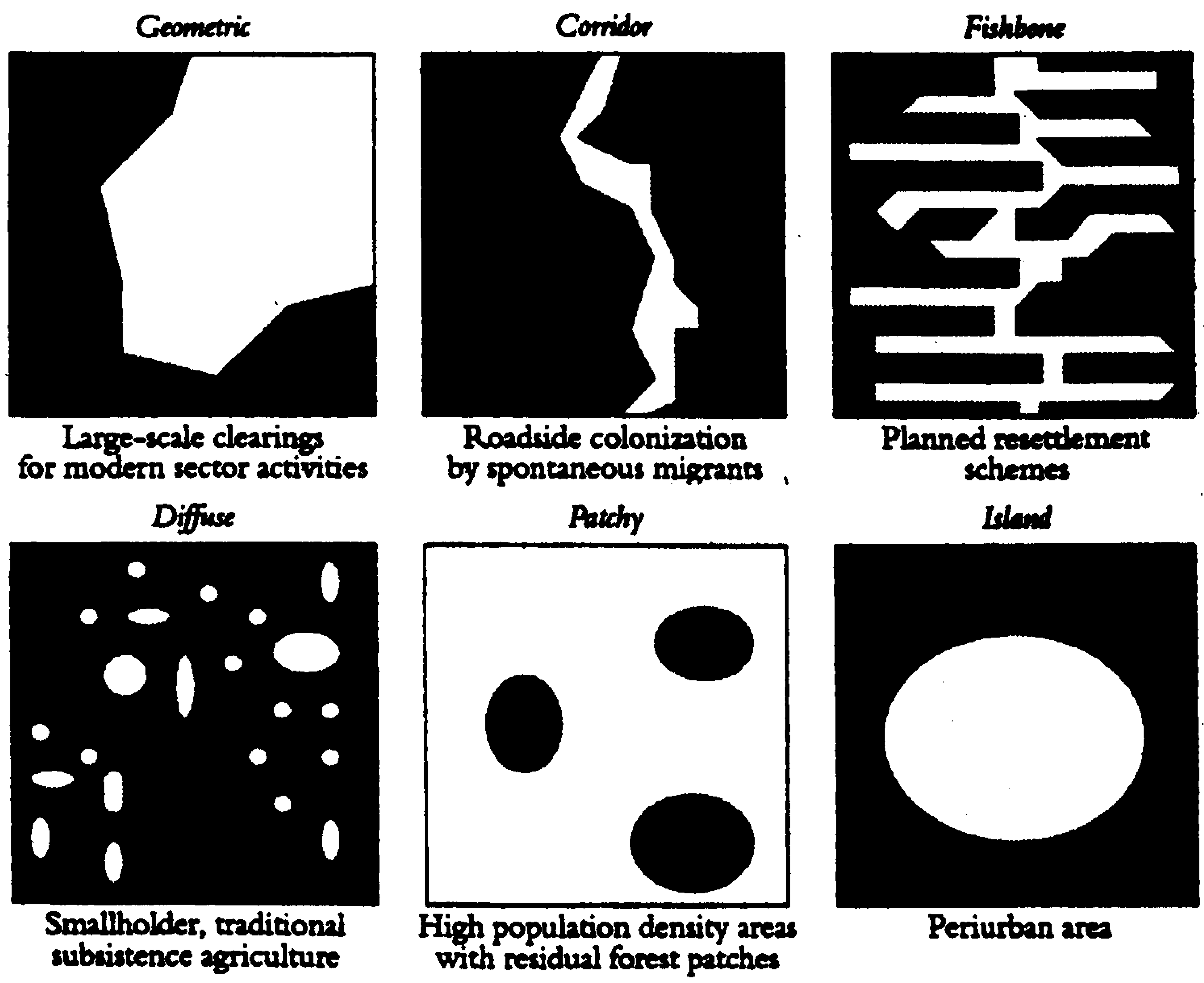
2.3.4.1 Qualitative descriptions.

Identifying different clearance patterns can help distinguish between clearance processes. The characterisations of the patterns are described as clearance typologies (Husson *et al.*, 1995) or morphologies (Lambin, 1997). Identifying these patterns has assisted researchers to formulate explanations of LULCC at deforestation 'frontiers'. Husson *et al.* (1995) recognised six typical typologies and explained the patterns (Figure 2.13). These patterns are:

- geometric – associated with large scale commercial ranching;

- corridor – associated with spontaneous migrants;
- fishbone – associated with planning and resettlement schemes;
- diffuse – small patches of deforestation which are predominantly cleared for subsistence needs;
- patchy forest remnants – where areas of exceptionally high population densites have developed; and
- island pattern – caused by deforestation around peri-urban areas.

Figure 2.13: Deforestation patterns and typologies. Source: Mertins *et al.* (1998) adapted from Husson *et al.* (1995)

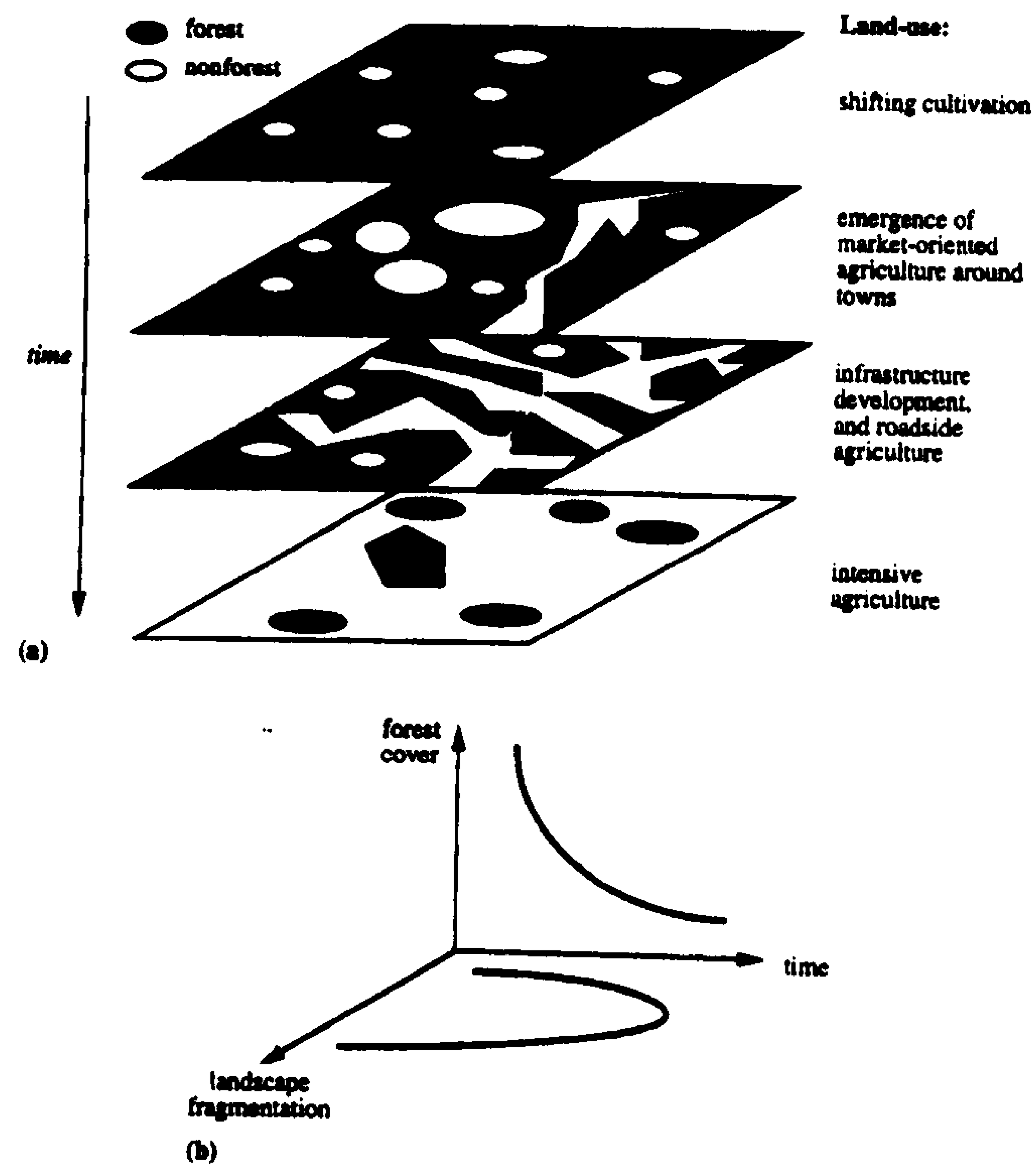


Imbernon *et al.* (2001) used forest/non-forest imagery to demonstrate how landscape configuration and complexity in the tropics varied between study sites in Peru, Brazil, Cameroon and Indonesia and illustrated how deforestation typologies could be characterised according to certain clearance situations, e.g. along rivers and roads and around settlements. There were also variations within the study sites, for example, in the Theobroma district of Brazil contrasting clearance patterns indicated the presence of small and large farms. Lambin (1997) described how one deforestation morphology (typology) may change into another because of the dynamic nature of the driving forces of deforestation through time. Hargis *et al.* (1997) agrees with this concept because when one land-cover becomes more dominant over another land-cover there will be an abrupt change in a landscape metric, in this case when the forest cover is dominated by the non-forest cover. As the morphology changed, Lambin (1997) related the progression of deforestation to changes in landscape fragmentation values which followed a parabolic curve. A deforestation trajectory could thus begin as a homogenous land-cover (with low indices of landscape fragmentation) then pass through a condition of heterogeneous land-cover (where landscape fragmentation indices are high) and, as forest clearance continues the land-cover becomes relatively homogenous again (with low fragmentation indices) (Figure 2.14). Lambin (1997) noted that there may be generic pathways in this model so there is scope for elaboration and testing. For example, the model assumes a unidirectional trajectory which does not account for post-disturbance succession and the fragmentation does not quantify or refer to a particular landscape metric or relate the metrics proportionally to total forest cover.

2.3.4.2 Quantitative descriptions.

The spatial arrangement of land-cover and the interaction of biota with different land-cover is a topic which concerns conservationists and ecologists involved in the planning, management and reclamation of the landscape, i.e. landscape ecology (Vink, 1983; Forman *et al.*, 1986; Haines-Young, 1993; Naveh *et al.*, 1994; Liu *et al.*, 2002). Landscape ecology is defined as a subject that describes the "effects spatial patterns have on ecological processes" (Turner, 1989).

Figure 2.14: Progression of land-use, landscape typology and changes in fragmentation characteristics. Source: Lambin (1997).



The patterns refer to the spatial arrangement of landscape components and the processes refer to flows of energy, materials and organisms between the components. A change in the spatial arrangements of the components has biological consequences for the ecosystem (Saunders *et al.*, 1991) such as habitats for birds and mammals (Andrén, 1994). Landscape patterns are commonly grouped under the following categories: spatial heterogeneity, fragmentation, edge characteristics and connectivity; and quantified as landscape metrics (Trani *et al.*, 1999) (Table 2.3). Table 2.3 shows that within each group are a number of landscape metrics which can be mathematically calculated from land-cover maps. Other examples of metrics are listed in Forman *et al.* (1986) and McGarigil *et al.* (1995). Time series analysis of landscape metrics can describe the variations in a landscape over time (in the same manner that Lambin [1997]

Table 2.3: Common landscape metrics. Source: Trani *et al.* 1999.

Metric group	Landscape metric
Spatial heterogeneity	Shannon Index
	Dominance index
	Number of (land-cover) classes
	Simpson index
	Landscape evenness
	Interspertion
	Binary comparison index
	Spatial diversity
Fragmentation	Fragmentation index
	Percent interior of class
	Number of patches
	Patch density
	Patch size
	Interpatch distance
	Percent cover of class
Edge Characteristics	Total edge
	Convexity index
	Patton index
	Compactness
Connectivity	Connectivity
	Contiguity index
	Spatial integrity
	Patchiness

suggested fragmentation changed over time for the tropical forests in Section 2.3.4.1) and indicate possible changes in landscape components and processes of an area. For example, as deforestation progresses, forests becomes fragmented into islands, the length of the forest edge and edge effects increase. Trani *et al.* (1999) calculated the variation in landscape metrics by simulation of the progressive shrinking of an intact forest to complete forest clearance. Selected metrics from their analysis are shown in Figures 2.15 to 2.18. Some metrics changed direction halfway through the simulation, whereas other metrics declined exponentially. The turning points in the curves often do not correspond. This suggests that the representation of fragmentation in Lambin's (1997) landscape fragmentation model may be too simplified and as he suggested that further evaluation is required.

Figure 2.15: The progression of Number of Patches (NoP) against the percentage loss of forest (Trani *et al.* 1999).

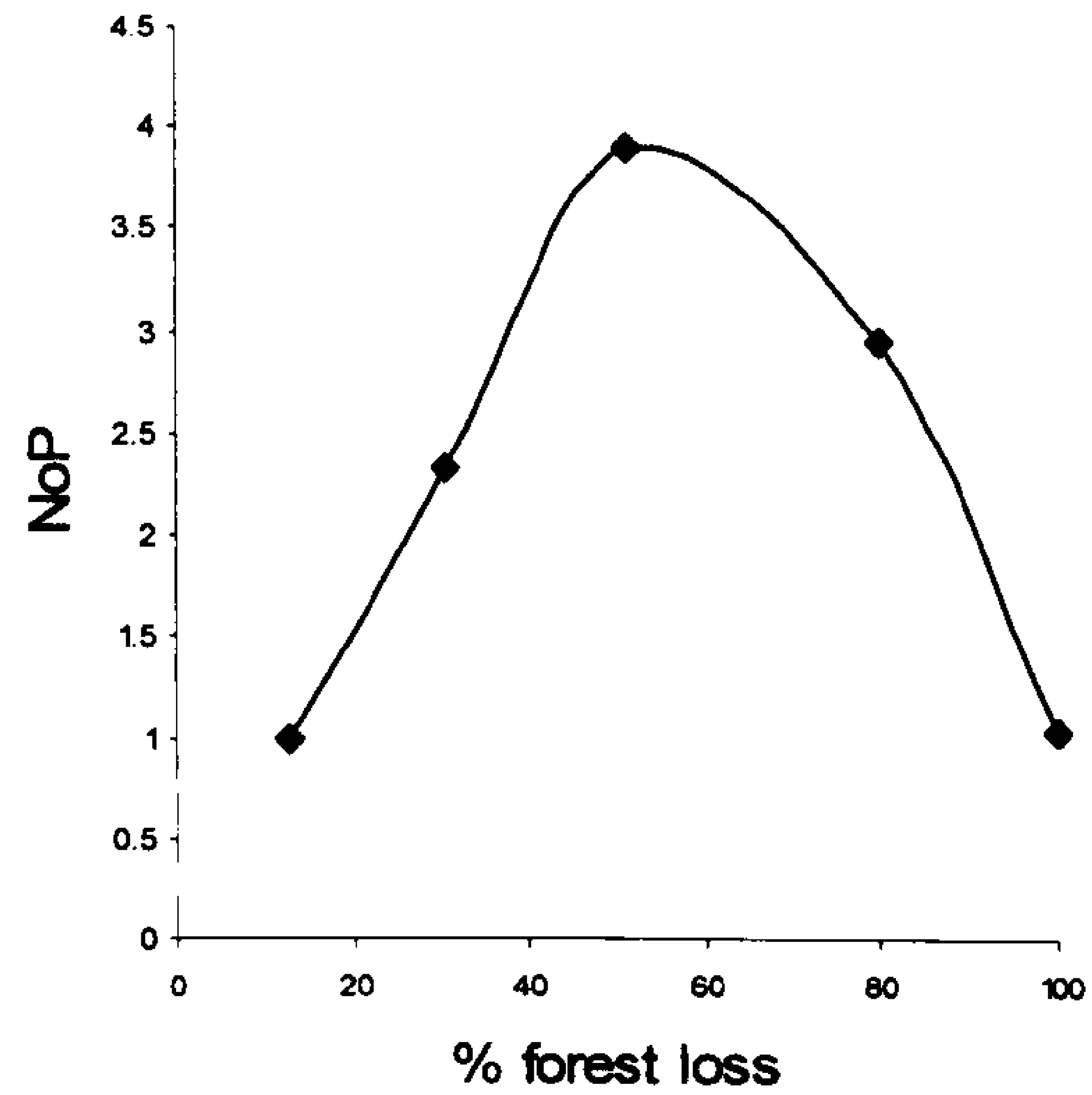


Figure 2.16: The progression of Total Edge Length (TEL) against the percentage loss of forest (Trani *et al.*, 1999).

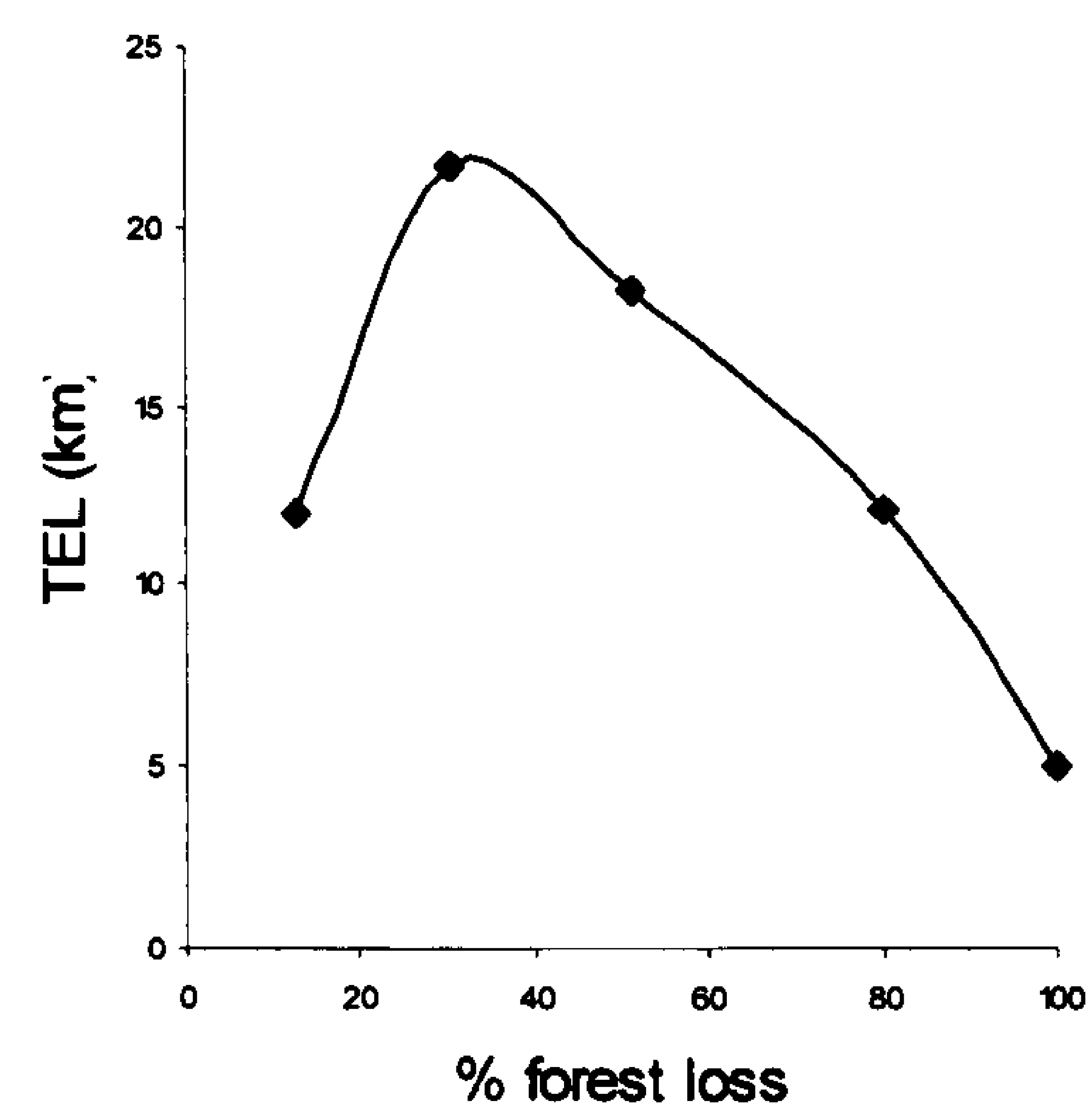


Figure 2.17: The progression of Mean Patch Size (MPS) against the percentage loss of forest (Trani *et al.*, 1999).

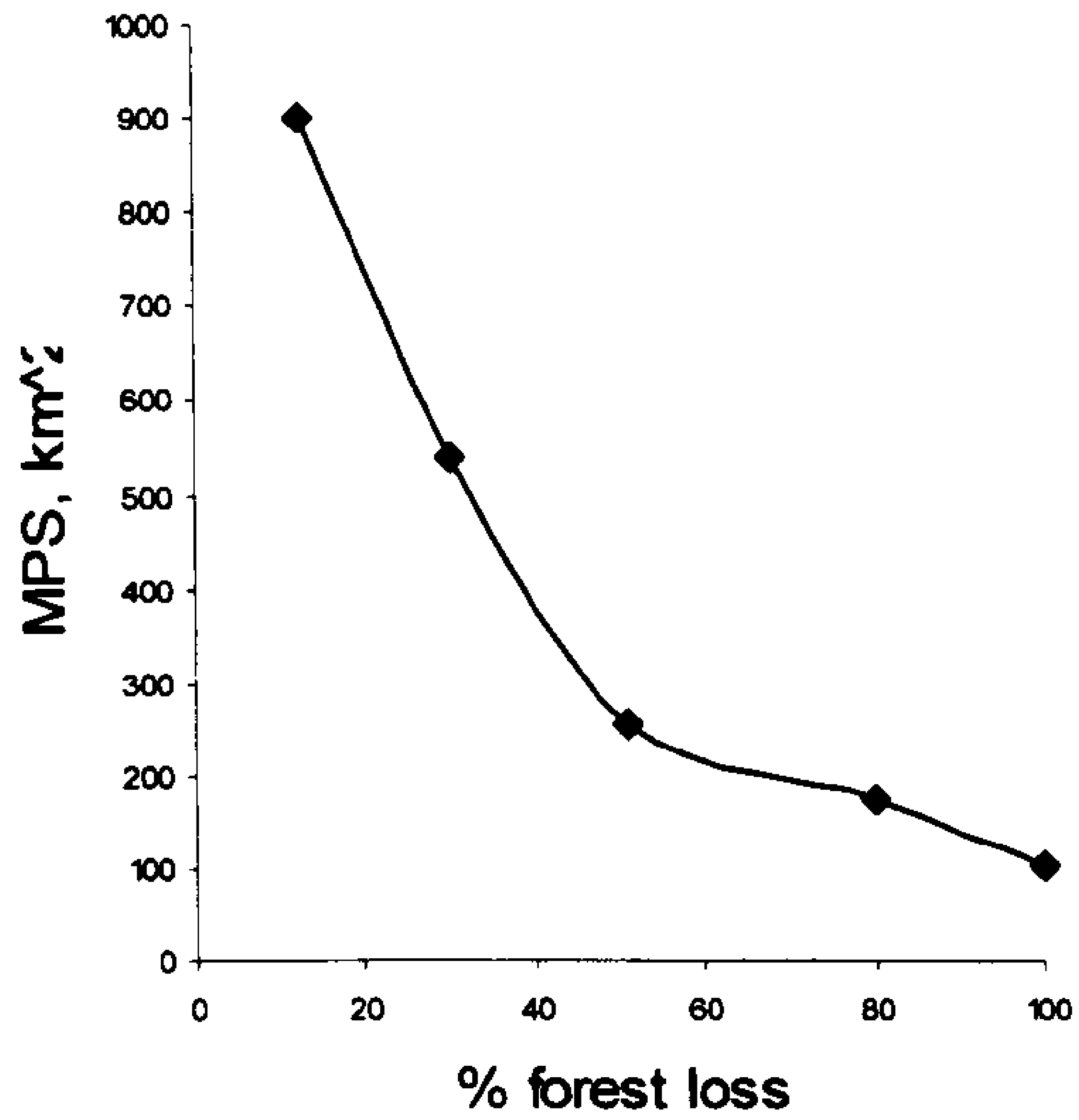
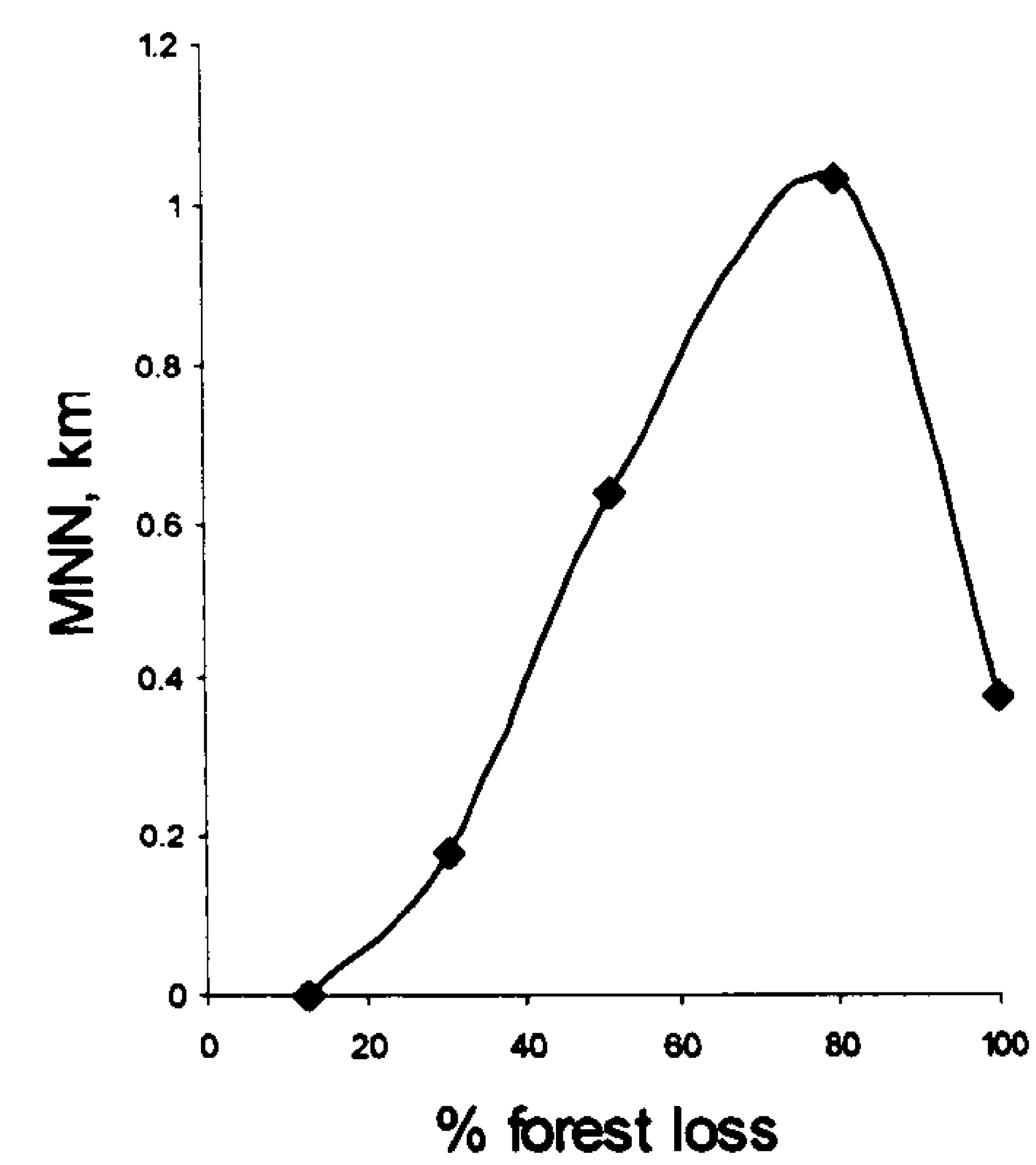


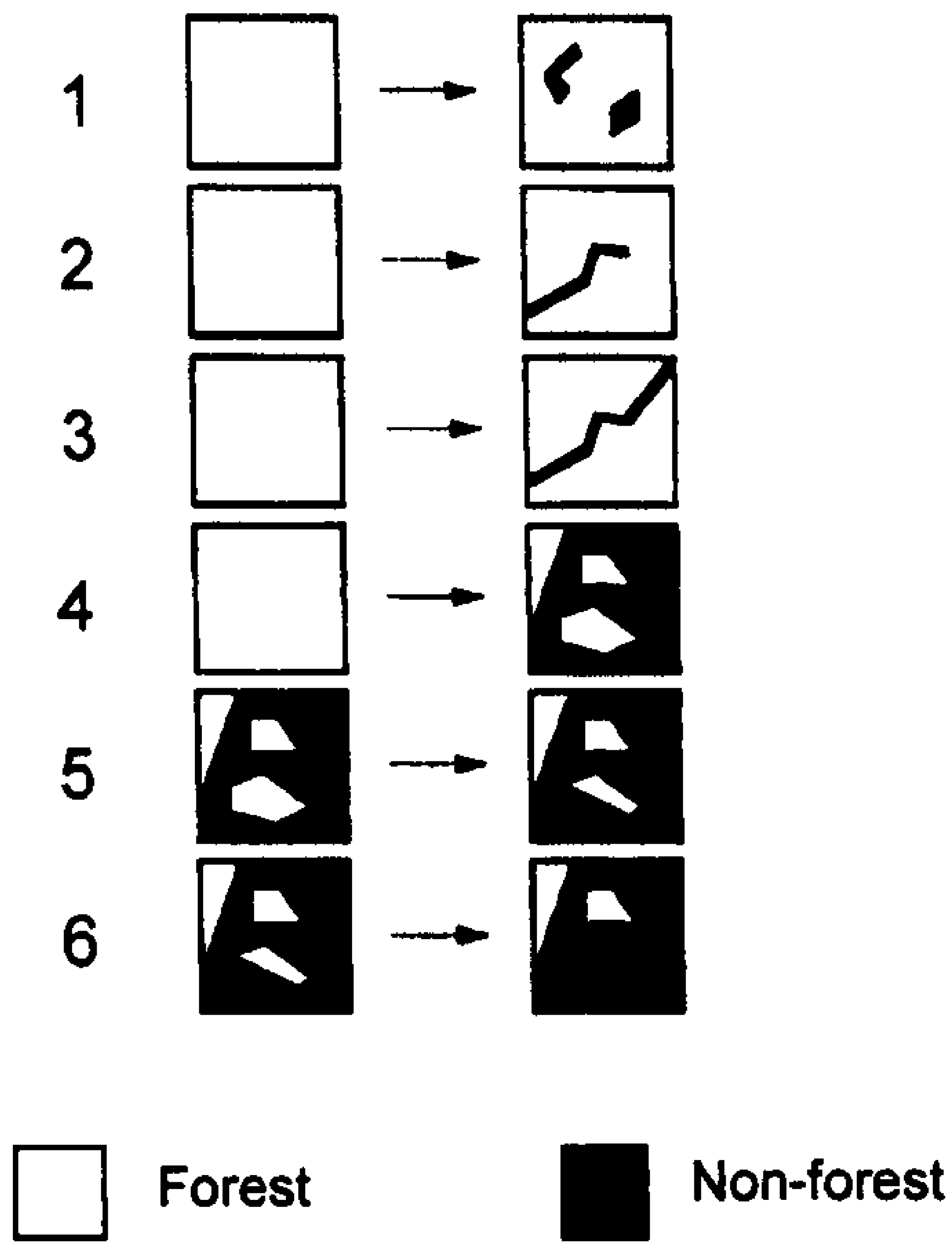
Figure 2.18: The progression of Mean Nearest Neighbour (MNN) against the percentage loss of forest (Trani *et al.*, 1999).



An ecologist can apply this model of simulated metrics to identify the ecological conditions of a real deforestation event. However, the simulation only discriminates between forest and non-forest and does not consider post-disturbance succession. Forman (1995) described how over time the structure of a landscape develops to exhibit phases of fragmentation with specific geometric characteristics. This was further developed by Jaeger (2000) into the phases of perforation, incision, dissection, dissipation, shrinkage and attrition (Figure 2.19).

Fragmentation patterns have been used at the global scale. For example, fragmentation of forest was calculated from the IGBP DIScover land-cover data set (Loveland *et al.*, 2000). Riitters *et al.* (2000) used a series of moving windows at different resolutions and identified patches, transitional, perforated edge and interior forest in order to identify and prioritise regions where land-cover and species impacts would be greatest. The resolution of the analysis affected the fragmentation pattern – the bigger the window the more the fragmentation tended to move towards the edge, transitional and patch categories. However, they were unable to detect a difference between natural and anthropogenic fragmentation patterns even with ancillary data.

Figure 2.19: Phases of fragmentation processes, 1 - perforation, 2 - incision, 3 - dissection, 4 - dissipation, 5 - shrinkage, 6 - attrition. Source, Jaeger (2000).



In relation to human impacts on forests, Peralta *et al.* (2000) described how fragmentation patterns related to the socioeconomic conditions of households in Acre, Brazil. The gradual increase in patch size was explained by the change from family groups practicing an extractive economy to one with larger patches created by a settled and well developed farming economy. Prior to 1975, farming economies were based on small scale extraction from the forest resulting in patches. By 1989, the patches were more regular, larger and numerous because farms were better developed in a region of permanent settlement. Imbernon *et al.* (2001) measured the decrease in percentage forest cover for several tropical deforestation sites in Brazil, Peru, Cameroon and Indonesia and using the Matheron index, noted how fragmentation of the forest increased and using the fractal dimension, how the complexity of the landscape increased. In the same study area the Matheron index increased for small farms in comparison to large farms because the edges of small farms were more irregular than those of large farms. Sierra (2000) reported from Napo, Ecuador, that during 20 years of colonisation 45% of the remaining forest area was in fragments of less than 10,000 ha. This deforestation was caused by the patterns of clearance which formed quasi-parallel lines along access roads. Millington *et al.* (2003) found that areas in a colonisation zone (Chapare, Bolivia, the same area that is the focus of this thesis) with different deforestation histories had specific fragmentation patterns. They also found that many landscape metrics were highly dependent on the pixel size of the image data they were calculated from.

2.3.5 Land-cover change trajectories

Examining the spectral properties of parcels of land for different image dates allows the trajectories of deforestation to be analysed. Deforestation can take two main forms. First, there is the conversion of the forest to another land-cover, e.g. forest to agriculture (Skole, 1994). Detection and quantification of forest conversion is often possible using a contextual approach by examining the location and pattern of the forest / non-forest edge. Secondly, there is the process of forest modification where the deforestation causes some alteration to the structure or function of the forest but the forest remains, e.g. selective logging of a forest rather than clear felling (Skole, 1994) and forest fires (Cochrane 2001; Cochrane *et al.*, 1999, 2002, 2003). Modification by unplanned selective logging is much more difficult to record than clear felling. For example, Asner *et al.* (2002) could not resolve canopy damage from logging activities with Landsat ETM+ because the pixel resolution was not detailed enough to detect disturbances of forest structural features which had been mapped on the ground. However, higher spatial resolution imagery from Ikonos has allowed developments in this area (Souza *et al.*, 2005).

There are various forms of post-disturbance succession (often referred to as secondary succession) and this trajectory of land-cover change can occur as a result of abandonment, degradation of cropland or pasture, or the immediate re-growth of cleared forest. The detection of post-disturbance land-cover has been used as an indicator of household management decisions in response to economic change (Moran *et al.*, 1996; Rudel *et al.*, 2002; Walker, 2003). The issue of secondary succession was addressed with little success until improvements in the spatial and spectral resolutions in Landsat TM (Moran *et al,*. 1994). Identification and mapping of secondary forest with Landsat TM has involved the use of botanical data because of the spectral subtleties between secondary succession types. To help overcome this problem Mausel *et al.* (1993) collected botanical field data in Altamira and Marajó Island, Eastern Amazonia, to help distinguish three classes of secondary succession (SS) in tall grass with a woody forest growth (SS1), eight to 12 metre high canopy secondary forest with high biomass (SS2), and, greater than 20m canopy secondary forest with similarities to mature forest (SS3). They found that in SS1 the visible bands had low spectral responses because of chlorophyll absorption and dense vegetation. The dense vegetation gave high mesophyll reflectance in the near infrared and, in comparison to pasture, a fall in middle infrared reflectance because of plant water absorption. In SS2 the green / red ratio was higher than in SS1 because of the higher biomass which in turn reduced the middle infrared reflectance because the complexity of tree geometry produced deep shadow in the canopy. In SS3 as the biomass increased, high chlorophyll absorption decreased all the visible reflectance. The deep shadow again decreased the near and middle infrared reflectance to below that of SS2. Sohn *et al.* (1999) calculated the spectral angles between spectral clusters and known reference signatures of land-cover to distinguish three stages of secondary succession (defined by descriptions used in Mayan land management) and agricultural land-cover in the Yucatan, Mexico. Foody *et al.* (1996) classified Landsat imagery acquired near Manaus, Brazil to research the composition of species in areas of secondary succession by making botanical surveys of former pasture areas. They found, depending on the clearance methods used, and the duration of pasture afterwards, that there were two different trajectories of secondary succession. Type I trajectory occurred in some land parcels following clearance and abandonment after one year of pasture and were dominated by *Cecropiaceae.* Type II trajectory parcels occurred where burning had been used in clearance and the area had then been used as pasture for several years and were dominated by vegetation in the Clusiaceae, Flacourtiaceae and Melastomataceae families. The identification of these two forest regeneration trajectories aided the identification of classification errors in the younger forest age classes.

Rates of secondary succession were seen to vary in Altamira, Brazil (Moran *et al.* 1994). The availability of agricultural subsidies was seen to encourage farmers to clear large areas of forest. However, a decline in subsidies coupled with the increased costs and difficulties in controlling weeds over large areas resulted in forest re-growth. Moran *et al.* (1996) used surveys of household land-use histories and vegetation structure to understand the role of secondary forest clearance as an indicator of policy shifts and economic conditions. They also noted households that located closer to markets were more likely to clear secondary succession forests during economically favourable periods than those farmers further away from urban areas.

2.4 Causal models of deforestation.

2.4.1 Political ecology.

Variations in deforestation rates at different locations indicate that processes and patterns of deforestation are variable in time and space. As methods to map and measure deforestation patterns have progressed, so the simplicities of some theories of environmental destruction have been exposed. Explanations of deforestation have commonly been assigned a single causal factor. For example, population growth has and still is used to explain deforestation in a neo-Malthusian context (e.g. Pahari *et al.*, 1999; Mather *et al.*, 2000). Growing populations have been blamed for creating pressures on forest resources in a number of different ways such as conversion of forest to agriculture, timber extraction, fuel wood collection, charcoal production, shifting cultivation, colonisation and re-settlement.

Political ecologists have been interested in deforestation (as a form of environmental degradation) since the 1970s and Holdren *et al.* (1974) described environmental degradation as a three term heuristic equation (Equation 2.1). In which, I = environmental impact, P = population, A = affluence (or consumption) of society and T = technology (degrading or enhancing). The equation described environmental impact as a product of population, affluence and technology. However there were problems in considering the environmental impacts in an equation form as this statistical summation ignored social science concerns, i.e. the internal structures of human populations, cultural differences and inter-population relations. Additionally the term 'I', was mediated by political economic forces that cannot be represented by quantitative terms (Durham, 1995).

$$(2.1) \quad I = PAT$$

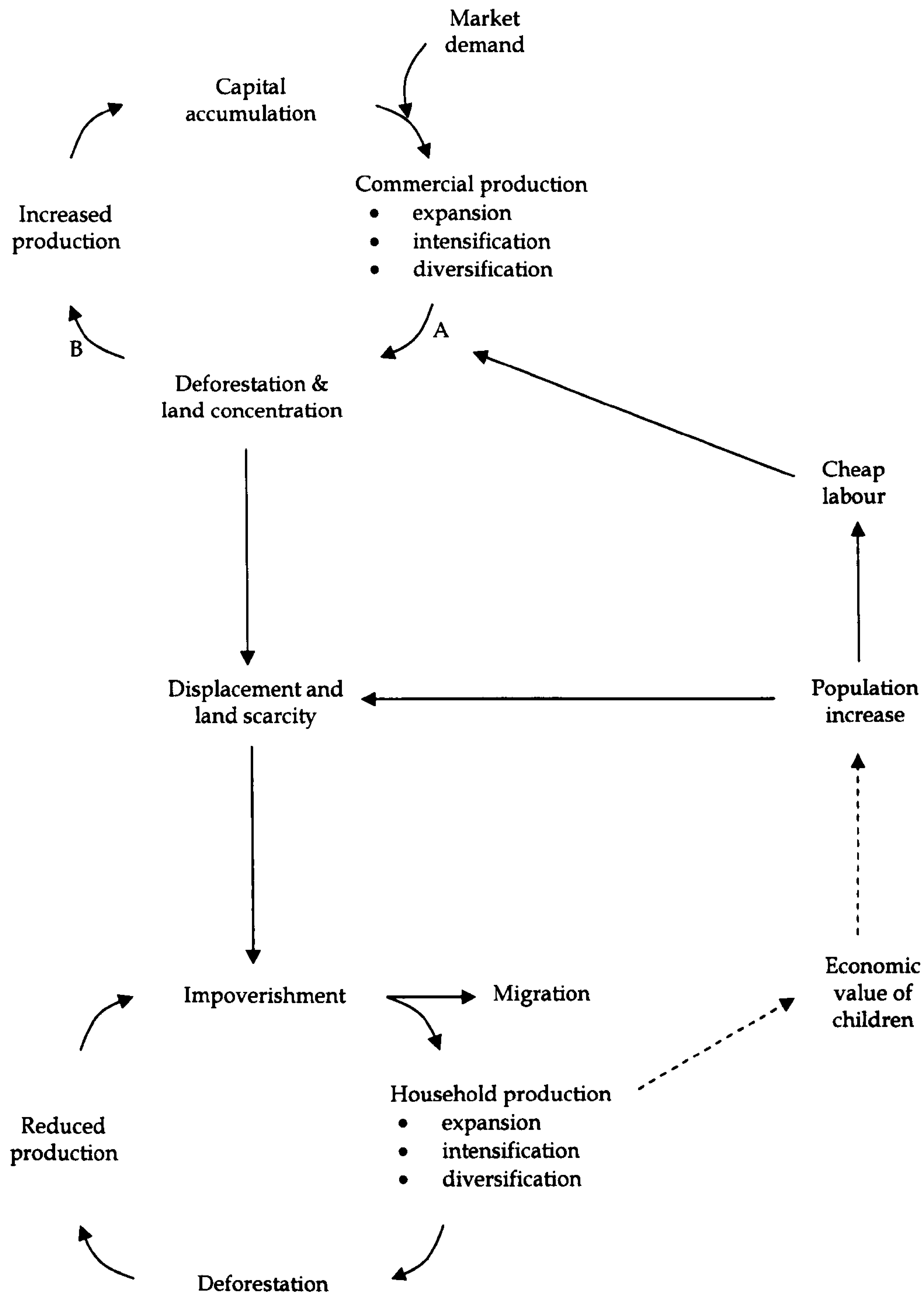
The 'I=PAT' equation was linked to orthodox conceptions of poverty and environmental degradation, but the equation did not acknowledge that it was not necessarily the poor who caused environmental degradation (Forsyth, 2003). Forsyth (2003) also argued between an orthodox and pro-orthodox stance of environmental degradation. In the case of tropical deforestation, orthodoxies concluded that pressures on the forest evolved from rising, mainly poor, populations, who searched for fuel wood or was caused by local agriculturalists practicing shifting cultivation, causing severe long lasting damage to the forest. Forsyth (2003: 39) identified authors who had a pro-orthodox stance, for example, Myers (1984), Mather (1992), Mather and Needle (2000) and Brown (2001).

The driving forces behind environmental destruction (in this case, deforestation) were much broader and more spatially distant than the activities of just those at the forest 'frontier' involving individual actors, histories and institutions (Forsyth, 2003). This realisation led to more complex conceptualisation of deforestation in political ecology and led to an anti-orthodox stance. Those holding anti-orthodox views now accept the role of population and poverty, but also consider that the actions of the agents of deforestation are also affected by government policies and / or political instability at frontiers (Forsyth, 2003). Deforestation will not always terminate with a complete change in land-cover, and farming communities may even contribute to the protection of forests. Examples of authors who have recently written in an anti-orthodox style include Barraclough *et al.* (1996), Angelsen *et al.* (1999) and Lambin *et al.* (2001), (Forsyth, 2003: 40). It is now also appreciated that there is no simplistic view of deforestation because the causes are often beyond the tropics. For example, scenarios of deforestation may have arisen by the demand for tropical products outside the tropics and the availability of foreign aid for developing nations (Park, 1992; Barraclough *et al.* 2002). Moreover, an explanatory scenario for tropical deforestation cannot be applied globally because there is no typical country profile in terms of demographic and economic factors (Reading *et al.*, 1995).

In Latin America, the social causes of tropical deforestation have been conceptualised as a dual cycle of capital accumulation and impoverishment (Durham, 1995) which linked international pressures with political and social systems at the locality of environmental degradation. Durham (1995) described how land scarcity close to commercial production displaced the population to new frontiers of development (or forest frontiers). As the impoverished population grew people migrated to new frontiers or returned to the commercial sector to seek employment. Once again because of land scarcity close to commercial production the impoverished were displaced to new frontiers (Figure 2.20). The model was applied to five case studies in Costa Rica, Honduras, Guatemala, Bolivia and Peru, but it was suggested that far more understanding was needed on feedback mechanisms, historical origins, cultural causes and responses to degradation alongside inequalities in race, gender, class and ethnicity.

Rudel *et al.* (1997) in a cross national study described deforestation in relation to the movement of population and government investment. They developed the frontier and immiserization theories. The frontier theory was applied to countries with large areas of forest where the government assisted entrepreneurs, companies and small farmers by improving infrastructure into forest regions. This was thought to result in an increase in Gross National Product (GNP). The immiserization theory was applied to

Figure 2.20: The cycles of capital accumulation and impoverishment. Source: Durham (1995).



countries where governments were in debt and could not invest in growth because of the low GNP. An absence of off-farm opportunities for a growing population would encourage farmers to deforest areas on marginal lands (most likely to be small remaining fragments of forest) close to their existing lands because of the lack of opportunities to migrate. Rudel *et al.* (1997) suggested that the two theories can alternate in response to fluctuations in GNP. A fall in GNP may result in a shift from the frontier to the immiserization theory. With a high GNP the frontier theory would persist, but a reduction in GNP would affect the population that had not migrated to urban areas. This group would be forced to utilise fragments of the remaining forest around existing infrastructure because the government no longer assisted further exploitation of forest through road building or created non-farm employment. A subsequent rise in GNP would open up new frontiers yet retard deforestation in the previously impoverished settled areas because of the increased opportunities in off-farm employment (Rudel *et al.*, 1997).

2.4.2 Economic models.

Modelling economic variables helps to evaluate the causative economic factors that are linked to deforestation thereby providing information for policies related to development and / or conservation of natural resources. Economists argue that deforestation is a process of development and can be considered desirable if the intended use of the resource is fulfilled whilst considering conservation. However, ecologists tend to argue that sustainable development is a scenario equal to agricultural development because it preserves biodiversity whilst achieving economic benefits to the inhabitants of the forest (Wibowo *et al.*, 1999).

There are three modelling strategies of deforestation (Angelsen *et al.*, 1999):

(i) analytical, consisting of mathematical expressions that assume how agents behave and how the economy works, with no empirical data being included;

(ii) simulation and equilibrium models using linear programming techniques; and

(iii) empirical models which use economic data in some form of regression model.

Economic models of deforestation can also be grouped into macroeconomic, microeconomic, government failure and neo-Malthusian models (Wibowo *et al.,* 1999). Macroeconomic models tend to examine the underlying causes of deforestation, for example, linking deforestation to debt, looking at the balance of imports and exports (often in relation to forestry and agriculture) and the distribution of money throughout the economy. Macroeconomic models represent 'distant' drivers of deforestation which influence individuals, households or companies, or other agents (Kaimowitz *et al.*, 1999) involved in land-use change at the forest / non-forest interface. Microeconomic models are related to the proximal causes of deforestation and in particular examine market influences which directly relate to the agents of deforestation (e.g. crop prices and labour). Models which account for government failures relate to misdirected policies (e.g. export bans and pricing policies) and corruption diverting funds away from their intended uses. Neo-Malthusian models examine the connections between population and deforestation.

Angelson *et al.* (1999) reviewed 140 economic models to analyse the causes of tropical deforestation. This paper questioned accepted ideas of deforestation because of the contrary or weak evidence used in the studies and suggested that research needed to focus on the impact of credit markets, technological change, poverty reduction and land tenure rather than, for example, conventional population studies. Shafik (1994), in an global analysis of 77 countries between 1962 and 1986, related both annual deforestation and total change in forested area to income, economic growth, investment and trade policies. The absence of any conclusive results was attributed to the assumption of similar macroeconomic behaviour between all countries over the same time period. Clearly though the stages and rates of development of countries, and their associations with markets, are highly variable; and Shafik (1994) concluded that microeconomic studies would be more relevant. However, Capistrano *et al.* (1995) linked four global economic trends between 1967 and 1985 to deforestation trends using data from 44 countries. Using least squares regression, they first grouped all countries together, and secondly, they grouped countries according to region, indebtedness and income. Although the model's predictive power fell over time (suggesting the explanatory variables were changing over time) the factors influencing deforestation switched over the time period. For example, in response to changes in export values of wood between 1967 and 1970, each percent increase in the unit export value of wood was associated with a 1.5% to 1.6% depletion of forest area. Between 1976 and 1980, forest depletion of 4.2% - 4.8% was associated with the devaluation of domestic currencies against the US dollar, suggesting exchange rate adjustments and foreign loans funded forest reduction. The results did not draw definite conclusions but drew attention to the expansion of agriculture at the expense of tropical forests as a means of reducing the impact of fluctuating import prices.

At the regional level, in Brazil Wiebelt (1995) tried to identify policies that would protect rainforest with the least economic cost. This involved splitting Brazil into three economic regions. Two regions which consisted mainly of the primary sectors of timber, livestock and mining and one sector, with secondary and tertiary manufactured products and services. Wiebelt (1995) found that devaluation of exchange rates to improve imports and exports encouraged exploitation of rainforest through expansion of timber, livestock and mining. Wiebelt (1995) concluded that macroeconomic modelling could be used in conservation because it was possible to identify policies that complement or counteract conservation. But the macroeconomic models needed to focus on regions where conservation was most needed to account for deforestation by specific localised activities. Deacon (1995) constructed a model to evaluate and simulate government policy changes on transport, taxes and royalties on timber, export controls, agricultural policies, tax incentives and employment. To help understand the consequences for the environment and employment opportunities, inputs in the model were changed to simulate different scenarios. These scenarios could then be utilised in order to identify potential mistakes in policy changes. Deacon (1995) also recognised that the deforestation literature tended to contradict equilibrium models and that too many assumptions were made in current deforestation models. He suggested that more empirical analysis was needed to connect the magnitude of deforestation and the relationships involved.

Focus on immediate causes of forest destruction tends to occur in localised models of deforestation. Walker (1987) looked at the issue of logging in a model that simulated the two-step process where loggers build an access road to log plots of mature forest. When they move on to the next plot the abandoned plot is then occupied by a farmer. Various concepts are explored including the offer of an incentive to re-seed the plot for regeneration and further logging. In reality, Walker (1987) notes that the contract length for a plot is not of a sufficient time scale to warrant re-seeding in the eyes of the logging companies. Bluffstone (1995) modelled the issue of labour in a Nepalese village with respect to the time taken for fuel wood and fodder collection. The model addressed access to fuel wood stocks and, because a source of fuel is always required, deforestation occurs. As deforestation spreads the labour force spends more time collecting fuel wood, and less time with herding stocks thus stabilising leaf biomass. However, the emphasis on fuel wood collection could be shifted if the labour force gained a pay increase. Because the farmers spend less time with grazing animals the forest biomass increases, but with more time on their hands to collect wood, fuel stocks still decrease. The poorer members of the village however can now find more work with grazing animals but this causes further forest degeneration. Mather *et al.* (2000) discussed the relationships of population influencing the other variables in different ways and offered reasons for conflicting ideas regarding deforestation trends. Although in their examples the explanations are placed on one variable, in order to construct the model properly, a number of other variables needed to be included.

Although some economists argue that deforestation is economically desirable, in order to gain a better understanding of the factors that drive deforestation, biophysical, political and social criteria (i.e. the sharing of common resources) need to be included along with the economic variables (Wibowo *et al.*, 1999). Most economic models lack a spatial dimension to describe where deforestation is occurring; however there are some studies that measure the economic impacts of distance, biophysical variables and population (Angelsen *et al.*, 1999). The development of this kind of analysis (with the use of GIS) at the regional level also has the power to spatially predict the location of deforestation. Laurance *et al.* (2001) boldly scaled up to the sub-continental level to predict deforestation in the Brazilian Amazon. Optimistic and pessimistic scenarios for 2020 were predicted using the policies of the 'Advance Brazil' program. However, vast linear tracts of rainforest destruction around proposed infrastructure are likely to be more complex. Spatial correlations have been made with market accessibility (Mertens *et al.*, 2000). Mertens *et al.* (2000) predicted the trajectories of deforestation and land-cover with a hypothetical example of the construction of a road through the Deng Deng Forest Reserve in Cameroon. Roads were found to increase access to the forest rather than encourage existing subsistence farmers to enter the markets. Chomitz *et al.* (1996) used GIS to predict the probability of land-use according to market access, land quality and tenure to predict the probability of commercial and semi-subsistence land-use in 1km grid squares in Belize. They concluded intensification of a road network around a market was a better trade off than extension of a network into the forest.

2.4.3 Meta analysis.

Theories of environmental degradation and economic models highlight and generalise the causes of deforestation but often they are not spatially explicit (with the exception of a few economic models outlined above) and do not quantify deforestation unless applied to a specific case study. Satellite remote sensing is an important tool which can measure the spatial extent of deforestation but sequences of satellite images cannot be used alone to explain the causes of deforestation (Lambin, 1999) and social determinants of deforestation are required to explain and project deforestation (Wood *et al.*, 1998). A challenge to the social sciences and the remote sensing community is how to link a pixelised landscape to a socio-economic aspect measured in a fixed area or link a time dependent variable to a discontinuous series of images (Liverman *et al.*, 1998). For example, the remote sensing and social science data sets need to have an appropriate spatial and temporal resolution (Rindfuss *et al.*, 1998) and because the analysis is for a number of processes in a small location the interpretations are unlikely to be valid beyond the regional level (Geoghegan *et al.*, 1998).

In recent years the land-use land-cover change community have described the complexity of deforestation and conceptualised the driving forces of deforestation. This type of conceptual model can be used to guide data collection and analysis, and give a coherent understanding of the scales of deforestation drivers – this is a goal of the IHDP-LUCC programme (Turner *et al.*, 1995). Giest *et al.* (2001, 2002) have examined a number of case studies in a meta-analysis to identify specific trends in deforestation. From 152 sub-national case studies they examined the proximate causes and underlying driving forces of deforestation which contested the single factor causation of deforestation. Their analysis illustrates that causes and drivers of deforestation cannot be attributed to single variables like shifting cultivation or population. In fact two or three processes may occur simultaneously, at both the proximate and underlying levels of deforestation (Figure 2.21). This type of meta analysis has allowed Lambin *et al.* (2003) to consider the regional contexts of tropical deforestation in South America, Southeast Asia, and West and Central Africa. For each region they identified the ecological factors which shaped the environmental trajectory and the changing institutional and socio-economic contexts which lead to dominant proximate causes and underlying driving forces of deforestation (in this context South America will be elaborated on in the next section). The Centre for Latin American Studies (University of Florida) similarly elaborated a framework for the driving forces of land-use change in the Amazon. Driving forces of land-use were divided into biophysical and socioeconomic drivers at global, landscape and local levels (Figure 2.22).

2.5 Tropical forest clearance studies in South America.

In South America deforestation can take place as traditional clearance, where indigenous groups change location and clear patches of forest (e.g. Coombes *et al.*, 2000) around villages (e.g. Pendleton *et al.*, 2002) and colonist clearance (e.g. Millington *et al.*, 2003), where migrants clear forest within property limits (Sections 2.5.1 to 2.5.3). This thesis will deal with mainly colonist agriculture.

2.5.1 Brazil.

There are several colonisation zones in Brazil and as a consequence there has been much research in the Legal Amazon. In Altamira in the state of Pará, the

Figure 2.21: The proximate and underlying causes of deforestation. Source: Geist *et al.*, 2001.

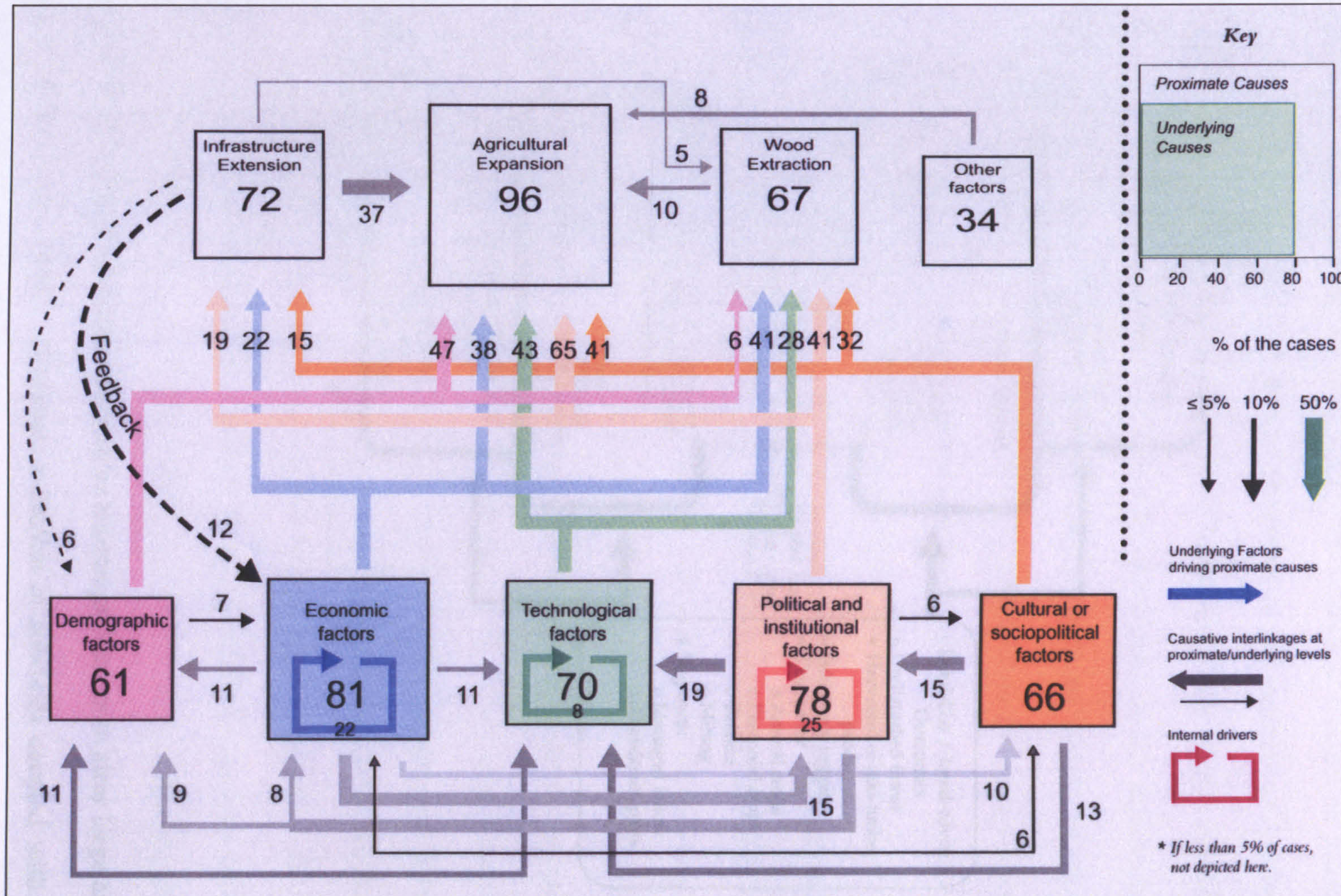
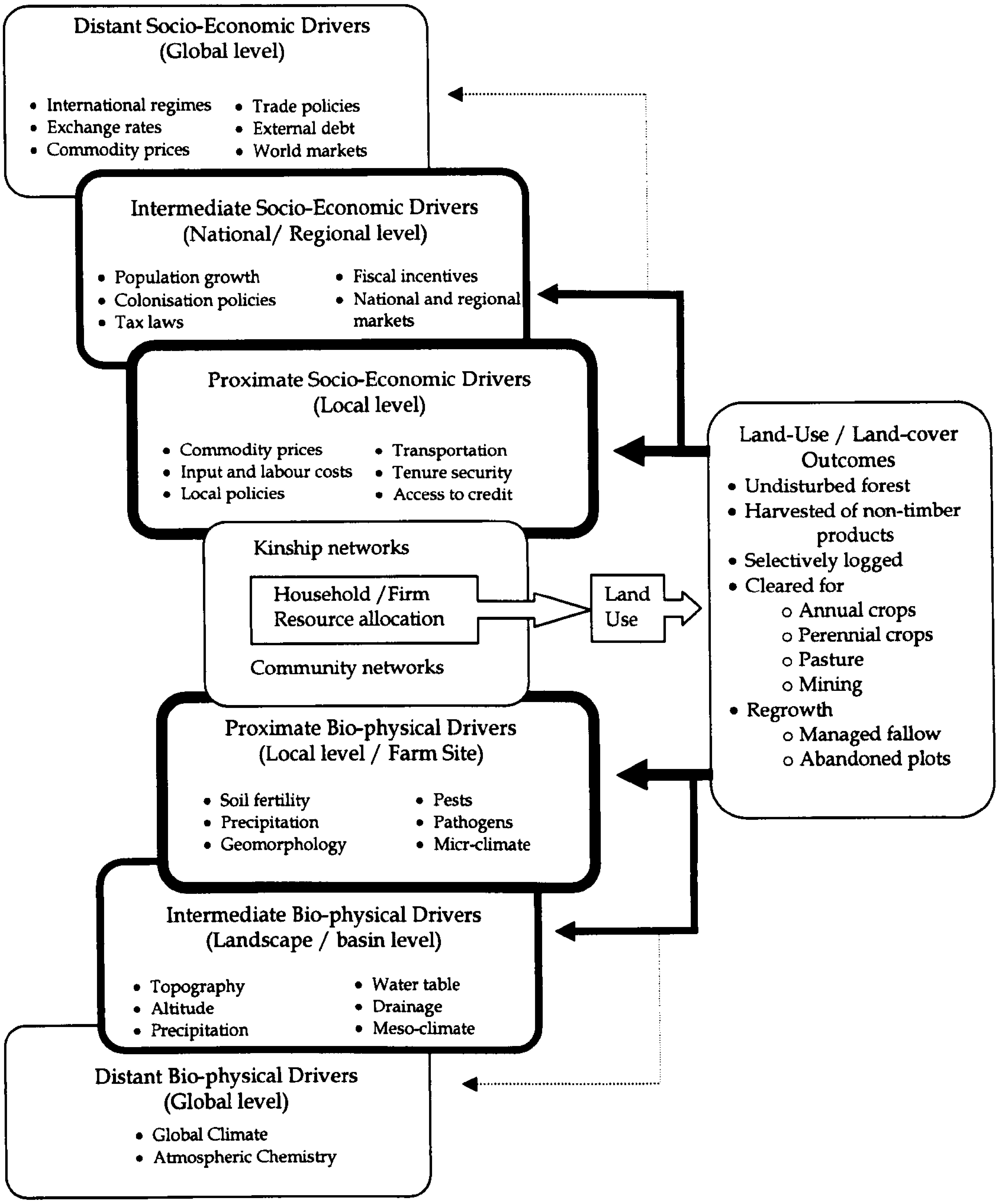


Figure 2.22: Conceptual model to explain the driving forces of deforestation. Source: Wood, 2002.



availability of agricultural subsidies was seen to encourage farmers to clear large areas of forest (Moran *et al.*, 1994). However, a decline in subsidies coupled with the increased costs of, and difficulties in, controlling weeds over large areas resulted in forest re-growth and rates of secondary succession were seen to vary (Moran *et al.*, 1994). Fujisaka *et al.* (1996) used interview data of colonist farmers and satellite image sequences to explain deforestation rates in Threobroma, Acre, Pedro Peixota and Rondônia. The clearance rates of the farmers were linked to changes in Brazilian government policies on road building, credit to corporations and ranches and investment in colonisation projects. Moran *et al.* (1994) and Brondizio *et al.* (1994) combined Landsat TM images with ethnographic and botanical surveys to identify differences in forest clearance between a site near Altamira and two sites on Marajó Island. In Altamira, intensive colonisation based on pastoral agriculture in previously forested areas had led to a mixture of degraded pasture, clearance and crops (Brondizio *et al.*, 1994). Their study showed that mechanised agriculture eliminated almost all mature forest on an upland site on Marajó Island because of the history of an agricultural co-operative around a mission (Moran *et al.*, 1994). However, it was found that they were no better off economically than other people on the island who caused minimal environmental impact through palm fruit extraction (Brondizio *et al.*, 1994). The impact that extraction had was rotation of flooded forest and palm forest in response to palm fruit prices through shifting agriculture. Moran *et al.* (1996) used surveys of household land-use histories and vegetation structure to understand the role of secondary forest clearance as an indicator in policy shifts and economic conditions. They noted households that located closer to the markets were more likely to clear secondary succession forests during economically favourable periods than those farmers further away the markets. In Altamira, McCracken *et al.* (1999) used satellite images to monitor deforestation on farm plots and analysed data from household surveys. They suggested that deforestation trajectories were related to demographic change in households and modelled the changing activities on the farm with the change in household numbers. In the same area Brondizio *et al.* (2002) divided the farms up according to the time of settlement and found that the rates of deforestation varied as time progressed. Brondizio *et al.* (2002) noted that these changes were related to subsistence, beginning with a perennial crop and then rotating crops with secondary forest; they termed the progression the 'colonist footprint'. The different times of settlement meant that each group were out of synchronisation but if a macroeconomic change occurred such as a subsidy for cattle ranching, the rates of all groups would be affected (this was described as a period effect). Moran *et al.* (2002) studied the relationships between soils, secondary succession and land-use in Altamira, Marajó Island, Igarapé Açu, Tome Açu (Brazil) and Tapú (Colombia). They found that the cutting of secondary succession was more frequent where the soils were poor and higher rates of secondary succession were generally related to greater soil fertility. After settlement in Altamira farmers were able to identify the better soils for cultivation of cocoa and sugar cane but if they cleared for pasture farmers tended to ignore the soil characteristics and did not take advantage of cultivating cash crops. Walker *et al.* (2000) used information from household surveys and imagery to describe how the cattle economy was driving deforestation in four areas in the state of Pará for groups of smallholders and cattle ranchers. Smallholder clearance and pasture expansion was related to farm creation and the evolution of household demography, whereas large scale ranchers brought in external capital and began to clear for pasture immediately. Walker *et al.* (2000) suggested that policies to mitigate a reduction in deforestation need to be targeted at specific groups. Alves (2001) discovered that better conditions of life occurred in the regions where income had improved through the clearance of forest for the development of cattle and agriculture in four areas in Brazil – Maranhão, Mato Grosso, eastern Pará, and Rondônia. This was achieved by comparing a 'condition of life' index and socio-economic statistics to deforestation rates derived from satellite imagery. In a later study, Alves (2002) described that between 1991 and 1996 the most intensely deforested zones in the Legal Amazon had the strongest links to national scale economic and social processes. The most intense deforestation was related to roads and pioneer colonisation zones.

In the state of Acre, Peralta *et al.* (2000) classified satellite images into forest and non-forest to examine the developments behind deforestation patterns. They derived shape indices of deforested fragments and recorded changes in the landscape to examine how patterns of land-cover change relate to extraction and permanent cultivation. Similarly Imbernon *et al.* (2001) examined the variation in fragmentation in Theobroma over a period of 25 years. By dividing up images into spatial sectors the differences in spatial indices (the Matheron index and fractal dimension) was helpful for identifying different types of farming.

2.5.2 Ecuador, Peru and Colombia.

In Ecuador the majority of studies were located in the north eastern deforestation front on the Colombian border. Pinchón (1997) assessed the clearance activities of colonist farmers here and discovered that farmers deviated from the peasant-pioneer cycle of forest clearance because they chose between cattle or coffee production. This choice was in part mediated by household demographic and socioeconomic circumstances. The patterns of land-use in the same area were also examined by Pinchón (2002). Areas where there was low deforestation corresponded to farmers that had invested in cash crops such as coffee. As high levels of labour were required to maintain cash crops the capacity for farmers to expand was limited. Conversely where farmers had invested in cattle rearing there were higher rates of clearance. This had low labour demands and was more lucrative for the farmers, thus there was a general shift towards the addition of pasture on plots. It was suggested that, to mitigate deforestation, policies needed to be directed towards multi-crop systems, rather then technical benefits that would just result in more forest clearance. In a slightly larger area over the Ecuador border into Peru and Colombia, Sierra (2000) used Landsat imagery acquired between 1976 and 1996 and census data to examine deforestation locations and rates. In Peru the deforestation rates were low as there were very few access roads. In Colombia the rates were slightly higher (0.9%/yr) than in Ecuador (0.65%/yr). In Ecuador deforestation was related to colonist agriculture and 46% of forest was lost between 1977 and 1996 in the areas of colonisation. In Colombia deforestation was related to coca leaf cultivation and guerrilla activity prevented detailed studies in the area. Walsh *et al.* (2003) used household surveys, imagery and GIS to examine LULCC and fragmentation in northeast Ecuador. One of the outcomes of the research showed that plots had become subdivided closer to the markets and the owners of the smaller plots had more intensive land-uses such as coffee rather than cattle rearing. In the same area Pan *et al.* (2004) examined the fragmentation patterns between 1990 and 1999. Using a generalised linear mixture model fragmentation was largely attributed to the subdivision of land holdings caused by demographic change, age of the plot and extension of infrastructure (i.e. roads and power supply). Walsh *et al.* (2003) and Pan *et al.* (2004) also avoided the northernmost part of the study area because of guerrilla activity and coca cultivation along the border with Colombia. In Peru, Mäki, *et al.* (2002) discussed the development of colonisation along the Iquitos to Nanta highway using evidence from aerial photographs and satellite imagery acquired between 1945 and 1995. Forest clearance initially occurred at the ends of the highway around Iquitos and Nanta and settlement locations were driven by the best soils. The variations in government policies between 1945 and 1995 meant the progression of a road between the two settlements occurred in stages. As the road progressed, zones of extraction, deforestation, agriculture and land neglect shifted. The 1980s saw a zone of large ranches develop around Iquitos. Next a new colonisation zone was developed and settled by unemployed oil workers during the 1980s and 1990s and this was the limit of the road construction at that time. Beyond this area the road had been marked and there was limited colonisation in the 1980s, the road deteriorated and many settlers abandoned the area. The major land-use here was extraction of timber. A similar sequence was seen along the highway from Nauta but there were no colonisation projects. Again people abandoned the area when the road deteriorated and the forest was used for timber extraction. Naughton-Treves (2004) studied deforestation trends along the Interoceanic Highway between Cuzco and Puerto Maldonado with Landsat MSS and TM data. In this area colonists were given 40 ha landholdings and used credit to cultivate perennial crops (rice and maize), but after the first few years cattle ranching became dominant. The rates of deforestation and secondary growth were noted for this area. Deforestation was rapid when there were good markets and plentiful agricultural credit between 1986 and 1991, but slowed between 1992 and 1997 after fiscal austerity measures were imposed. By the end of the second period 20% of the study area had forest re-growth.

2.5.3 Bolivia.

Stienninger *et al.* (2001) reviewed deforestation at the departmental level in Bolivia. Using Landsat data from the 1980s and 1990s forest loss was recorded as 15,500 km^2 in the mid 1980s rising to 24,700 km^2 in the early 1990s. More than 60% of this deforestation had occurred in the Santa Cruz Department. The forest losses are shown in Table 2.4. The increase in area deforested was attributed to a depressed economy and migration from the mining areas to the agricultural areas during the 1980s and 1990s. Most of the deforestation was within 30 km of roads and the main causes were soya bean cultivation in Santa Cruz, coca cultivation in Cochabamba and indigenous groups practicing shifting cultivation in the remaining departments, although rubber plantations in Beni and Brazil and nut collectors in Pando were also noted.

Table 2.4: The area of forest loss in Bolivia by department for the 1980s and 1990s in km². Excludes areas with <1000mm precipitation per year and south of 19 °S. Source: Stienninger *et al.* (2001).

Department	Deforested area (km^2) 1980s	Deforested area (km^2) 1990s	Area of forest loss between 1980 and 1990 (km^2)
Beni	1,220	2,455	1,235
Cochabamba	1,315	2,264	950
Chuquisaca	0	0	0
La Paz	1,195	1,694	449
Pando	615	1,357	743
Santa Cruz	11,187	16,933	5,745
Total	15,532	24,703	9,171

Kaimowitz *et al.* (1999) elaborated on the contribution of structural adjustment to deforestation after 1985. He suggested that increased deforestation for soya bean production alongside rice, maize and cattle production was promoted through the encouragement of mechanised agriculture and improvement to the transport infrastructure around Santa Cruz. Most of the land was under large scale farms and not a result of migration and / or creation of small scale farm plots. However, migration was suggested to have led to the deforestation in Chapare where there was small scale farming of coca leaf. Kaimowitz *et al.* (1999) suggest that deforestation rates were kept low in Chapare because most households could not maintain more than a hectare of coca without hiring in labour, so they cleared less land than an economy based on annual crops. Mertens *et al.* (2004) modelled deforestation in the Santa Cruz region following preliminary work by Kaimowitz *et al.* (2002). They included biophysical factors as well as socio-economic factors in their model. The region was split into several zones and the deforestation rates and causes of deforestation were described. In the 1960s the area around the city of Santa Cruz was deforested by small scale colonists and the main activities were the cultivation of sugar cane and cotton as well as some cattle rearing. The emphasis shifted to wheat and soya in the 1980s, and in the period from 1989 to 1994 around 4.1% of forest was lost. To the east of Santa Cruz in the 'expansion zone' soya bean and wheat were encouraged in the 1980s with improvements to access, mechanisation and grants to Mennonite and wealthy farmers established in Brazil. There were few colonists in the area and forest was lost at the rate of 3.0% per year. To the north of Santa Cruz forest losses were again at 3.0% but this was caused by small scale shifting agriculture for rice by colonists who first arrived in the 1970s. To the northeast deforestation was due to forest concessions and small scale agriculture for rice and pasture. Forest losses were low at 0.7%. In the remaining areas of Santa Cruz there was little forest loss and this was due to the dominance of ranching and small scale farming. Overall the model's results suggested that deforestation prior to 1989 was related to wetter areas with good soils close to the road network of Santa Cruz. After 1989 the major areas of deforestation then moved from areas close to the city. This shift was related to agricultural subsidies which favoured soya bean production.

Stienninger *et al.* (2000) examined the fragmentation patterns in an area to the northeast of Santa Cruz using satellite images acquired between 1975 and 1998. In this period the total area and size of fragments increased until by 1998, 98% of the forest was within three kilometres of agriculture. Fragmentation patterns were related to state colonisation, unplanned colonisation, Mennonite colonies and agro-industrial farming. State-planned colonisation and unplanned colonisation mainly led to smallholder colonies and they produced a complex mosaic of crops, secondary forest and forest remnants. Where the areas of colonisation were planned from growth poles colonists gradually cleared the surrounding matrix of forest in a series of wedges radiating from the central point. Areas where unplanned colonies existed were fragmented quickly because clearance occurred as parallel roads and where perpendicular secondary roads developed. Mennonite colonists tended to clear in long strips about 250m wide into the forest and these strips coalesced into large blocks of non-forest. Land for agro-industrial purposes cleared their boundaries with narrow strips of agriculture to leave a block of forest which was then progressively reduced to leave no forest at all. Similarly Millington *et al.* (2003) divided up the Chapare (Appendix 3.1) and examined the development of fragmentation patterns with the use of landscape metrics. Between 1986 and 2000 the numbers of forest fragments between 0.1 and 10 ha were different between Tunari – Chimoré Sector, the oldest colonisation zone, and the Ichilo sector, the last area to be colonised. In 1986 in the Ichilo Sector there were 64 forest patches between 0.1 and 10 ha and in 2000 there were 754 small forest patches between 0.1 and 10 ha. In the Tunari-Chimoré Sector in 1986 there were 300 forest patches and in 2000 there were 286 forest patches in the 0.1 to 10 ha range. The increase in Ichilo was due to recent clearance from new colonists and the slight decrease in Tunari-Chimoré was suggested to be due to maturing tree and shrub crops cultivated by the earlier colonists.

2.5.4 Colonist clearance characteristics.

Colonist agriculture in South America is generally characterised by distinct patterns of forest fragmentation e.g. the fishbone pattern in the Brazilian states of Para, (McCracken *et al.*, 1999), Mato Grosso and Acre, (Fujisaka *et al.*, 1996), along highways, often with colonisation programs, e.g. the inter-oceanic highway, (Naughton-Treves, 2004), and Iquitos to Nanta highway (Mäki, *et al.*, 2002) in Peru; as parallel axes of roads in Napo (Sierra 2000; Walsh *et al.*, 2003) in Ecuador, and where patterns depended on the nature of settlement and the type of agriculture in Santa Cruz, Bolivia (Section 2.5.3) (Stienninger *et al.*, 2000).

In Para and Acre clearance has developed from feeder roads stemming from a major highway. Plots of near equal proportions are claimed by each colonist family. The amount of forest cleared varies according to the distance from the road (Fujisaka *et al.,* 1996) and in Para cohorts of colonisation progressively claim plots at the extremities of feeder roads (Brondizio *et al.*, 2000). In these examples farmers adopt slash and burn methods from the most accessible parts of their plots and clear from the front to the rear. Colonist's plots are arranged back-to-back so there is no access at the rear. The clearance of plots in the 'fishbone' pattern creates a number of non-forest intrusions into the forest along the secondary feeder roads with narrow passages of forest in between. When clearance in back-to-back plots met, the narrow forest passages are fragmented into small patches of forest.

In the Napo region of Ecuador clearance began from the initial penetration roads constructed by oil companies. Plots (or *fincas*) were claimed along the main feeder road. When all *fincas* were claimed on the road a parallel road (or *linea*) was constructed at the back of the plots. New colonists began clearing in the same way and when all the plots were allocated another *linea* was constructed. Up to seven or eight *lineas* were constructed. Forest fragmented into corridors between the quasi parallel roads. The corridor became blocked when a plot between the two *lineas* was totally cleared (Sierra, 2000). The forest corridors have also been perforated with isolated patches of forest because of extensification of agriculture and / or land division between families on individual *fincas* (Pan *et al.*, 2004). Forest corridors are also disrupted when colonists clear their *finca* boundaries to secure ownership of the land (Sierra, 2000).

The clearance patterns created by smallholders also contributed to the fragmentation of forest because of the variations in rates of clearance between plots and the land-use chosen by the farmers. Data on rates of deforestation within smallholder plots are generally quoted as forest loss for whole study areas, but some statistics on smallholder clearance are collated in Table 2.5.

Table 2.5: Smallholder clearance rates, land-use and plot sizes for selected colonisation areas in South America.

Location	Plot Size (mean)	Rate (ha yr^{-1})	Time length studied	Land use	Author
Thoebroma, Brazil	76 ha	3	8 years	pasture and subsistence	Fujisaka *et al.* (1996)
Pedro Peixota, Brazil	88 ha	2	9 years	pasture and subsistence	Fujisaka *et al.* (1996)
Para, Brazil	~100 ha	3 2-5 in 'initial' years	1988 to 1991	pasture and perennials	McCracken *et al.* (1999)
Santarem-Cuiaba corridor, Brazil	88 ha	3.1	1992	annuals and perennials	Scatena *et al.* (1996)
Joya de la Sachas, Ecuador	44 ha and < 60 ha	~1.2	20 years	coffee, cocoa, fruit	Sierra (2000)
Pucallpa, Peru	88 ha	~4	1987 to 1988	annual crop then pasture or perennials	Loker (1993)

Clearance rates were generally above 3 ha yr^{-1}. Exceptions were Pedro Peixota, where pasture is a common activity in all the areas, and in Joya de la Sachas, where coffee cultivation was the major activity. Table 2.5 only provides a small sample of deforestation rates in colonisation areas in South America and illustrates that most studies of deforestation patterns, land-use activities and clearance rates related to the farm plot are linked to legal economies. Given the number of areas linked to coca cultivation in South America (MacGregor, 1993) LULCC studies have largely ignored this illicit cash crop.

2.6 Summary.

Land-use and land-cover change in tropical forest areas has been mapped and monitored on global, regional, national and local scales and has led to numerous estimates in change of forest cover. There is considerable uncertainty in these estimates because of data inconsistencies, resources, and methodological issues. The causes have been explained with theories and with economic models, which tend to be generalised and not spatially specific. However, local studies which combine remote sensing, social and environmental sciences have contributed to a wider understanding of LULCC in tropical forest regions with interpretations of land-cover change patterns and land-use trajectories as well as elucidating many causal factors. In South America deforestation hotspots often coincide with population concentrations and / or agricultural activities in areas designated for development. The rates and patterns of forest clearance determined by socio-economic and biophysical factors acting on the location, are shown to be highly variable from location to location. Chapter 3 introduces one such area in Chapare, Bolivia where a designated colonisation area has been dominated by the illicit activity of coca leaf cultivation.

Chapter 3

Study sites

Chapter 3

Study sites

3.1 Introduction

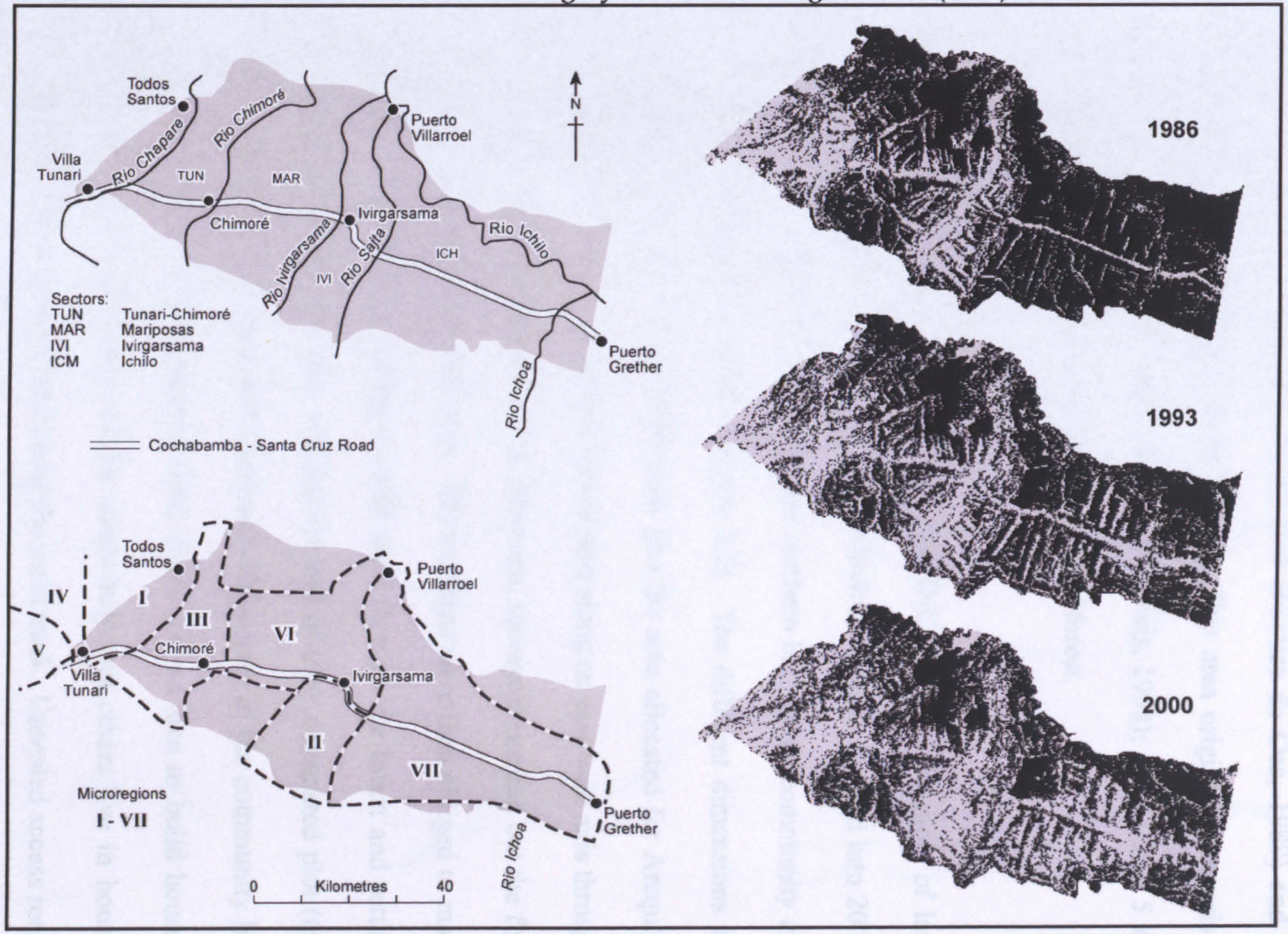
This chapter introduces the locations, physical characteristics, settlement histories and the contemporary agricultural activities of the three communities in Chapare where LULCC and fragmentation were studied in detail. To maintain confidentiality of the communities they are not located precisely and assume the names of Arequipa, Bogota and Caracas. The communities are located by microregion, which were defined in Plan Integral de Desarollo y Sustitucion (PIDYS) (MACA, 1991) as areas that were suitable for specific crops and agricultural development and deforestation sectors where different deforestation histories could be identified (Millington *et al.*, 2003). Figure 3.1 shows the location of these microregions and sectors and a broader view of the deforestation between 1986 and 2000 in Chapare. The deforestation history and fragmentation of the area is discussed in Millington *et al.* (2003) and is included in Appendix 3.1 (this publication is included as an appendix as I am a co-author). In Chapter 4 (Section 4.2.2.1) the reasons for the choice of these particular communities are provided.

3.2 Arequipa

3.2.1 Location and aspect

The community of Arequipa is located in the Ichilo sector (Millington *et al.*, 2002) or subregion VII (MACA, 1991) of Chapare (Figure 3.1). The community covers approximately 12 km^2 on relatively flat land at an altitude of about 250 m.a.s.l. The east and west boundaries of the area are demarcated by rivers which run roughly north to south through the area from the Andes to the south to the Río Mamoré

Figure 3.1: Sectors and deforestation in Chapare from 1986 to 2000. Top left, deforestation sectors (Millington *et al.*, 2003). Bottom left, microregions of PIDYS (MACA, 1991). Right, the progression of forest clearance between 1986 and 2000 - forest areas are in black and the non-forest areas are in grey. Source: Millington *et al.* (2003).

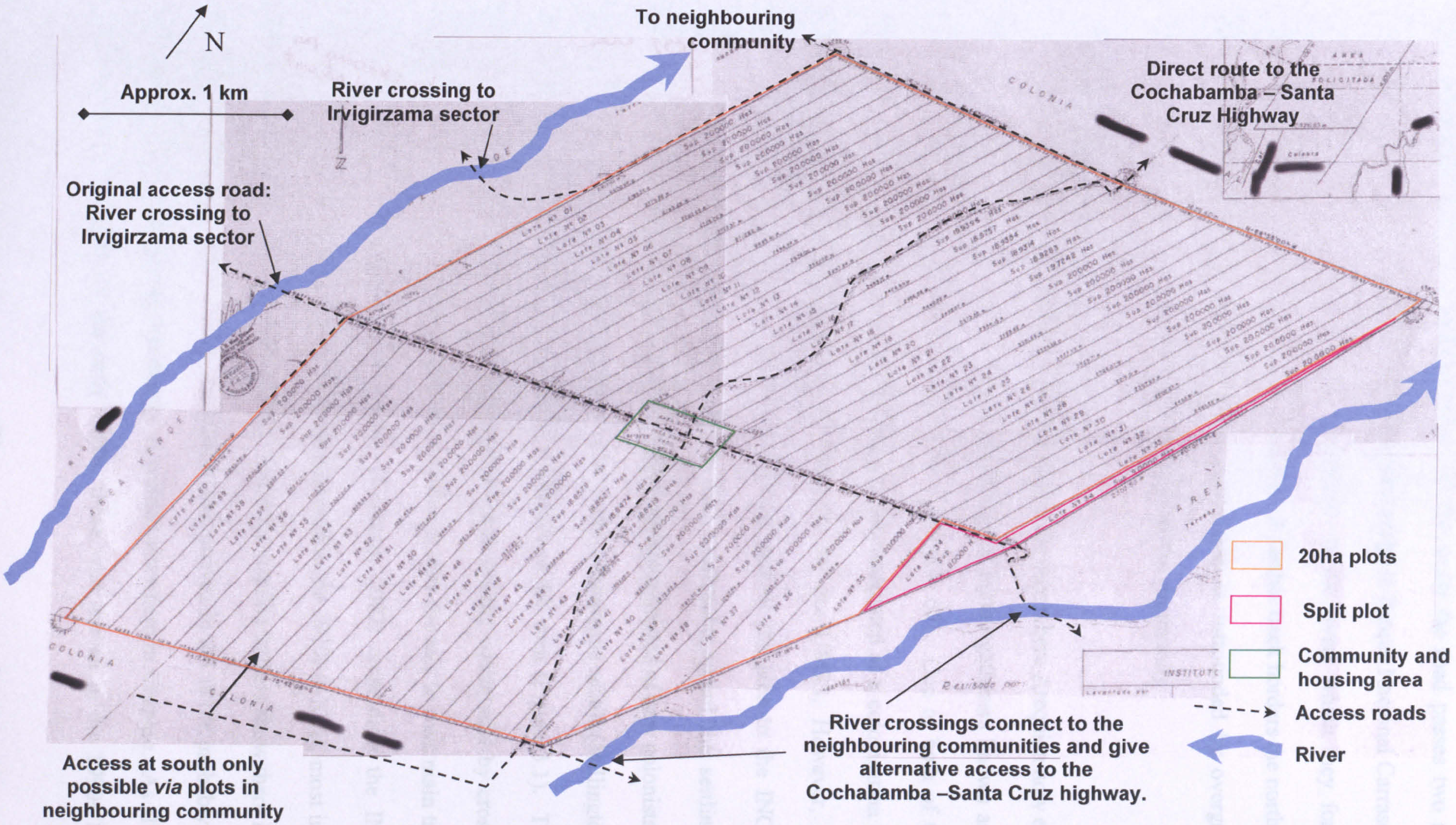


in the Amazon basin, smaller tributaries to these rivers drain the areas between the rivers. The estimated average annual temperature is 24 °C to 26 °C and mean annual rainfall is 2,500 mm (Maldonado, 1990). The climate has been classified as Af - Tropical always humid, in the Köppen classification (Montes de Oca, 1989) and as humid under the Thornthwaite (1943) classification. This area originally comprised tropical moist forest, which was seasonally inundated (Jones, 1998); a little over 5 km to the south, the lowland forest grades into lower montane forest.

3.2.2 Structure and attributes

The area of the community is 1,220 ha. The INC surveyed 60 plots of land (referred to as *chacos* by the farmers) in Arequipa which are mostly divided into 20 ha areas with dimensions of ~70 m by 2,500 m in the northern half of the community and ~100 m by 1,900 m in the southern half (Figure 3.2). The different dimensions are likely to have come about in order to fit 60 plots into the area allocated for Arequipa and so each plot has access to the main track which runs along an east-west axis through the community. When the colonists arrived in Arequipa, surveyors marked out the first few 10s of metres of the plot limits with pegs. The colonists were then obliged to mark out the rest of their plot limits by cutting a small track through the forest and setting more pegs at regular intervals until they reached the end of their designated plot (this method was also employed in Bogotá and Caracas). The centre of the community has been set aside for a church, school, playing field, shops and an area to build houses. Many of the farmers live in the centre of the community, but others live in houses constructed at the end of their plots of land along the main track. Unsealed access roads radiate from the centre of the community to the north, south, east and west. The main access is to the north, a gravel road which leads through other communities to Sajta on

Figure 3.2: Plan of the community of Arequipa (INRA 1983). The diagram shows the arrangement of the plots, access to the community, bordering rivers and tracks passable by vehicle in 2003.



the Cochabamba to Santa Cruz highway. To the south the road passes two more communities before meeting the first (impassable) range in Parque Nacional Carrasco.

The tracks extend beyond the community to the rivers which they ford to connect with tracks to neighbouring communities. A further track borders the northwest limit of the community. The rest of the community is surrounded by overgrown pathways cut through the forest to define the limits of the community.

3.2.3 History

Before Chapare was opened to colonisation, the area where Arequipa now exists was in the marginal areas of the indigenous groups of hunter-gatherers known as the Yuracaré and Yuquis (Montes de Oca, 1989: Table 2.1: 65). One or both of these groups may have used this area. After Chapare was designated as a colonisation area, the area became part of a reserve administered by the UMSS. However, high administrative costs caused the UMSS to give up part of the area to the INC for colonisation. Documents archived at INRA in Cochabamba record the settling of Arequipa around 1983 (INRA, 1985). The initial settlers consisted of new colonists and members of a nearby cattle rearing community in the Ivirgasarma sector (Millington *et al.*, 2002) or subregion II (MACA, 1991) of Chapare to the west (Figure 3.1). These settlers initially gained access from the original cattle rearing community by crossing the river to the west and entering the forest on what is now the east to west main track. Interview data from the BioAndes project (Lazcano, 2002) contradicts the INRA documents suggesting that some of the settlers arrived in the 1970s (~10%), most in the 1980s (55%) and a few in the 1990s (~5%). Since the satellite images show there is no clearance of the forest area in 1976, the settlers who arrived in the 1970s probably had properties in the cattle rearing community or resided elsewhere in Chapare. As all the properties were occupied by the early 1980s, those who arrived in the 1990s have bought plots from farmers who have decided not to continue farming in the area, or inherited land through the death of a family member. A majority of the settlers migrated, mainly from the highlands from the departments of Cochabamba (27%), Potosí (40%), Oruro and Sucre (30%) and the remainder from the local Irvigarsama sector (3%), (Lazcano, 2002). Satellite images show the extent of deforestation between 1976 and 2000 (Figure 3.3).

3.2.4 Contemporary activities

The land use in Arequipa is predominantly agricultural and the community shows a diverse range of activities (Table 3.1, Figure 3.4). Farmers grow for subsistence (which includes rice, maize, cassava and fruits) and the major products sold to market are bananas, rice, coca leaf, cassava, heart of palm and black pepper. No farmers indicated that they cultivated citrus and had pasture for cattle grazing in the interviews, but these activities were observed in the field in 2002 and 2003.

Farmers explained that the plots are cleared by slash and burn. At first this is for rice, maize and, sometimes, manioc cultivation while nutrient levels were high. This is then normally followed by perennials such as coca bushes, bananas or heart of palm.

Table 3.1: Agricultural activities in Arequipa. * see glossary (Appendix 1.1) for details on the units of sale. Source: interviews; sample number n = 13.

Product	Responses	Unit of sale*	Approximate price per unit (2002)
Banana	8	*Chipa*	~ 3-10 Bs
	1	*Cabeza*	~ 2.5 Bs
Orange	1	100 units	~ 8 Bs
Rice	8	*Quintales*	~ 20 - 40Bs
	2		~ 70 - 90Bs (at market)
Cassava	8	*Quintales*	~ 8 - 10 Bs
Coca	1	*Carga*	~ 700 Bs
	1	*Paquete*	~ 70 Bs
	1	*Libra*	~ 200 Bs
Heart of palm	4	*Tallo*	~ 0.60 – 1.00 Bs
Black pepper	6	*Quintales*	New product

Figure 3.3: The extent of deforestation in the vicinity of Arequipa in 24 years from 1976 (top) to 2000 (bottom). Dark green areas are forests and rivers are pink or blue ribbons of colour, the white patches are clouds. There is no evidence of clearance in 1976 but by 2000 a majority of the forest has been converted to agriculture, identified as pink and light green tones. The area of the image is approximately 7 by 5km. The top image is a MSS false colour composite (FCC) bands 231, path 249 row 072, 01/07/1976, and the bottom image is an ETM FCC bands 741, path 232 row 072, 14/07/2000.

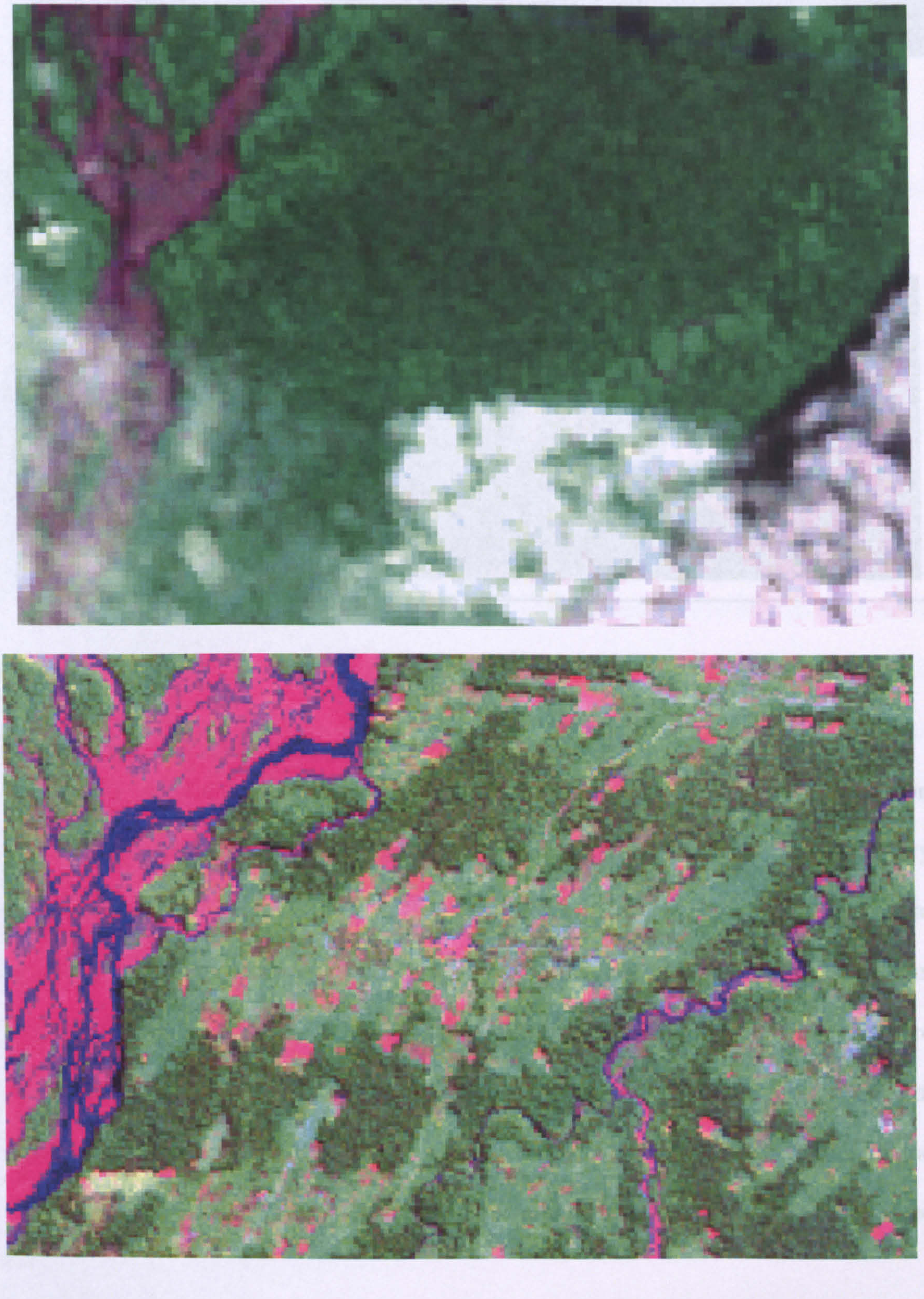


Figure 3.4: Some activities in Arequipa.

Right; rice crop on newly cleared land. The forest in the background will be cleared in 2-3 years when the rice yield falls. In the final year the rice is often intercropped with a perennial e.g. bananas.

Left; preparation of fresh stem of palm, the 'heart of palm' - known locally as a *tallo*.
Below, admiring the black pepper crop - *pimiento*. In the left background there is a stand of palm.

3.3 Bogotá

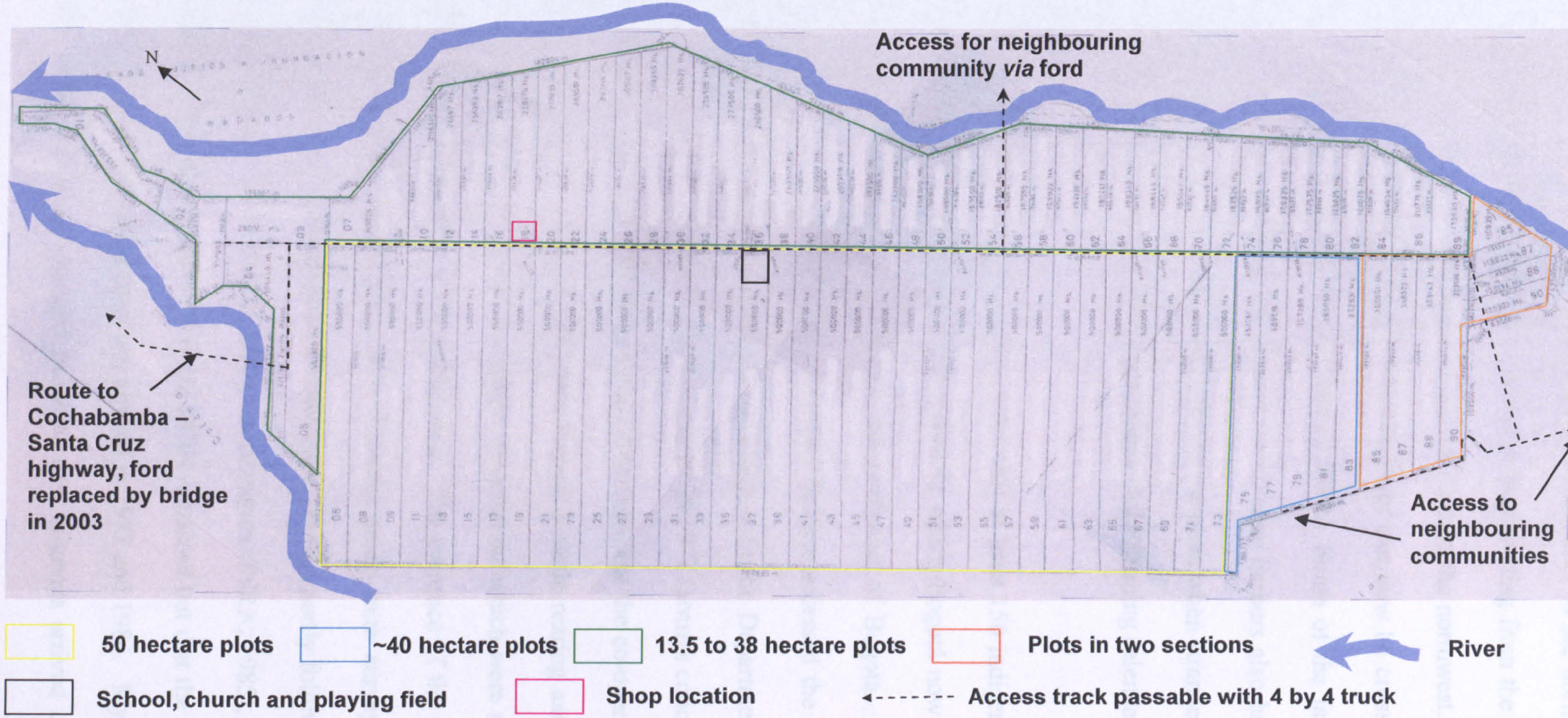
3.3.1 Location and aspect

The community of Bogotá is located to the east of the Ichilo sector (Millington *et al.*, 2002) or subregion VII (MACA, 1991) of Chapare (Figure 3.1). The community is approximately 30 km^2 in extent. The northern part of Bogotá is relatively flat land at an altitude of about 250 m.a.s.l. which increases to a ridge crest in the southwest with an altitude close to 350 m.a.s.l. The northeast and the northwest of the community are bordered by two rivers which join near the northwest corner of the community. Several small streams dissect the ridge and run northwest into the larger river bordering the northwest of the community. The estimated average annual temperature is 24 °C and rainfall is between 1,200 mm and 1,800 mm yr^{-1} (Maldonado, 1990). The climate has been classified as Af - Tropical always humid, in the Köppen classification (Montes de Oca, 1989) and as humid under the Thornthwaite (1948) system. Bogotá was originally tropical moist forest which borders a series of ridges of lower tropical montane forests to the south.

3.3.2 Structure and attributes

The area of the community is 3,196 ha. The INC surveyed 90 plots of land in the community. Most of the plots are 200 m in width and have access to an unsealed road which runs northwest to southeast through the community, but the length of the plots varies from 750 m to 2,500 m depending on the location of the plot in the community (Figure 3.5). The shorter plots are northeast of the road through the community and vary from 13.5 to 30 ha because a river forms the limit of possible cultivation. The longer plots are in the southwest of the road and generally vary from 40 ha to 50 ha. At the southeast end of the community there are four plots of land which are additional areas allocated to four of the shorter plots making the combined area of both close to 50 ha. There is a playing field, school and church situated in one plot – number 37 – and there is a shop in plot 18. Bogotá is bordered by other communities on all sides, but rivers run along the northeast and northwest limits. At the southern limit the road turns southwest towards the neighbouring communities and eventually to a guard post for Parque Nacional Carrasco. This road also facilitates access to the rear of the southernmost properties.

Figure 3.5 Plan of the community of Bogotá annotated with access roads, plot sizes, community facilities and rivers in the vicinity. Sizes of the plots are outlined and annotated in the key showing access roads passable with a vehicle (dotted lines). For an idea of scale, each of the 50 hectare plots is 2,500 m long by 200 m wide



There is also a road exiting from the centre of the community to the northeast which connects to the neighbouring community. The main road leading from the community to the Cochabamba – Santa Cruz highway crosses a river to the northwest. In 2003 a 100m long concrete bridge was constructed so the river can now be crossed all year round (also benefiting a number of other communities). Some of the farmers have houses on their plots and live in them all year, while other farmers also have another house in the nearby town and may use the houses on the plots when stranded by floods or when farmers are working long hours at busy times in the farming calendar.

3.3.3 History

Montes de Oca (1989; Table 2.1: 65) notes that at least 150 indigenous hunter gatherers known as the Yuqui populated the region in which Bogotá now falls. The Yuqui have since been settled in a village to the northwest of Bogotá. Before the Cochabamba to Santa Cruz highway was completed farmers accessed the community from the Yapacaní colonisation zone to the east which is in the Department of Santa Cruz. Bogotá was originally settled as a co-operative. In 1972 farmers concentrated on cultivating rice in one small area of the present community but the co-operative failed because of low rice prices. The colonists then formed a cattle rearing association in 1973. The area was divided up into two separate associations which were supposed to consist of 50 ha plots, either side of the spinal road. The presence of the river to the northeast determined that smaller plots with different areas were surveyed on the northeast side of the road. Unification of the two associations shortly followed but the date of this is uncertain. Documents in INRA Cochabamba (INRA, 1985), record that in 1985 a handful of the early settlers from the 1970s remained but that the majority of farmers (over 70 colonists and their families) arrived in 1983 and 1984. My interviews confirmed that plots have since changed hands as new migrants arrived in the early

1990s. Data from the BioAndes project (Lazcano, 2002) shows that settlers in Bogotá migrated in small numbers in the 1950s – 1970s (~10%), but most arrived in the 1980s (~75%) and in the 1990s (~5%). Most colonists arrived from Cochabamba (25%) and Potosi (17.24%) departments though thirty eight percent came from a combination of other departments and seven percent from the local area. Those that migrated during the 1950s and 1960s would have arrived before clearance began and probably had previously settled in other colonisation areas nearby, perhaps in Chimoré or Yapacaní. Those that arrived in the 1990s would have purchased and taken over ownership of plots of land since all plots were occupied in 1985 according to the INRA documents. The extent of deforestation from 1975 to 2000 can be seen in Figure 3.6.

3.3.4 Contemporary activities

The land use in Bogotá, (Table 3.2, Figure 3.7) is mainly orientated around the production of meat and milk.

Table 3.2: Agricultural activities in Bogotá. * see glossary (Appendix 1.1) for details on the unit of sale. Source: interviews; sample number n = 16.

Product	Responses	Unit of sale*	Approximate price per unit (2002)
Cattle Breeds			
Criollo	10	Head	700 – 1500 Bs
Pordo	1	Head	1400 Bs
Holandez	1	Head	1000 Bs
Cebu	1	Head	2200 Bs
Crops			
Banana	1	Raciones	2.5Bs
Cassava	5	Quintales	4 – 10 Bs
Orange	1	100 units	10 Bs
Mandarin	1	100 units	10 Bs
Rice	9	Fanegas	120 – 190 Bs
Nuts	1	Quintales	70Bs

The price of a head of cattle varies according to the breed and weight of a carcass. The Criollo breed is the most popular, but does not necessarily attain the highest price. Rice and cassava crops are the commonest alternative sources of rent to

Figure 3.6: The extent of deforestation in the vicinity of Bogotá in 25 years from 1975 (left) to 2000 (right). Dark green areas are forests and rivers are pink or blue 'ribbons' of colour. Clearance, pink and light green areas, began as a small block in the lower right quarter of the left image and expanded to consume a majority of the forest in 2000. The area of the image is approximately 9 by 10 km. The image is a MSS FCC bands 231, path 248 row 072, 16/09/1975. The lower image is an ETM FCC bands 741, path 231 row 072, 05/06/2000.

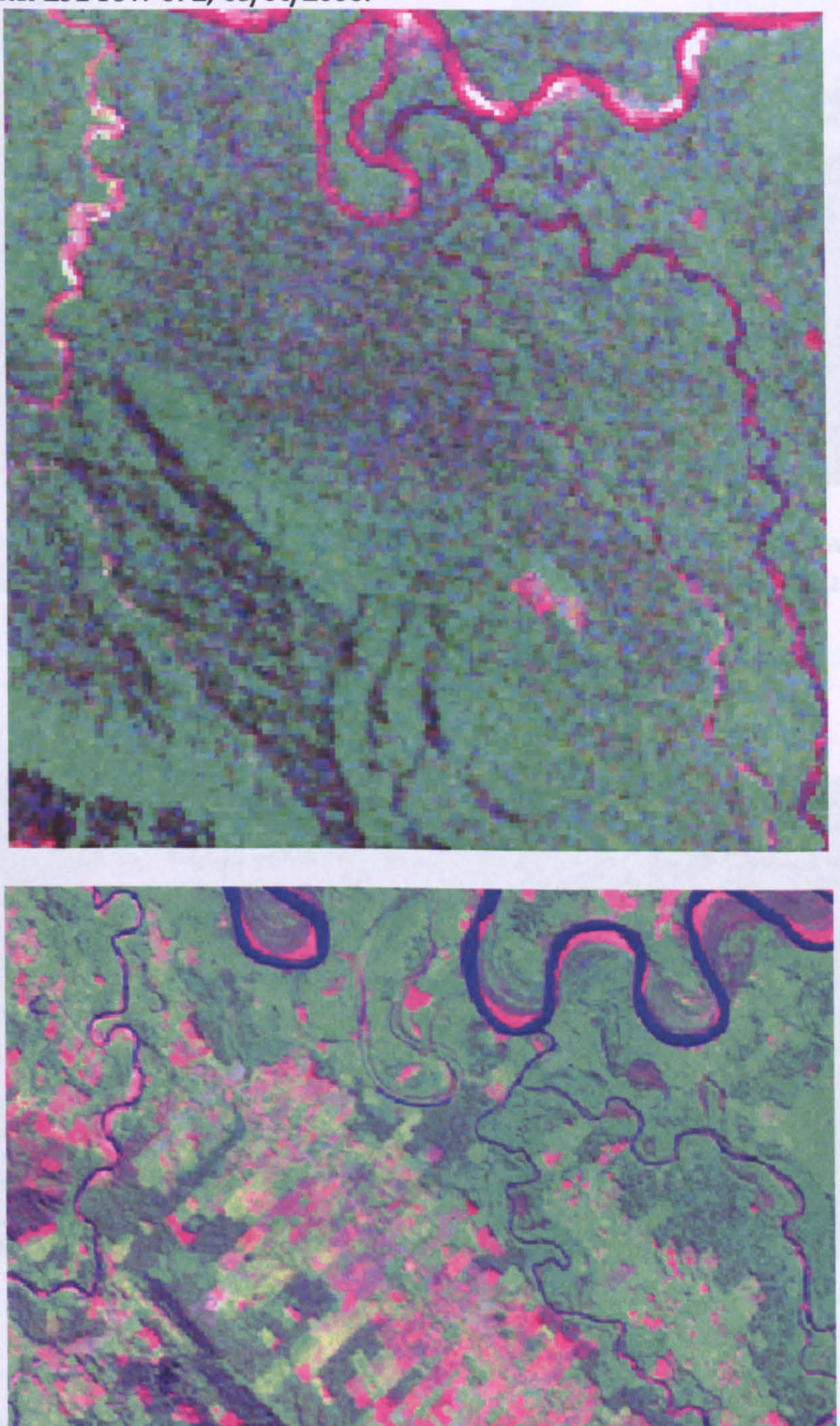


Figure 3.7: Some activities in Bogotá.

Upper picture: pasture land in Bogota, citrus trees provide shade for the cows and the erection of fences prevents cattle straying onto a neighbour's plot.

Lower picture: the forest in the background will be cleared for rice cultivation by slash and burn methods. In two or three years seed will be sown to create pasture.

cattle although citrus cultivation provides a source of income for some farmers. I observed coca in several locations although nobody admitted to cultivating it. Land is cleared by slash and burn. First a combination of rice, manioc and subsistence crops are cultivated to take advantage of the high nutrient levels in the soil immediately after burning. The land is then sown for pasture after two or three years. There was evidence of secondary re-growth and fallow indicating that some rotation of land-use may be occurring.

3.4 Caracas

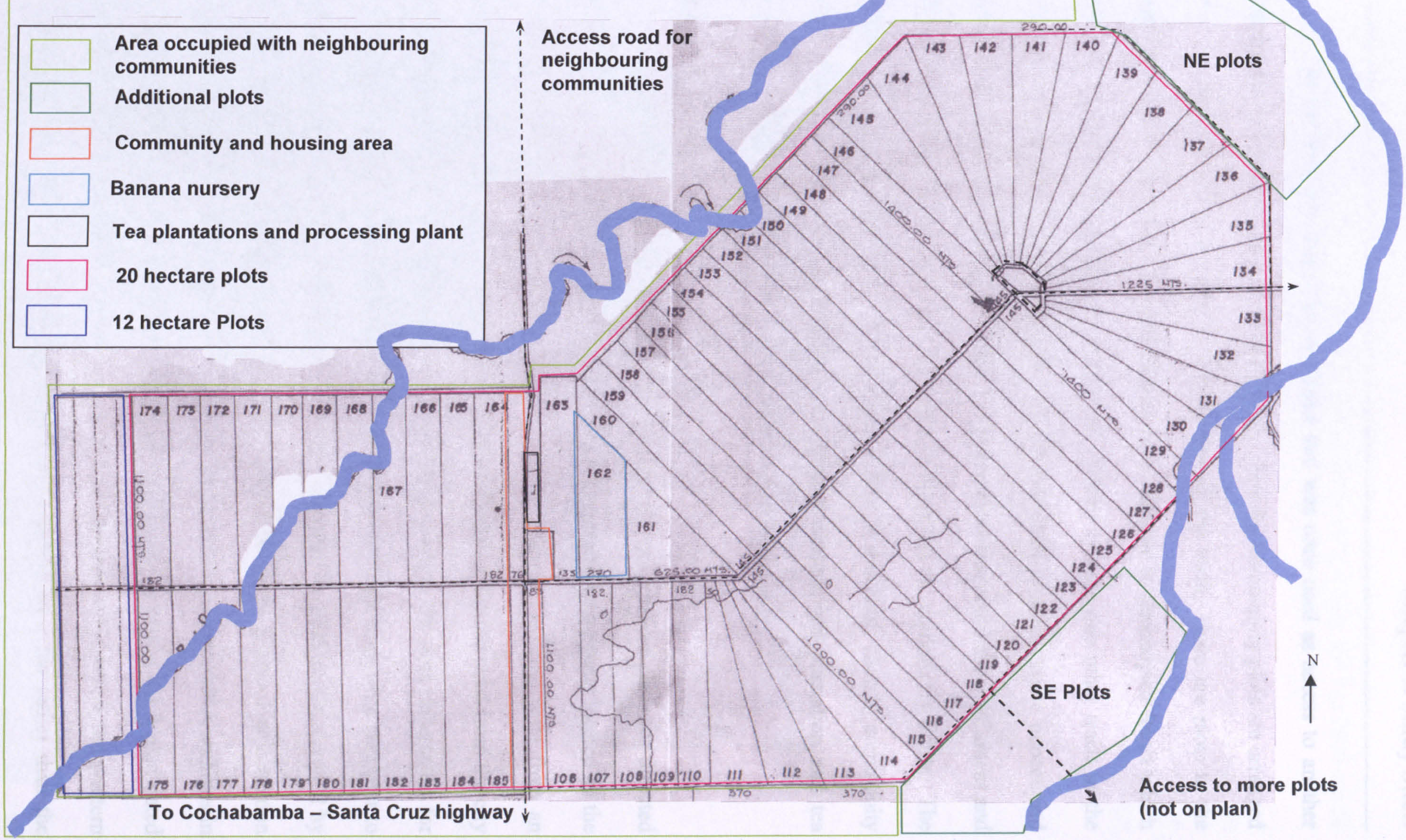
3.4.1 Location and aspect

The community of Caracas is located in the Tunari sector (Millington *et al.*, 2002) or subregion III (MACA, 1991) of Chapare, Figure 3.1. The community covers approximately 17 km^2 on relatively flat land at an altitude of approximately 220 m.a.s.l. The east of the community is slightly higher than the west which is bordered by a large river. Two eastward draining tributaries of this river roughly border the southern and northern edges of the community to the east, but one dissects the western side of the community. The estimated average annual temperature is 24 °C and rainfall is ~ 2,800 mm yr^{-1} (Maldonado, 1990). The climate is classified as Af - Tropical always humid, under the Köppen classification (Montes de Oca, 1989) and has hyper-humid conditions under the Thornthwaite (1943) scheme. Prior to clearance the vegetation was humid tropical forest, seasonally inundated to the east and *terra firme* to the west of the community.

3.4.2 Structure and attributes

The area of Caracas is 1,745 ha and contains 110 plots of land. These are mostly 20 ha in area though some are only 12 ha (Figure 3.8). The central point of the community is at a road junction where a cobbled road runs from the north linking Caracas and neighbouring communities to the Cochabamba to Santa Cruz highway to the south. Most of the farmers have constructed their houses in two parallel rows along the length of this road. Roads to the east and west provide access to farm plots.

Figure 3.8: Plan of Caracas, access roads passable by vehicle marked by dotted lines

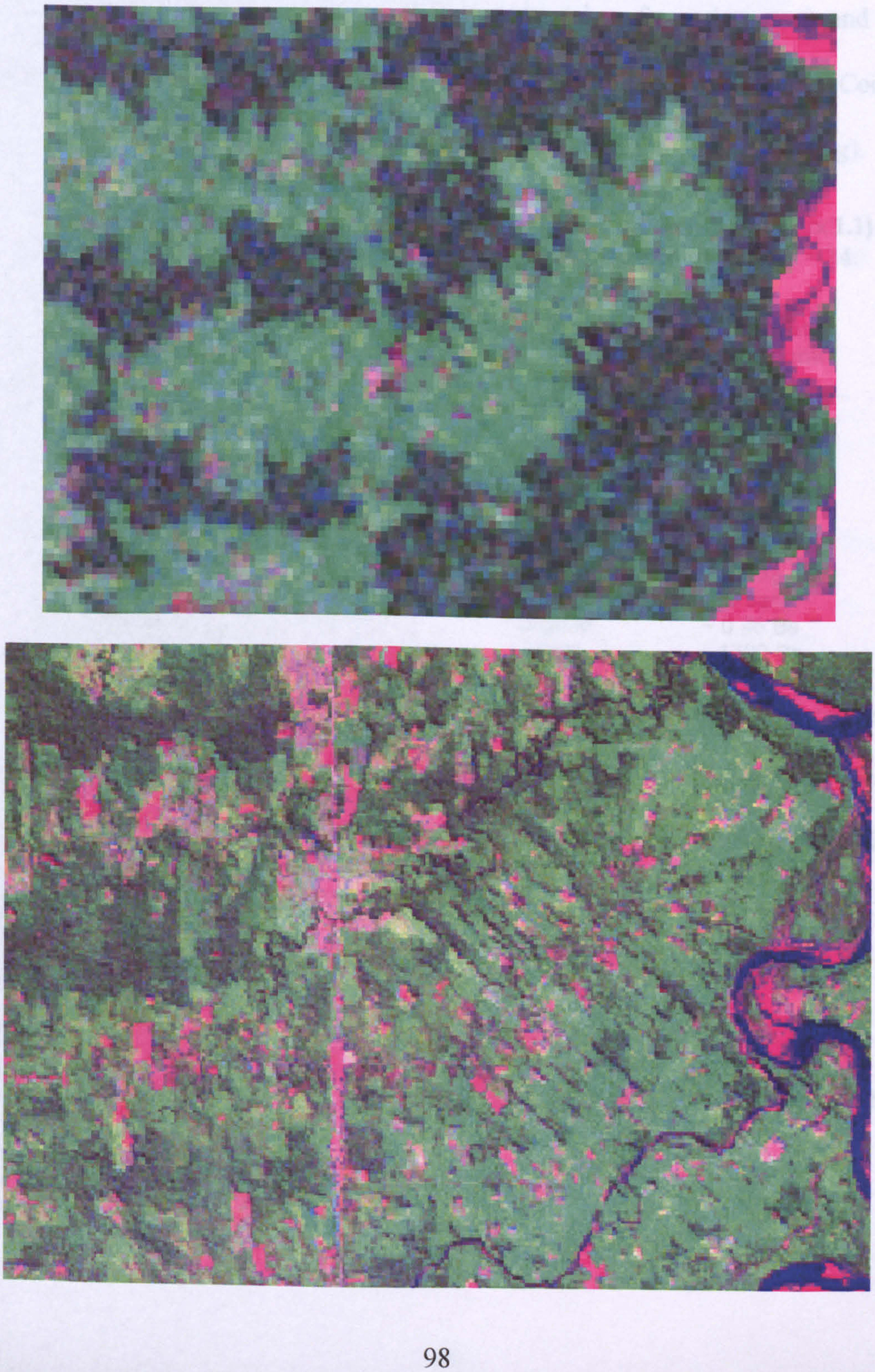


To the west the road turns northeast and was once used as access to another community on the other side of the large river. Here the community plots are arranged in a fan form to allow equal access at the end of the track. There are plots to the northeast of the fan which were established more recently in unoccupied forest which was not surveyed for the original settlement. There is only one other track in the community – along the southeast limit – which was built to access more unoccupied forest to the southeast of the community. A pathway has been cut between Caracas and the neighbouring community to the southwest to mark out the community limits. The 'centre' of the community is at the junction. There is a school, church, community centre, playing field, and some shops. A banana nursery, tea plantation and tea processing plant occupy plots close to the centre of the community.

3.4.3 History

The community was founded in 1963 as part of government plans for directed colonisation in the Cochabamba lowlands. This is celebrated by a plaque located by the roadside at the centre of Caracas. Members of the original *sindicato* were from an evangelist group who lived on the altiplano near to Potosí. They travelled from the city of Cochabamba and, with the help of the military, reached the area designated for colonisation and cut a four metre wide track north into the forest from what was later to become the Cochabamba to Santa Cruz highway. The area was previously occupied by an indigenous group known as the Yuracaré and in the early years of colonisation conflicts between the settlers and the Yuracaré were common. At the INRA archives in Cochabamba there are no details on individual land holdings except for a plan dated September 1977, this differs slightly from a plan in Henkel (1973) where the western end of the community was originally drafted to terminate as a fan rather than the repeated rectangular plots shown. The extent of deforestation from 1975 to 2000 can be seen in Figure 3.9.

Figure 3.9: The extent of deforestation in the vicinity of Caracas in 24 years from 1976 (top) to 2000 (bottom). Dark green areas are forests and rivers are pink or blue 'ribbons'. Clearance, light green and pink colours, was already well established in 1976 and continued to 2000. The area of the image is approximately 7 by 4 km. The top image is a MSS FCC bands of 231, path 249 row 072, 01/07/1976. The lower image is an ETM FCC bands of 741, path 232 row 072, 14/07/2000.



3.4.4 Contemporary activities

Most farmers grow, rice, maize, manioc and fruits for subsistence. The main cash crops cultivated in Caracas are predominantly tropical fruits, mainly bananas and citrus fruits (Table 3.3, Figure 3.9). Additionally, there are minor cash crops including the cultivation of rice (subsistence needs may be taken from this crop) and a few farmers cultivate tea and heart of palm or rear cattle for milk and meat. Coca was observed in small amounts and grown for household consumption (i.e. chewing).

Table 3.3: Agricultural activities in Caracas * see glossary (Appendix 1.1) for details on the unit of sale. Source: interviews; sample number n = 14.

Product	Responses	Unit of sale	Approximate price per unit (2002)
Banana	9	*Chipa*	~ 15-18 Bs
Banana (sweet)	2	*Carga*	~ 1.50 Bs
Orange	11	100 units	~ 3-15 Bs
Mandarin	10	100 units	~ 3-15 Bs
Rice	2	*Quintales*	~ 40Bs
Pineapple	1	Unit	No data
Tea	1	Kilogram	~ 2Bs
Coca		*Carga*	No data
Heart of palm	1	*Cogollo*	~ 0.96 Bs
Cattle	1	Head	~ 1700 Bs

Slash and burn is the main method of clearance. A number of farmers are currently leaving areas to regenerate into secondary forest and they plan to clear this after three to eight years. Rice and maize are grown first in the nutrient-rich soils and are then followed by perennial crops such as bananas, plantain or citrus. Intercropping of a perennial crop like bananas with fruit trees is not uncommon because of the length of time for a citrus crop to mature. There are a few plots with up to a hectare of tea which supplies the tea processing facility in Caracas. Tea plantations in other Chapare communities also supply the facility.

Figure 3.10: Some activities in Caracas

Above: Citrus orchards are commonplace in Caracas. It can take seven years for a tree to mature and produce fruits.

Left: Harvesting bananas. After approximately 9 months the bunches (known as *chipas*) are cut. The bunches are then hung on overhead rails which lead to a preparation shed where they are packed for export.

Chapter 4

Methodology

Chapter 4

Methodology

4.1 Introduction

To understand LULCC it is necessary to contextualise the evidence obtained from satellite image sequences. Changes in the spatial patterns of land-cover from imagery constitute the dependant variable of land-cover change, and the independent variables are the parameters representing the drivers of change. A methodology to link the spatial patterns with the driving forces of change requires knowledge of the actors in the study area and the influences on these actors from outside their communities. To achieve this, a methodology was adopted which loosely follows the framework of the IHDP-LUCC programme which, according to Fox *et al.* (2003), has been of great value to researchers when considering methodological and practical issues associated with land-use and land-cover dynamics such as data generation, collection and analysis.

In this chapter I describe the data sources used, the different stages in data processing, the kind of information that I extracted for analysis as well as data quality issues. First I describe how socio-economic data was obtained. This section is divided in two parts; obtaining evidence from the agents of deforestation acting on the area (Section 4.2), and obtaining evidence on economic and policy drivers acting on area (Section 4.3). The final part is concerned with how satellite images were used to provide information on the temporal trends and patterns of LULCC (Section 4.4). This research involves the production of forest and non-forest maps and the use of landscape metrics to quantify forest fragmentation.

4.2 Community and farm surveys

4.2.2 Community surveys

Chapare is the main illegal coca growing area in Bolivia and in 1986 85% of coca growing families in the country lived in Chapare (MacGregor, 1993). Therefore, because of the sensitivity over growing coca illegally, participation of communities and individuals required building a level of trust before embarking on conversations with farmers about their land management activities. This section describes how information on land-use within this difficult and sometimes volatile region was gathered and used to establish the basis for the image classification. First, the choice of communities is described. Secondly, the methods of engagement with the community members are presented.

4.2.2.1 Selection of communities and farmers

As a consequence of the dangers in the Chapare region, the communities chosen for research relied on established connections through joint international research projects between the University of Leicester, the UMSS – CBG in Cochabamba, and links through a non-governmental organisation (NGO) operating in Bolivia. Contact with two of the communities – Arequipa and Bogotá (Chapter 3) – already existed through research undertaken between 1999 and 2002 under the BioAndes Project (Chapter 1, Footnote 1). Research in the third community – Caracas (Chapter 3) – was negotiated by my field assistant Felix Huanca Viraca (FHV) – through Centro Desarrollo Integral an NGO based in Cochabamba which has links with communities through twinning of their churches. The communities practice a range of agricultural activities found in Chapare and they were also settled at different times. Arequipa is predominately a fruit growing community, and was settled in the early 1980s. Bogotá is a cattle rearing community, where the original inhabitants settled in the mid 1970s but the majority of settlers arrived in the early 1980s. Caracas, is also a predominately fruit growing area with some cattle, but was originally settled in the early 1960s.

The general model of entry to each community was to first approach community members who had been elected to the head of a community organisation (*dirigenties*) and were known through previous research (BioAndes) or existing links with FHV. Community organisations included the *sindicato* (the community agricultural union), school groups, women's groups and church groups. Making contact with these individuals helped endorse my presence with a respected community member which allowed me to:

(i) identify and approach, or be recommended to, other members of the community; and

(ii) be invited to the *sindicato* meetings and other community meetings such as church services and school committee meetings.

After we had recruited farmers, information was gathered through Rapid Rural Appraisal (RRA) techniques (McCraken *et al.*, 1988), for example, participation in meetings, semi-structured interviews based around open ended questions on a questionnaire, farm walks and farm mapping, and group discussions (Section 4.2.2.2). The data collection was often a retrospective view of how agricultural preferences had changed over time, so during the interpretation care needed to be taken regarding the respondent's recall of memories and changing of circumstances through time (Rindfuss *et al*, 2003; 2004). Prior to the fieldwork, assessment of the Chapare region by browsing satellite imagery helped focus the questioning with respect to LULCC. The advantages of this remote sensing data for RRA in the pre-fieldwork stage are discussed in deCastro *et al.* (2002).

4.2.2.2 Data gathering using RRA approaches

(a) Participation in meetings

As large numbers of people would attend these meetings our (myself and FHV) presence served three purposes:

(i) safety – the community members recognised us as 'accepted' researchers in the community;

(ii) to recruit more farmers to interview; and,

(iii) to understand how networks and institutions functioned in the community.

To retain the relationships with the communities for possible future research and a gesture to the community for their participation, a complete football strip, footballs and basketballs were presented to each *sindicato* in the communities.

(b) Semi-structured interviews based on questionnaires

The questionnaires were developed in discussions with social scientists at UMSS to ensure the inquiry would not provoke too much suspicion or incorrect interpretations of my motives for the study[1]. In addition I was advised to keep visits to two or three days at a time in order to avoid time for discussion within the community which could potentially have lead to opposition of the study and, perhaps, compromise our safety. The questionnaires were designed to cover the following points:

(i) To maintain clarity of the objectives between myself and the field assistant (neither of us spoke each others first languages fluently).

(ii) To ensure consistency in baseline information gathered from each farmer by covering a specific set of topics related to LULCC.

(iii) As a means to document information and encourage participation of the farmers by sketching a plan of their plots and their management of them.

[1] There is still some bad feeling in the region after the coca eradication policies of the 1980s and 1990s. In the interview process the potential dangers were reinforced when one farmer talked of the shooting of a lone *gringo* in the locality of his community.

(iv) To document details about the farmer and his plot for future surveys.

(v) To reference the farm plot to the cadastral maps made by the Instituto Nacional Reforma Agraria (INRA).

The questionnaire (Appendix 4.1) was structured to examine current agricultural management, early development of the plots, major changes in economic activities and future use of the farm plots. The gathering of household data could then be compared with imagery to interpret LULCC.

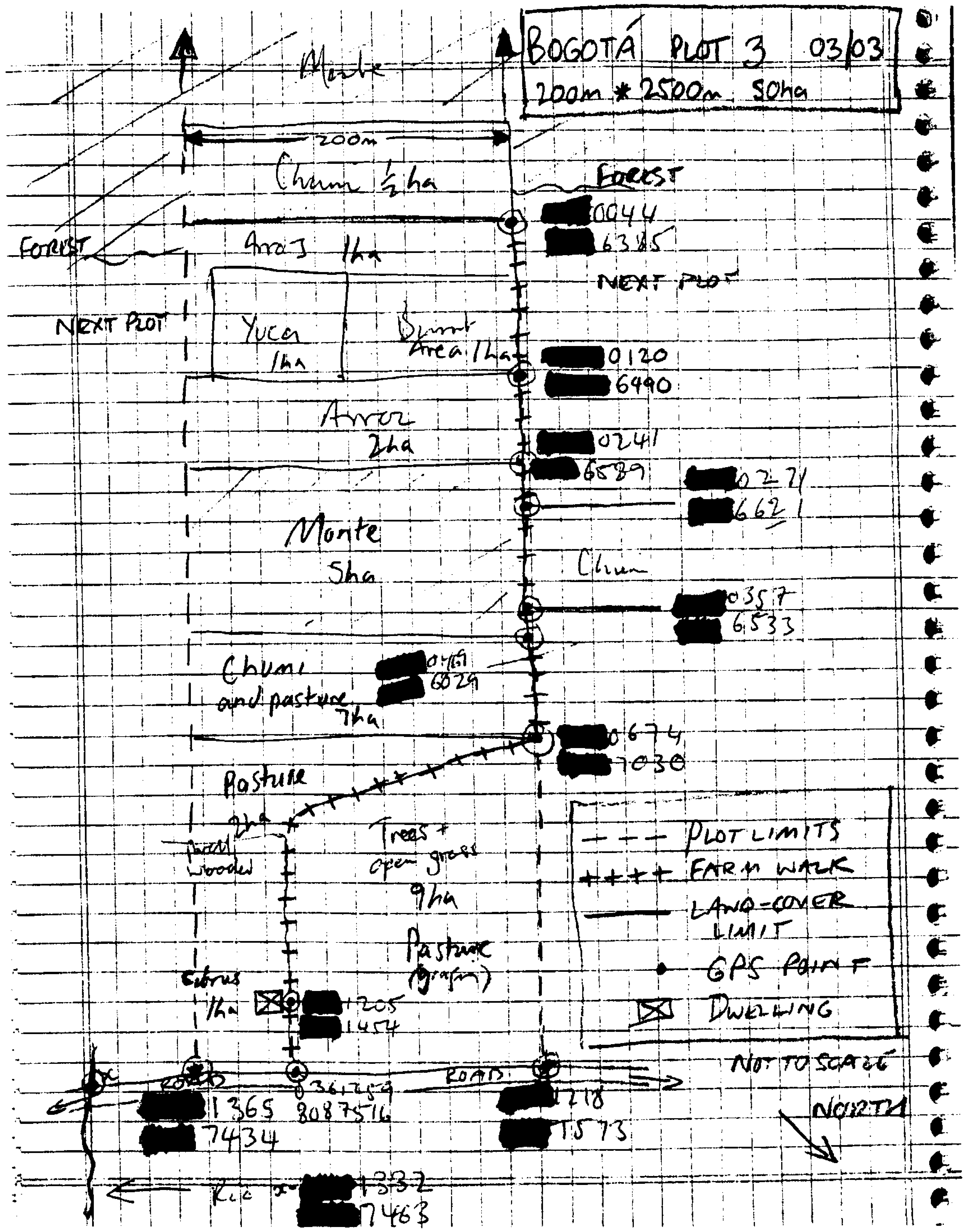
(b) Farm walks and farm mapping

The objective of the farm walks was to discuss informally, observe and map the spatial organisation of land use on an individual plot with the owner. These opportunities also gave me the chance to verify the information on land use management activities occurring on the plots obtained in the interview survey. It was an informal method of gathering information not covered by the interview. Walks also provided an opportunity to map land-cover and record map co-ordinates with a handheld Global Positioning System (GPS). I had to be tactful about the use of the GPS as the implications of taking co-ordinates near coca crops may have been misunderstood as 'government surveillance' by the farmers. A field sketch was made of each plot (Figure 4.1).

4.3 Economic and policy trends

To investigate the underlying causes of LULCC I needed to gather information on market and policy trends. Economic data is important in contemporary LULCC studies as these are indicators behind the short term economic and technological factors which lead to land-use and cover change (Lambin *et al.*, 2003).

Figure 4.1: Example of a field sketch of a plot in Bogotá showing the spatial aspect of land management of a farm plot in 2002. The access road, farm walk, parcels of land-cover types and GPS locations are shown. The first few digits of the GPS reading has been covered to retain anonymity of the location. *Monte, Chumi, Yuca* and *Arroz* are Spanish for mature uncut forest, forest re-growth, manioc and rice respectively.



4.3.1 Economics

Production of agricultural goods is mainly driven by the demands of the markets. I needed to find out the structure of the market and at what scale the markets operated i.e. local, regional, national or international, and what competition exists at these different levels. This information gave me insights into the extent of the demand for particular products and what was leading farmers to choose which crops to grow. In other words, how wide reaching is the political economy that influences the decisions of farmers creating LULCC?

The cultivation of different crops has implications on land-use management which indicate pressures to clear more forest, so the approach adopted aimed at finding the spatial and temporal variations in products grown in the communities. For each product / crop I obtained details on prices to identify inter-annual and seasonal fluctuations, and to identify other significant price variations. Some of these details, such as farm gate prices and market networks, could be established from interviews, farm walks and tours and informal discussions in the field (Section 4.2.2.2). For a more accurate record of prices beyond the memory of farmers I visited documentation centres which held long term market price records. In this context I relied mainly on the Institute Nacional de Estadisticas (INE), the GoB Statistics Centre, and USAID libraries in Bolivia.

4.3.2 Policies

Policymaking is a constantly changing underlying cause of LULCC. Macroeconomic policies and development policies have a temporal influence on the regions of Bolivia and the approach needed to find out what the major policy shifts were during and leading up to the satellite image sequence. The historical context of Bolivia outlined in Section 1.3.2 describes that in the period after the agrarian reform (1952) leading up to the beginning of the 1970s, when the image sequence begins, highland impoverishment was becoming more acute and the country had become reliant on a mineral export economy. These factors were constraining national economic development and a number of economic policies were needed to counter these problems. The research here needed to explore the impacts of:

(i) national development policies applied by Bolivian governments to Bolivia as a whole. This included macroeconomic policies affecting colonisation, agriculture, transport and energy, which may have subsequently been revised or abandoned i.e. the particular underlying causes that have driven LULCC in Chapare.

(ii) The recent history of coca leaf cultivation has attracted international attention to the Chapare region. Evaluation of the policies designed to counter the cultivation of coca leaf was necessary and the impacts of these measures adopted were considered in the light of evidence of LULCC in Chapare.

In both cases the time scale for policy evaluation included the run up to the start of the image sequence (i.e. 1950s) as well as during the image sequence (1975 to 2000). To gather this information I interviewed Bolivian historians and staff in the USAID offices in Cochabamba.

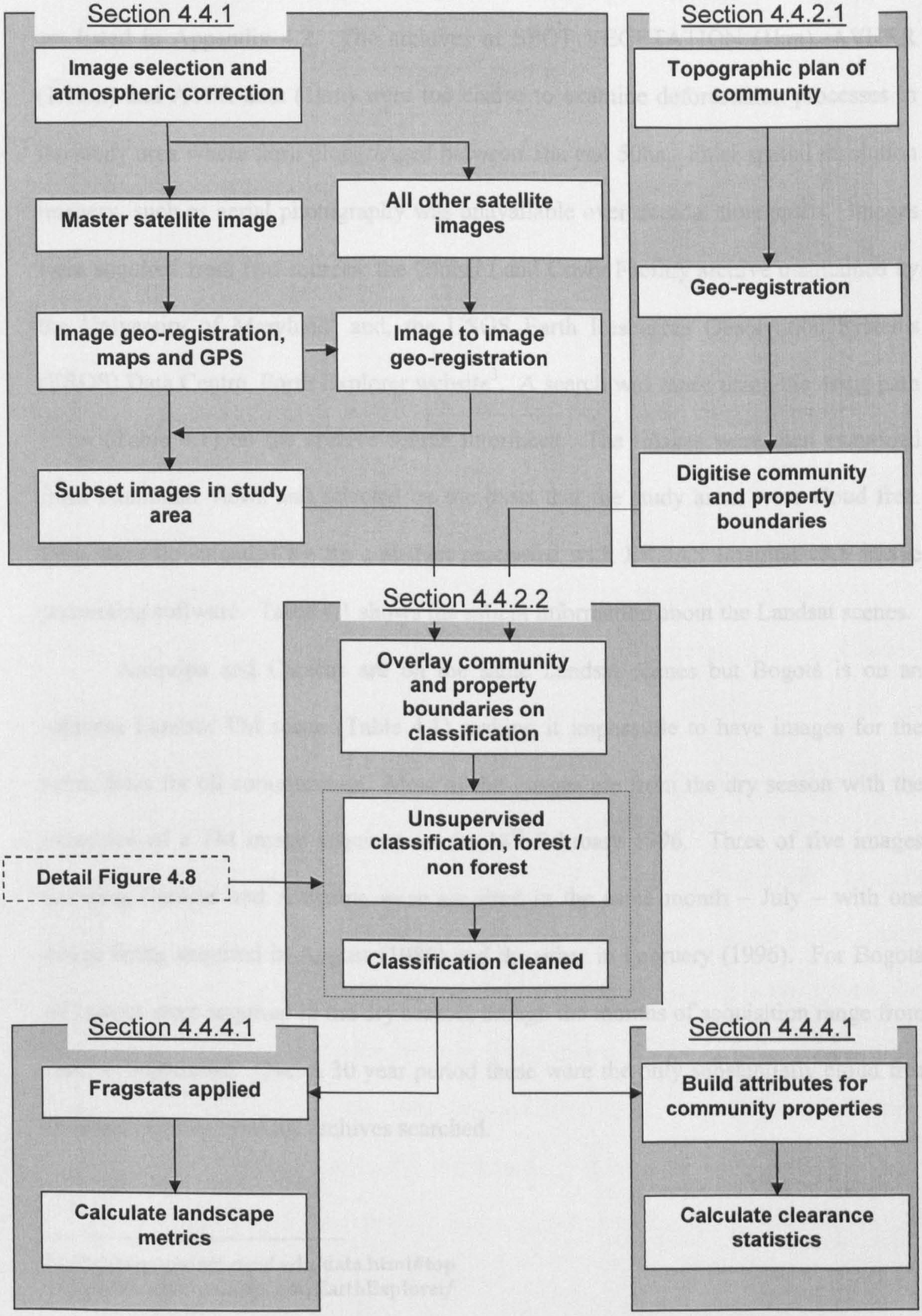
4.4 Determining LULCC trends and patterns with satellite imagery

A flowchart of the methodology (Figure 4.2) describes how other data sources were combined to give added value to the satellite images to determine the LULCC trends and patterns.

4.4.1 Source and selection of images

Landsat imagery was chosen as it has been found to be appropriate for the study of LULCC processes at the scale to be examined (e.g. McCraken *et al.*, 1999), the

Figure 4.2: Flow chart of the methodology. Boxes are titled to indicate the relevant sections in the text.



Landsat data set is readily available at low cost (Janetos, 2004) and the Landsat mission has been ongoing since 1972 (Morain, 1998; Goward *et al.*, 2001). The spectral and spatial details of Landsat satellite missions can be found in Campbell (1996: 164) and are listed in Appendix 4.2. The archives of SPOT VEGETATION (1km), AVHRR (1.1km) and ATSR data (1km) were too coarse to examine deforestation processes in the study area where farm plots ranged between 5ha and 50ha. Finer spatial resolution imagery, such as aerial photography was unavailable over decadal time spans. Images were acquired from two sources; the Global Land Cover Facility archive maintained by the University of Maryland[2] and, the USGS Earth Resources Observation Systems (EROS) Data Centre, Earth Explorer website[3]. A search was made using the using path / row (Table 4.1) on the archive search interfaces. The images were then examined from thumbnail views and selected on the basis that the study areas were cloud free. Data were downloaded by ftp and then processed with ERDAS Imagine v8.5 image processing software. Table 4.1 shows the salient information about the Landsat scenes.

Arequipa and Caracas are on the same Landsat scenes but Bogotá is on an adjacent Landsat TM scene (Table 4.1) making it impossible to have images for the same dates for all communities. Most of the images are from the dry season with the exception of a TM image acquired on the 18th February 1996. Three of five images covering Caracas and Arequipa were acquired in the same month – July – with one image being acquired in August (1986) and the other in February (1996). For Bogotá all images were acquired in the dry season, though the months of acquisition range from June to September. Over a 30 year period these were the only substantially cloud free images available from the archives searched.

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[2] http://esip.umiacs.umd.edu/data.html#top
[3] http://edcsns17.cr.usgs.gov/EarthExplorer/

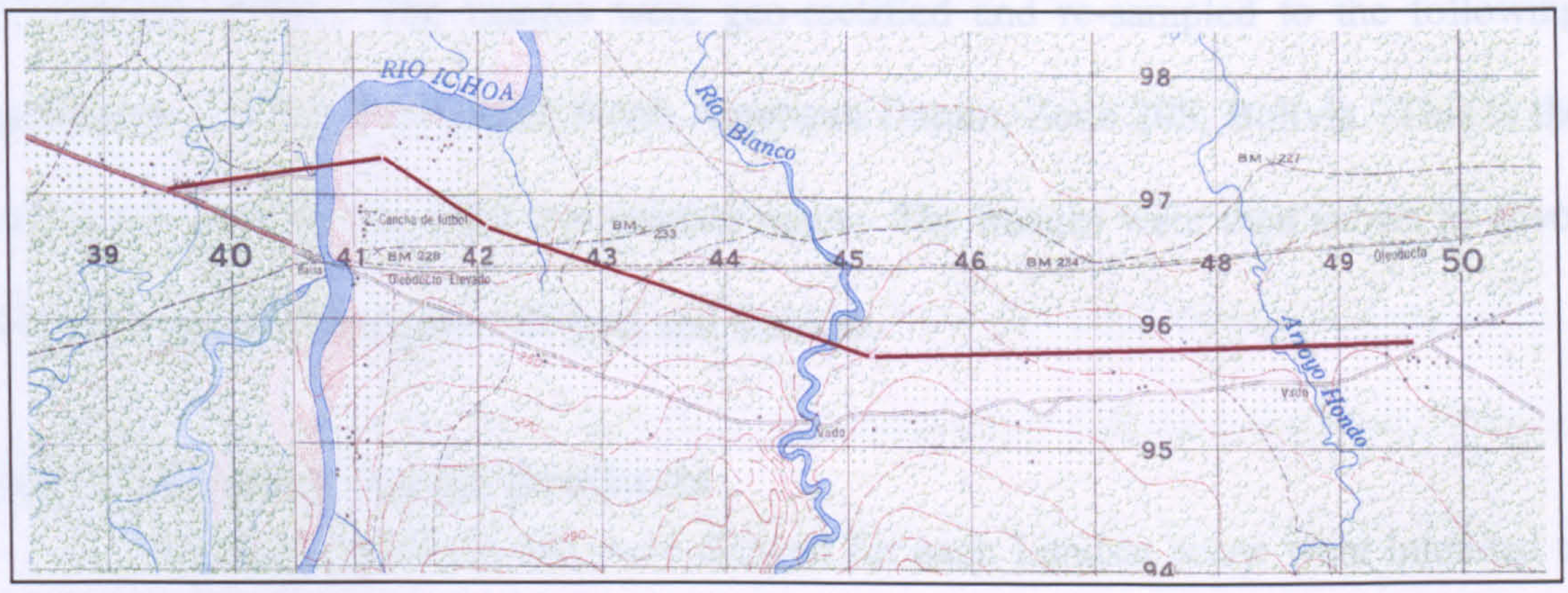
Table 4.1: Details of satellite image scenes. RMS refers to the root mean square of distance between the newly transformed co-ordinates calculated from the GCPs used to resample the images during geo-rectification (ERDAS, 2001)

Landsat mission/ sensor	Path / row	Date	Local Time (hrs)	Sun azimuth (degrees from north)	Sun elevation (degrees)	Root mean square (RMS)
			Arequipa & Caracas			
2 / MSS	249 / 072	01/07/1976	09.34	47	32	0.17
		04/10/1986	09.43	74	52	0.01
5 / TM	232 / 072	18/07/1993	n/a	n/a	n/a	0.20
		18/02/1996	09.43	89	44	0.23
7 / ETM	232 / 072	14/07/2000	10.14	41	39	0.01
			Bogotá			
2 / MSS	248 / 072	16/09/1975	09.34	66	47	0.28
		25/07/1986	09.39	49	36	0.21
5 / TM	231 / 072	09/07/1992	n/a	n/a	n/a	0.07
		05/08/1996	n/a	n/a	n/a	0.13
7 / ETM	231 / 072	05/06/2000	10.08	38	40	0.12

Atmospheric correction was applied to the images to remove the radiation reflected from the atmosphere which is included in the pixel brightness values. Water bodies were used to examine the pixel brightness values for each band because the least energy is scattered from dark objects. Clear water absorbs strongly in the NIR thus water should have pixel values close to zero if atmospheric scattering is absent (Chavez, 1975). The images were then atmospherically corrected using the histogram minimum method (Campbell, 1996).

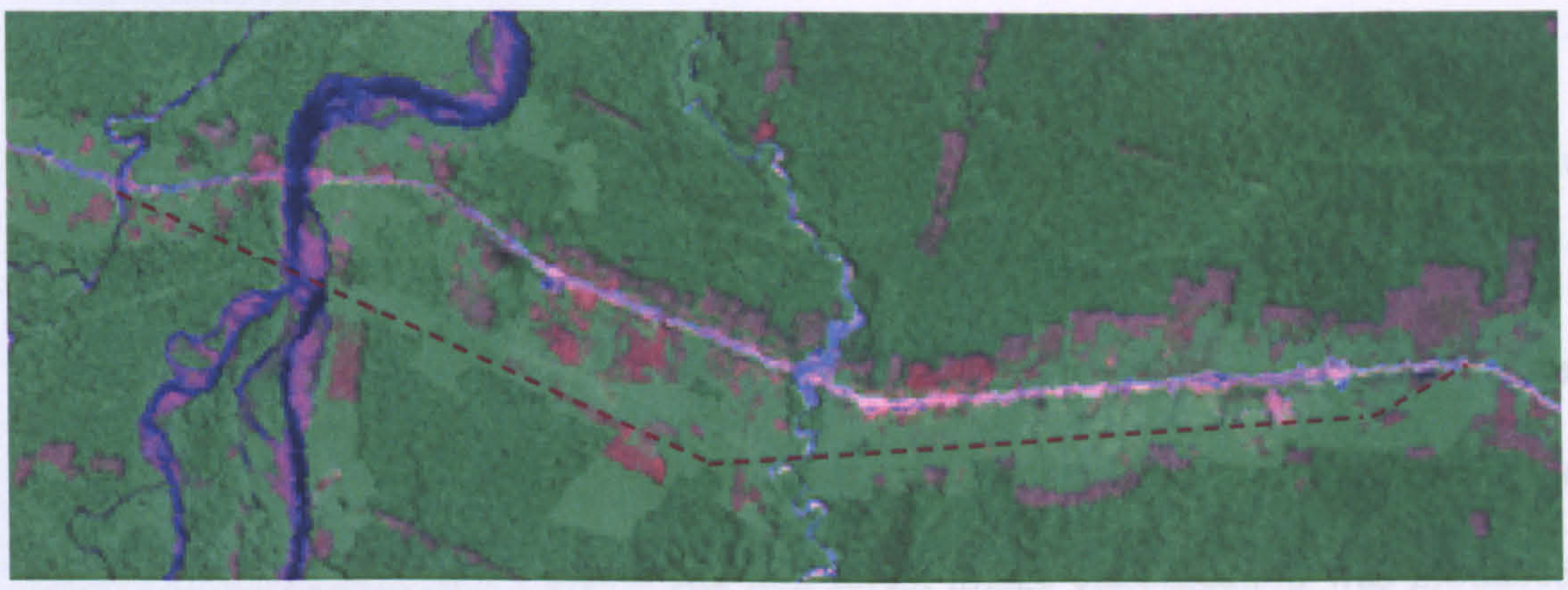
The images were geo-rectified to allow accurate change detection to be undertaken using image-to-image registration. The TM scenes 04/10/1986 (for path 232, row 072) and 25/07/1986 (for path 231, row 072) were selected as the master images, because these images were the closest dates corresponding to the 1984 aerial photographs used to produce the Instituto Geográphico Militar (IGM) 1:50,000 scale topographic maps of Bolivia; the latest maps available for the area. Even so differences were observed between the maps and the images. For example, Figure 4.3 (a) and (b) illustrates a new major road on an image which had not been recorded on the topographic map published two years earlier.

Figure 4.3: Referencing a map to an image. An example of discrepancies between the topographic map (a), created from 1984 aerial photographs and, satellite image acquired on 11th April 1986 (b) close to the Río Ichoa. Minor changes in water courses and re-routed roads were some of the problems encountered. Renewed forest clearance patches (reds, pink and light green) associated with the new road (pink line) are visible



1986 Road

(a) 1984 Extract from topographic map sheets 6642 II and 6742 III, © IGM.



1984 Road

(b) Image, 11 April 1986

The location of ground control points (GCPs) on the map thus required careful consideration of new road engineering projects and variations in water courses. Table 4.1 indicates the Root Mean Square (RMS) values for the re-sampled master images and the images subsequently geometrically corrected to the master images. A user defined threshold (Jenson, 1986) was considered the best threshold to ensure that after re-sampling, pixels were only statistically offset by an RMS equal to 0.3 pixels. The nearest neighbour algorithm was used to resample the images to avoid changing pixel brightness values. The other algorithms available in the ERDAS software were bilinear interpolation – which creates new pixel values – and cubic convolution – which produces more attractive images but pixel brightness values are drastically altered (Campbell, 1996). The images were geo-rectified and re-sampled to the following projection – UTM, Provisional South American Datum, Zone 20S, Bolivia. This is the projection used for the IGM topographic maps. The images were then subset to cover the study areas of Arequipa, Bogotá and Caracas.

4.4.2 Deriving image products

The image products that were derived for each Landsat scene were intended to serve two purposes:

1) to create forest / non-forest land-cover maps for each year that could be used for LULCC calculations; and
2) to create a sequence of land-cover change maps for use in discussions about the history of each community and maps for field verification on a second field visit.

The following section describes how the statistics and maps were created from the subsets of the imagery. First, the community plans were digitised and superimposed on the imagery. Secondly, a forest and non-forest image classification was produced. Finally, for each corresponding plot marked on the plans the areas of forest and non-forest was calculated. Clearance areas, rates and trends were calculated at the community and plot levels.

4.4.2.1 Overlay of community boundaries on the imagery

Three studies that have previously linked deforestation to colonisation in the tropics have used different methods to link LULCC to land tenure. In Altamira, Brazil, plot allocations have been described to follow a predictable herringbone pattern and were initially digitised from satellite imagery (McCraken *et al.*, 1999). In Ecuador, detailed aerial photography was used to identify farm boundaries (known as *fincas*) (Walsh *et al.*, 2003) and in Thailand cadastral maps with plot limits relating to deeds, held in land reform offices were digitised (Rindfuss *et al.*, 2003). I was unable to use the herringbone clearance pattern to map directly onto the imagery as these patterns were not obvious for the Chapare study area (Figure 3.1) and no aerial photographs were available to estimate the boundaries. Instead I used a method that was closest to that used by Rindfuss *et al.* (2003). Cadastral plans and legal details of early settlers (*asentamientos*) who were members of the community agricultural unions (*sindicato*) of Arequipa, Bogotá and Caracas were available in folders archived by INRA in Cochabamba (INRA, 1985; 1986a,b). The plans are annotated with details of community dimensions, plot limits and areas for all plots in each community. Each plot has a number and sometimes an owner's name written on the plan. The plans were critical in providing information on land tenure arrangement of individual plots in the communities. These data relate to the time of the survey in 1985 and 1986 and do not indicate any changes in ownership or possible division of plots up to the field visits in 2002 and 2003. The plans were then:

(a) geo-rectified, re-sampled and digitised;

(b) overlain on the images; and,

(c) checked for any major discrepancies between the image and plans.

The topology was then built for the digitised data in Arc/Info and the vector layers were used to query the satellite image products of forest and non-forest to measure land-cover change within the community and the individual plots.

(a) Geo-rectification, re-sampling and digitising of INRA plans

It was only possible to make A4 sized photocopies of the plans in Bolivia. These were scanned as jpeg files at Leicester. The jpeg files were then joined together in CorelDraw9 software and imported into ERDAS Imagine as image files. Correct geo-referencing of the plans required the positioning of ground control points on attributes of the plans e.g. *arroyos* (streams), community limits, tracks and boundaries marked on the topographic maps. Co-ordinates of these features had been recorded in the field using a non-differential GPS (12 channel Garmin GPS XL 12)[4]. In addition, because the ground control points were recorded during the farm walks, I was able to triangulate farmer's comments on plot arrangements with the INRA plans. The plans were then re-sampled to the same projection as the images and the community and plot boundaries were digitised on screen to create a polygon vector layer for use in ArcMap.

(b) Overlay on imagery

After geometric rectification and digitising of the vector layer it was apparent that some plot boundaries were not consistent with agricultural clearance patterns observed on the imagery. During digitisation it was found that parts of the plans had become slightly distorted through the processes of photocopying, creating the mosaic and geo-rectification. Superimposition of the plans on the imagery also indicated that some plots in particular communities did not conform exactly to the plans as drafted by the topographers. On initial settlement, farmers described how surveyors marked out the community limits and the first few tens of metres of their plots (Figure 4.4). The owners were then responsible for completing their boundary limits within the first year of settlement. Thus some boundaries may have been subject to surveying errors caused by topography and inaccurate extension of the survey by settlers. However, very few farmers mentioned disputes with neighbouring plots in the same community. The only

[4] Potential errors of the GPS were unknown at the time of collection as they were not differentially corrected, but assumed to be within 15m (at least 1 Landsat pixel) of the ground location (manufacturer's specification). The GPS co-ordinates therefore could only be used as a guide to identify features on the imagery - nevertheless this proved to be a very helpful tool. The US selective availability program which degrades the GPS system by up to 100m has been deactivated since May 1st 2000 and remained so after the period of the fieldwork. (http://www.igeb.gov/sa/)

disputes mentioned were over plots which backed onto neighbouring communities. This was a particular problem in the oldest of the three communities, Caracas, where disputes over its western and south western limits are ongoing. Figure 4.5 illustrates this point showing how the intersection of the three communities land, deep in forest has been surveyed at three different positions at different times. The discrepancies in the three surveys indicate the general point that in reality the intended superimposition of the topographic plans may not have been achieved on the ground and farmers have land parcels which deviate from the intended boundaries. Alongside the survey errors are those generated during image processing as it is possible that warping of the images during the geo-rectification may have produced some image distortion. A component of this error may be due to the nearest neighbour analysis as this re-sampling algorithm which can cause positional errors which are noticeable in linear features (Campbell, 1996).

To combat these errors, sections of the plans were re-digitised to coincide with features visible on the imagery like tracks, bridges and plot boundaries (seen as corridors of clearance) with attributes marked on the plans. These features were best seen on the Landsat TM 741 false colour composites (FCC) on the following subscenes – Caracas 18/07/1996, Arequipa 14/07/2000 and Bogotá 05/06/2000. Using the FCC the most recent image dates were best for plot boundary mapping because progression of forest clearance along plots boundaries could be identified. In order to ensure the plan dimensions were consistent for the other image dates the polygon files were copied and re-aligned over the other image dates in the sequence, again using features visible on the other images. Plot areas were calculated after polygon topologies were built

Figure 4.4 (right): Plot boundary in Arequipa. The boundary was marked by clearing a straight line into the forest and marking it with stakes in the first year of settlement (1983). The picture shows one of the stakes, the next stake is approximately 50m away next to the farmer (circled).

Figure 4.5 (below): Errors in boundary limits. This is the meeting point of three communities. The post with the yellow marker (A) appears to have been surveyed by PRAEDAC in 2002, using GPS, perhaps DGPS. Prior to this a small concrete marker (by rucksack and hat B) had been the official marker (surveyors and date unknown). Going back earlier a concrete block inscribed with 1983 under the feet of my field assistant, FHV (C) on the left represents the first survey of the community boundaries in the forest.

using Arc/Info software. However, some minor biases between the topographic and digitised plans remained after this.

(c) Differences between cadastral plans and the digitised plans

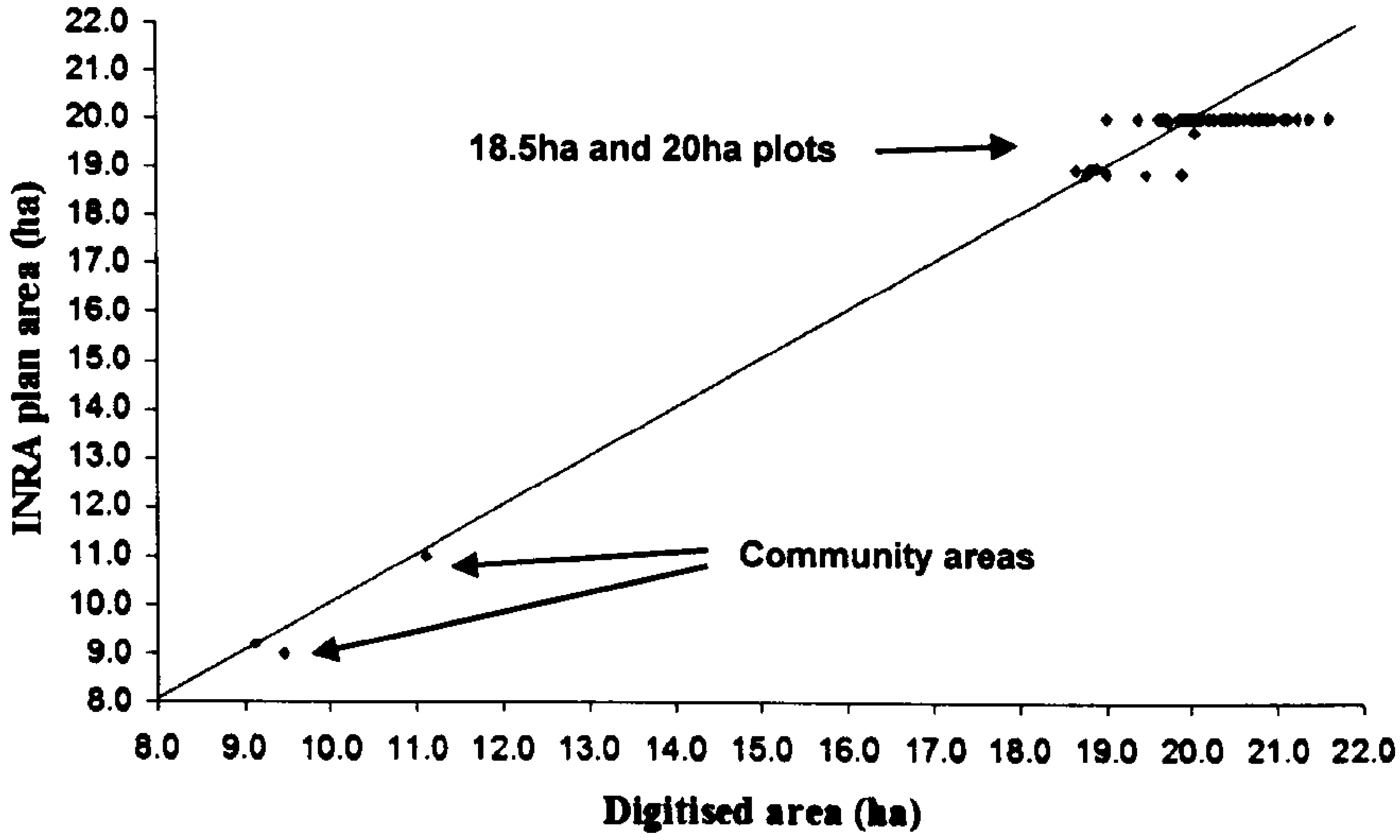
With the combined errors of digitising, GPS survey, image rectification and evidence for errors in ground surveys, it was difficult to correct the plans perfectly because no single cause for error could be isolated. However it was possible to identify the root mean square errors of the digitised plans and the topographic plans. Comparisons of the intended areas of plots from the INRA cadastral plans against the digitised overlays are provided in Figure 4.6.

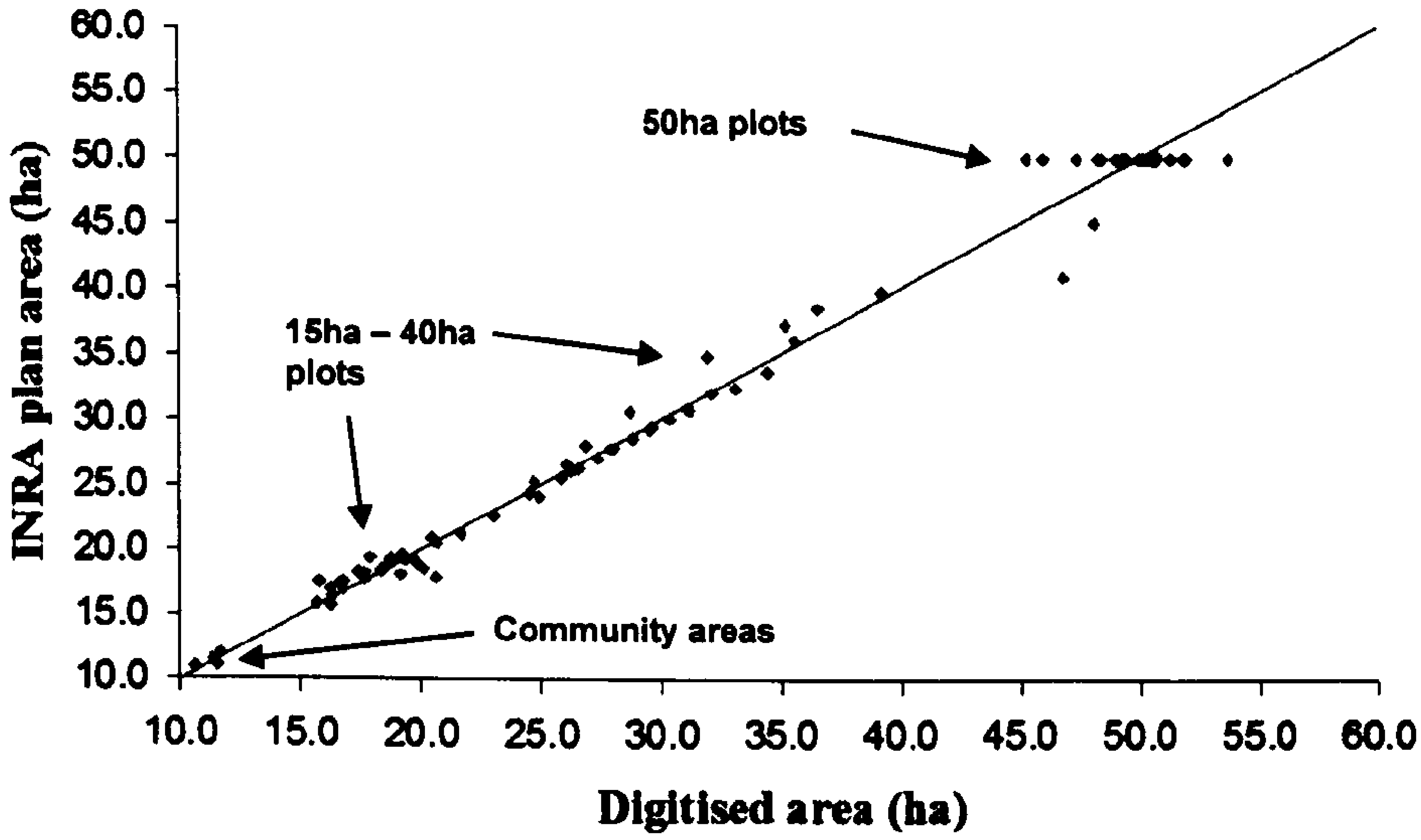
In Arequipa, plots are elongated trapezoids with no consistent dimensions. As they were very narrow (~ 90m, i.e. less than three TM pixels wide) plot boundaries often fell within pixels, making it difficult to re-digitise and align plot boundaries with clearance corridors. In Bogotá plots tended to diverge from the plans towards the south-east of the community. Here it was easier to re-digitise the clearance along plot boundaries in Bogotá as the plots were ~ 200m wide. In Caracas the accuracy of parts of the topographic maps were limited as some plots had only been sketched on the plans. Here polygons could be digitised easily and arranged next to each other as they followed a regular repeated pattern. The most recent plots, which were not included on the plans, were digitised manually from information given by farmers and from the farm surveys. The corner plots in the south of Caracas tended to be poorly matched with their expected areas as there was insufficient information about dimensions on the plans.

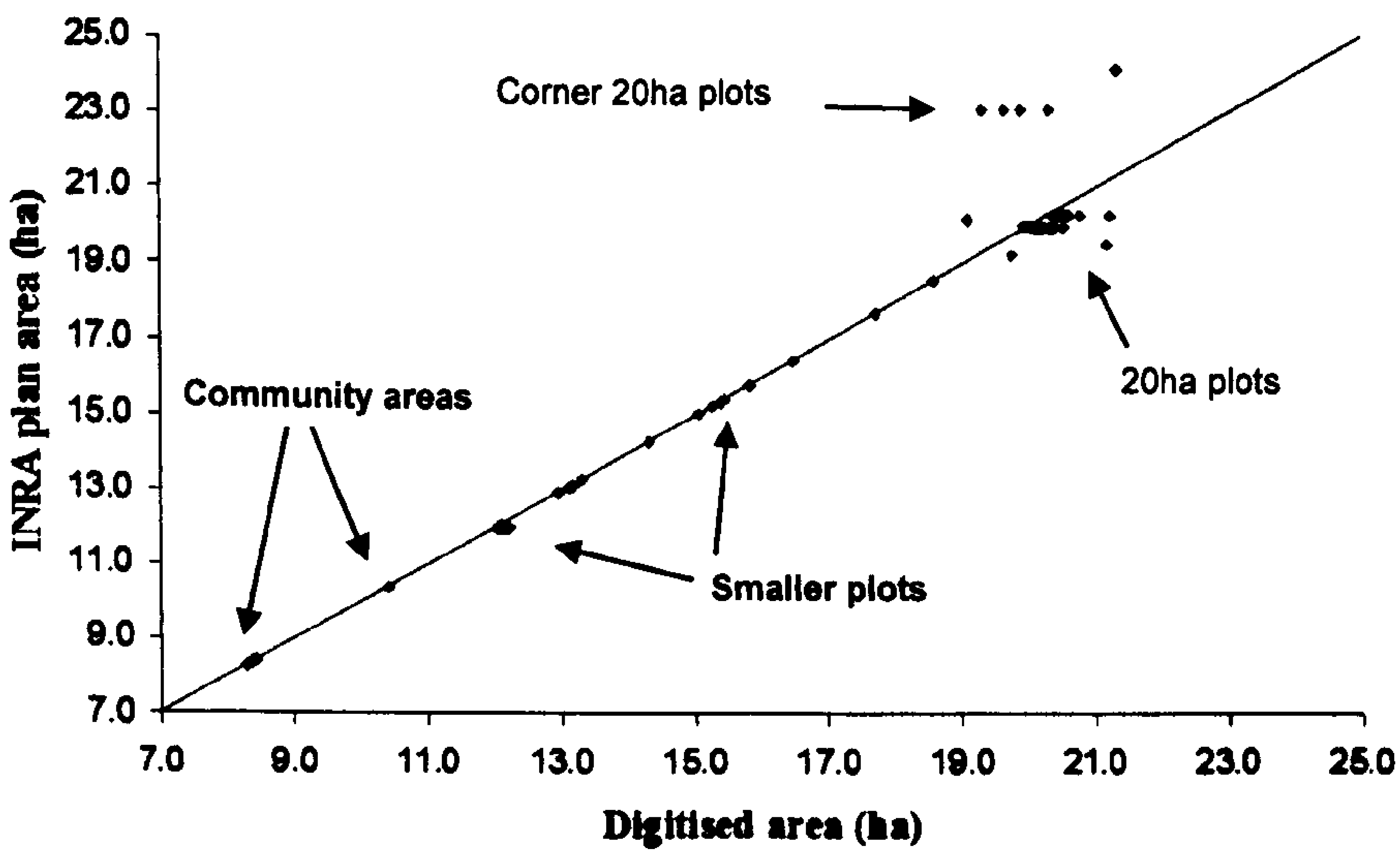
4.4.2.2 Image classification

A classification was used to map different land-cover types for the region which were then grouped into forest/non-forest cover types for further analysis. ISODATA

Figure 4.6: Comparison of areas from the INRA and digitised plans. Diagonal line represents ratio of 1:1 in area; top, Arequipa R^2=0.954, middle, Bogotá R^2=0.991, bottom, Caracas R^2=959.







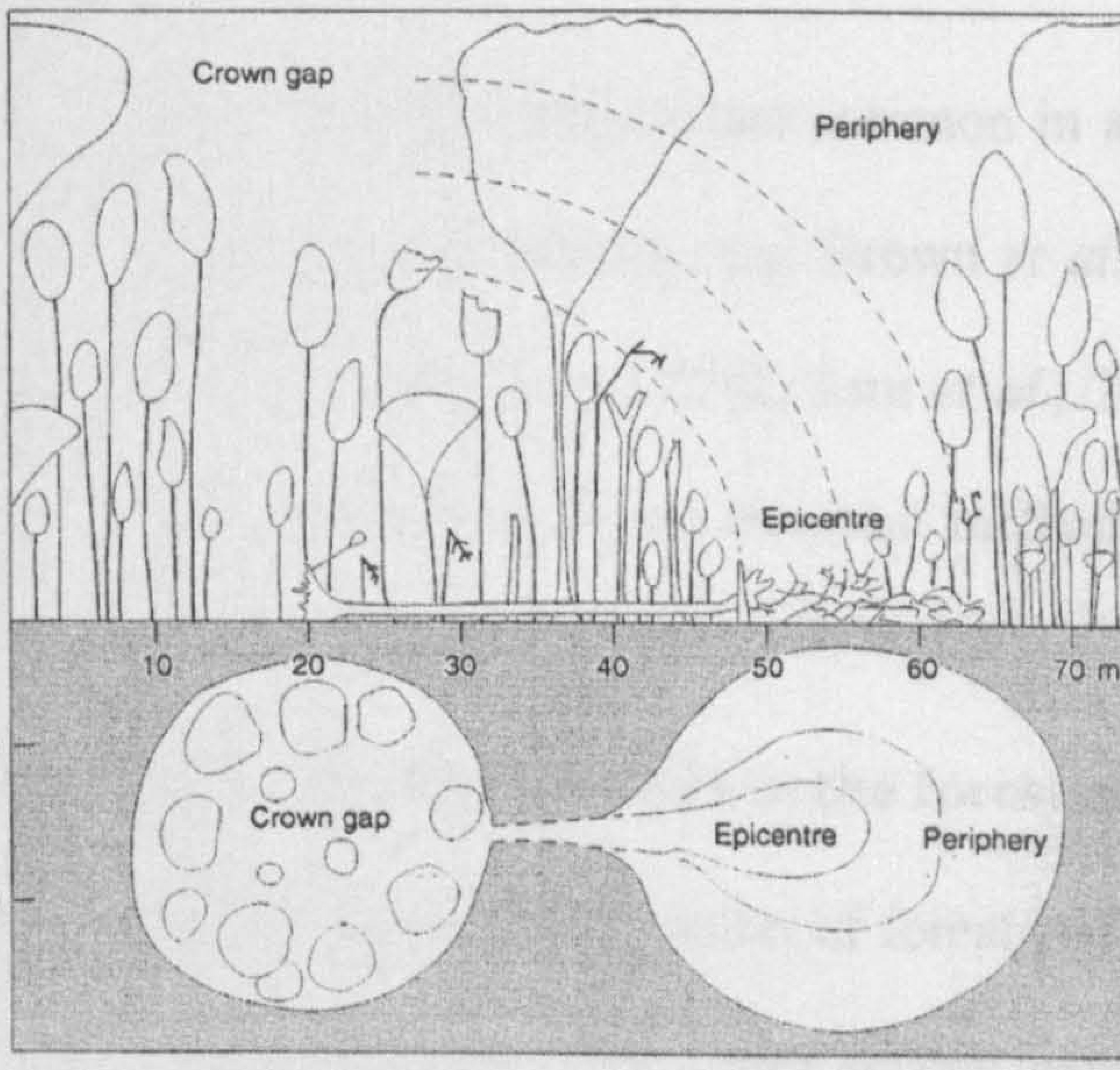
(Iterative Self Organising Data Analysis Technique) in ERDAS Imagine v8.5 (ERDAS, 2001) was used to create unsupervised classifications of the images. I used ten pixel groups in the ISODATA algorithm based on observations and talking to farmers on the 2002 field visit and after discussions with my supervisor, biologists, and social scientists who has been working in the region since 1991. The classification decisions I used are summarised in Appendix 4.4. Lunetta *et al.* (2002) used a similar approach by applying the knowledge of a number of local experts to identify land cover classes in an unsupervised classification of an MSS image of Mexico. There were ten land-cover types anticipated to be represented with the pixel groups generated in the unsupervised classification: water; roads and towns; bare ground; dense forest (*terra firme*); sparse forest (*terra firme*); inundated forest (*monte llanura*); field crops; orchard crops; bananas and grassland. This classification procedure was applied to all images for the three communities. After masking out water bodies, each of the classes from the unsupervised classification were then easily contextualised and grouped into simpler forest and non-forest categories. The results were binary images of forest and non-forest land cover.

Preliminary classification assessment.

After examination of the initial unsupervised classifications a number of difficulties with using ISODATA method to create a forest / non-forest classification were identified:

(i) **Non contiguous non-forest pixels in the forest.** This is a problem because non-forest classes were appearing in the forest as either individual pixels or in small clusters of pixels. Although the small groups of pixels may well be agriculture, individual pixels in the forest are unlikely to be agriculture. Some of the non-forest pixels in forest may be from natural breaks in the canopy due to tree falls or from selective logging (Figure 4.7). An overestimate of forest clearance by agriculture would occur if all the pixels were counted as non-forest. Methods that would reclassify individual pixels from the non-forest class to forest class were explored.

Figure 4.7: Tree fall and crown gaps. Note the dimensions of the crown gap or the epicentre and periphery fall just inside a Landsat TM pixel (from Reading *et al.*, 1995). The contrast in spectral bands in disturbed forest areas between vegetation / soils and surface litter is described in Asner *et al.* (2002).



(ii) Forest classes confused as non-forest because of illumination on hill slopes. This occurred where farmers had not cleared forest for agriculture on north east facing slopes which were illuminated by the sun in Bogotá. Overestimates of clearance were created if the illuminated areas were not considered as forest.

(iii) Shadowing by trees in the non-forest areas. This was a problem along the boundaries of forest and non-forest classes where the forest edge faced south east and strong shadows were cast. Inclusion of shadow on cleared areas of agriculture in the forest class would have led to an underestimate of clearance.

(iv) Ambiguous classes which could be forest or non-forest.

This problem arose at the forest / non-forest interface where a class contained pixels that could have represented either forest or agricultural land-cover types. It was difficult to distinguish whether the class was forest or non-forest because pixels of the same class were also observed to a lesser degree well inside forested areas or non-forested areas. At the forest/non-forest interface this class probably represents the ecotonal boundary of forest and when it occurs in a forested or non-forested area it represents 'mixels' (mixed pixels) of forest and non-forest land-cover types.

Resolving the issues

Most of the problems highlighted above are common in areas where (tropical) forests have been studied with remote sensing (e.g. Brown *et al.*, 1998; Alves, 2000; King, 2002; Lunetta *et al.*, 2002; Roy *et al.*, 2002; Lira *et al.*, 2003; Monteiro *et al.*, 2003). The appropriateness and selection of the eventual methods used to resolve the problems encountered are discussed below.

(i) Non-contiguous, non-forest pixels in the forest class.

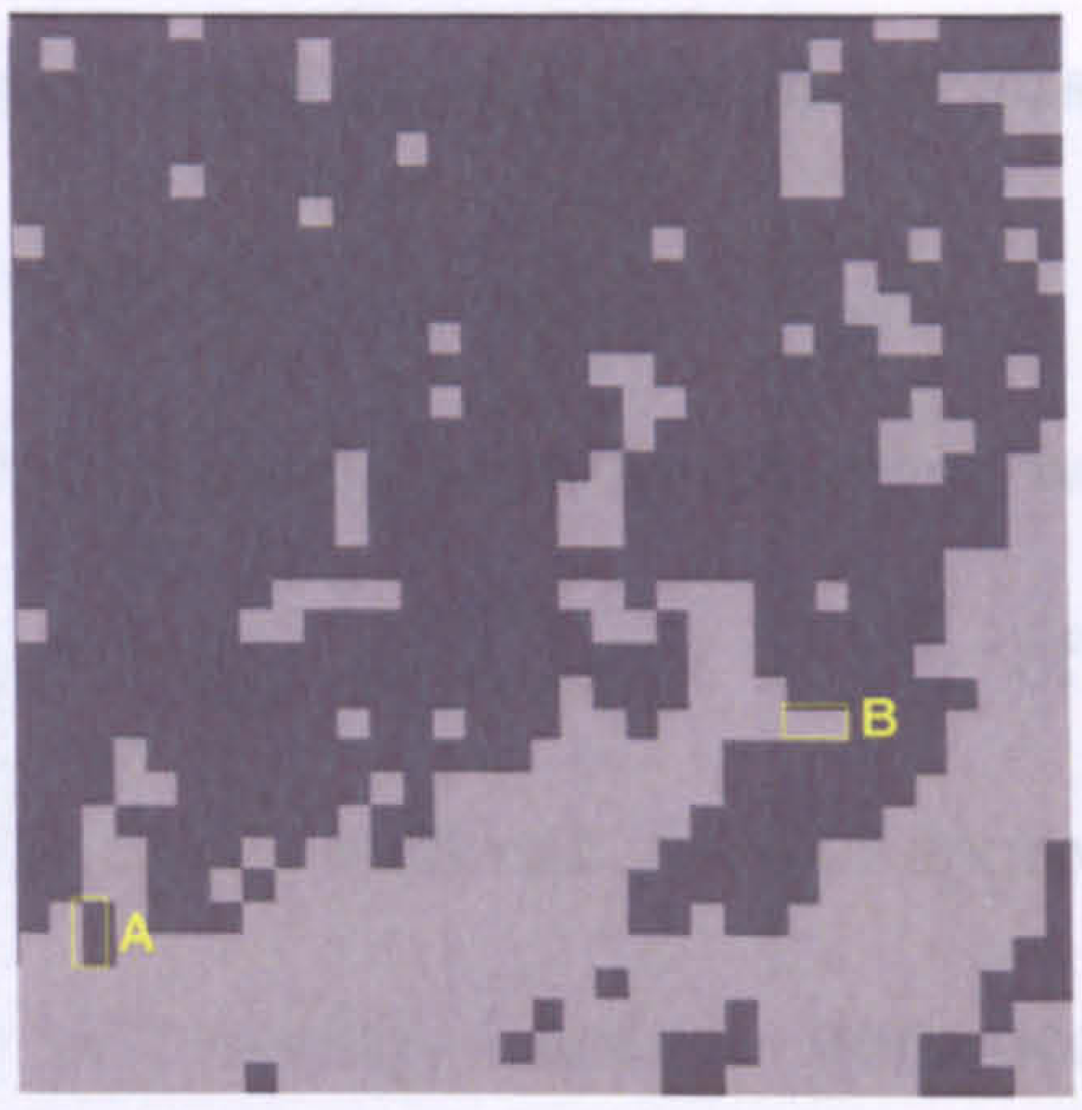
Figure 4.8 (a) shows the initial classification of forest and non-forest in a small area in Arequipa. The figure shows that there area several individual pixels of non-forest within the forest class, these are the non-contiguous non-forest pixels. Roy *et al.* (2002) used median filtering to smooth wide swath IRS-1 Wide Field Sensor data of forests in north east India to resolve a similar problem. King (2002) revised his supervised classification in several study areas in southern Sumatra with a 7 by 7 filter, following results obtained for forest mapping of eastern Paraguay (Brown *et al.*, 1998). He found that using both a bottom-up classification (knowing the land-use activities on the ground), combined with a top-down statistical approach was more successful than a statistical approach alone. Lira *et al.* (2003) made a vegetation classification for the State of Michoacán, Mexico with a Landsat TM image and used a 3 by 3 majority filter to alleviate the problem of mixed pixels and merged illuminated classes of vegetation to the same vegetation class unaffected by illumination. In each case these filters were passed over the forest / non-forest classifications using the functionality of ERDAS software. Figure 4.8 (b) shows the results of applying a 3 by 3 majority filter. The filter did remove all of the individual pixels but in comparison with the original classification, Figure 4.8 (a), the forest/non-forest limits were generalised – which generated false forest / non-forest limits and some forest, and non-forest pixels in contiguous areas have changed class. The filtering approaches used by Brown *et al.* (1998), King (2002) Roy *et al.* (2002) and Lira *et al.* (2003) were not satisfactory for this research because their results were too generalised for the scale of the study of LULCC in this research. However, Monteiro *et al.* (2003) used a clump filter on a Landsat TM image to remove isolated pixels from a forest / non-forest classification in the Mato Grosso State, Brazil and I found this method more satisfactory. ERDAS Imagine image processing software was used to 'clump' then 'eliminate' pixels. The procedure was as follows:

(i) The 'clump' algorithm was used to identify clumps of contiguous pixels with a minimum specified group size, in this case individual pixels, in the forest and non-forest classes; and

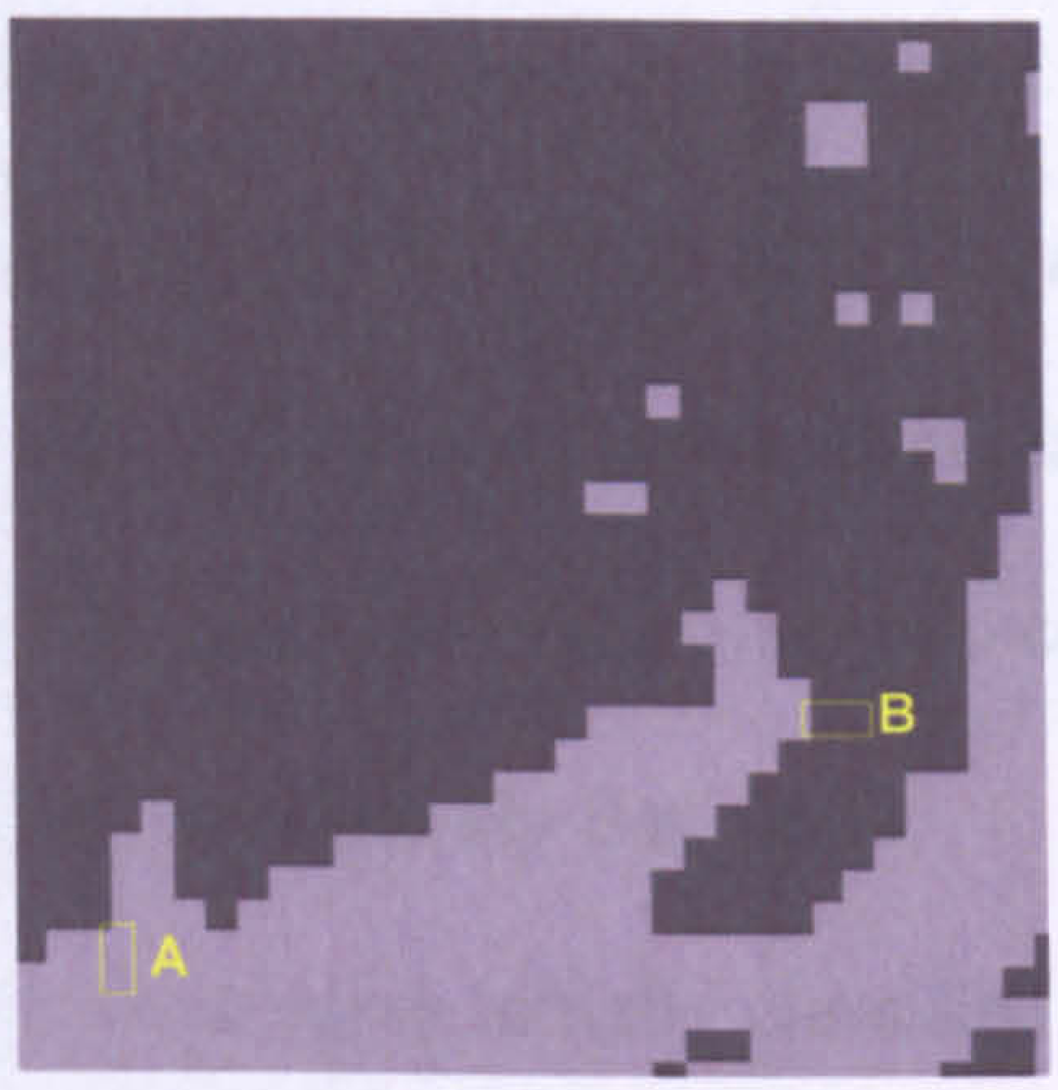
(ii) The 'eliminate' algorithm was then used to iteratively change the clumps into the neighbouring thematic class, i.e. non-forest into forest (ERDAS, 2002).

Using these two algorithms it was found that all the non-contiguous individual pixels had been removed (Figure 4.8 (c)) and that this had been achieved without altering the classification of contiguous pixels. In addition, there was no generation of artificial forest and non-forest class boundaries and the boundary between forest and non-forest did not become

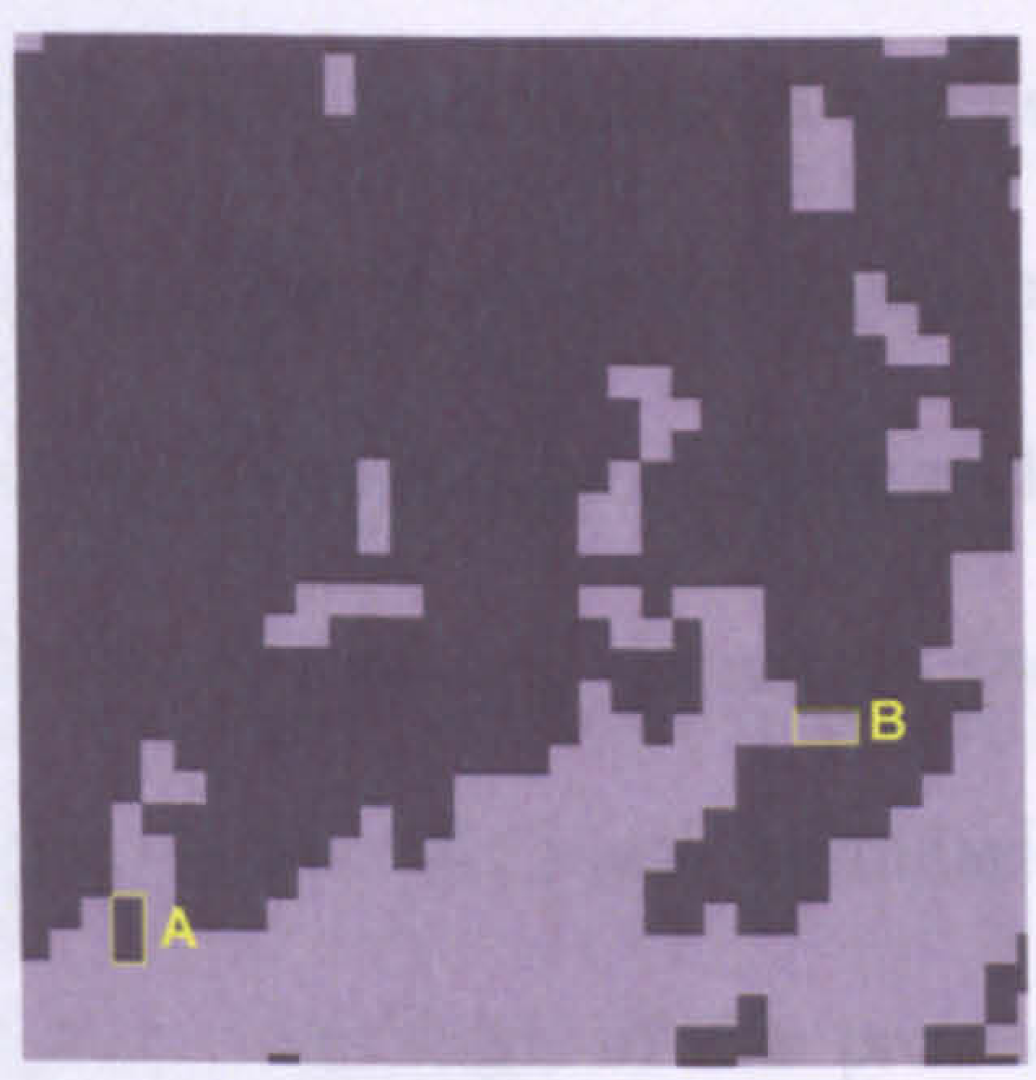
Figure 4.8: Comparison of the original classification (a) and methods used to remove non-contiguous pixels (b) and (c), Dark grey: forest, light grey: non forest. The classification subset is from the Arequipa time series (1996).



(a) Initial classification, single pixel and clusters, A - forest, B, non-forest.



(b) Results using 3 by 3 median filter. Single pixels and clusters removed, but generalisation of forest/non-forest limits and changes in class in the boxed areas A - forest to non-forest and B - non-forest to forest.



(c) Results using the 'clump' and 'eliminate' functions. Single pixels are removed, there is no generalisation of the forest/non-forest limits and pixels are not switched between classes see for example the boxed area; A - forest, B, non-forest areas.

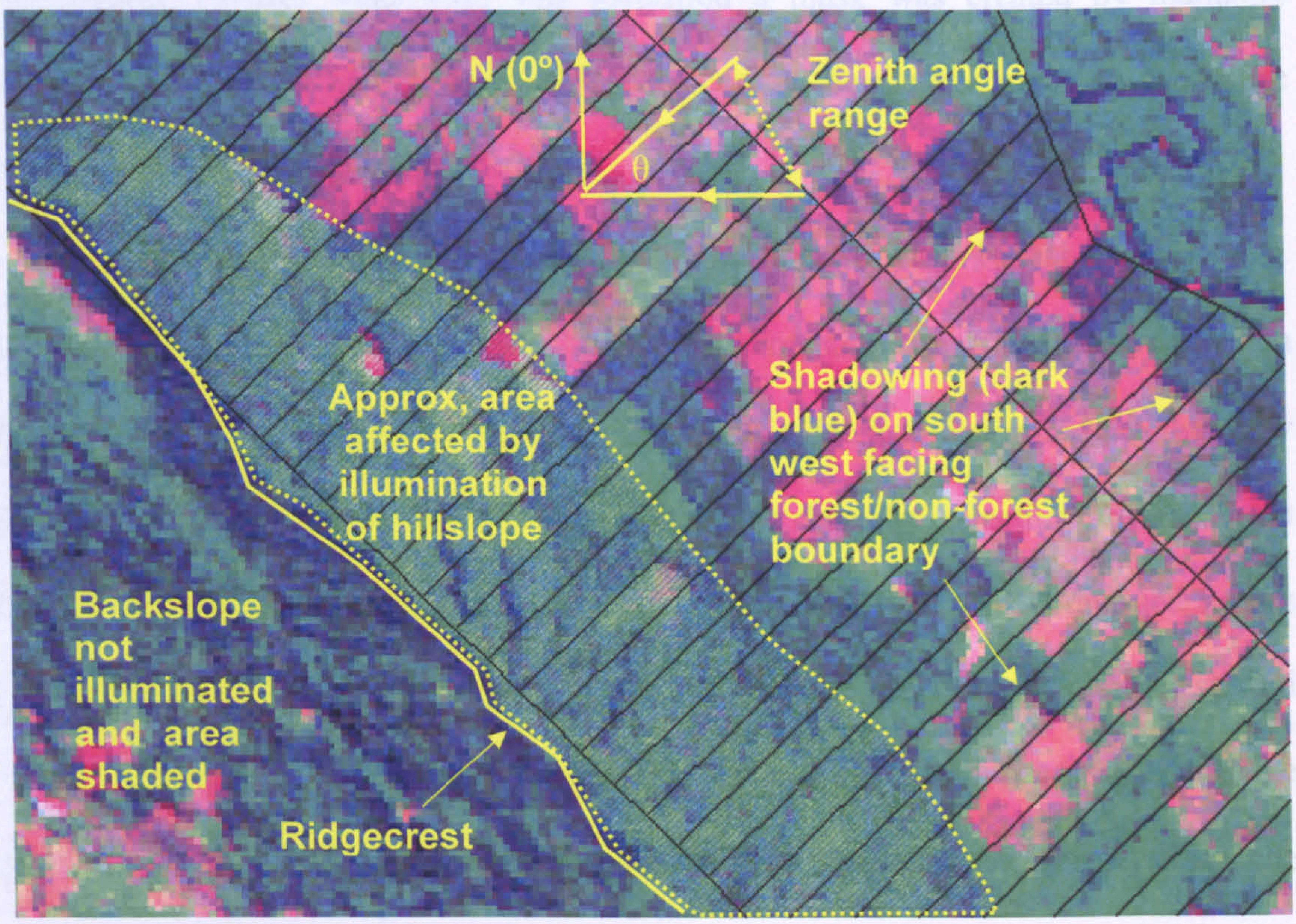
generalised as with the 3 by 3 filter, Figures 4.8, (a) and (c). This clump and eliminate method was deemed satisfactory for this method of research.

(ii) Forest classes confused as non-forest because of illumination effects on hill slopes.

Confusion of the forest class with the non-forest class was a particular problem in Bogotá. Here a short steep ridge with slope angles of around 20 degrees (field measurement) running northwest to southeast rises to approximately 100 m.a.s.l. along the southwest edge of the community. Images were acquired from early morning satellite overpasses, between 9.30 hrs and 10.30 hrs (Table 4.1), with sun azimuths varying between the north east (41°) during the wet season to east (89°) during the dry season and sun zenith angles ranging from 30° to 52°. The aspect and inclination of the ridge opposes these angles and caused more direct illumination of the forested slopes. Illumination effects were not encountered in the other two communities because of their location of the communities on the relatively flat plains.

The illuminated forest areas were initially classified as non-forest. The removal of individual pixels described in the previous section was not sufficient to eliminate the effects of illumination because clusters of pixels were commonplace (Figure 4.10). The slopes had been identified in the 2002 field visit so it was possible to locate the slope on the image. A mask was then digitised to cover the problem area caused by illumination on the northeast facing slope and recoded into the image classification as forest. In the 1996 and 2000 images areas of agricultural clearance (non-forest classes) were also observed on this slope (Figure 4.9) so the mask boundaries were altered to allow for clearance in the illuminated area. The logic of this process was used by Alves (2000) who made forest / non-forest decisions in the Brazilian Amazon using a visual interpretation of Landsat TM and MSS images.

Figure 4.9: Illumination and shadow effects on the 1996 TM image for the community of Bogotá. Pink and light green areas are deforested areas, dark green is old-growth forest, plot boundaries are represented by the black lines, the longest plots are 2.5km in length.



(iii) Shadowing by trees in non-forest areas.

Shadowing of non-forest areas along the forest / non-forest boundary was a problem in two of the communities – Bogotá and Caracas – and often led to confusion with the water class. These effects were most obvious on southwest facing forest edges where the forest/non-forest boundaries were orientated in a northwest to southeast direction on the image, examples are shown in Figure 4.9. The shadowing was caused by tall forest trees casting shadows over the non-forested agricultural and fallow areas. As with the illumination effects on the northeast facing slope in Bogotá, this only occurred along northwest – southeast orientated forest edges because of the range of sun azimuth and zenith angles and the early morning satellite overpass times (Table 4.1). The use of a 3 by 3 median filter, or the clump and eliminate algorithms described in (i), did not remove this problem. Instead, shadowing was removed manually by examining the ETM and TM images alongside the forest / non-forest classifications in each of the communities. Where shadowing was identified a mask was created by manually digitising around the problem areas and then recoding the masked areas on the image classification as non-forest.

(iv) Ambiguous classes which could be forest or non-forest.

The classes identified as containing 'mixels' of forest or non-forest are shown in Appendix 4.4. Each of these classes was examined in detail to determine whether they represented a forest or non-forest class. This was done by selecting 100 pixels at random from the ambiguous class. The context of each pixel was examined i.e. its location in relation to the forest and non-forest classes and other pixels in the class, and it was assigned to either the forest or non-forest class; the results were tallied. If the proportion of the ambiguous class exceeded 70% of forest (or non-forest) class, the ambiguous class was assigned to the forest (or non-forest) class. If the proportion of the ambiguous class fell below 70% the class remained uncertain.

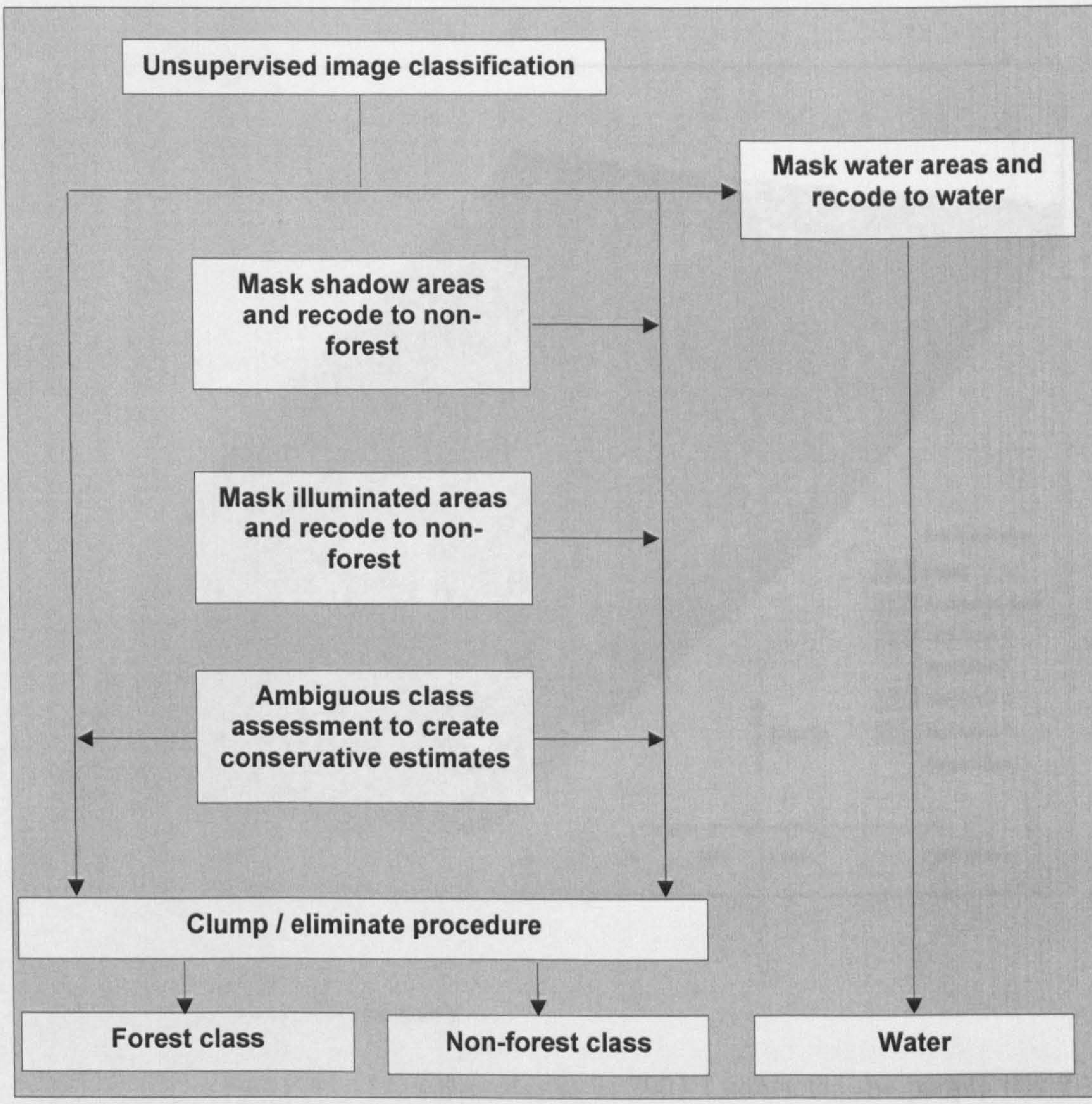
The class could not always be resolved because the ambiguous class pixels probably represented the ecotone that spans the forest and non-forest classes. However, leaving this class as an ecotone, created a potential problem in that, for some image maps of communities, there would be a third class that was neither forest nor non-forest. This would make it difficult to generate meaningful data on spatial patterns of deforestation, deforestation rates and landscape ecology metrics from binary forest / non-forest maps. The transition through a forest and savannah ecotone has been addressed in Bolivia using fuzzy logic approaches (Arnot, 2004; Arnot *et al.*, 2004). In this research, rather than adopt this fuzzy logic approach the uncertain ecotonal class was allocated to forest because the research questions required the calculation of a series of landscape ecology metrics related to the non-forest land-cover to test the parabolic landscape fragmentation curve (Lambin, 1997) and the colonist footprint (Brondizio *et al.*, 2002) models. In addition, during interviews farmers were at ease with the concepts forest and agricultural (non-forest) areas but explaining the representation of ecotones on the imagery was a little more trying. Finally the research of Arnot (2004) was contemporary research in progress during my research and as it was being tested on a savannah – dry forest ecotone I was uncertain of its efficacy on the relatively abrupt boundaries found between forest and agriculture. The most certain binary classification of forest and non-forest was therefore chosen for later analysis, in this research this involves excluding the ambiguous class from the non-forest land cover to provide a conservative estimate of forest loss. The final sequence of the image processing steps is shown in Figure 4.10.

4.4.3 Field verification

During the field visit in 2003 I used the land cover classification maps produced in Leicester in order to:

a) examine the land-cover classification of forest / non-forest, the issues of hill slope illumination, shadowing and the problem of the ambiguous classes; and
b) discuss the trajectories of land-cover change with farmers of the three communities in the community during the period of the image sequence.

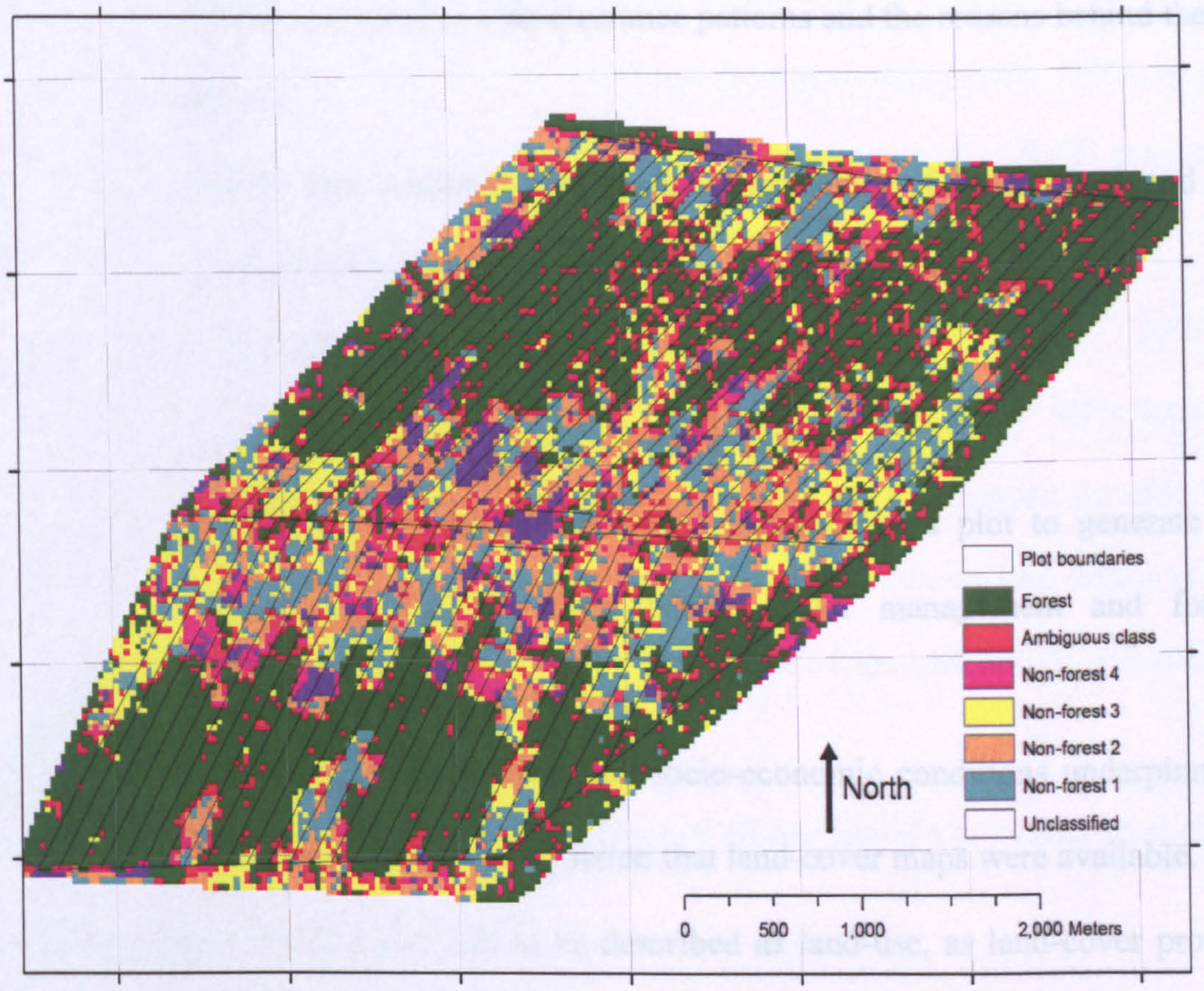
Figure 4.10: The image processing pathway (expanded from Figure 4.2) for the binary classification of forest and non-forest.



a) Land-cover classification

Maps of forest, non-forest and the ambiguous classes coded in different colours were used in the field (Figure 4.11). The classifications of the 2000 images were used as they were closest in time to the field survey. The verification process involved stopping at each individual farm plot (between the plot boundary markers) along the main access roads, taking a GPS reading, and identifying forest or non-forest cover with the aid of a sketch of the land-cover made from the back of a 4 by 4 truck.

Figure 4.11: Example of land-cover classification of Arequipa 2000. This classification was used in the fieldwork for 2003. Green - forest, red -ambiguous class, all other colours - non-forest.



b) Land-cover change trajectory

When I returned to the communities in 2003 I contacted the people that I had interviewed in 2002. This was beneficial as the interviews proceeded with ease because of the familiarity between myself and the informants. This included the former and present agricultural union heads and long-term community members. The informants were shown the land-cover maps in chronological order beginning from the most recent, as I assumed that recall would be best for the most recent image classification, from all years when imagery had been acquired with the objective of exploring the following:

(i) In terms of the community as a whole to:

a. identify the classes in the land-cover classification;

b. discuss the history and development of land-cover change in the community using the sequences of land-cover maps to try and identify general community-wide clearance patterns and the reasons behind them; and / or

c. identify the temporal and spatial dimensions of biophysical and or socioeconomic causes behind land-cover types and change.

(ii) In terms of individual plots, the objectives were to:

a. explain the spatial organisation within plots;

b. describe the progression of forest clearance in a plot to generate an understanding of the links between plot management and forest fragmentation patterns; and,

c. to discuss the biophysical and socio-economic conditions underpinning land clearance during the period that land-cover maps were available.

In these discussions land-cover had to be described as land-use, as land-cover proved too difficult a concept for the majority of farmers to grasp.

4.4.4 Quantification of spatial and temporal land-cover change patterns

Forest and non-forest areas were generated in Arc/Info by clipping a vectorised version of the image classification with, first, the community boundaries to produce a community level data set and, second, the plot boundaries to produce a plot boundary data set, using Arc/Info clip, union and build commands. This above process was repeated for all years in each community.

Landscape metrics for each of the three communities were calculated (Section 4.4.4.1) and the amounts of forest cleared (in hectares) and rates of forest clearance (in hectares per year) were calculated for each plot (Section 4.4.4.2).

4.4.4.1 Landscape metrics

Throughout the image sequences LULCC evolved in response to its drivers. Landscape metrics are a way of quantifying spatial patterns of land-cover and can be used to help determine the processes of landscape pattern change (Trani, 1999; Jaeger, 2000). Patterns of land-cover can also be used as an indicator of LULCC processes (Husson, 1995; Lambin, 1997 and Giest *et al.*, 2000).

Structural metrics were selected as this thesis is concerned with LULCC patterns and changes in landscape configurations rather than studying the influences of landscape change on ecological processes when a number of other metrics are used. A description of the metrics used from McGarigil *et al.* (1994) follows (the details of the calculation, units and range of units for each of the landscape metrics are provided in Appendix 4.5):

- **Class Area (CA)** is the sum of the areas of all patches of a particular land-cover type. The units are in hectares;
- **Number of patches (NoP)** is the number of patches in the landscape of a particular land-cover type (forest or non-forest);
- **Patch density (PD)** is the number patches of a particular land-cover type divided by the total landscape area. The units are in hectares;
- **Mean Patch Size (MPS)** is the average size of patches for a particular land-cover type. The units are in hectares and the metric is reported with patch size standard deviation **(PSSD)** and patch size co-variance **(PSCV)**;
- **Total Edge Length (TEL)** is the total length of the edges of a particular class. The units are in meters;
- **Edge Density (ED)** is the total length of the edges of a particular class divided by the total landscape area. The units are in metres;

- **Mean Nearest Neighbour (MNN)** is the edge to edge distance of the nearest patch of a particular land-cover type divided by the number of patches with a neighbour. The units are in metres and the calculations are reported with standard deviation **(PSSD)** and co-variance **(PSCV)** of MNN.

Landscape metrics were calculated using FRAGSTATS v 2.0 (McGaragil *et al.,* 1994). Metrics were generated for both forest class and the non-forest class for each image acquisition date. The area of each of the three study sites was greater than the minimum area of 9.18 km^2 required for the calculation of reliable landscape metrics using FRAGSTATS (Hargis *et al.*, 1997).

4.4.4.2 Quantification of clearance at the community and plot levels

For each community, information was generated for each plot on (a) the area cleared in hectares for each image acquisition date, and (b) the rate of clearance between image acquisition dates in ha yr^{-1}.

(a) Area cleared

The areas cleared were calculated by using the clip feature in Arc/Info to create forest / non-forest maps using plot boundaries generated from the INC plans. The topology of the resulting polygons was then built in order to calculate the area of forest and non-forest for each plot. The area of forest and non-forest was simply a sum of the areas of each class in all the plots (Equation 4.1), where, x_{CAj} = mean area cleared (ha), *CA* cleared area, *i* = plot, *j* = community, *n* = number of plots in the community.

$$(4.1) \quad x_{CAj} = \sum_{i=n} \frac{CA_{ij}}{N}$$

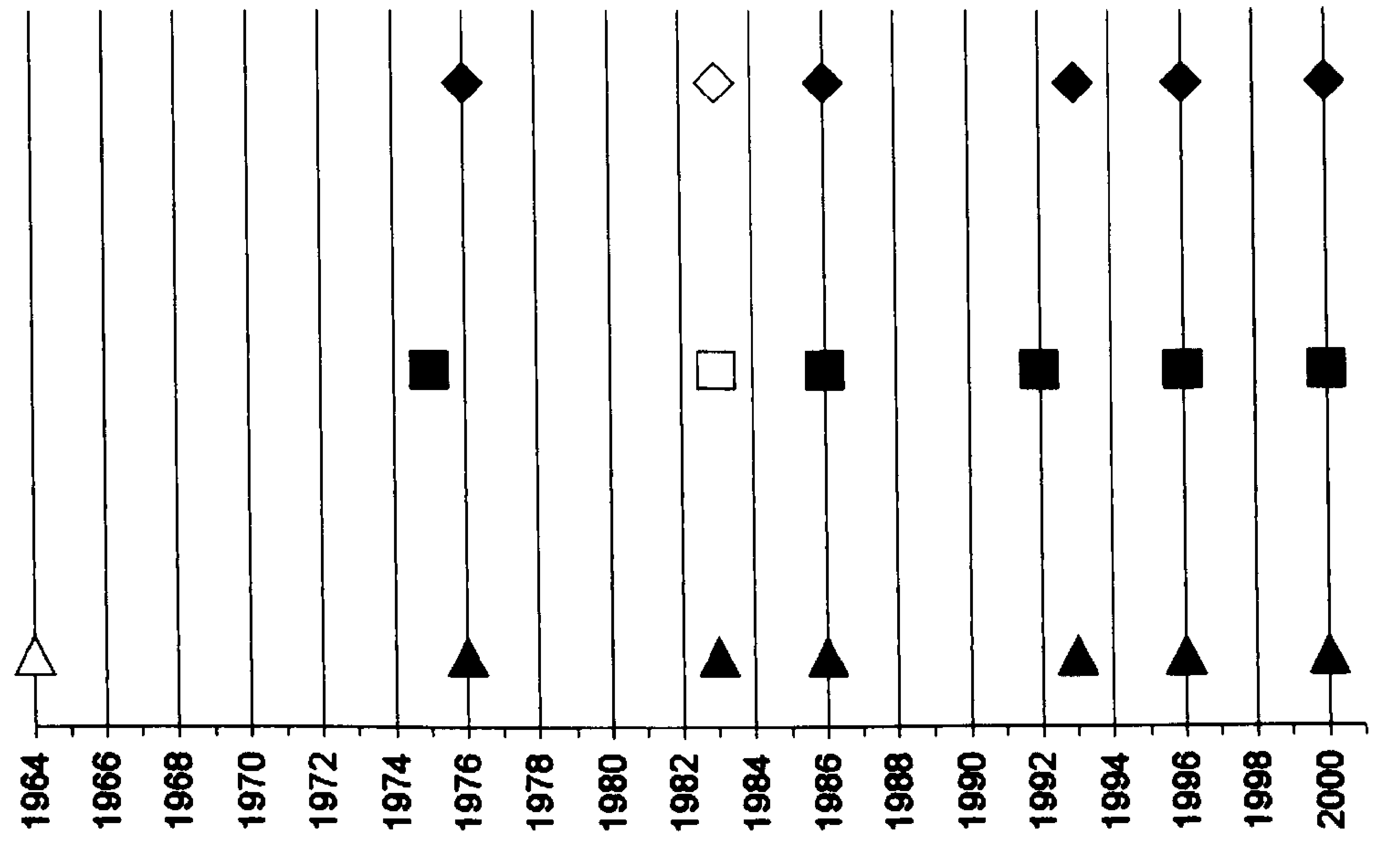
(b) Rate of forest clearance

Rates of forest clearance were calculated from the differences in areas cleared for each plot between consecutive images and dividing the resulting area by the number of years between each image (Equation 4.2), where, r = rate of clearance (ha yr^{-1}), CA cleared area, i = plot, j = community, k = year, n = number of plots in the community, t = *time point.*

$$(4.2) \quad r_j = \sum_{i=n} \frac{(CA^{t+1}_{ij} - CA^{t}_{ij})}{(k^{t+1} - k^{t})}$$

Figure 4.12 illustrates the time intervals used to calculate clearance rates. For the first time interval, the date of settlement to the date of acquisition of the first image was used. The areas cleared and the rates of clearance were then aggregated for the whole community, to give the average cleared areas and average rates of clearance.

Figure 4.12: Time intervals used for the calculation of forest clearance: diamonds - Arequipa; squares - Bogotá; triangles - Caracas. The solid shapes are image acquisition dates and the shapes, in outline, are the approximate dates of initial colonisation of the community.



The results of the RRA, market and policy analyses, LULCC calculations and fragmentation analyses are described in the next chapter. They are then discussed in both temporal (Chapter 6) and spatial (Chapter 7) context.

Chapter 5

Describing land-use and land-cover change (LULCC)

Chapter 5

Describing land-use and land-cover change (LULCC)

5.1 Introduction

Following the methods described in Chapter 4, the aim of this chapter is to describe LULCC in each of the three communities during the period that image data were available. The results are presented in separate sections for each of the communities because of the different land-use activities between the communities and the different dates of settlement identified in Chapter 3. The description begins at the community level and then scales down to the plot level.

For each community, the satellite images and the land-cover estimates are described to show the change in land-cover during the satellite image sequence. This is followed by a summary of the landscape metrics at the community level. The chapter then describes land-cover at the plot level. First, the average forest and non-forest areas and rates of clearance for plots are presented. Each of the sample plots is then compared to illustrate the diversity of clearance patterns. Examples of the different stages of plot management are described and, finally the information from the individual plot descriptions was compiled to create synopses of land-use for each community.

5.2 LULCC development in Arequipa

In this section a series of satellite images show the extent of forest and the conversion of forest to agriculture over time. The land-cover of the area that would become Arequipa in 1976 was contiguous humid tropical forest in an area approximately 5 km to 6 km between two rivers (Figure 5.1). The FCC shows forest as green and the rivers as pink as these images were acquired in the dry season when low flow expose the river sediment. The land-cover map below the image indicates that there was no clearance of forest and there was no detectable evidence of sedentary agriculture. Indigenous tribes of Yuracaré and Yuquis probably used this area for hunter-gathering activities creating minor forest disturbances. Natural disturbance of the forest would have been through fires, tree falls, inundation and migrating river channels.

The colonists entered the area from the west (Figure 5.2) and cleared forest from the primary end of their plots to the north and south of the east-west access track which runs through the centre of the community. These areas of forest clearance are shown as light green and pink on the FCC (Figure 5.2). Other communities (marked OC on Figure 5.2) bordering Arequipa also began clearing forest in a similar fashion at this time, i.e. from the ends of their plots which bordered an axial track. In the land-cover map there are a few small isolated patches of forest inside the agricultural area, indicating that farmers did not always fell all the trees as they cleared into their plots.

By 1993 (Figure 5.3) forest clearance continued outward from the community access road and extended along an access road running north to south through Arequipa. Access along tracks along the borders of the community allowed clearance to take place in the northwest, north and northeast of the community. Clearance had also begun on the southern side of the community where farmers could gain access to the other end of their plot through the community to the south. As individual plots were cleared at different rates the interface between the forest and non-forest became more crenulated increasing the length of the forest / non-forest boundary at the same time as the forest area decreased. Overall the non-forest area had increased since 1986 and there were isolated patches of clearance at the secondary ends of many plots and within some plots.

In the next FCC for 1996 (Figure 5.4), clearance had progressed along the plots and had extended furthest where the north to south access road (Figure 5.3) passed through the community. Where clearance had begun at the secondary ends of the plots in 1993 there was further conversion of forest to agriculture. Isolated patches of clearance were evident in the interior of the community where farmers had moved deeper into the forest within their plot limits to create agricultural clearings.

In the FCC for 2000 (Figure 5.5), clearance in the northwest and along the northern perimeter had coalesced because more farmers had made use of the access along the northern edge of the community. Where the north to south road passed through the community, areas of clearance had almost merged and the forest was beginning to fragment into smaller patches. This created contiguous patches of agriculture between the neighbouring communities to the north and south parts of Arequipa. Clearance continued along the plots at different rates extending the cultivated area and creating elongated protrusions of non-forest into the forest.

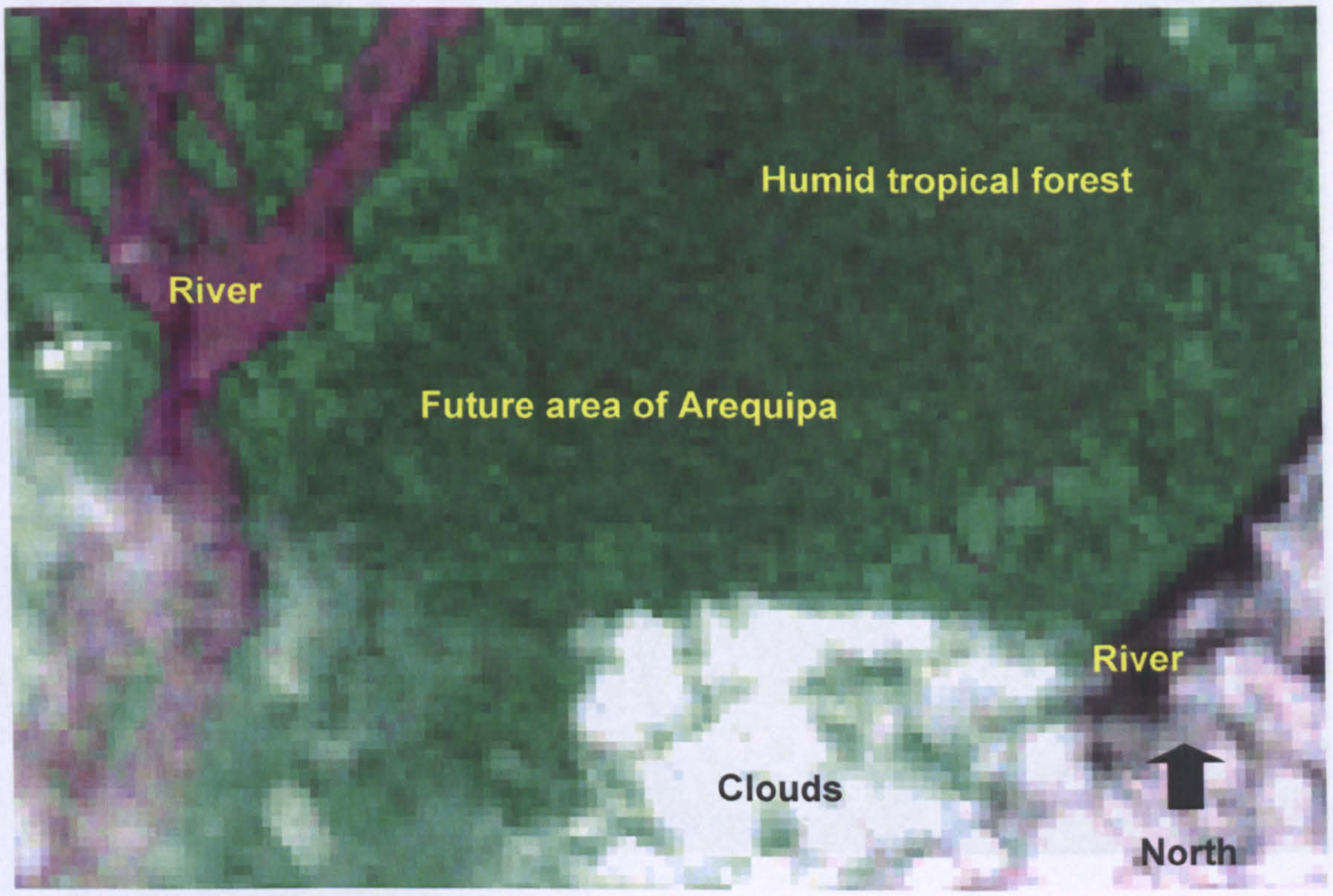
5.2.1 Community level forest fragmentation and land-cover estimates: Arequipa.

This section summarises the fragmentation statistics at the community level in Arequipa. The results of the FRAGSTATS calculation are presented in Table 5.1, and described in the following sections.

5.2.1.1 Class area: forest.

The estimate of forest areas from 1986 to 2000 is shown in Figure 5.6. The forest had decreased by 57.51 ha to 986.13 ha from 1986 to 1993. Between 1993 and 2000 there was a more marked decrease of 104.13 ha. The area of forest in 2000 – 652.59 ha – was 66% of the area in 1986.

Figure 5.1: Landsat MSS FCC bands 231 and land cover map showing the extent of forest in the vicinity of Arequipa, 1976. The land-cover map shows that there is no clearance of forest and all the plots are completely forested.



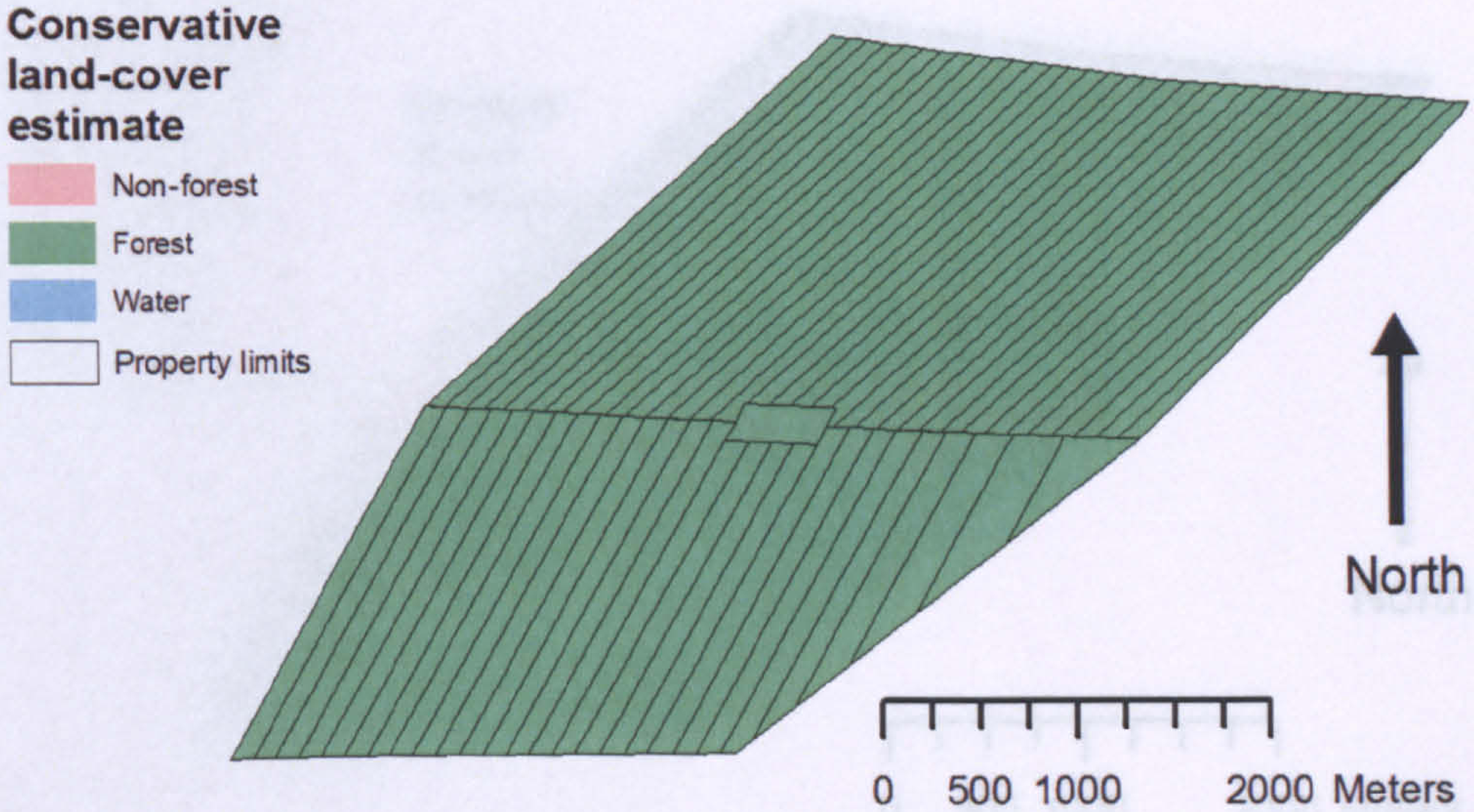


Figure 5.2: Landsat TM FCC bands 741 and land-cover map showing the extent of forest and progression of agriculture in the vicinity of Arequipa, 1986.

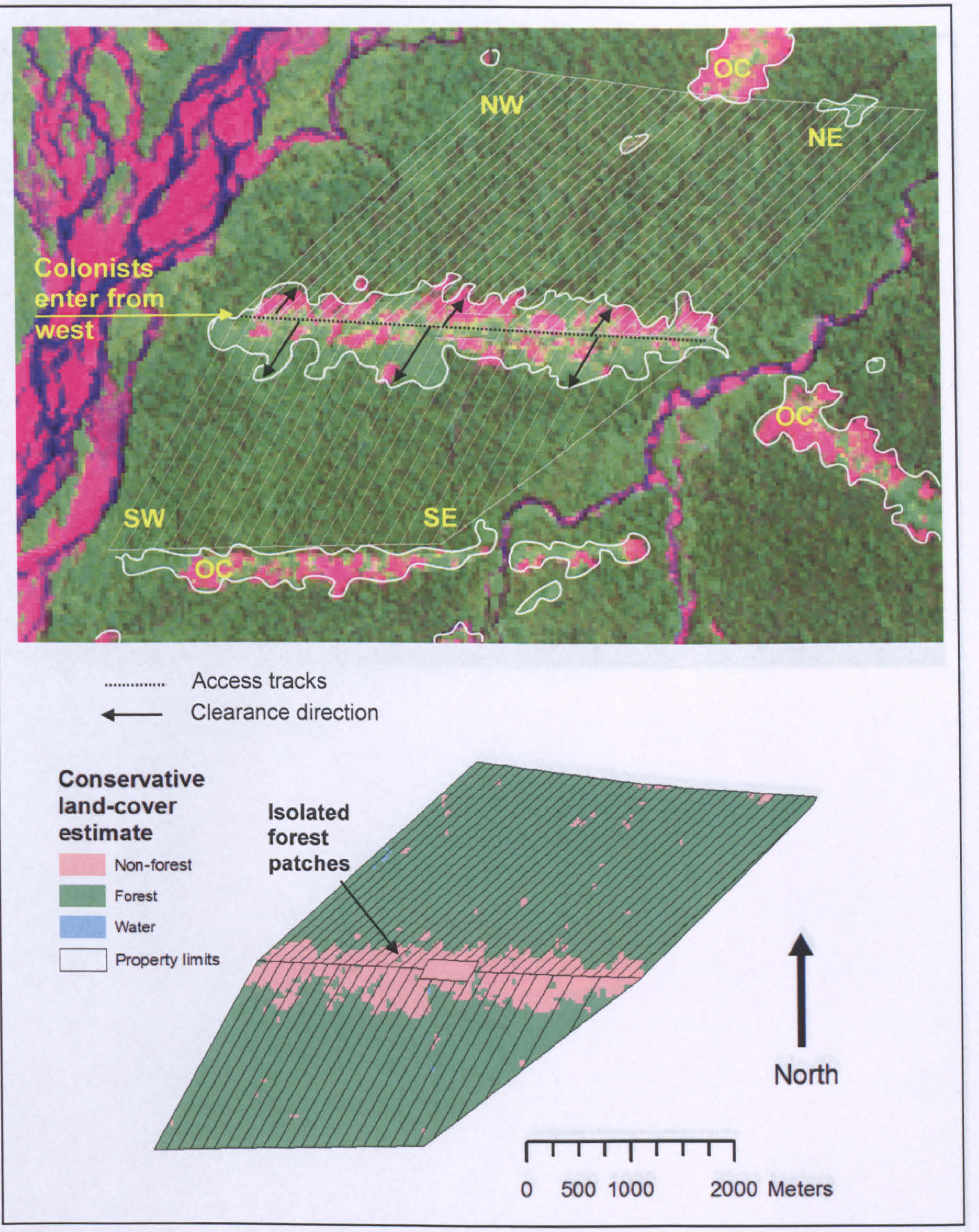


Figure 5.3: Landsat TM FCC bands 741 and land-cover map showing the extent of forest and progression of agriculture in the vicinity of Arequipa, 1993.

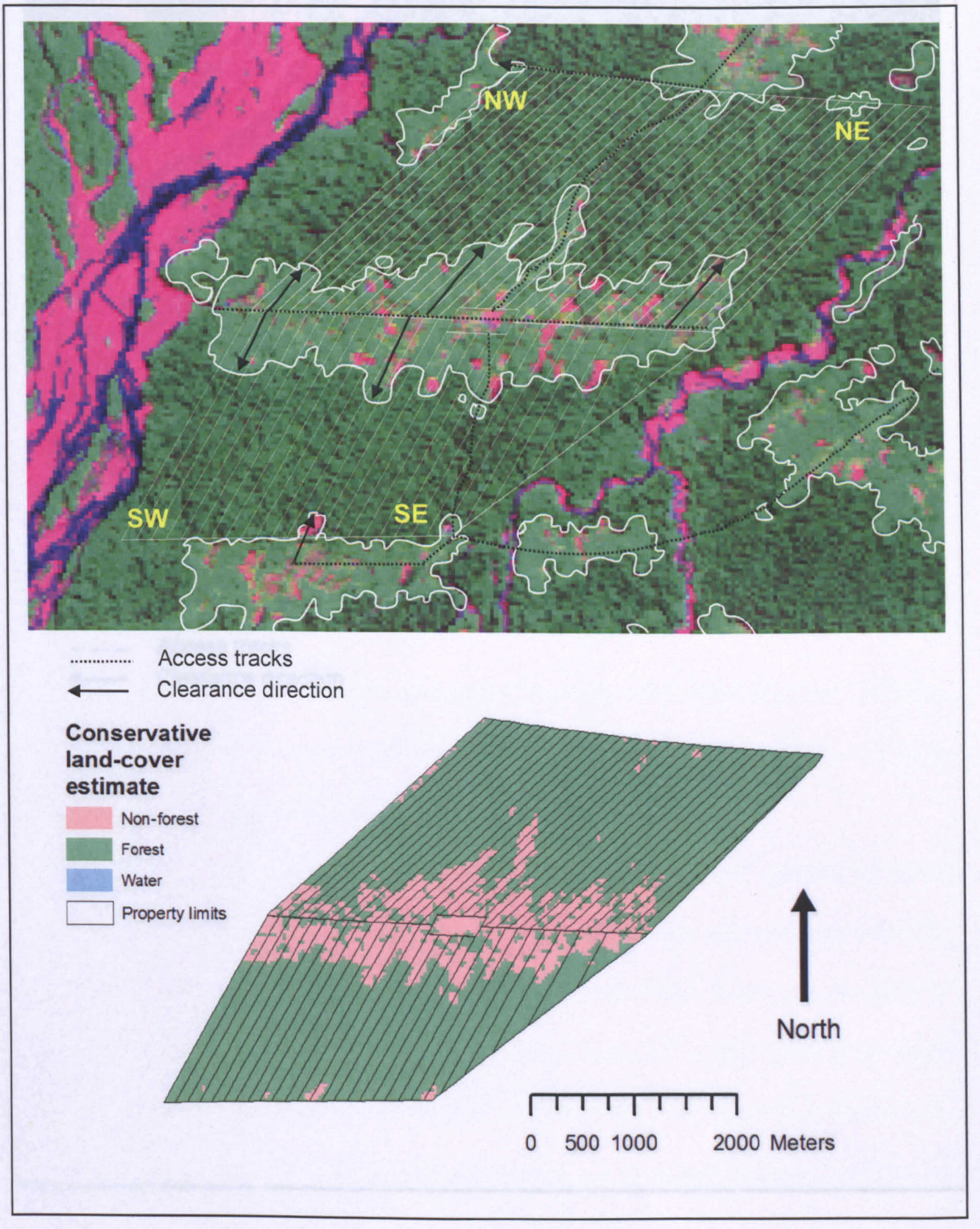


Figure 5.4: Landsat TM FCC bands 741 and land-cover map showing the extent of forest and progression of agriculture in the vicinity of Arequipa, 1996.

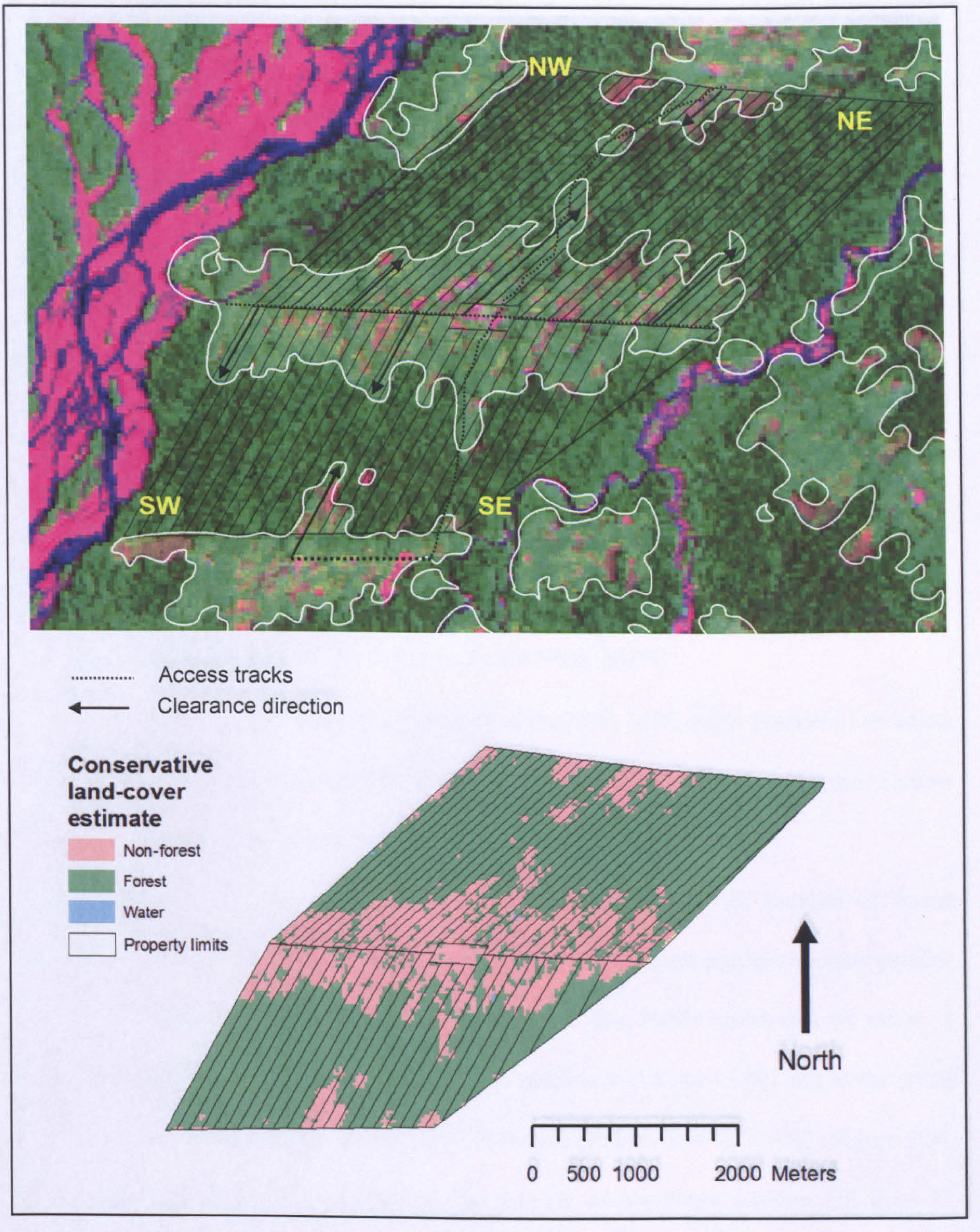


Figure 5.5: Landsat ETM FCC bands 741 and land-cover map showing the extent of forest and progression of agriculture in the vicinity of Arequipa, 2000

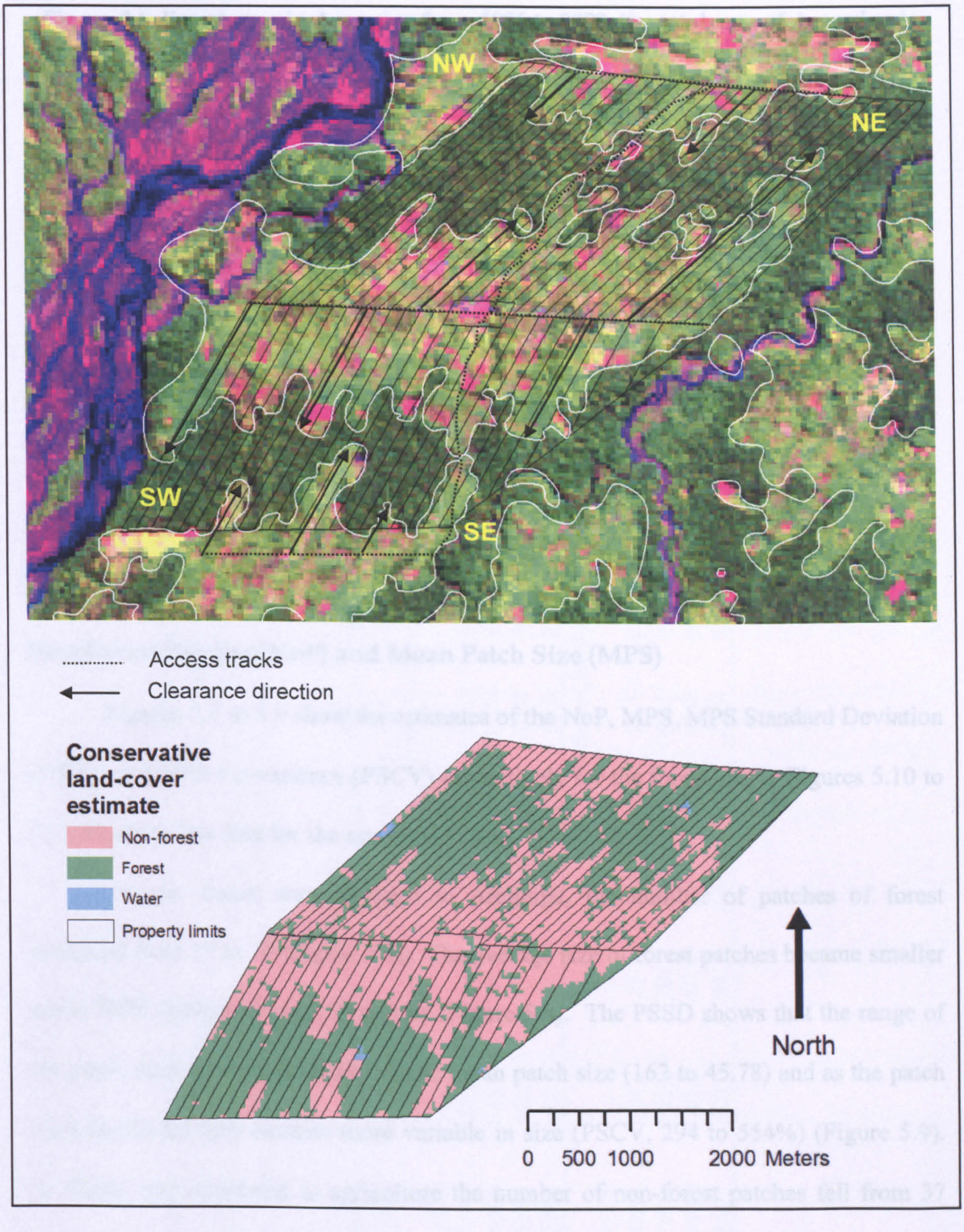
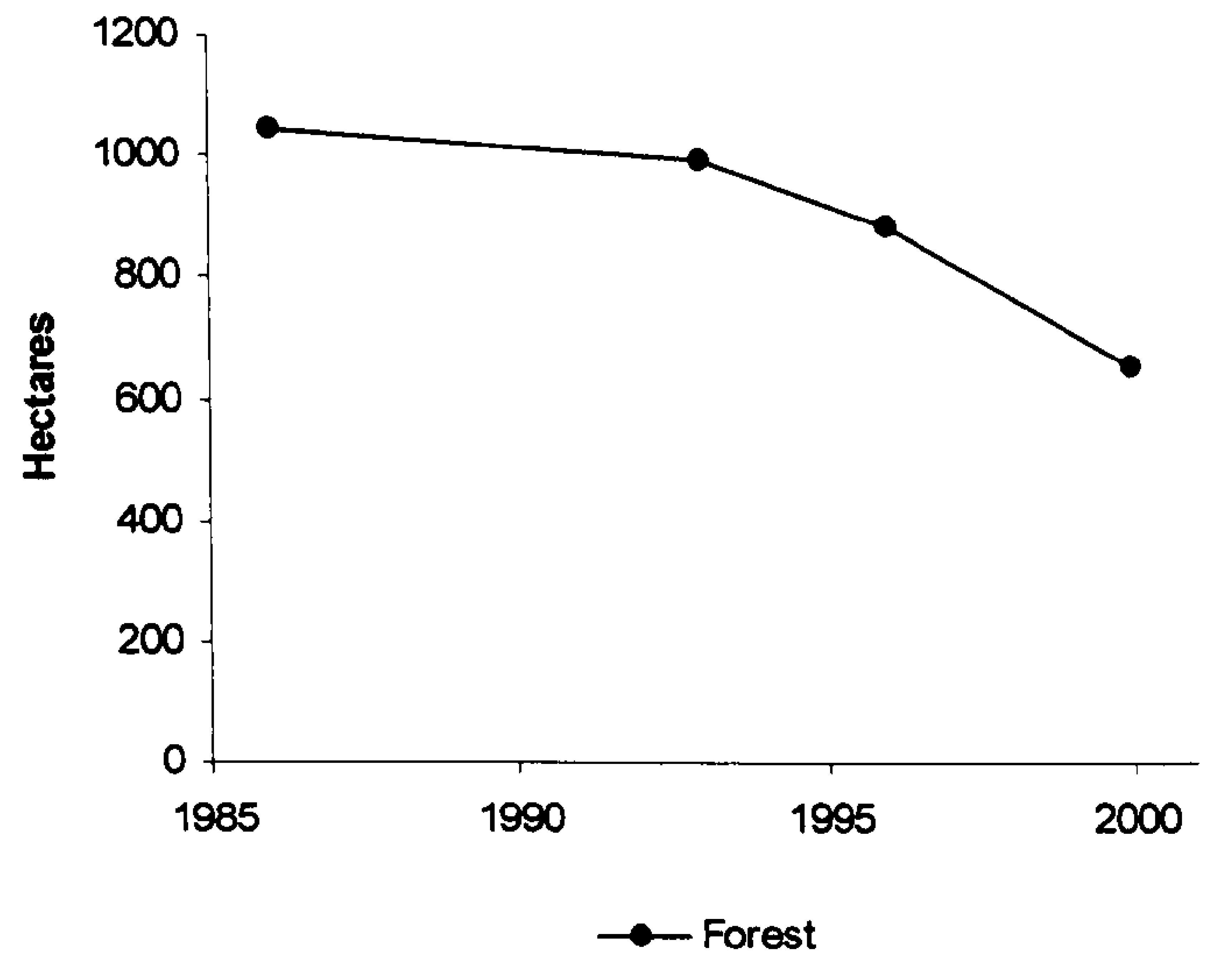


Figure 5.6: Forest area in Arequipa from 1986 to 2000, the total area of Arequipa is 1,220 ha.



5.2.1.2 Structural metrics

Number of Patches (NoP) and Mean Patch Size (MPS)

Figures 5.7 to 5.9 show the estimates of the NoP, MPS, MPS Standard Deviation (PSSD) and MPS Co-variance (PSCV) respectively for the forest class. Figures 5.10 to 5.12 illustrate this data for the non-forest class.

As the forest area declined in Arequipa, the number of patches of forest increased from 19 to 79 (Figure 5.7). The average size of forest patches became smaller as the MPS decreased from 55 to 8 ha (Figure 5.8). The PSSD shows that the range of the patch sizes decreased relative to the mean patch size (162 to 45.78) and as the patch sizes decreased they became more variable in size (PSCV, 294 to 554%) (Figure 5.9). As forest was converted to agriculture the number of non-forest patches fell from 37 (1985) to 29 (1983), then increased to 48 by 2000 (Figure 5.10). The PSSD did not follow this trend and increased at each time point indicating an

Table 5.1: Selected landscape metrics for the forest and non-forest land-cover estimate in Arequipa; CA, Class Area; NP, Number of Patches; PD, Patch Density; MPS, Mean Patch size; PSSD, Patch Size Standard Deviation; PSCV, Patch Size Co-variance; TEL, Total Edge length; ED, Edge Density; MNN, Mean Nearest Neighbour; MNSD, Mean Nearest Neighbour Standard Deviation; NNCV, Mean Nearest Neighbour Co-variance

Metric	CA	NP	PD	MPS	PSSD	PSCV	TEL	ED	MNN	NNSD	NNCV
Units	ha		NP/ha	ha	ha	%	m	m/ha	m	m	%
Forest land-cover											
1976	-	-	-	-	-	-	-	-	-	-	-
1986	1,043.6	19	1.6	54.9	161.7	294	31,380	25.8	49.1	28.5	58
1993	986.1	45	3.7	21.9	100.4	458	56,460	46.3	42.1	16.9	40
1996	882.0	56	4.6	15.8	78.8	500	76,740	63.0	39.3	17.0	43
2000	652.6	79	6.5	8.3	45.8	554	101,730	83.5	47.0	26.2	56
Non-forest land-cover											
1976	-	-	-	-	-	-	-	-	-	-	-
1986	174.2	37	3.0	4.7	26.1	555	30,420	25.0	176.3	199.0	113
1993	232.6	29	2.4	8.0	40.1	499	56,460	46.3	145.9	182.3	125
1996	335.9	40	3.3	8.4	42.5	507	76,620	62.9	102.2	96.6	94
2000	563.0	48	3.9	11.7	64.2	547	100,740	82.7	68.4	51.6	75

increasingly wider range of non-forest patch sizes (Figure 5.11). The values of PSCV were relatively high between 499 – 555% and did not vary much.

Mean Nearest Neighbour (MNN) statistics.

Figures 5.13 to 5.16 show the MNN, the mean nearest neighbour standard deviation (NNSD) and nearest neighbour coefficient of variance (NNCV) for Arequipa. In the forest category MNN did not vary much from 1986 to 2000 as the forest land-cover decreased and were between 39 and 49 m (Figure 5.13). The NNSD showed that the range of distances from the mean was narrow at each time point with a SD between 16 and 29 (Figure 5.13). The NNCV was also relatively constant and had a relatively low variance ranging from 40 to 58% (Figure 5.14).

The trends in the MNN metrics for non-forest land-cover were more distinct than for the forest class. (Figure 5.15) As the non-forest area increased the MNN of non-forest patches decreased from 176 to 68 m, correspondingly the NNSD and NNCV decreased from 199 to 52 m (Figure 5.15) and 113 to 75 m (Figure 5.16) respectively.

Total Edge Length (TEL)

Figure 5.17 shows the variation in total edge between the forest and non-forest classes. As the non-forest cover increased in Arequipa TEL increased from 30,420 m in 1986 to 100,740 m in 2000.

Figure 5.7: Number of forest patches (NoP) and decrease in area of forest (ha).

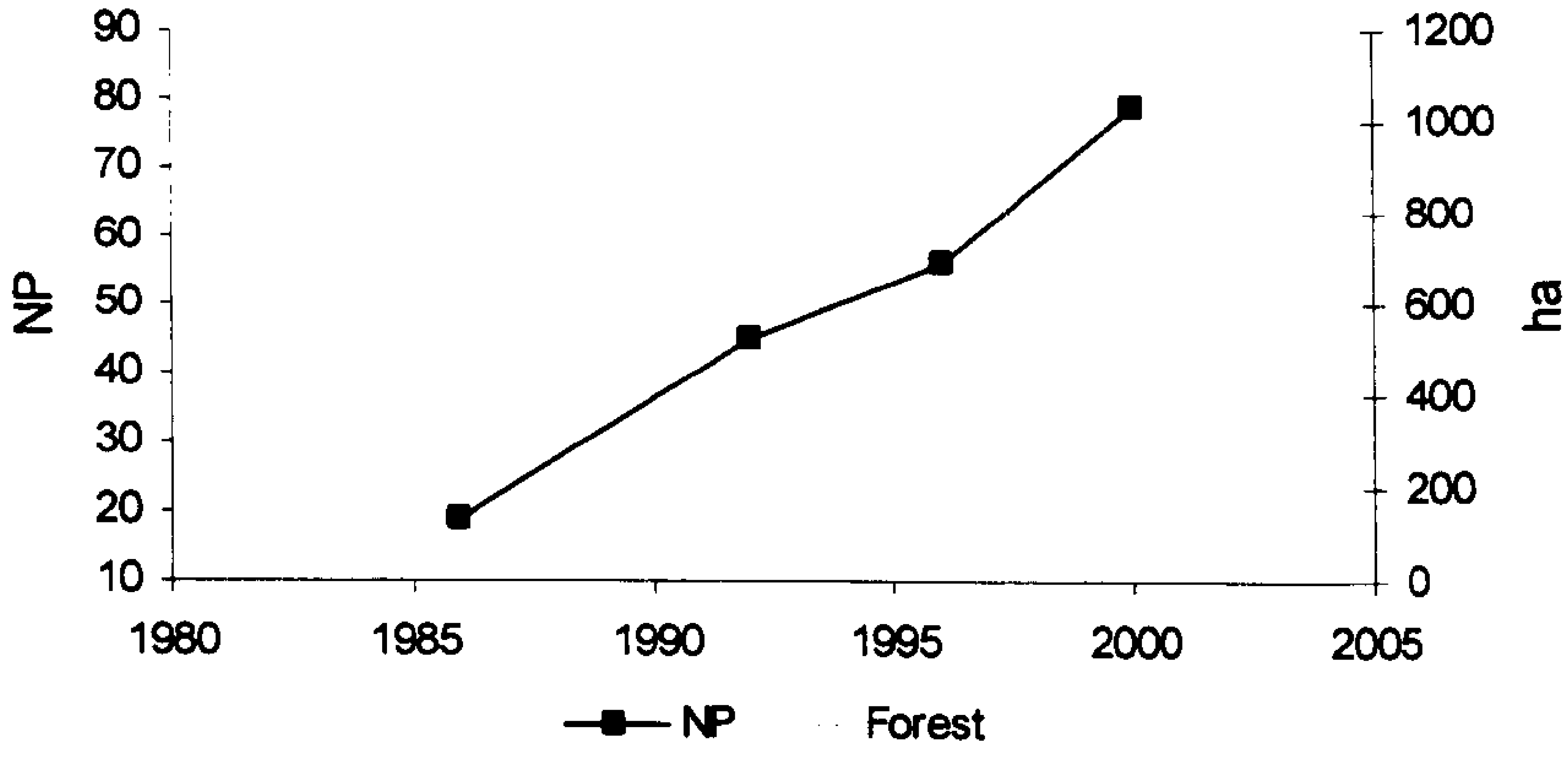


Figure 5.8: MPS (ha) and PSSD (error bars on MPS curve) of forest patches and the decrease in the area of forest (ha).

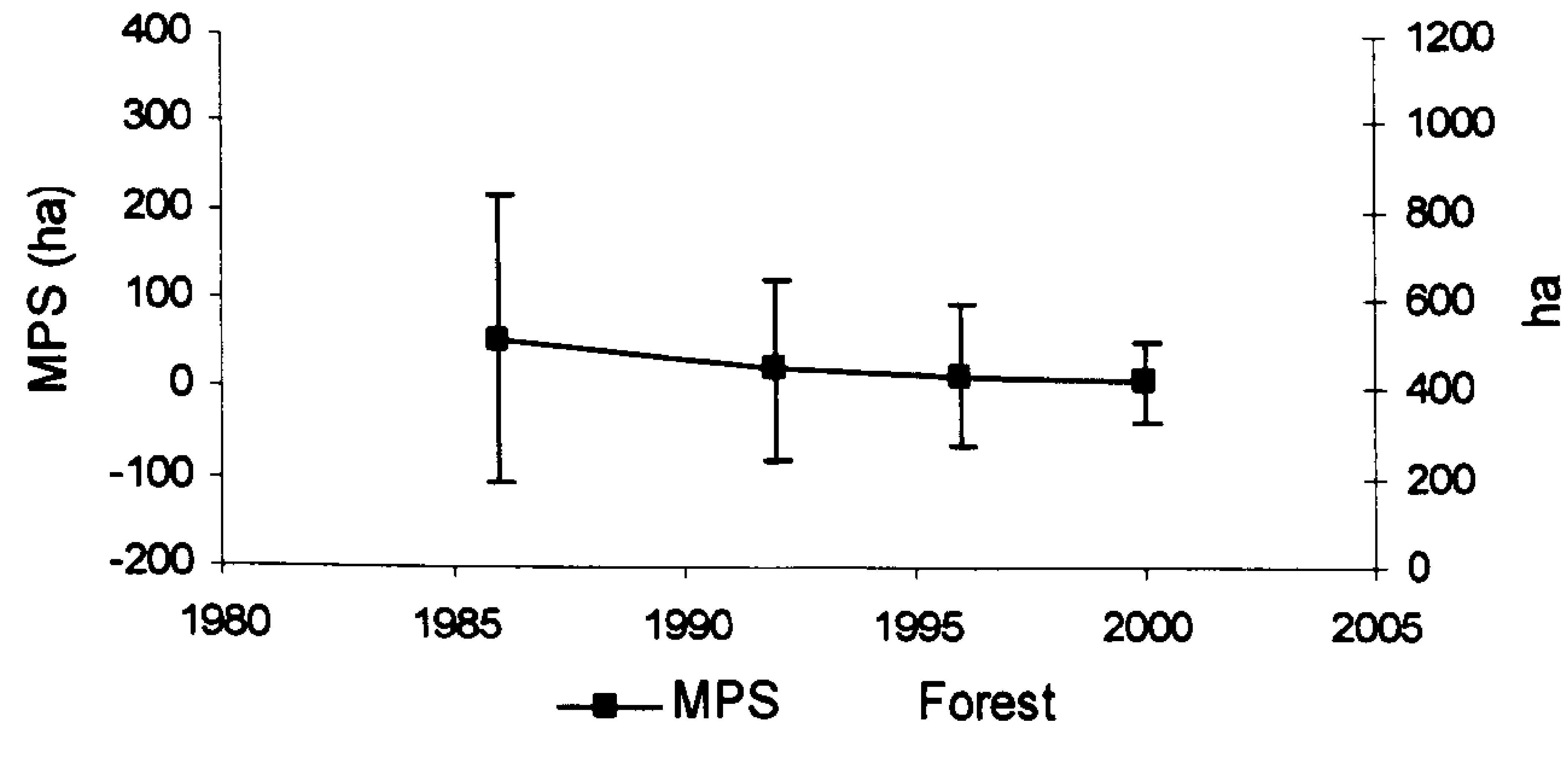


Figure 5.9: MPS (ha) and PSCV (error bars on the MPS curve) of forest patches and decrease in area of forest (ha).

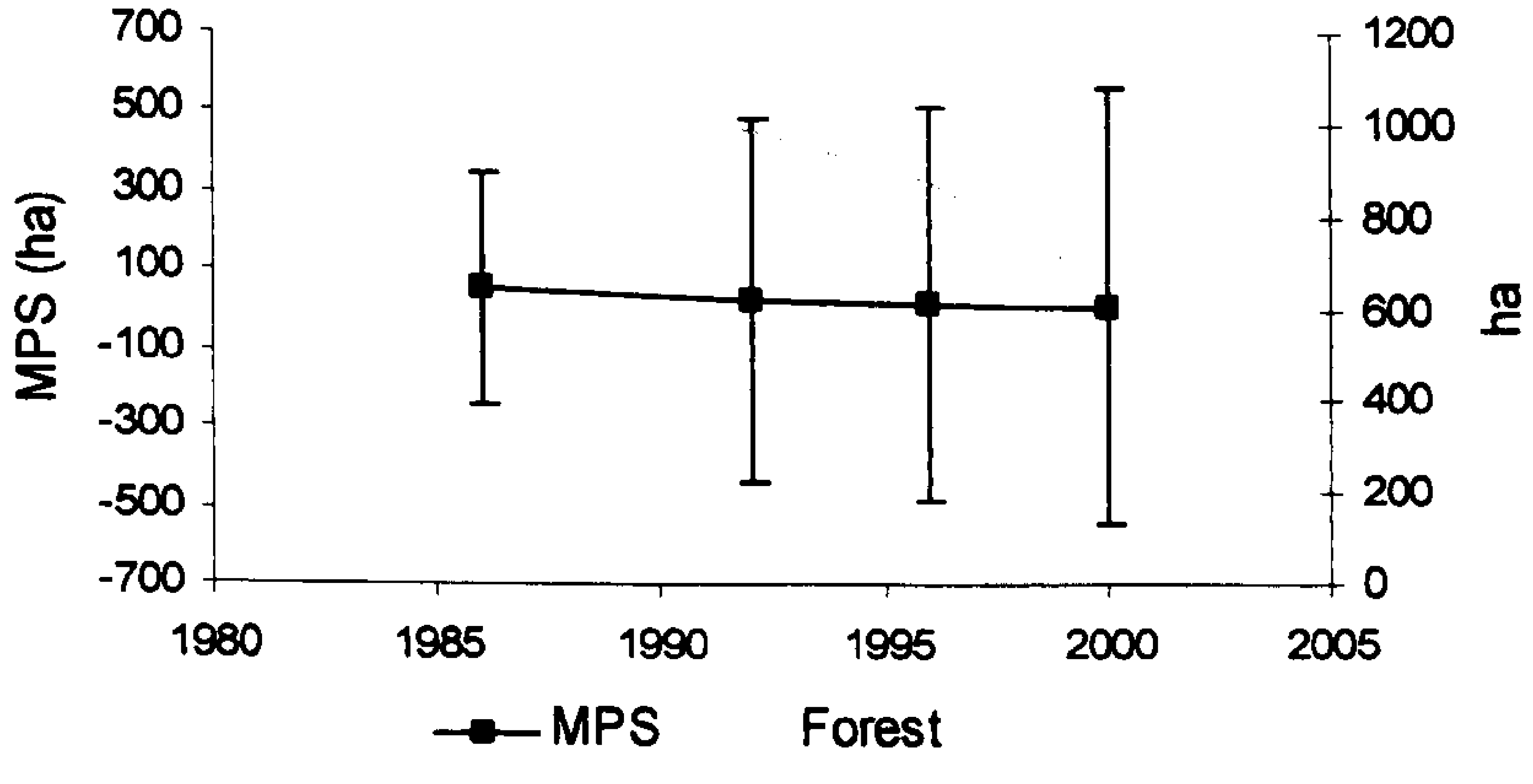


Figure 5.10: Number of non-forest patches (NoP) and increase in non-forest area (ha).

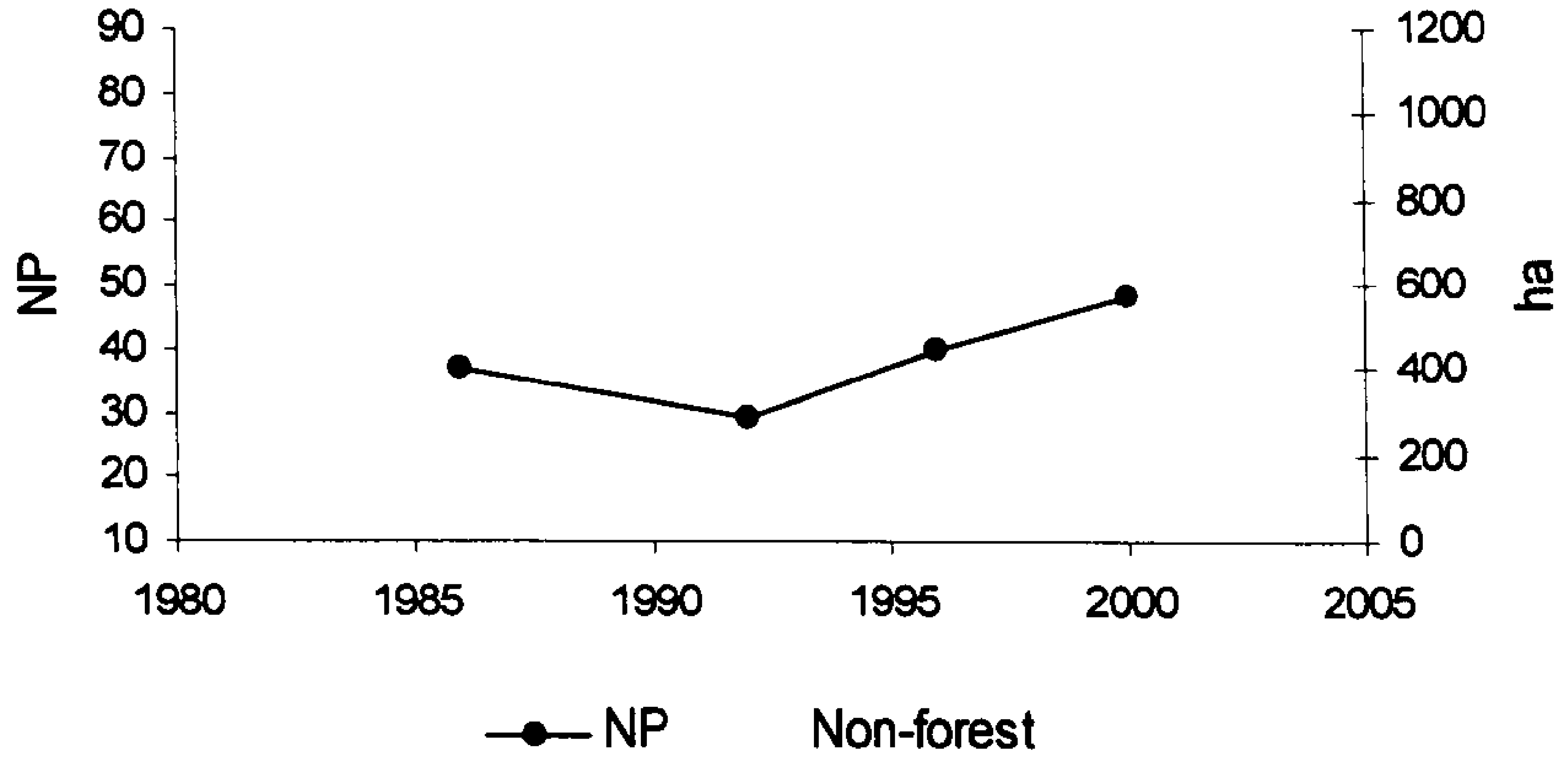


Figure 5.11: MPS (ha) and PSSD (error bars on the MPS curve) of non-forest patches and increase in non-forest area (ha).

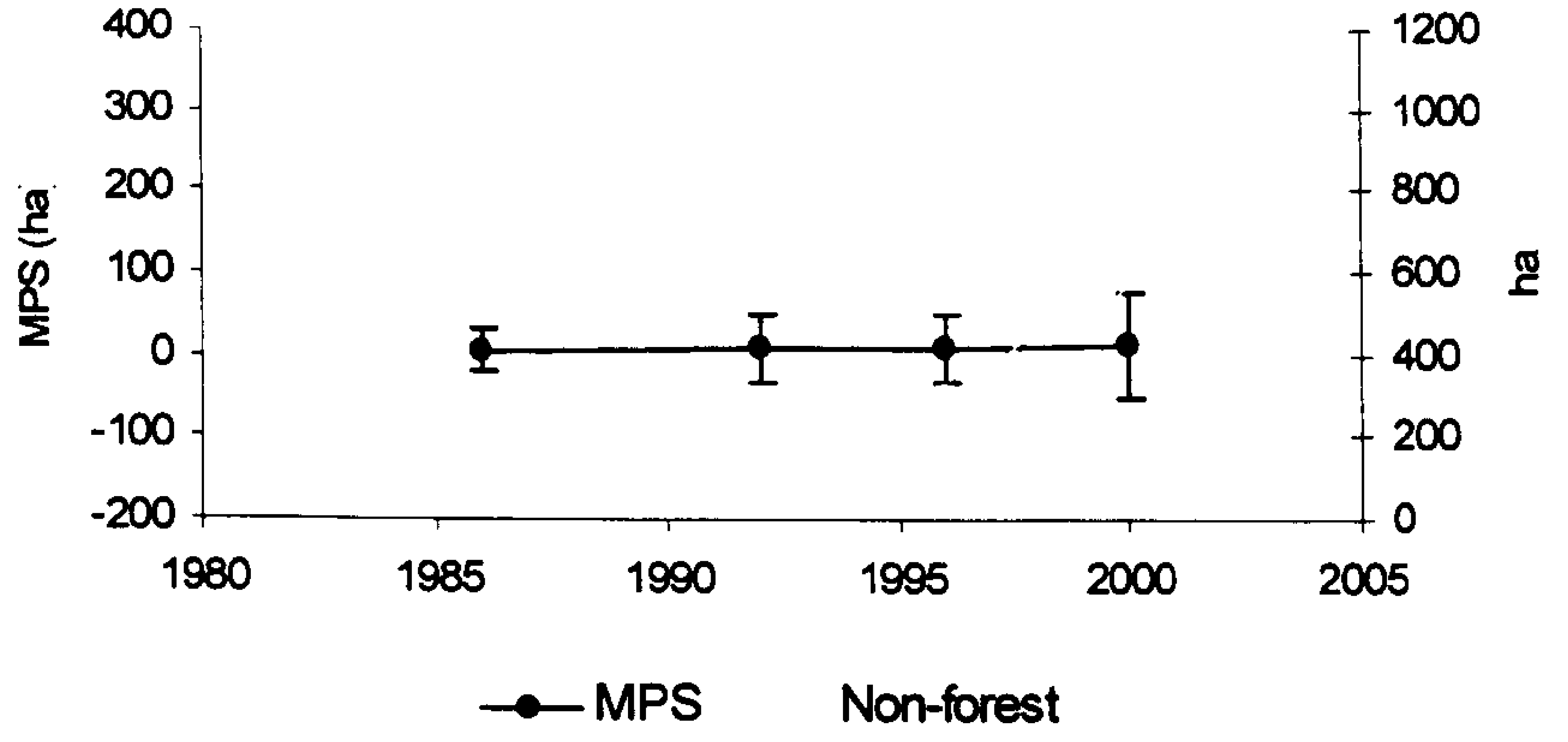


Figure 5.12: MPS (ha) and PSCV (error bars on the MPS curve) of non-forest patches and increase in non-forest area (ha).

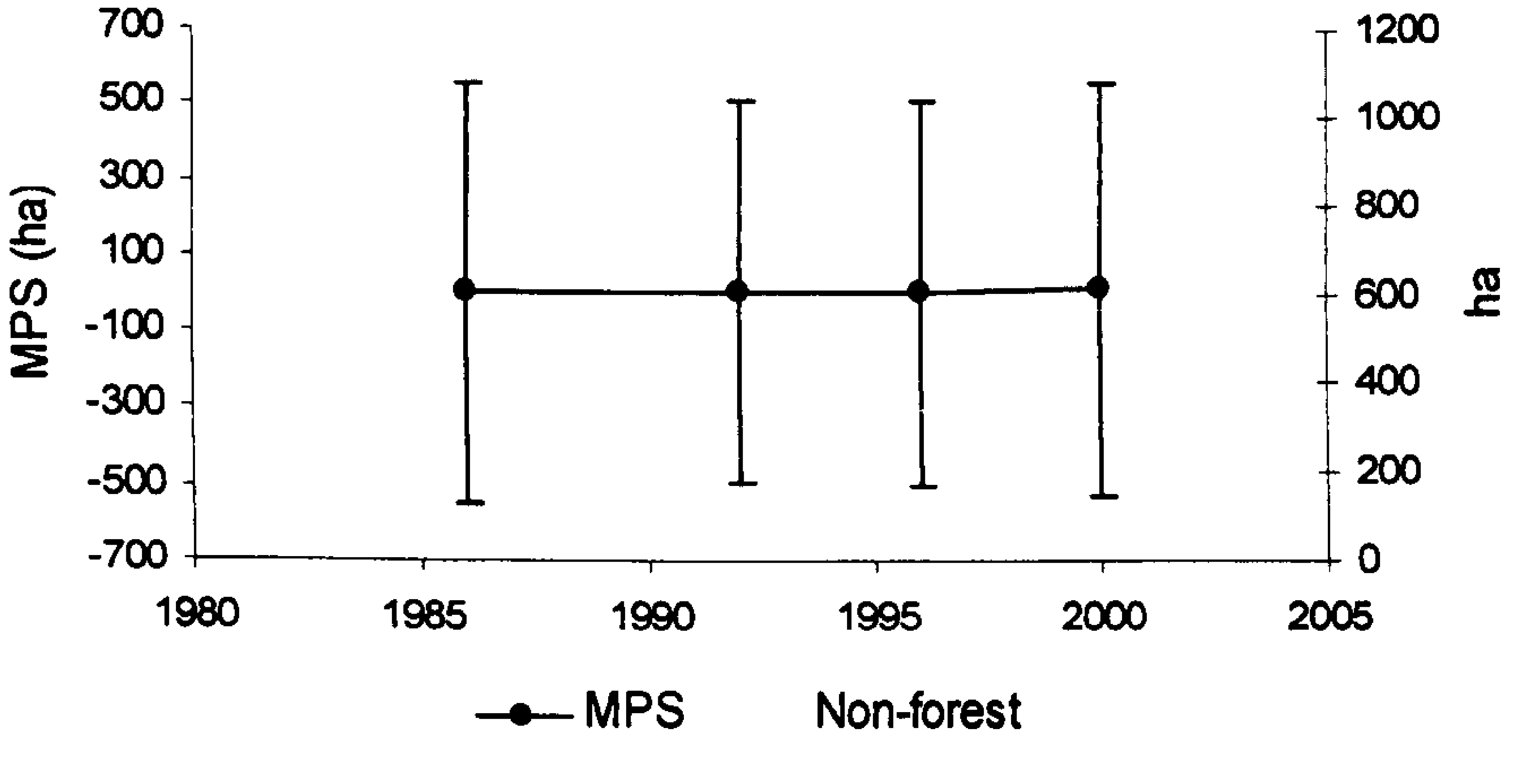


Figure 5.13: MNN (m) and NNSD (error bars on the MNN curve) of forest patches and decrease in area of forest (ha).

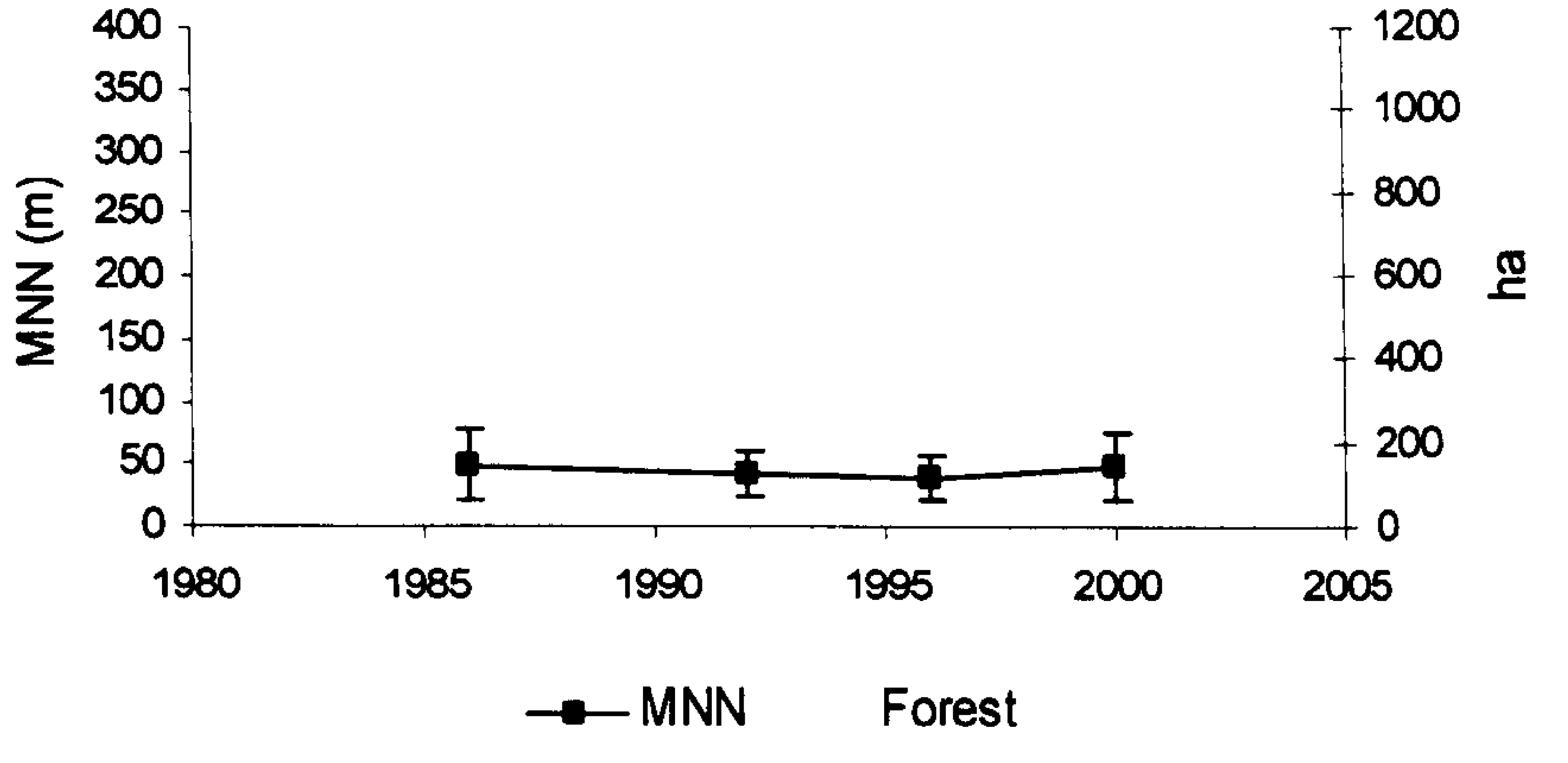


Figure 5.14: MNN (m) and NNCV (error bars on the MNN curve) of forest patches and decrease in area of forest (ha).

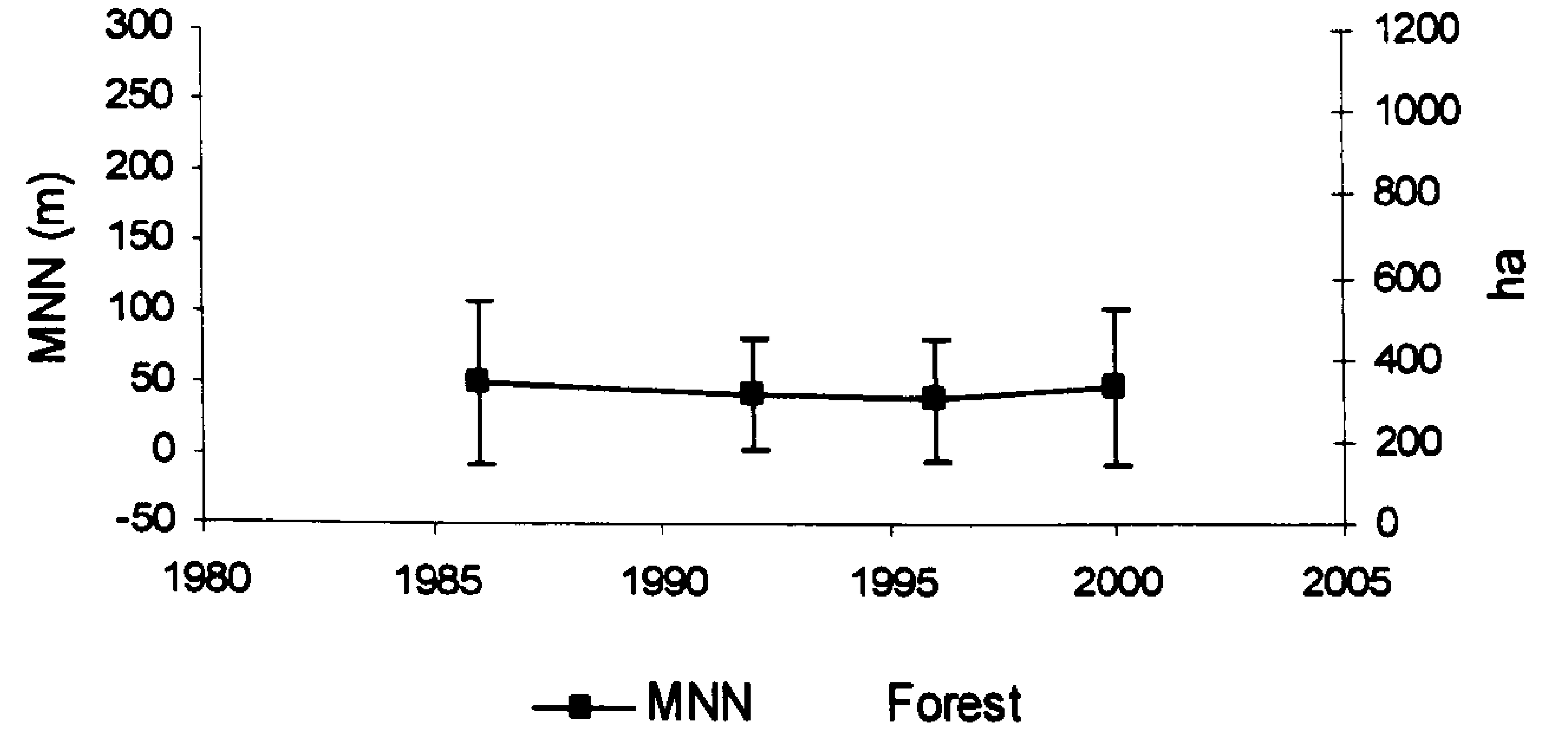


Figure 5.15: MNN (m) and NNSD (error bars on the MNN curve) of non-forest patches and increase in non-forest area (ha).

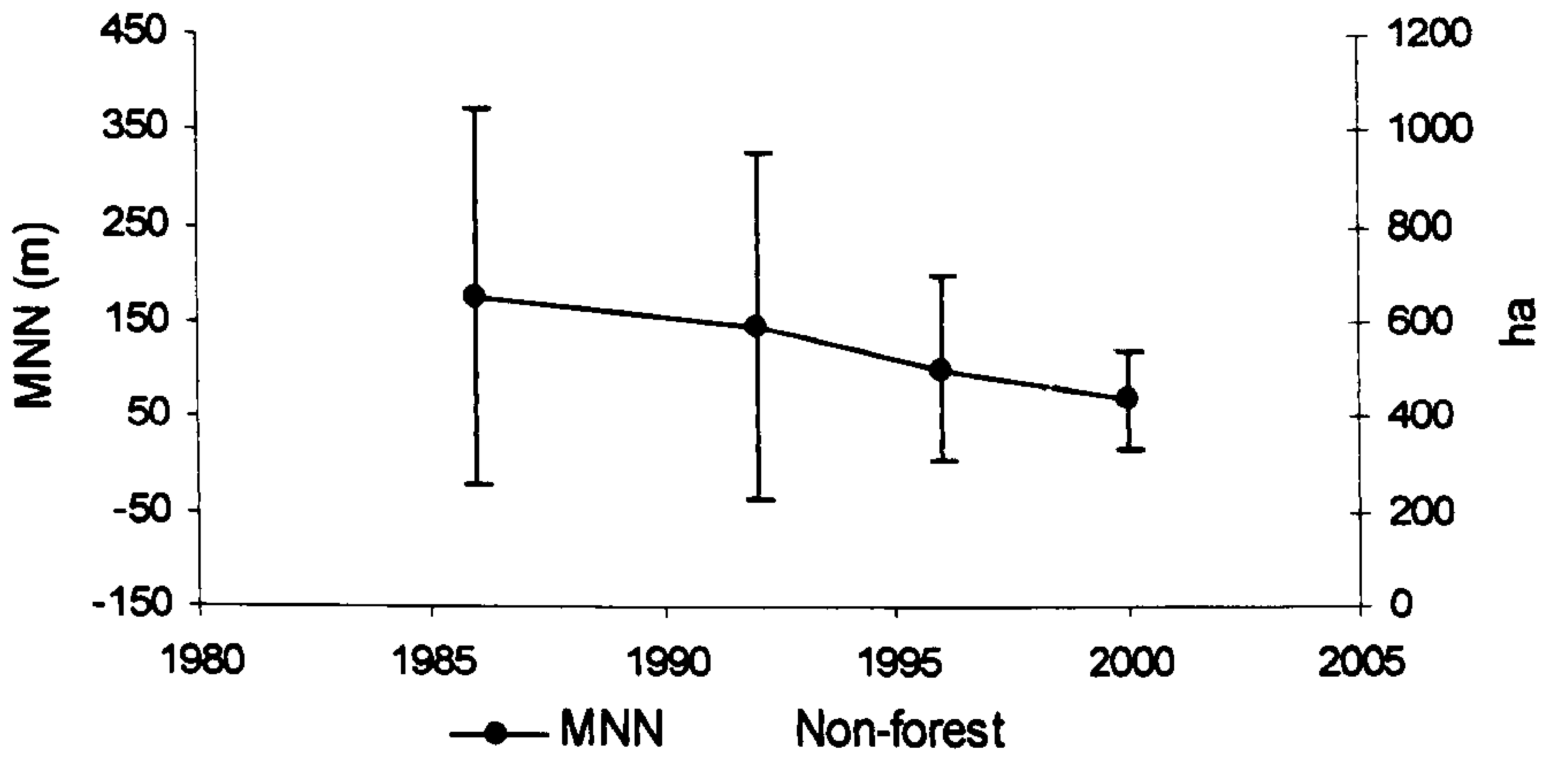


Figure 5.16: MNN (m) and NNCV (error bars on the MNN curve) of non-forest patches and increase in non-forest area (ha).

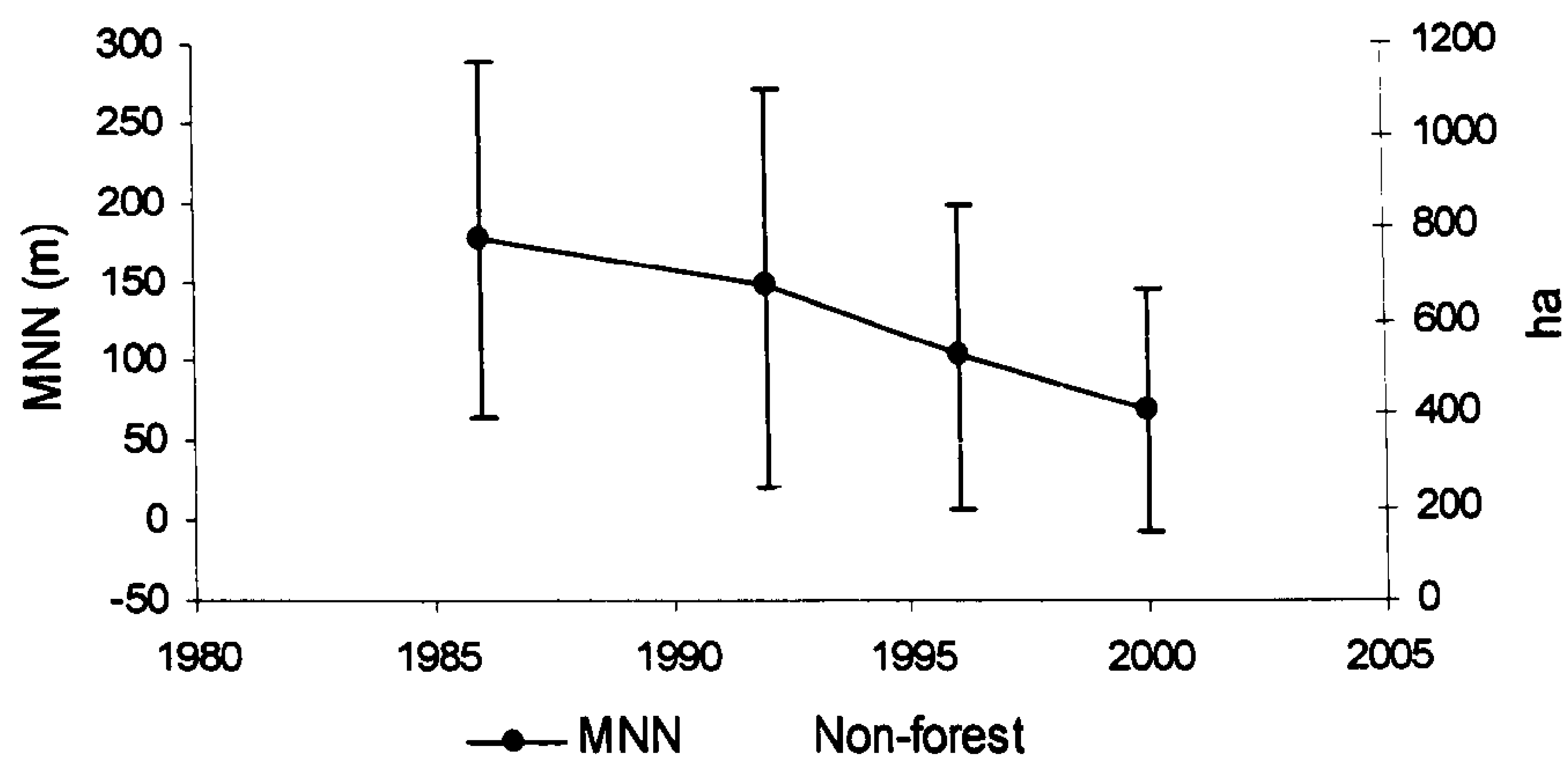
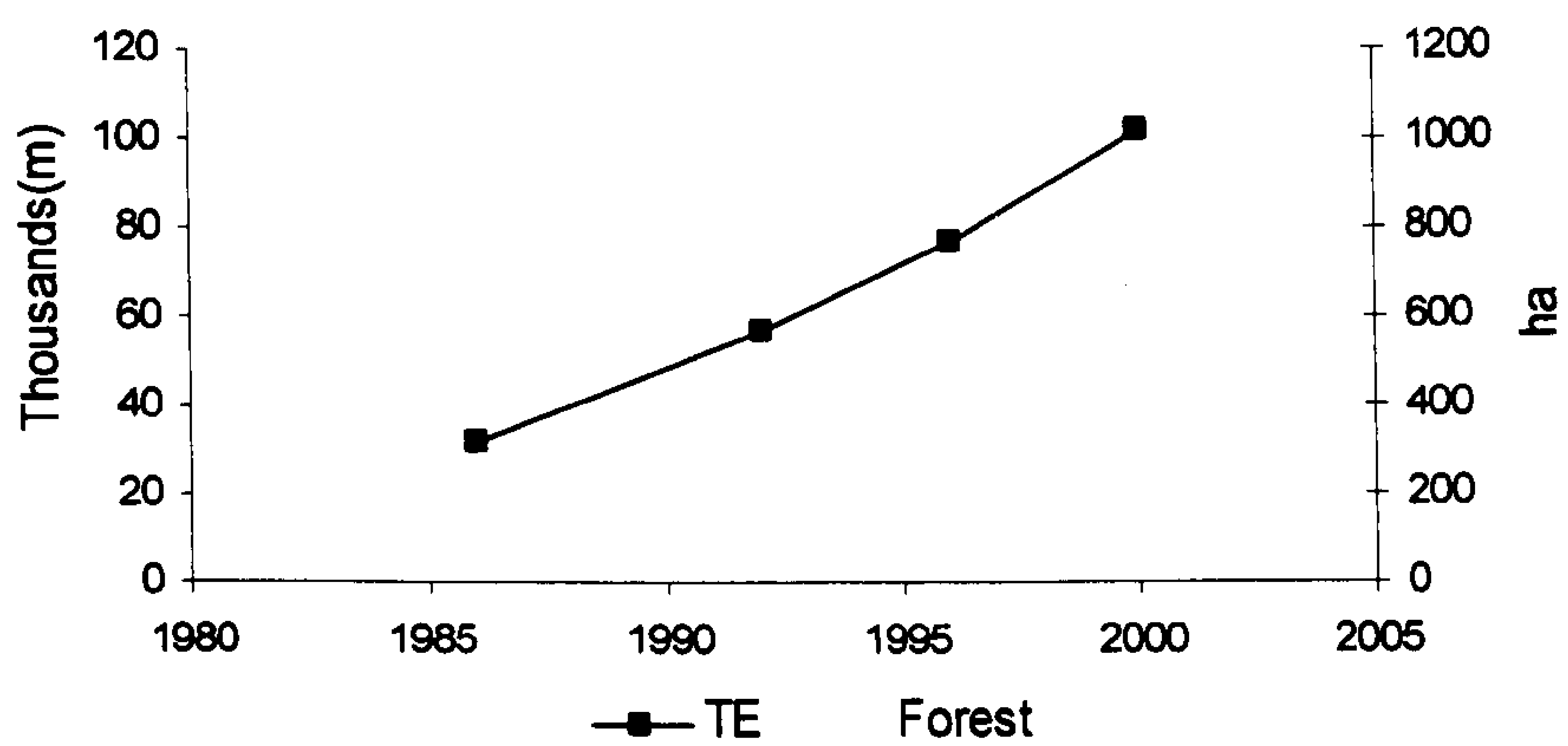


Figure 5.17: Total edge length (TEL) in metres along the forest and non-forest limits from 1986 to 2000, and decrease ion forest area.



5.2.2 Average plot clearance characteristics: Arequipa

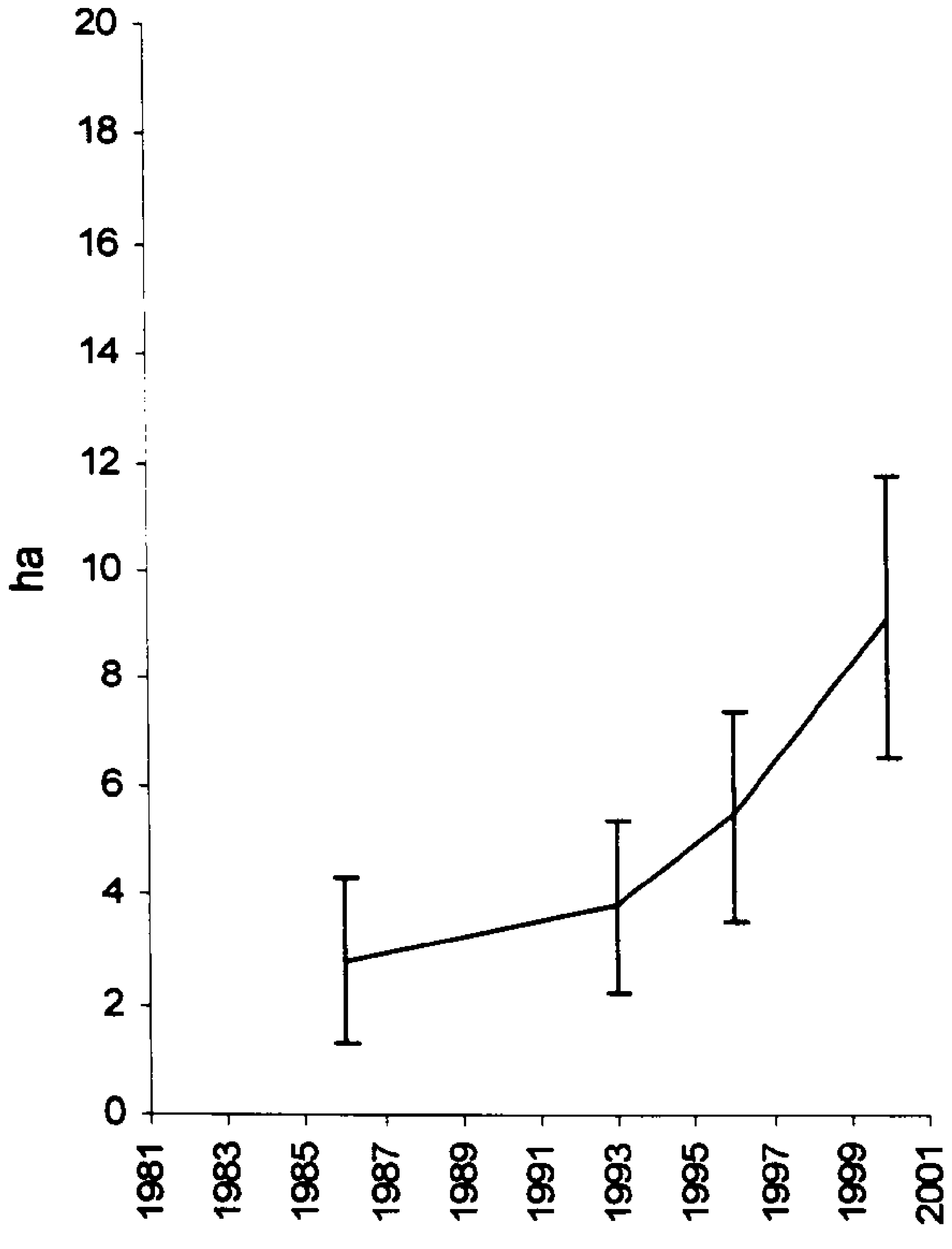
In the following section the clearance pattern of plots in Arequipa are described using the calculations for average cleared area and average rates of clearance described in Section 4.4.4.2.

5.2.2.1 Average cleared area

In 1986 an average 2.8 ha of forest per plot had been cleared (Figure 5.18). By 1993 this had increased to 5.5 ha and by 2000 this had almost doubled to 9.2 ha per plot (i.e. almost half of each 20 ha plot was cleared). The increase in the standard deviation

(1.49 to 2.6) over the period between 1986 and 2000 indicates that the amount of forest cleared within the plots became more variable.

Figure 5.18: Areas of non-forest land (ha) for individual plots between 1986 and 2000. Plot sizes are 20ha, the error bars are one standard deviation from the mean.



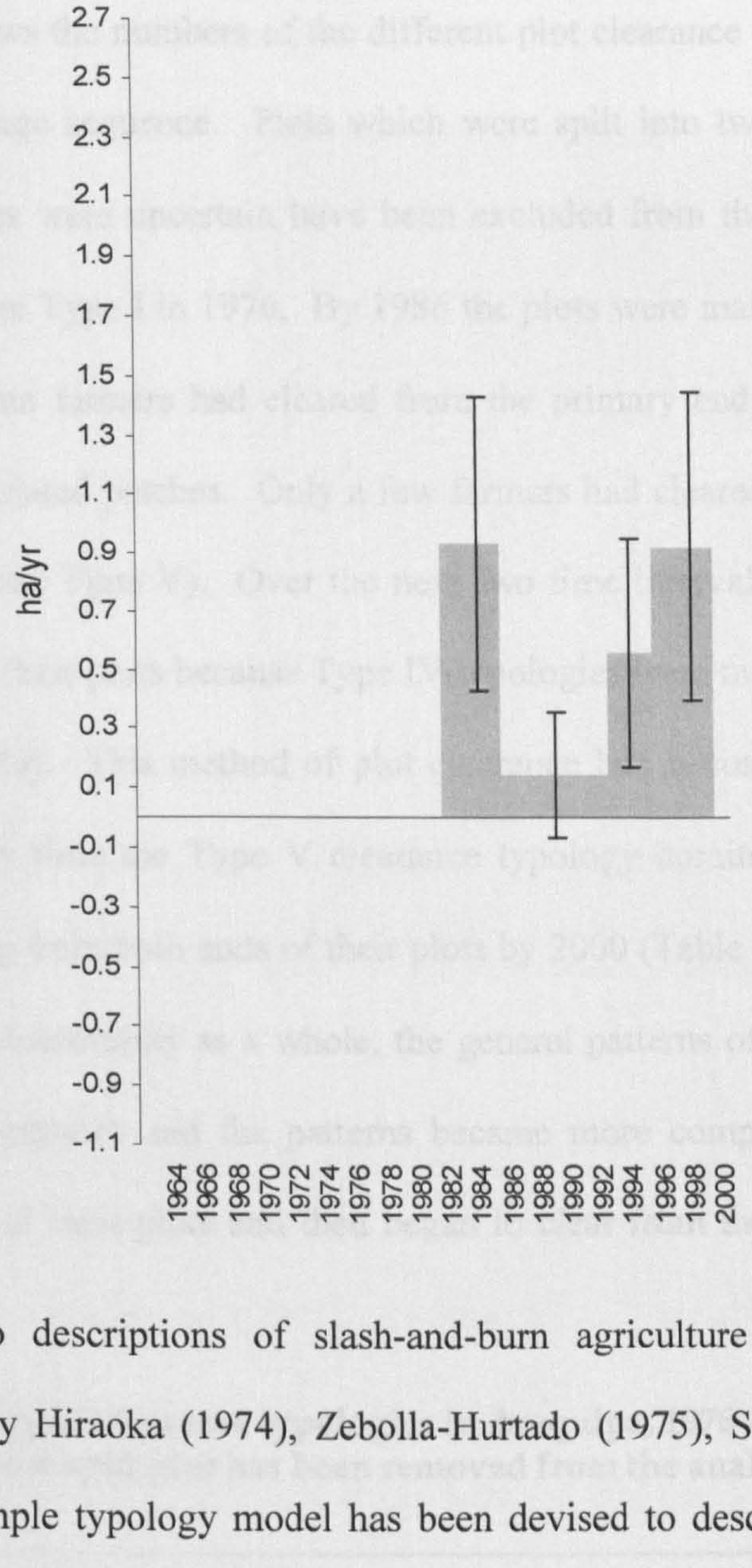
5.2.2.2 Average clearance rates

The highest rate of clearance – 0.93 ha yr^{-1} – occurred during the initial period of settlement from 1983 to 1986 (Figure 5.19). The lowest rate of clearance – 0.14 ha yr^{-1} – occurred from 1986 to 1993. The rate increased between 1993 and 1996 to 0.56 ha yr^{-1} and then increased further to 0.92 ha yr^{-1}.

5.2.3 Plot clearance typologies: Arequipa

The descriptions of forest clearance from satellite imagery (Figures 5.1 to 5.5) indicate that clearance of the forest can occur from either end of a plot or in the forested 'centre' of a plot.

Figure 5.19: Average rates of clearance for individual plots between 1986 and 2000. Plot sizes are 20ha, the error bars are one standard deviation from the mean and indicate the variability in clearance rates. Between 1993 and 1996 the error bar goes below the *x*- axis because some plots experienced replacement of forest.



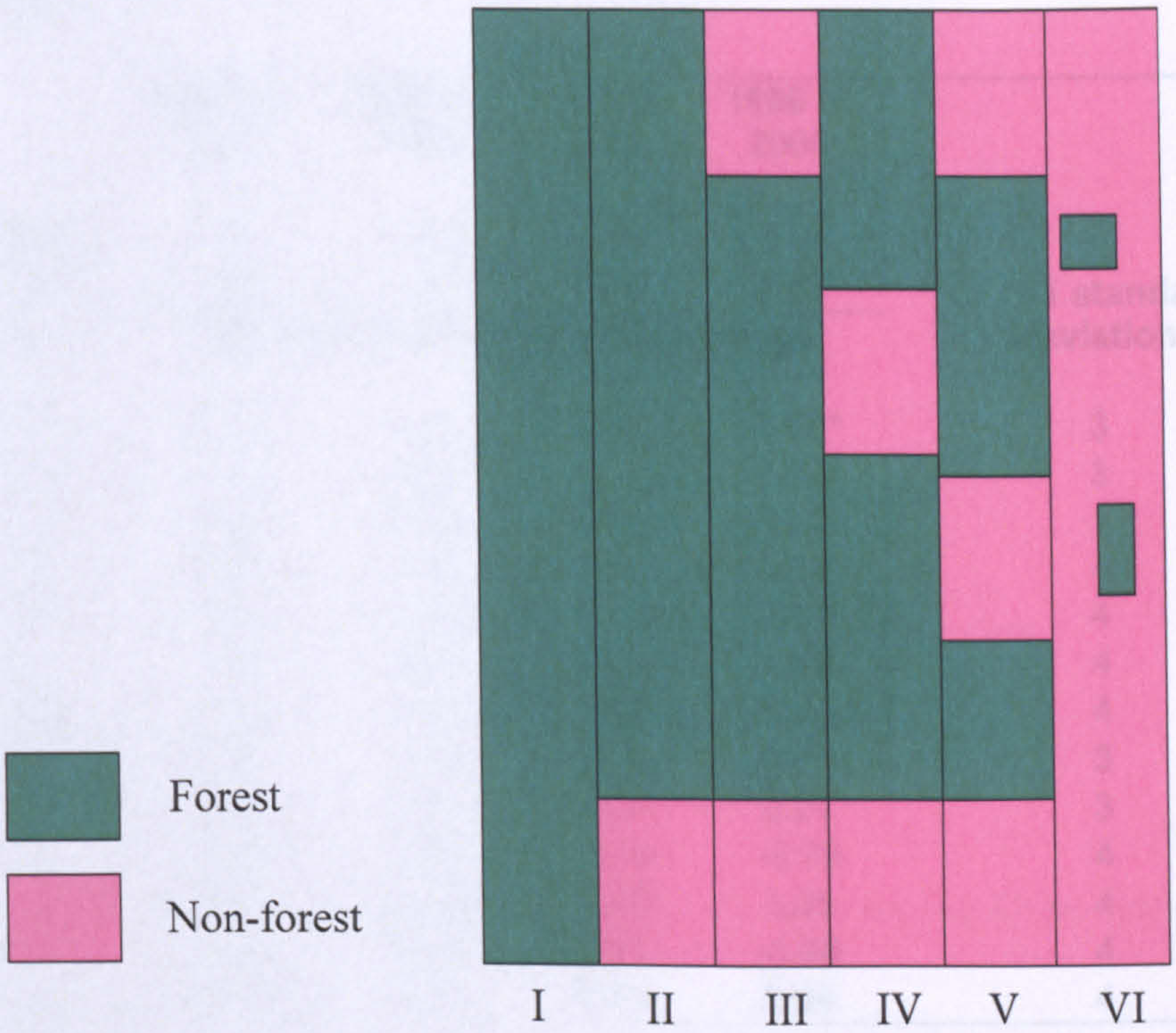
This is contrary to descriptions of slash-and-burn agriculture in other Bolivian colonisation areas by Hiraoka (1974), Zebolla-Hurtado (1975), Stearman (1976) and Hess (1980). A simple typology model has been devised to describe the patterns of forest clearance in each plot. Each plot has a primary end, which refers to the initial point of access to the plot, and a secondary end, which refers to the opposite end of the plot from the primary end. Figure 5.20 shows the possible methods of clearance in individual plots. The numbering is not intended to imply a sequence of clearance from I to VI, although plots will always begin as Type I as this represents an area of forest prior to occupation of a plot. After Type I, normally a plot will become Type II, but after this any typology is possible. The typology classification has been applied to all plots in each community.

Table 5.2 shows the numbers of the different plot clearance typologies for each time point in the image sequence. Plots which were split into two or more parts or where plot boundaries were uncertain have been excluded from the analysis. All the plots in Arequipa were Type I in 1976. By 1986 the plots were mainly Types II (47%) and IV (41%) as some farmers had cleared from the primary ends of their plots and others had cleared isolated patches. Only a few farmers had cleared from both ends of the plot, (Types III and Type V). Over the next two time intervals farmers tended to clear in the centre of their plots because Type IV typologies were most frequent in 1993 (64%) and 1996 (61%). This method of plot clearance had become less common by 2000 because by this time the Type V clearance typology dominated (59%). Many farmers were clearing from both ends of their plots by 2000 (Table 5.2) and continue to do so. Thus, in the community as a whole, the general patterns of clearance began as simple one-ended clearance and the patterns became more complex as farmers also cleared from centre of their plots and then began to clear from the secondary ends of their plots as well.

Table 5.2: Summary of clearance typologies in Arequipa, 1976 - 2000 for 59 plots (n.b. one split plot has been removed from the analysis).

Type	1976	1986	1993	1996	2000
I	59	0	0	0	0
II	0	28	14	14	5
III	0	2	2	2	7
IV	0	24	38	36	12
V	0	5	5	7	35
VI	0	0	0	0	0
Total	59	59	59	59	59

Figure 5.20: Plot clearance typology: I, no clearance; II, clearance from the primary end of the plot; III, clearance from both the primary and secondary ends of the plot; IV, clearance from the primary end of the plot with isolated patches of agriculture deeper in the plot; V, clearance at both ends of the plot and isolated patches of clearance deeper in the plot; VI, total clearance of the plot (may contain isolated patches of forest). Types IV, and V may have multiple patches and have been represented in their simplest form.



5.2.4 Land-cover change at the plot level

This section illustrates how representative the plots sampled in detail (Section 4.2.2.1) are of the average cleared statistics (Section 5.2.2.2) area for the community as a whole. For each plot the cleared areas was compared to the average cleared area for the community. In Table 5.3 the differences between the community mean and the actual cleared area of the sample plots for each time point have been calculated, and the number of times the plot value fell within one standard deviation of the community average is shown. The plot that was selected as typical of the community was the one that was closest to the average cleared area for the community for all the four time intervals (A_M) and the plot chosen to represent atypical clearance trends was the one which deviated most from the average clearance patterns (A_C).

Table 5.3: The difference between the average cleared area for the community and the areas cleared in the sample plots: Arequipa. Where a plot falls outside +/- 1 standard deviation it is marked with an asterisk and the number of times the cleared area in a plot falls within 1 standard deviation of each time interval is shown in the final column.

	1983 to 1986	1986 to 1993	1993 to 1996	1996 to 2000	
Average	2.80	3.80	5.48	9.16	
SD	1.50	1.57	1.94	2.62	+ / - 1 standard deviation
Plot	Difference from community average				
A_A	-0.68	-1.50	-0.84	-3.40*	3
A_B	-1.23	-2.03*	-1.77	0.50	3
A_C	-0.06	-2.86*	-2.21*	-5.20*	1
A_D	-0.91	-0.51	1.13	0.65	4
A_E	-0.66	-1.30	-1.15	-1.29	4
A_F	-1.49	-0.29	0.08	1.69	4
A_G	-1.00	-0.61	-1.84	-0.15	4
A_H	-0.78	-0.70	-2.42*	0.55	3
A_I	0.04	1.11	2.15*	0.21	3
A_J	-1.15	-0.37	-0.70	-0.79	4
A_K	0.93	-0.12	-1.03	1.55	4
A_L	-0.07	0.61	0.01	-1.48	4
A_M	-0.49	0.70	0.71	0.94	4

Typical plot clearance: A_M

Plot A_M was not the closest to the mean average cleared area for all time points (Table 5.3) but it was closest to the average cleared area of the community (Figure 5.21). According to INRA (1986), plot A_M (105 by 2,050 m) was settled in 1983 and clearance began from the primary end of the plot. By 1986 the original owner had cleared around 2 ha for subsistence and then began to cultivate citrus fruits (INRA, 1986). Figure 5.22 shows the access into the plot, direction to market and the distribution of crops in 2002. An isolated patch of non-forest near the secondary end of the plot in 1986 was forested over again by 1993 (Figure 5.23).

Figure 5.21: Plot A_M and the average cleared area for all plots in Arequipa.

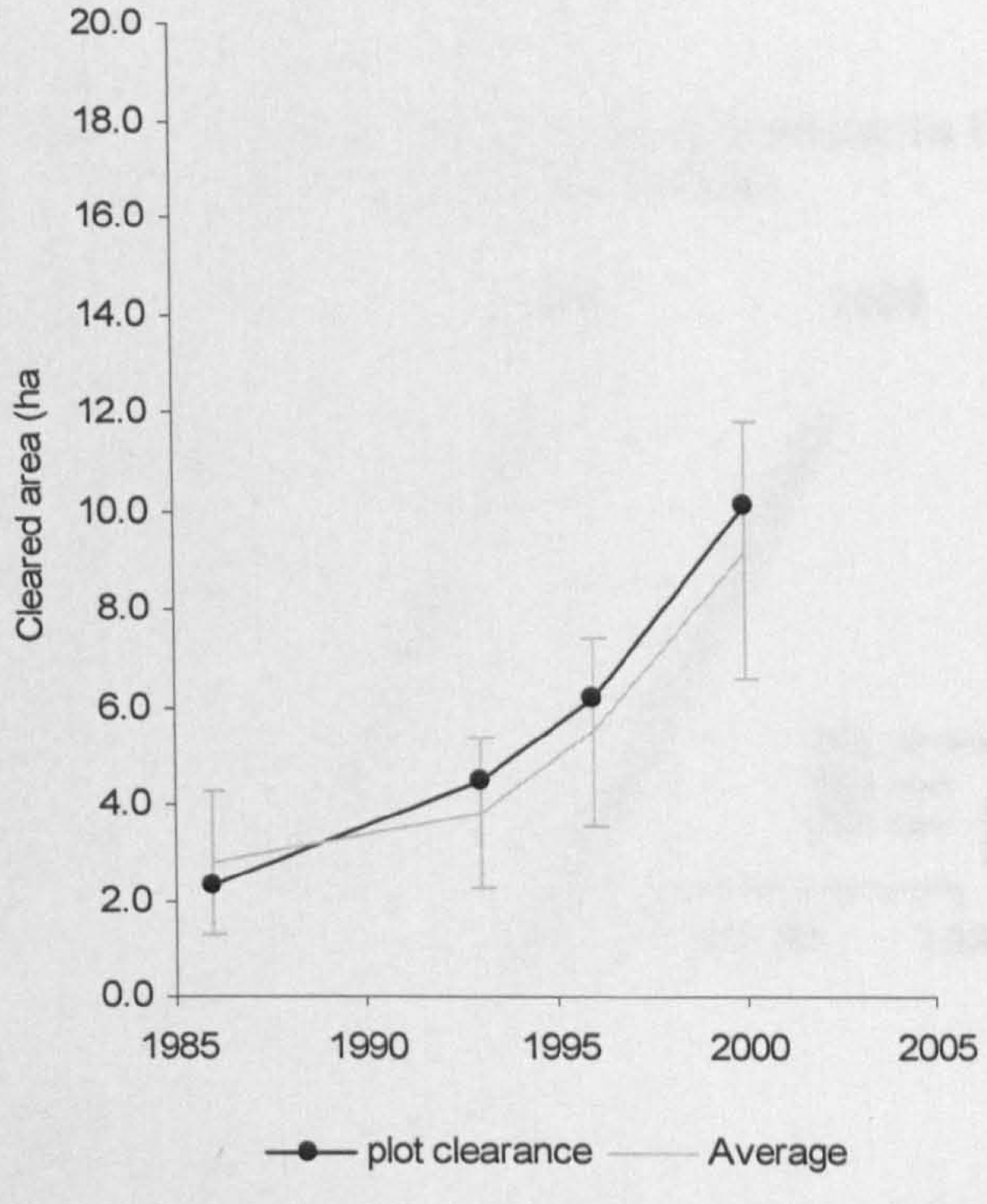
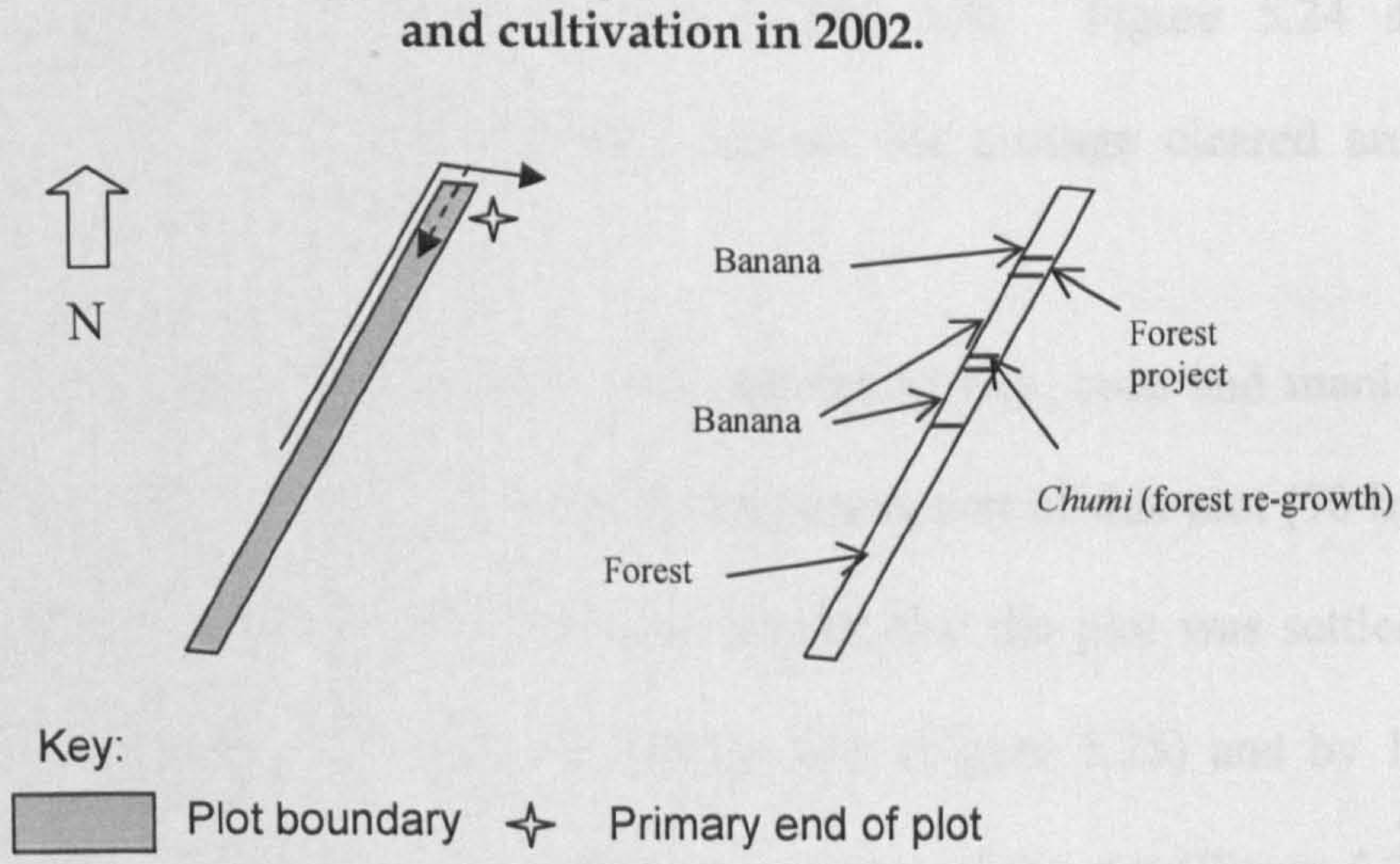
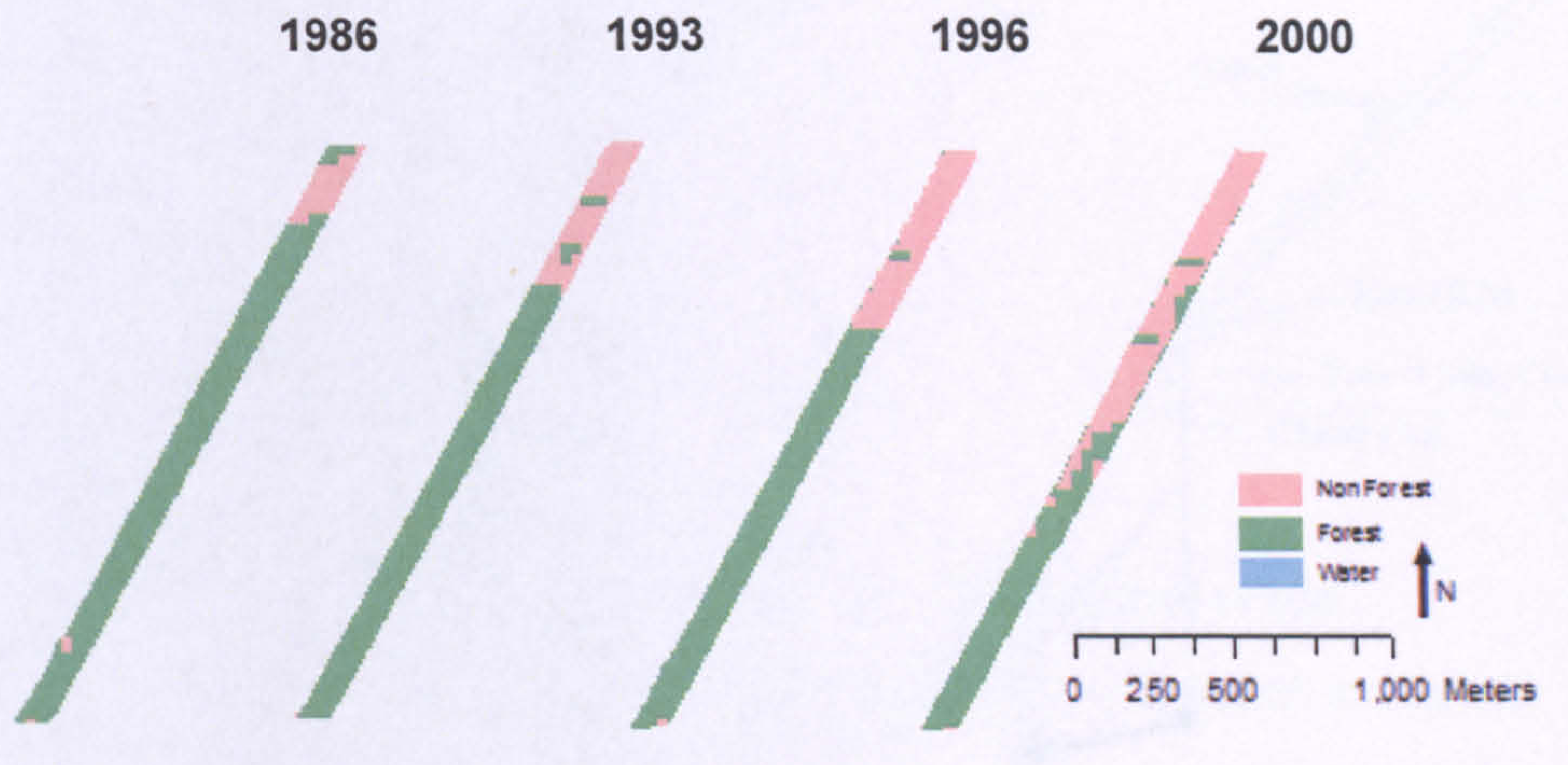


Figure 5.22: Schematic diagram of the plot of Rubán Toribio Díaz, showing access and cultivation in 2002.



In 1996 Rubán Toribio Díaz took possession of the plot. Rubán has always grown rice and bananas for domestic consumption and sells them at the local market on the Cochabamba to Santa Cruz highway. In addition he had one hectare of forest which was used for extractive purposes with financial and technical support from the FAO tropical forestry department in Chapare (he did not give any details of the forest products). His family labour force includes his spouse and four children under twelve.

Figure 5.23: Progression of forest clearance for agriculture in the plot of Rubán Toribio Díaz, 1986 to 2000.

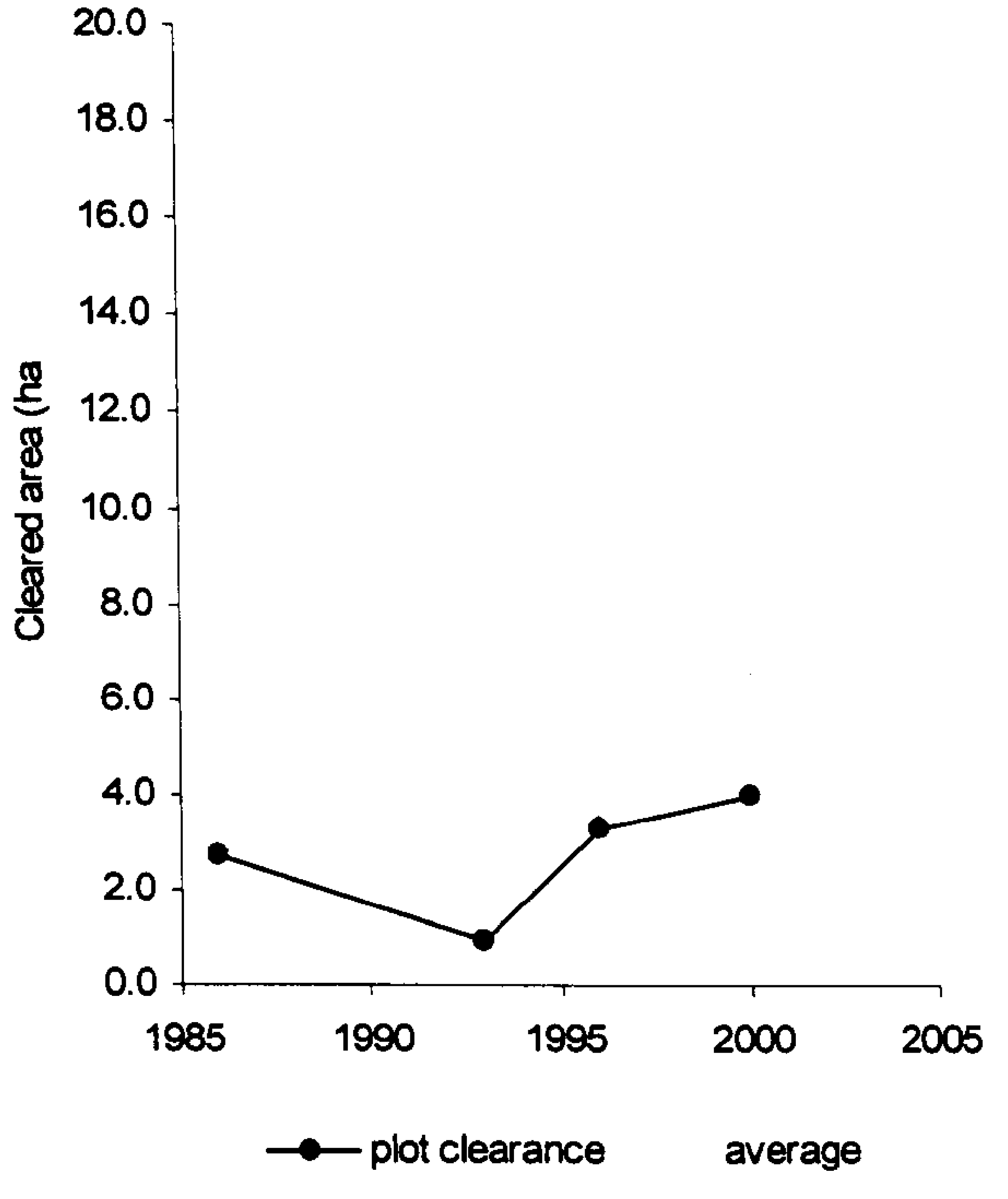


Atypical plot clearance: A_C

Plot A_C does not fit the trend of average cleared area for the community well and deviates substantially from the mean (Table 5.3). Figure 5.24 shows the progression of cleared area for plot A_C against the average cleared area for the community.

In 2003 Juan Reynoso (age 35) was cultivating rice, coca and manioc on plot A_C with his wife (age 45). He recalled taking possession of this plot (90 by 2800 m) in 1985 although the INRA (1986) records indicate that the plot was settled in 1983. Forest clearance began at the south end of the plot (Figure 5.25) and by 1986 some isolated patches of non-forest were evident in the centre of the plot (Figure 5.26). These isolated patches had disappeared by 1993 and the non-forest area had decreased.

Figure 5.24: Plot A_C against the average cleared area for all plots in Arequipa.



There was little variation in the size of area cleared from the primary end of the plot between 1996 and 2000. Figure 5.26 shows that there was some clearance at the secondary end of the plot by 2000 but Juan did not acknowledge any activity there. However, in 2003 I visited the areas that had been cleared at the secondary end of the plot and noted that it had since become *chumi* (forest re-growth). Juan described how he has always rotated coca, manioc and rice with a fallow period of forest re-growth (or *chumi*) and has not been involved in any alternative development support for crop substitution. The crops he produces are sold locally. According to Juan the soil is good for coca cultivation.

Figure 5.25: Schematic diagram of the plot of Juan Reynoso, showing access and cultivation in 2002.

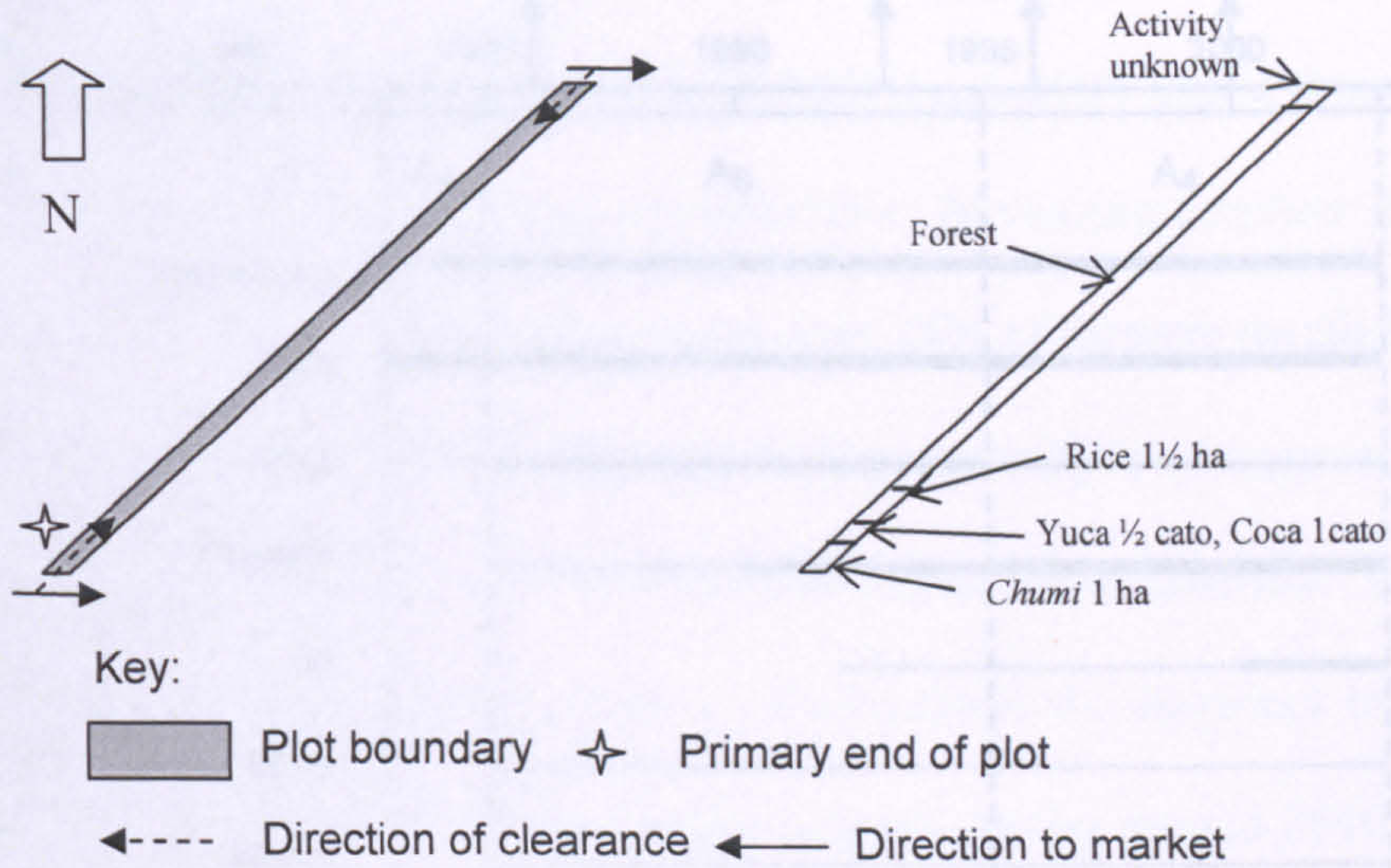
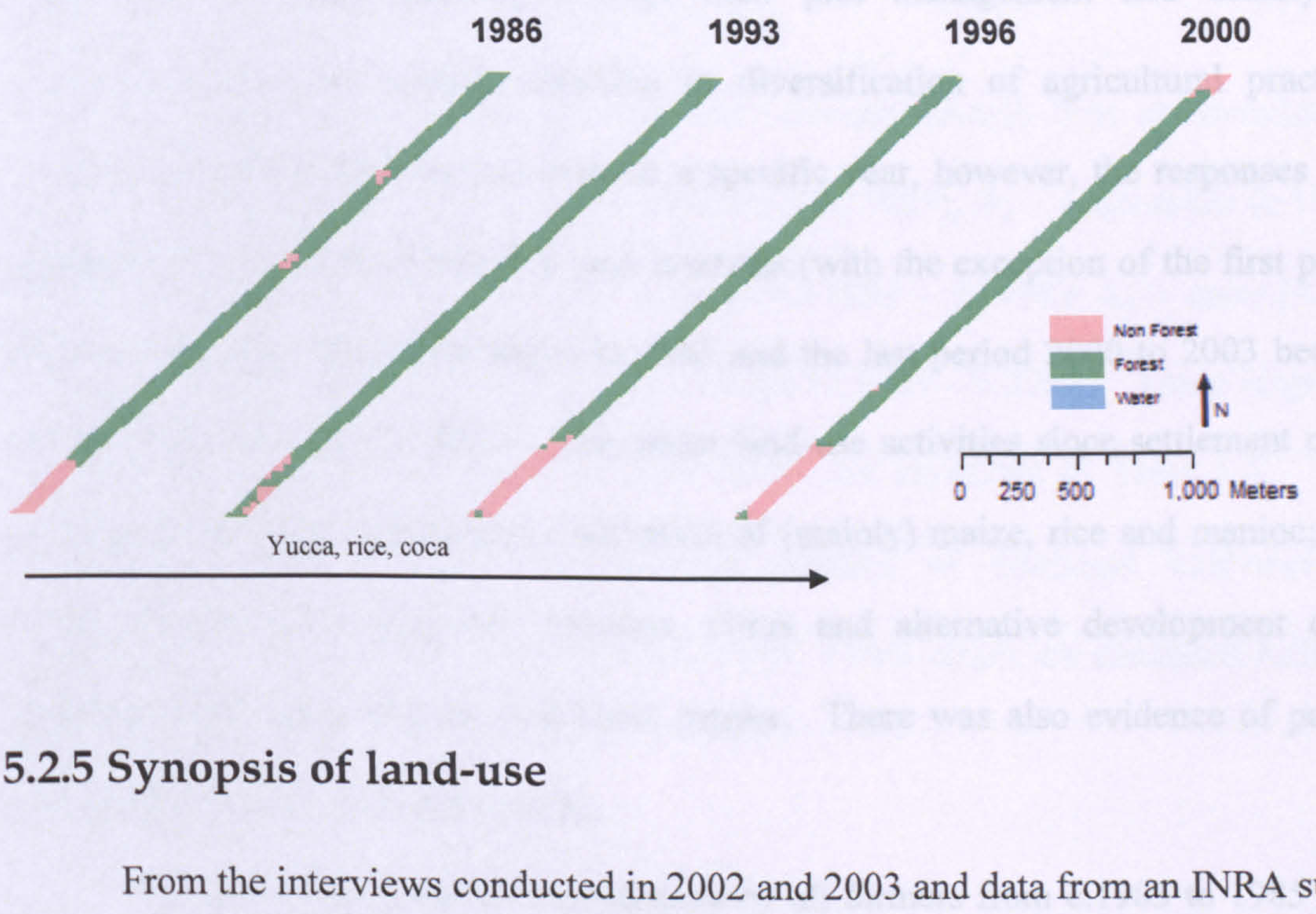


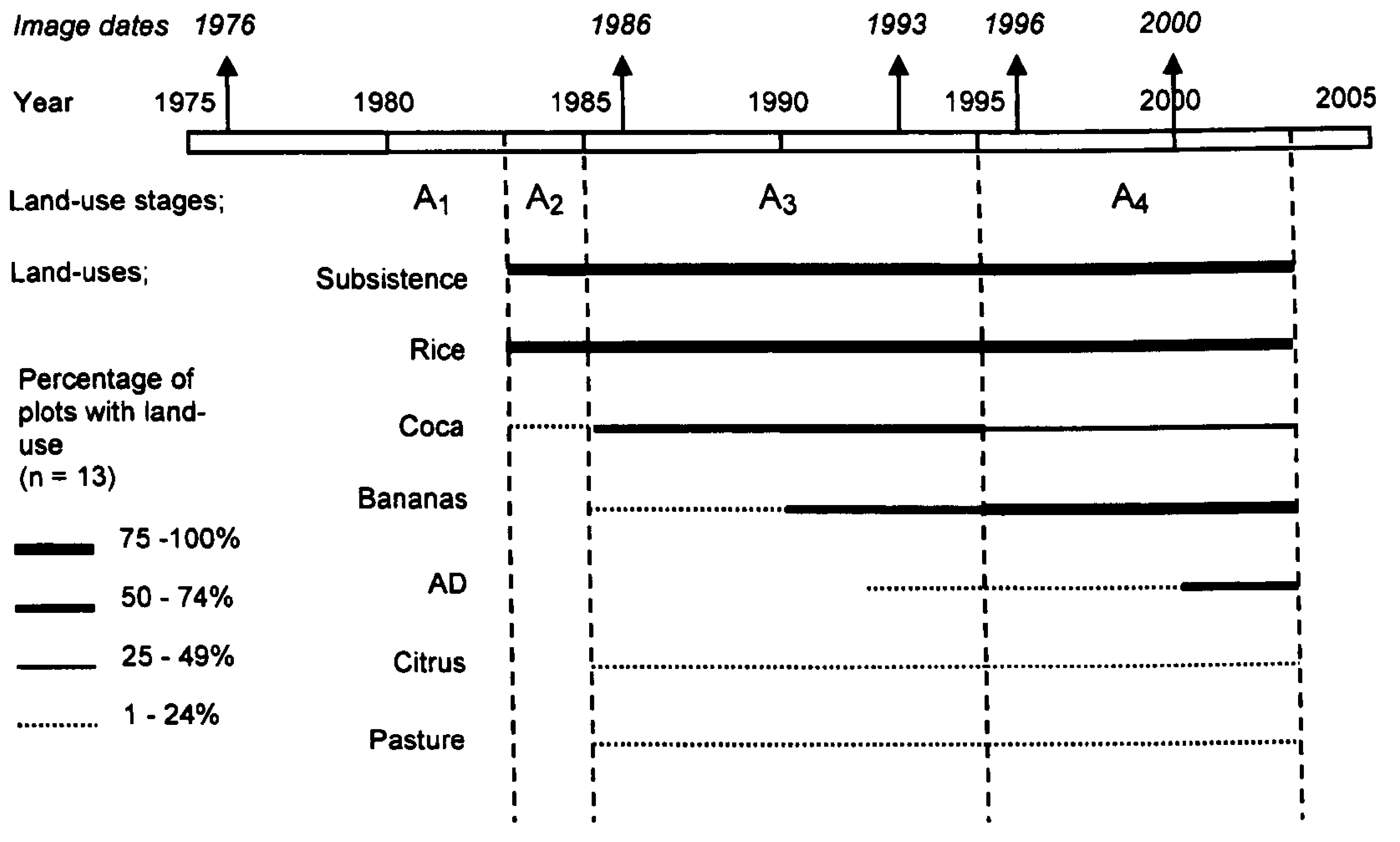
Figure 5.26: Progression of forest clearance for agriculture in the plot of Juan Reynoso, 1986 to 2000.



5.2.5 Synopsis of land-use

From the interviews conducted in 2002 and 2003 and data from an INRA survey (1986), Figure 5.27 provides a summary of the land-use activities since colonisation in 1983.

Figure 5.27: Synopsis of land-use activities in Arequipa 1983-2003. Source: INRA (1986) and interviews in 2002 and 2003.



Each of the major land-uses has been identified. The interviews indicated that farmers do not simultaneously change their plot management and usually act independently of one another resulting in diversification of agricultural practices. Farmers referred to land-use activities in a specific year, however, the responses were aggregated in Figure 5.27 into five year intervals (with the exception of the first period 1983 to 1985 as colonisation began in 1983 and the last period 2000 to 2003 because the last field visit was in 2003). The major land-use activities since settlement of the community included: subsistence cultivation of (mainly) maize, rice and manioc; cash crops included rice, coca leaf, bananas, citrus and alternative development crops, including mint, heart of palm and black pepper. There was also evidence of pasture land being set aside for cattle grazing.

Subsistence cultivation was practiced by all farmers from c.1983 to 1985 but it was a key land-use throughout the time period for at least 75% of the farmers sampled. Rice crops, which form part of the subsistence management of plots have also been cultivated for economic rent throughout the period by at least 75% of farmers. Coca leaf has been cultivated continuously since colonisation contributing to economic rent. From the early 1980s until the mid 1990s at least 50% of the farmers indicated that they were growing coca, this number fell to at least 25% from 1995 when fewer farmers described coca as one of their major land-use activities. Increasing numbers of farmers have cultivated bananas since colonisation. Less than 24% of farmers recalled this as a major activity prior to 1990, at least 25% of the farmers cultivated bananas between 1990 and 1995 and since then 75% said that bananas were a major land-use. From 1993 onwards farmers began to recall the presence of alternative development crops. The interviews did not reveal that these were a major activity, but by around 2000 the recall of specific alternative development products like heart of palm and black pepper increased. Less than 24% of farmers noted pasture and citrus as forms of land-use but, despite the low numbers these two activities have been recalled since 1985 and fruit trees and pasture were observed in the field visits.

For the purposes of this research, the land-use through time at Arequipa has been divided into key stages; A_1 – *no clearance* (pre 1983); A_2 – *subsistence* (c.1983 – c.1985); A_3 – *coca (<74%), rice and bananas* (c.1985 – c.1995); A_4 – *coca (<49%, rice, bananas and alternative development crops* (c.1995 – c.2002). These stages are shown in Figure 5.27 and details of these stages are expanded in Table 5.4. These stages are transitional but they represent patterns of dominant land-uses and diversification of land-use within the community. These stages are discussed further in Section 6.4.

Table 5.4: Land-use stages in Arequipa

Community	Stage	Land-use description
Arequipa	A_1	*No clearance* Before 1983 no colonists had yet settled in Arequipa.
	A_2	*Subsistence* (c.1983 – c.1985). Households were dependant on their produce. Normally around 2-4 hectares was sufficient for subsistence. Coca was also being cultivated.
	A_3	*Coca (<75%), rice and bananas* (c.1986 – c.1995). During this period coca was the major source of economic rent. If not being consumed for household needs, surplus rice was a commercial crop allowing farmers to take advantage of the high soil nutrient levels immediately after slash and burn type clearance. A hectare (sometimes two) was normally cultivated. Some farmers grew bananas, often up to 3ha, but this was not a major activity in the community but provided an alternative economic rent to coca. Towards the end of the period a few plots supported alternative development crops, e.g. mint.
	A_4	*Coca (<49%), rice, bananas and Alternative Development crops* (c.1996 – c.2002). This was a period of increased diversification of crops. The beginning of this period was marked by an increase in banana cultivation. Coca remained an important source of economic rent in some households but it's importance was beginning to decrease within the community as a whole. More alternative products were grown by 2000 with heart of palm and black pepper being the most frequent. The interviews indicated that land-set aside for pasture was increasing.

5.3 LULCC development in Bogotá

In 1975 (Figure 5.28) the area was almost contiguous humid tropical forest (approximately 9 by 10 km). The FCC shows how the community is surrounded on three sides by two river networks running northwards into a larger river which flows from east to west (Figure 5.28). As was the case with Arequipa, there was disturbance of the forest through natural forces and the Yuquis (hunter-gatherers) whose territory included this region. The beginning of sedentary agriculture had resulted in a small patch of forest clearance in the south of the community, which can be seen on the land cover map. By 1986 (Figure 5.29) the area of agriculture had increased because the new colonist farmers began clearing forest from the ends of their plots from the central access road (Figure 5.29). All the plots were cleared simultaneously to form a northwest to southeast non-forest area in the forest cover. In the northeast corner of the community there was complete clearance of some plots from the road to the river. In addition to the main zone of clearance some isolated non-forest patches had developed. Similarly strips of clearance along other community (OC on Figure 5.29) access roads were occurring in the same fashion. The forest in the southwest of the image was virtually undisturbed at this time and the extensive floodplain to the northeast was also forested.

By 1992 (Figure 5.30) clearance had progressed along each plot extending the width of the non-forest area created between 1975 and 1986. The isolated patches in the 1986 FCC to the southwest side of the community had expanded by 1992 and coalesced as more plots were cleared deeper into the forest. Forest clearance had also taken place along the southwest facing border of Bogotá and had formed an elongated patch of non-forest. The forest area continued to decline through to 1996 (Figure 5.31), some of the isolated patches cleared in the previous years became connected to the main area of non-forest as clearance progressed from the primary ends of the plots (Figure 5.31). Large forest fragments were being isolated between plots where farmers had cut through the forest and cleared to the river banks at the end of some of the plots. Conversely in the northeastern plots, previously isolated forest patches were reconnected to the existing forest patches because forest had returned. There were also several patches of isolated forest within the non-forest area, where farmers had not completely cleared their plot. Finally in the 2000 image (Figure 5.32) a number of plots were almost or completely cleared and in some cases the clearance passed beyond the community limits up to the rivers. The remaining forest patches were further fragmented with agricultural expansion and back-to-back clearance of plots with the neighbouring community to the southwest caused coalescing of non-forest areas.

5.3.1 Community level forest fragmentation and land-cover estimates: Bogotá.

5.3.1.1 Class area: forest

Table 5.5 shows the results of the FRAGSTATS calculations for Bogotá. The forest area between 1975 and 2000 is shown for Bogotá in Figure 5.33. Through the second half of the 1970s up to 1986 there was a decrease of 506.88 ha. By 1992 the area of forest loss had doubled to 1,157 ha. From 1992 to 1996 the trend in forest loss continued and there was a further loss of 447 ha. By 2000 the loss of forest had decreased slightly leaving 44% of the initial area of forest, 1,367 ha.

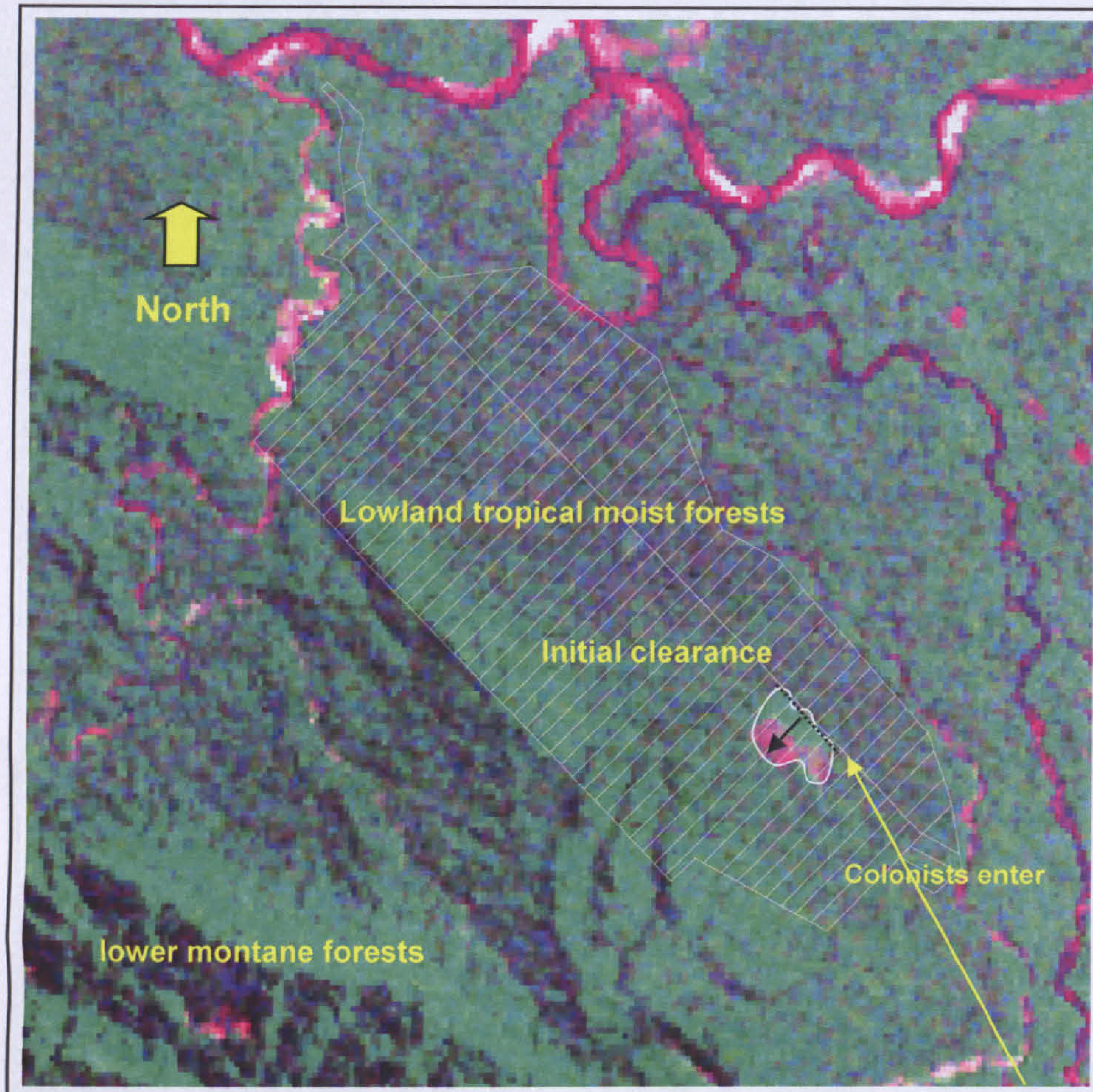
5.3.1.2 Structural metrics

Number of Patches (NoP) and Mean Patch Size (MPS)

Figures 5.34 to 5.36 illustrate the estimate for the NoP, MPS, MPS Standard Deviation (PSSD) and MPS coefficient of variance (PSCV) respectively for the forest class and similarly Figures 5.37 to 5.39 for the non-forest class from 1975 to 2000. The fragmentation statistics for 1975 cannot be directly compared with the other dates because they have been derived from images of a different spatial resolution Landsat MSS and TM. However the metrics are included in the time series because they indicate the early stages in development of the fragmentation patterns.

As the area covered with forest decreased the number of patches generally increased, rising from 1 (1975) to 149 (2000) (Figure 5.34). As the patches became more numerous they also decreased in size (MPS, 3,130 to 9ha) and the standard deviation decreased (Figure 5.35). The PSCV was 766% (1986), decreased to 541% (1992) and increased to 771% (by 2000) (Figure 5.36).

Figure 5.28: Landsat MSS FCC bands 231 and land-cover map showing the extent of forest and progression of agriculture in the vicinity of Bogotá, 1975.



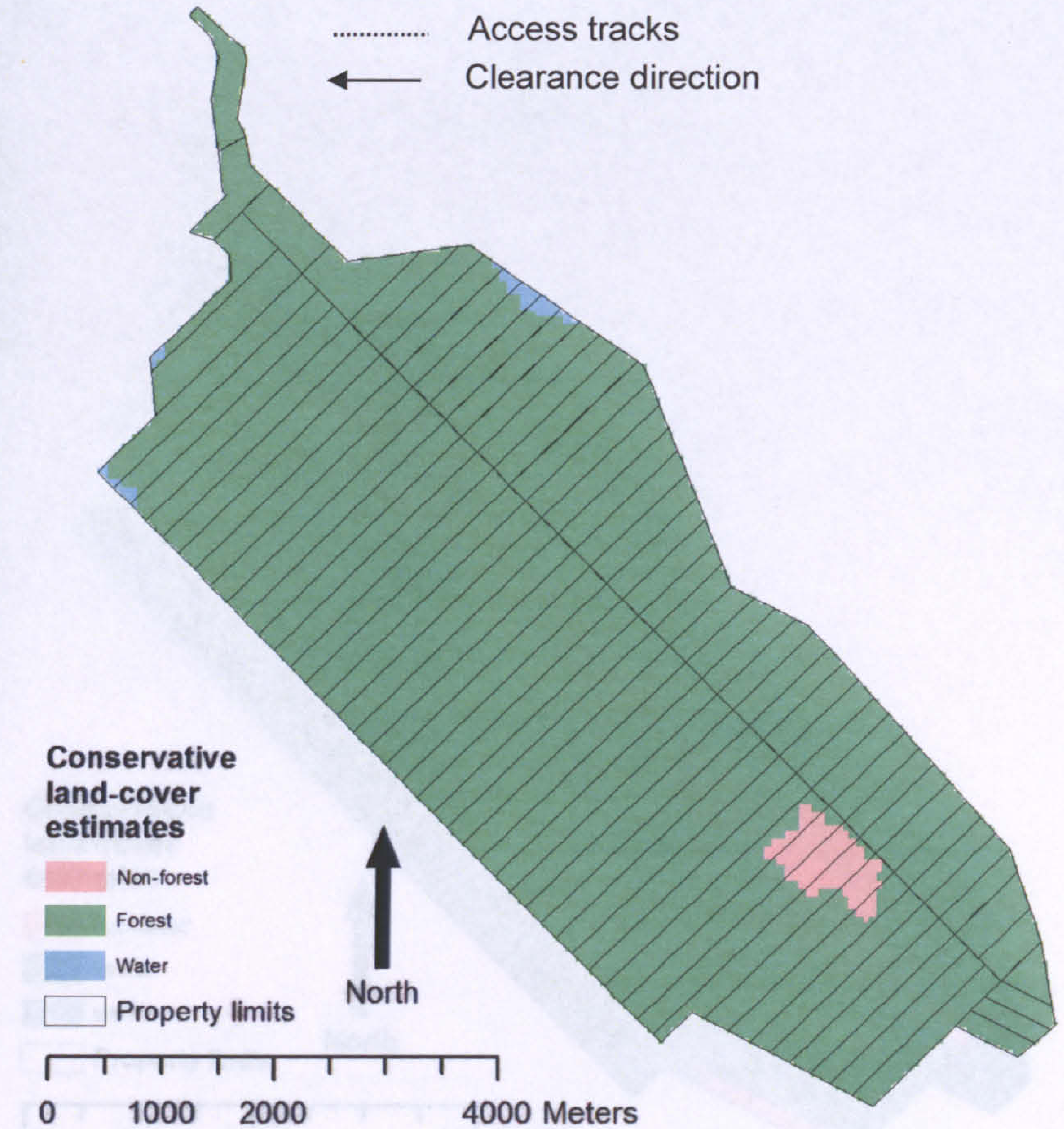


Figure 5.29: Landsat TM FCC bands 741 and land-cover map showing the extent of forest and progression of agriculture in the vicinity of Bogotá, 1986.

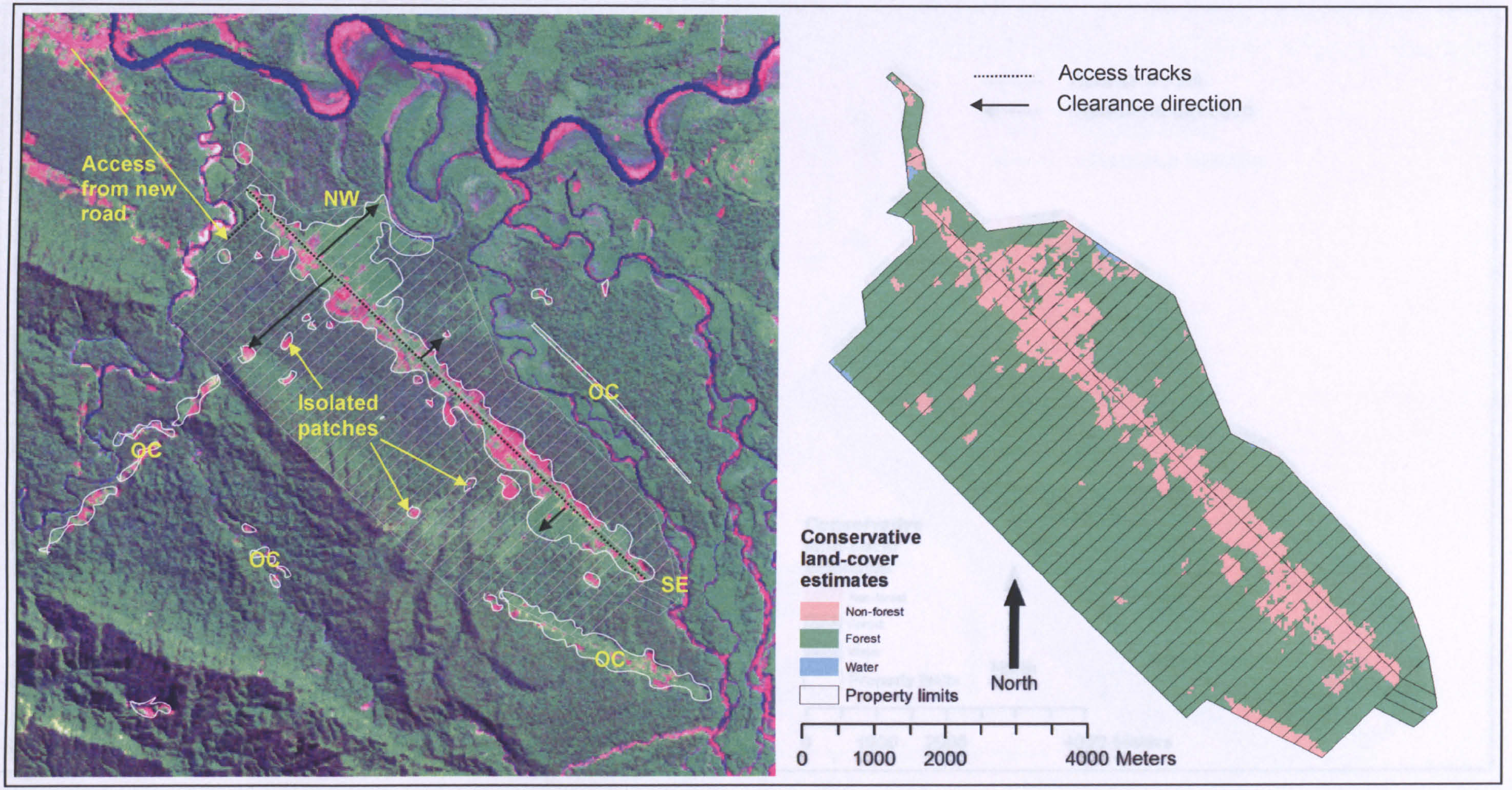


Figure 5.30: Landsat TM FCC bands 741 land-cover map showing the extent of forest and progression of agriculture in the vicinity of Bogotá, 1992.

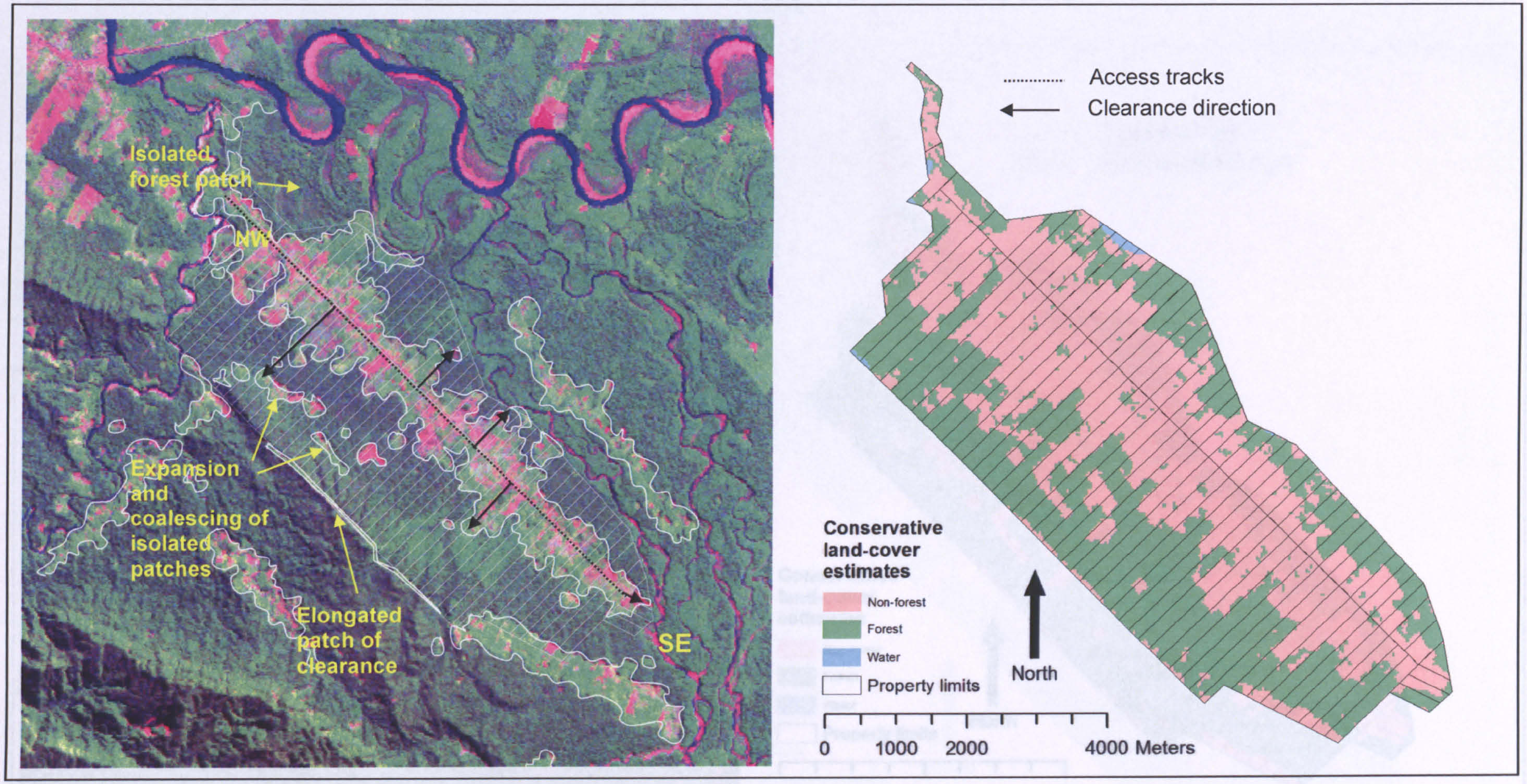


Figure 5.31: Landsat TM FCC bands 741 image and land-cover map showing the extent of forest and progression of agriculture in the vicinity of Bogotá, 1996.

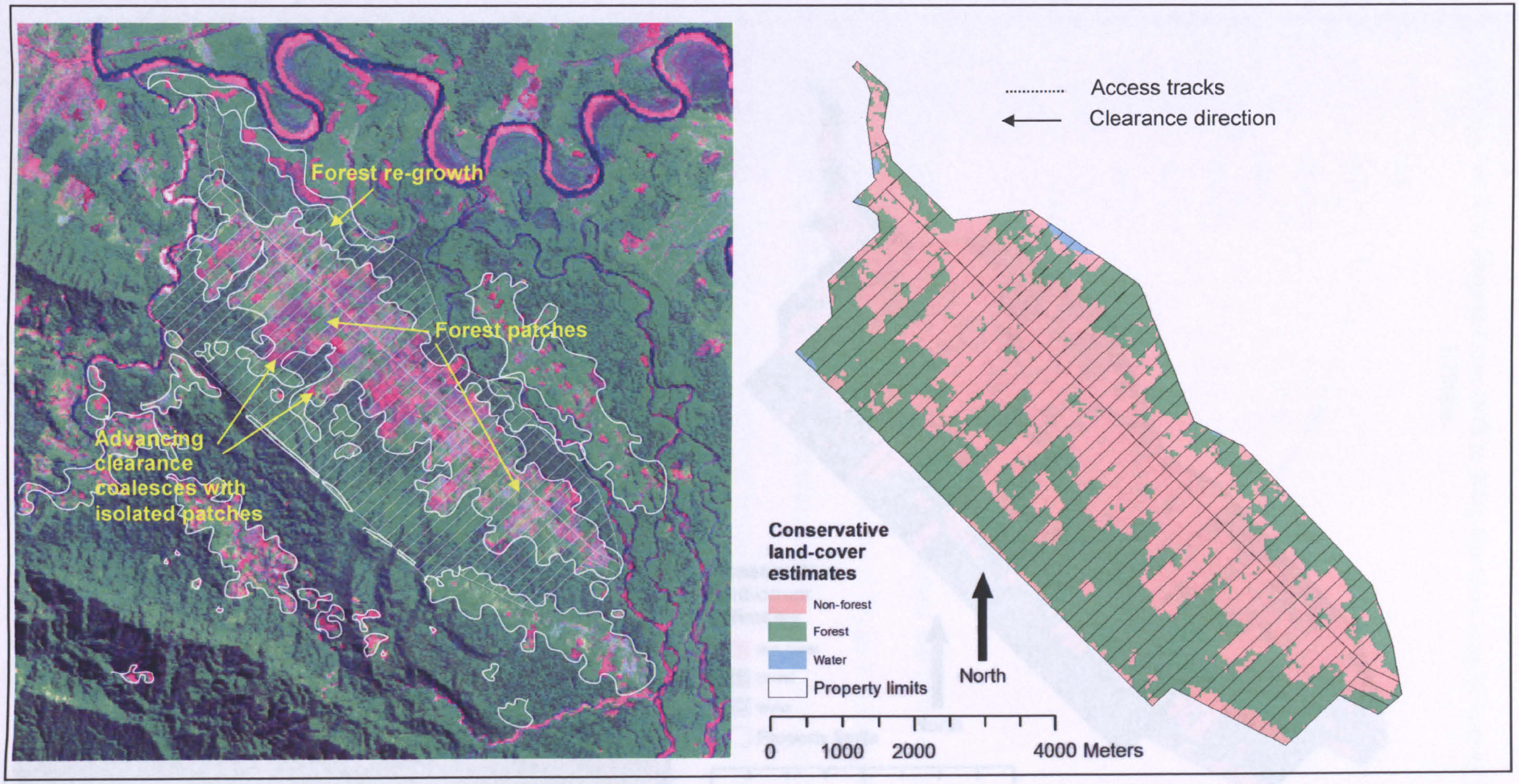


Figure 5.32: Landsat ETM FCC bands 741 image showing land-cover map and the extent of forest and progression of agriculture in the vicinity of Bogotá, 2000.

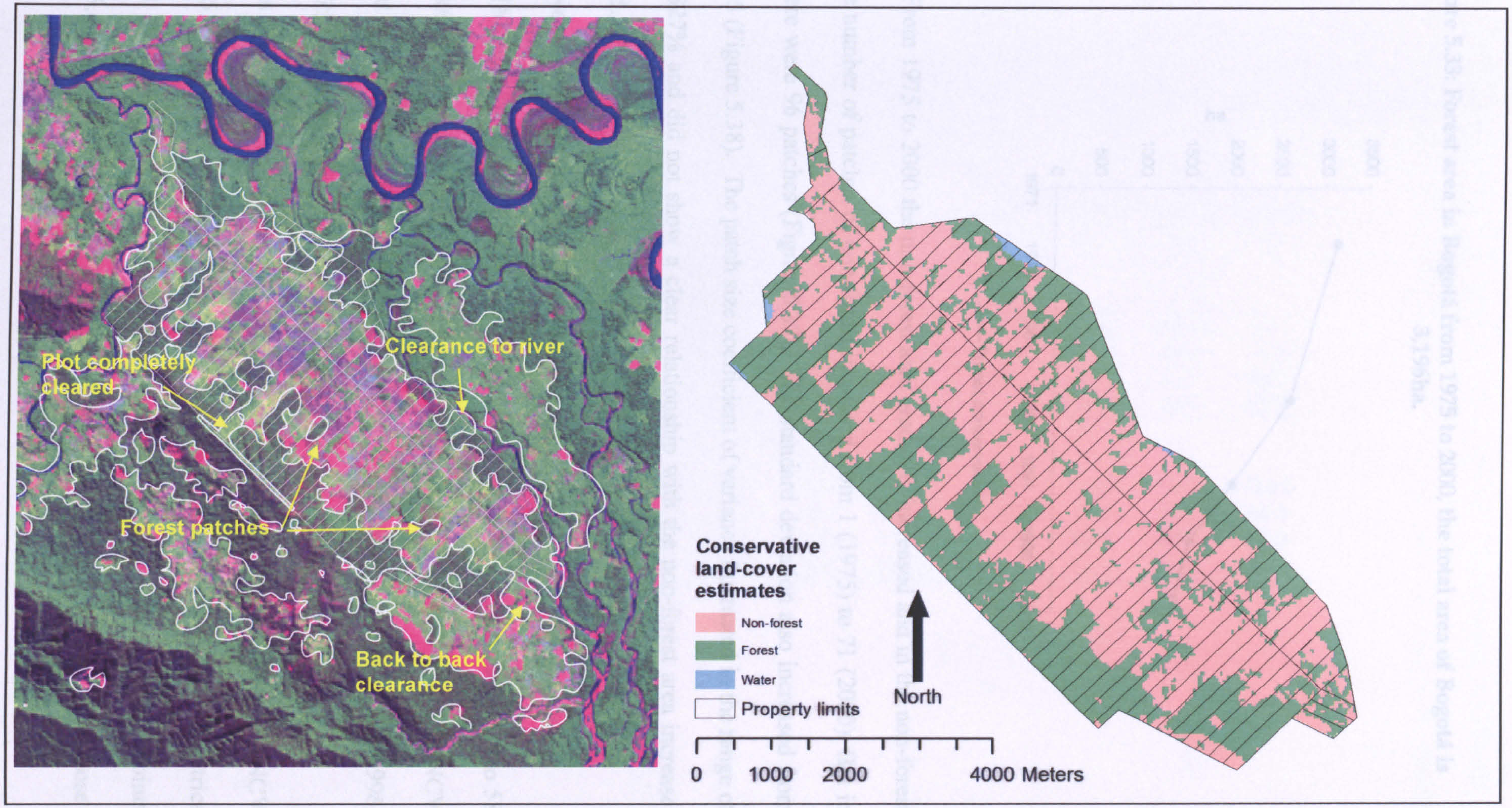
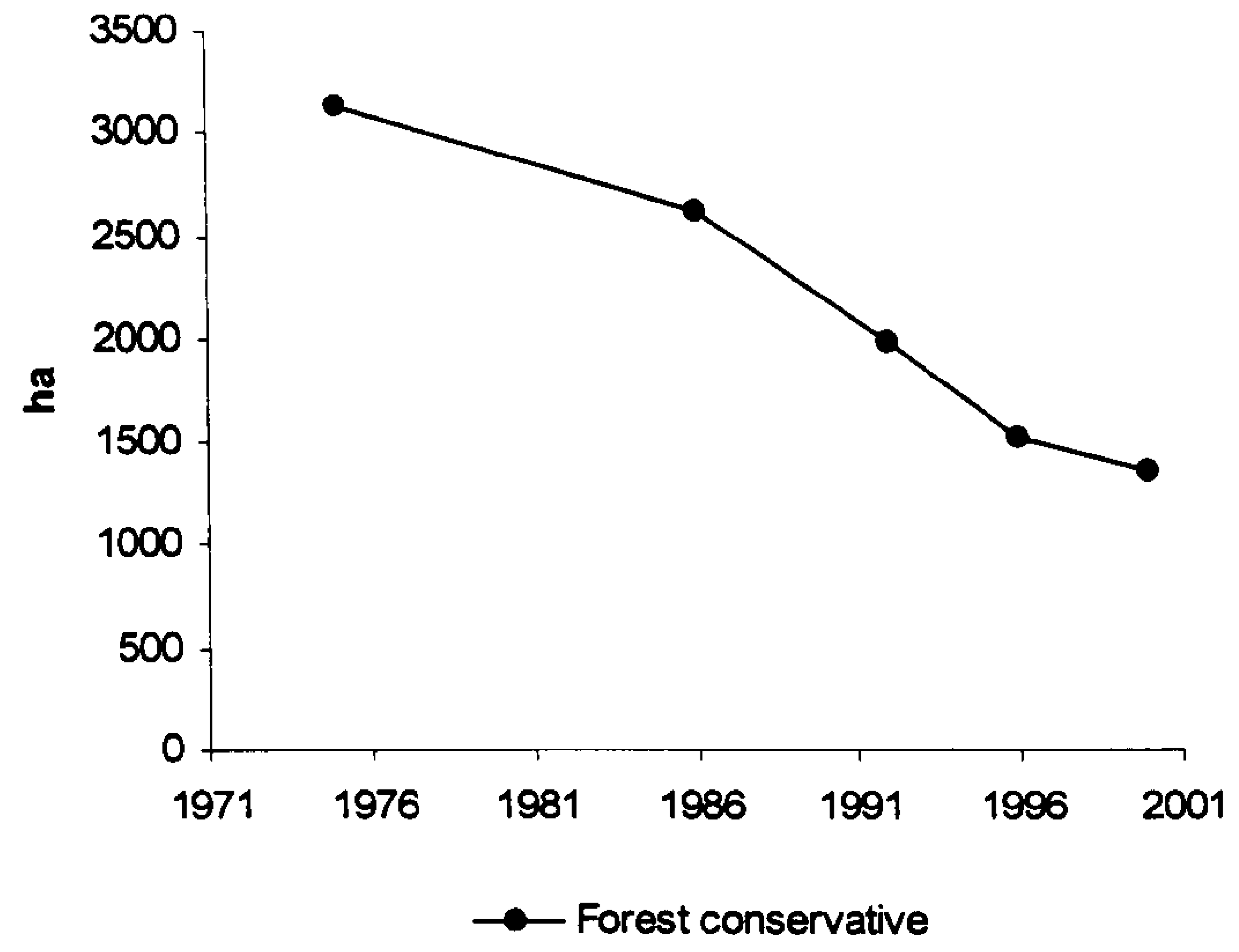


Figure 5.33: Forest area in Bogotá from 1975 to 2000, the total area of Bogotá is 3,196ha.



From 1975 to 2000 the non-forest area gradually increased and in the non-forest class the number of patches of non-forest increased from 1 (1975) to 71 (2000). But in 1992 there were 96 patches (Figure 5.37). The standard deviation also increased from 72 to 205 (Figure 5.38). The patch size coefficient of variance fluctuated in the range of 539 to 827% and did not show a clear relationship with the non-forest area increase. (Figure 5.39).

Mean Nearest Neighbour (MNN) statistics.

The MNN increased from 45 m (1986) to 84 m (1996), but then decreased to 58 m by 2000 (Figure 5.40) as the forest area decreased. Similarly the NNSD and NNCV increased up to 1996 and then decreased by 2000, with the highest values in 1996, NNSD, 75 (Figure 5.40) and NNCV, 88 (Figure 5.41).

In the non-forest category the trends of MNN, NNSD (Figure 5.42) and NNCV (Figure 5.43) were similar over time. In 1986 the highest values of all the metrics occurred, the MNN was 150 m and then remained close to 78m for the other time points (Figure 5.42). Accordingly the NNSD values were high (185), and then remained close

Table 5.5: Selected landscape metrics for the for the forest and non-forest land-cover estimate in Bogotá; CA, Class Area; NP, Number of Patches; PD, Patch Density; MPS, Mean Patch size; PSSD, Patch Size Standard Deviation; PSCV, Patch Size Co-variance; TEL, Total Edge length; ED, Edge Density; MNN, Mean Nearest Neighbour; MNSD, Mean Nearest Neighbour Standard Deviation; NNCV, Mean Nearest Neighbour Co-variance

Metric	CA	NP	PD	MPS	PSSD	PSCV	TEL	ED	MNN	NNSD	NNCV
Units	ha		NP/ha	ha	ha	%	m	m/ha	m	m	%
Forest land-cover											
1975	3,130.1	1	0.03	3130.1	0	0	6,690	2.1	.	.	.
1986	2,623.2	62	1.9	42.3	324.2	766	99,180	31.0	45.0	29.6	65.9
1992	1,972.8	52	1.6	37.9	205.4	541	143,790	45.0	63.0	46.5	73.8
1996	1,526.2	79	2.5	19.3	125.3	648	144,630	45.4	84.5	74.7	88.5
2000	1,366.9	149	4.7	9.2	70.8	772	217,950	68.2	57.9	38.1	65.9
Non-forest land-cover											
1975	53.6	1	0.03	53.6	0	0	4,440	1.4	.	.	.
1986	566.6	42	1.3	13.5	72.8	539	97,410	30.5	149.8	184.9	123.5
1992	1,211.7	96	3.0	12.6	104.4	827	142,920	44.7	76.8	64.5	84.0
1996	1,648.4	68	2.1	24.2	181.6	749	143,730	45.1	82.1	68.2	83.0
2000	1,816.3	71	2.2	25.6	205.3	803	217,290	68.0	74.6	64.5	86.5

to 66 for the remaining time points (Figure 5.42). The NNCV also began in 1986 with a high value of 123% which then decreased to 83% for the remaining time points (Figure 5.43).

Figure 5.34: Number of forest patches (NoP) and decrease in area of forest (ha).

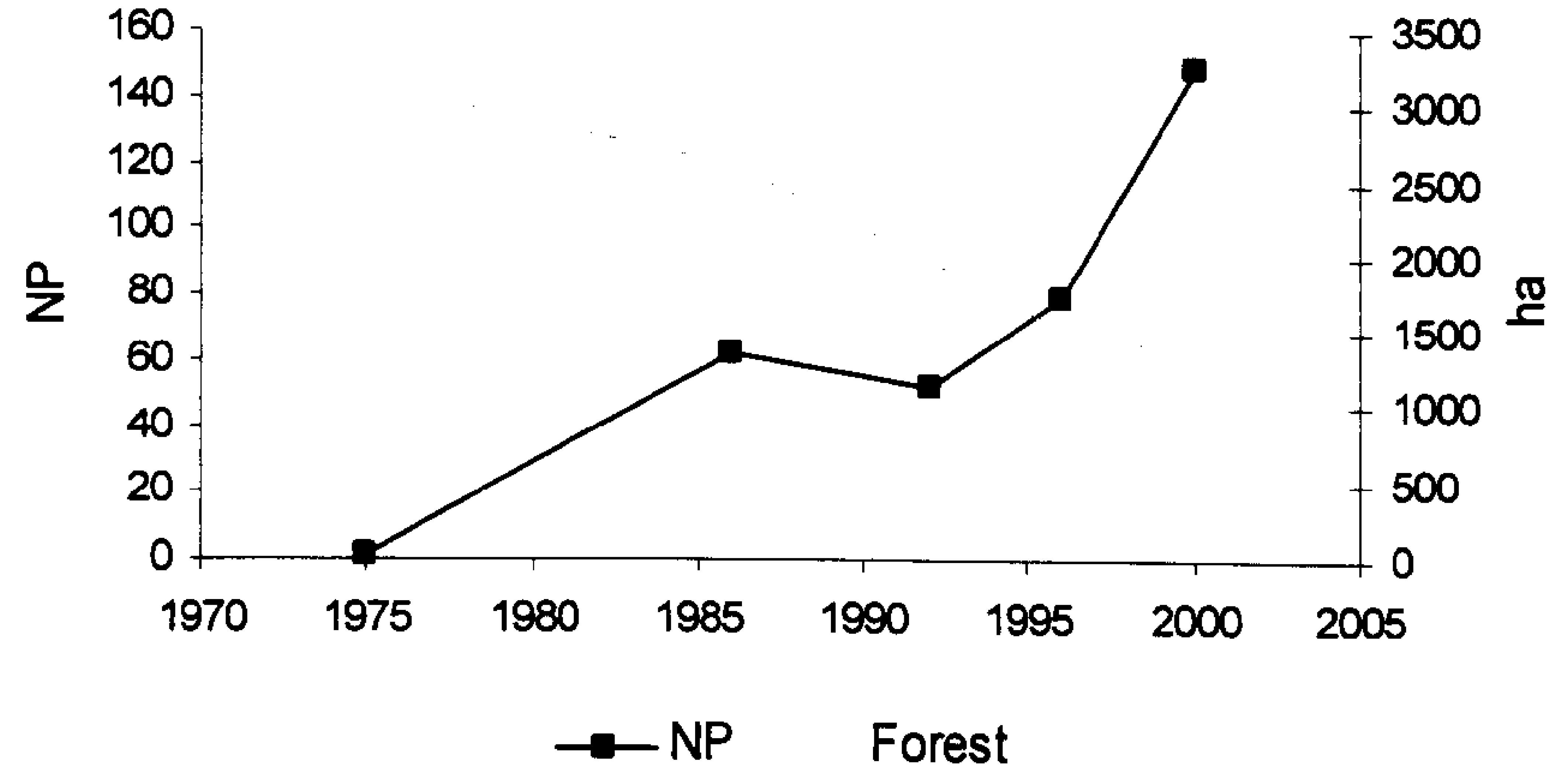


Figure 5.35: MPS (ha) the PSSD (error bars on MPS curve) of forest patches and decrease in area of forest (ha).

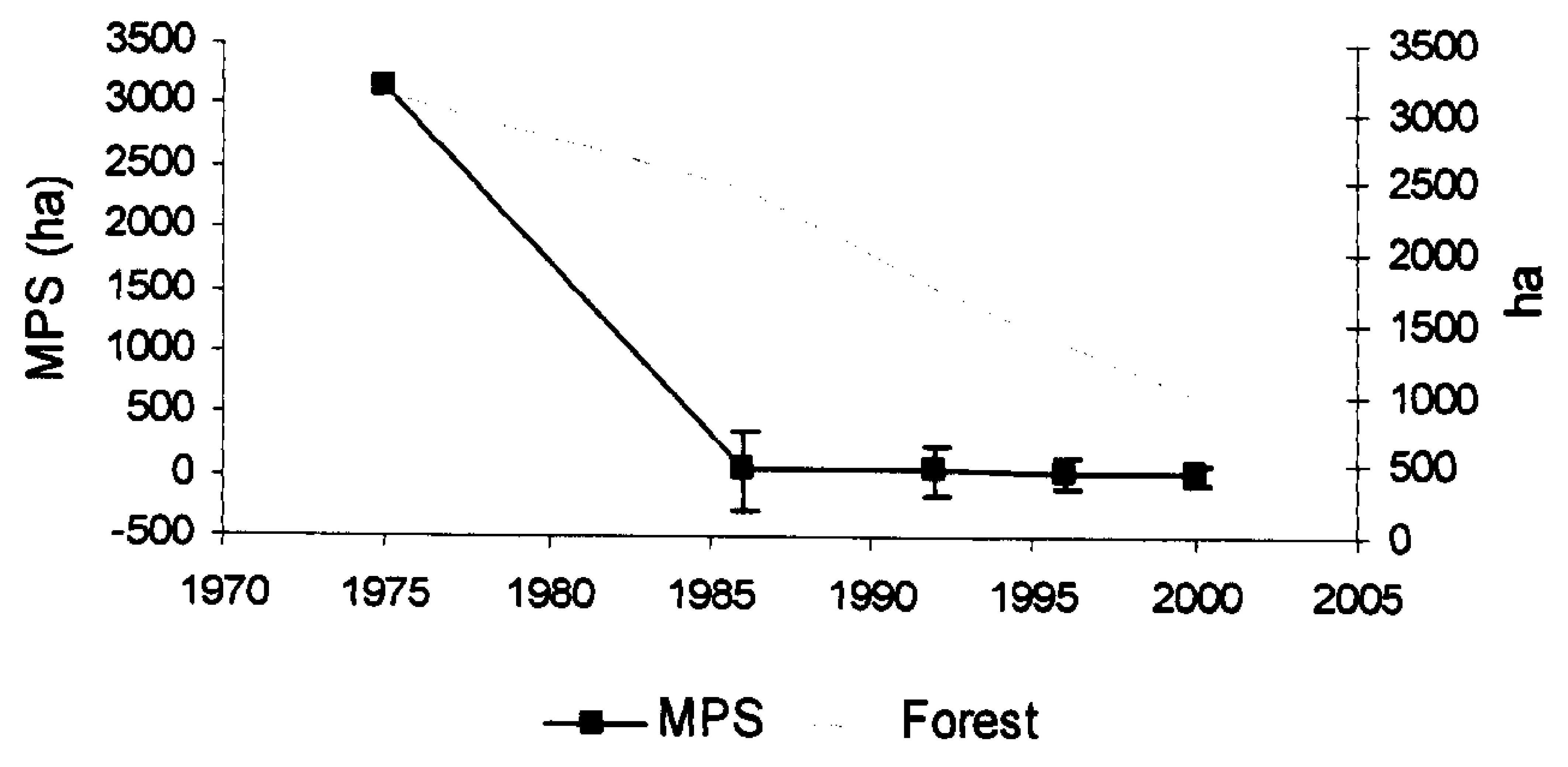


Figure 5.36: MPS (ha) and PSCV (error bars on MPS curve) of forest patches and decrease in area of forest (ha).

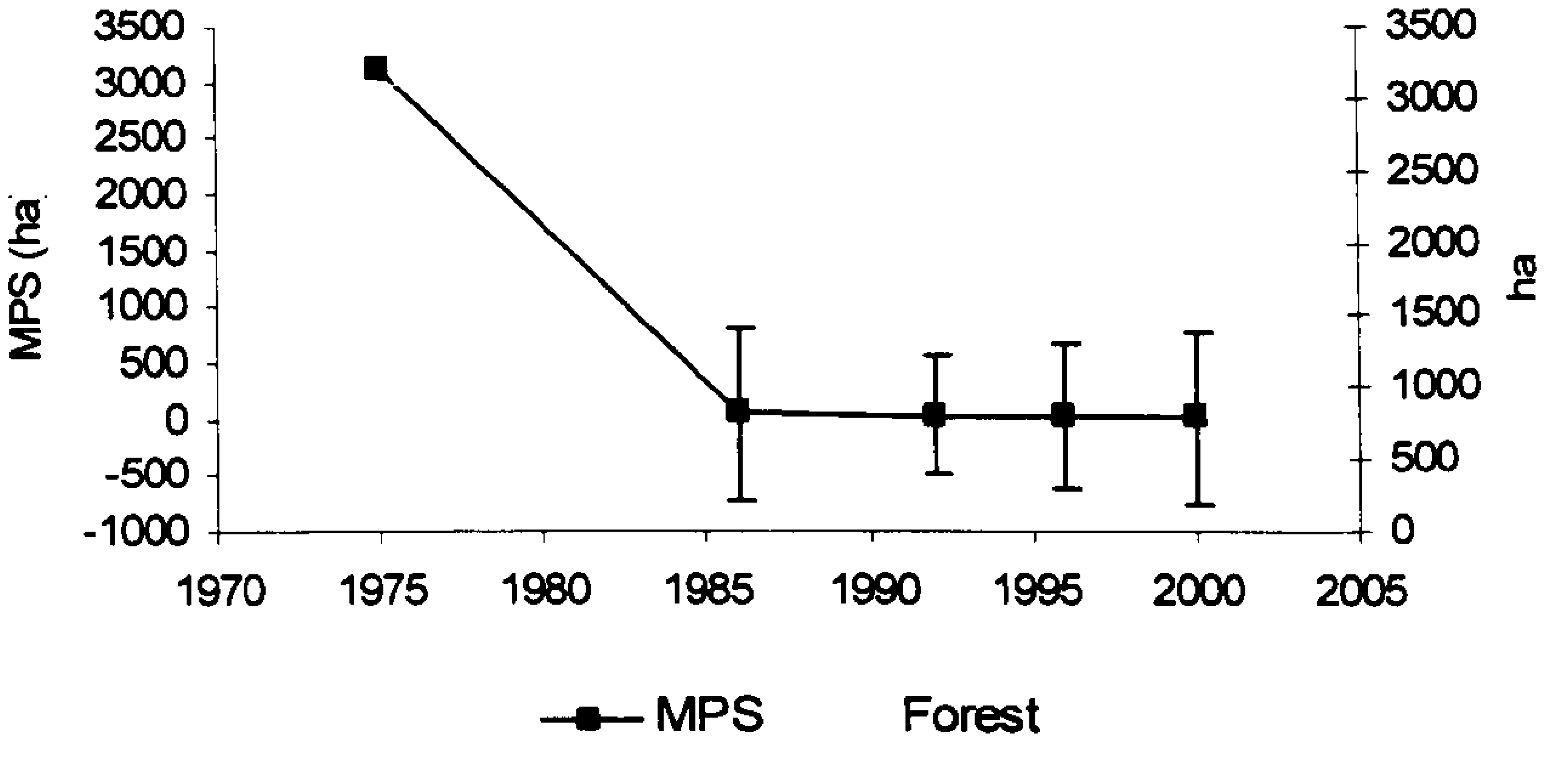


Figure 5.37: Number of non-forest patches and increase in non-forest area (ha).

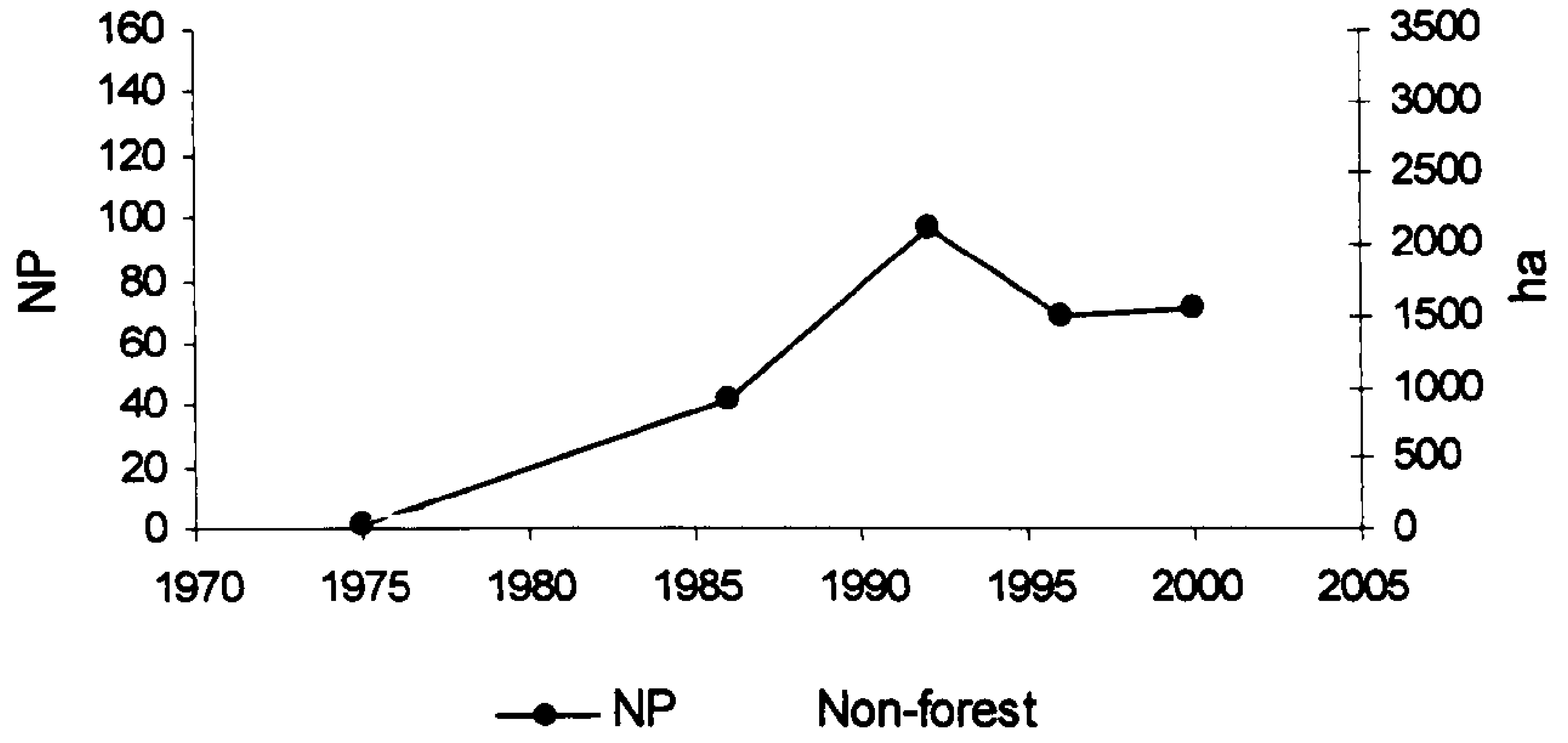


Figure 5.38: MPS (ha) and PSSD (error bars on MPS curve) of non-forest patches and increase in non-forest area (ha).

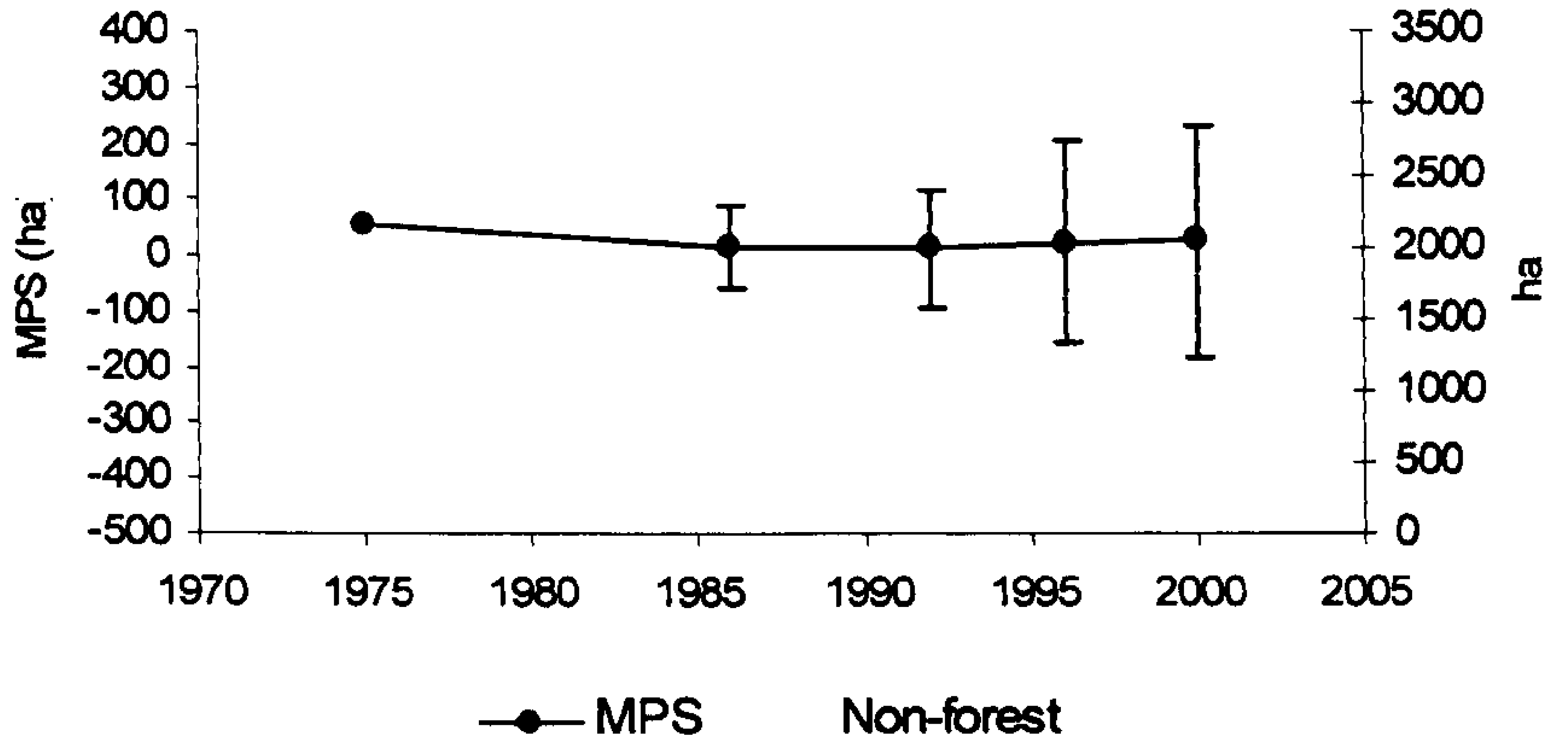
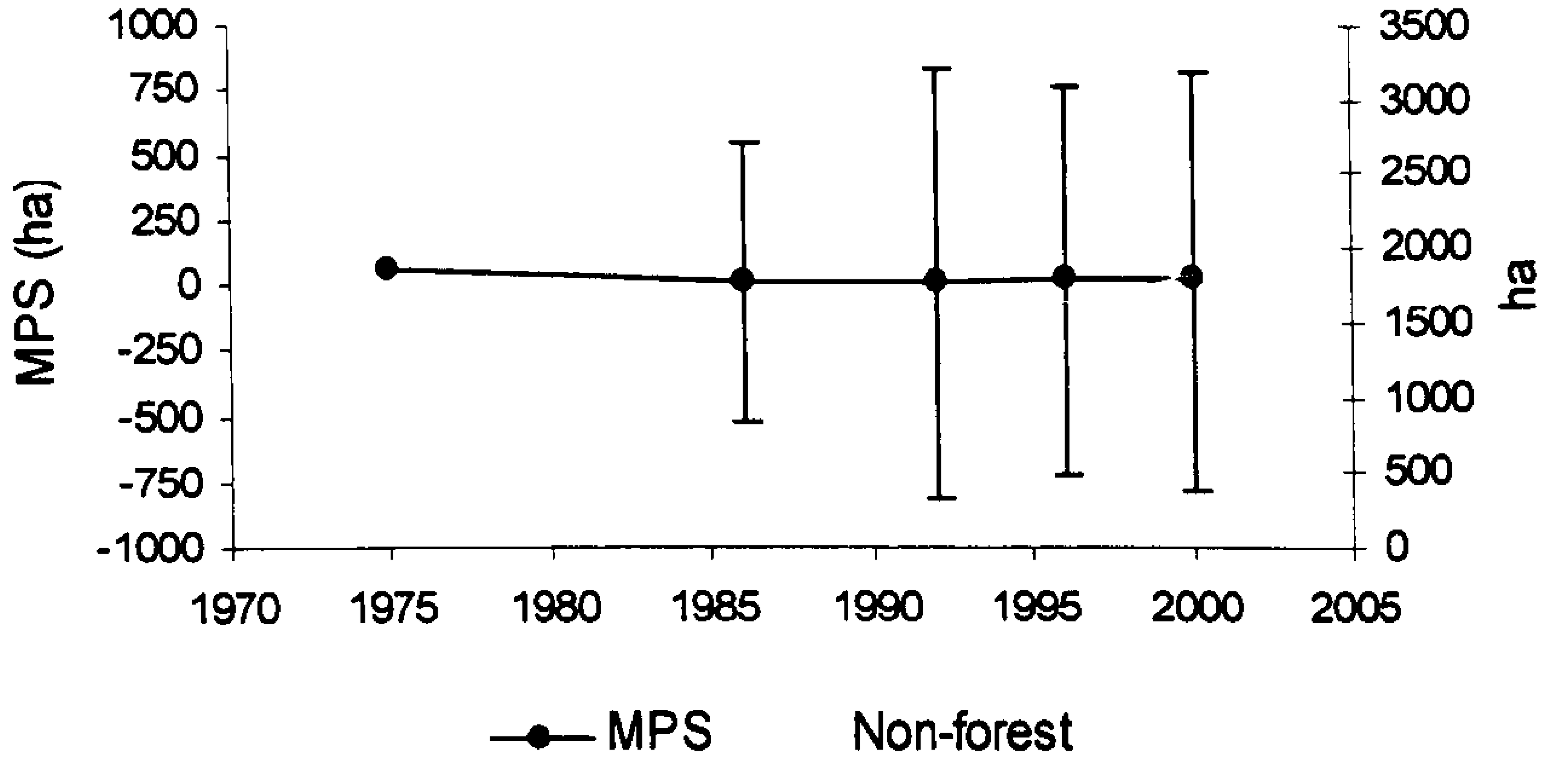
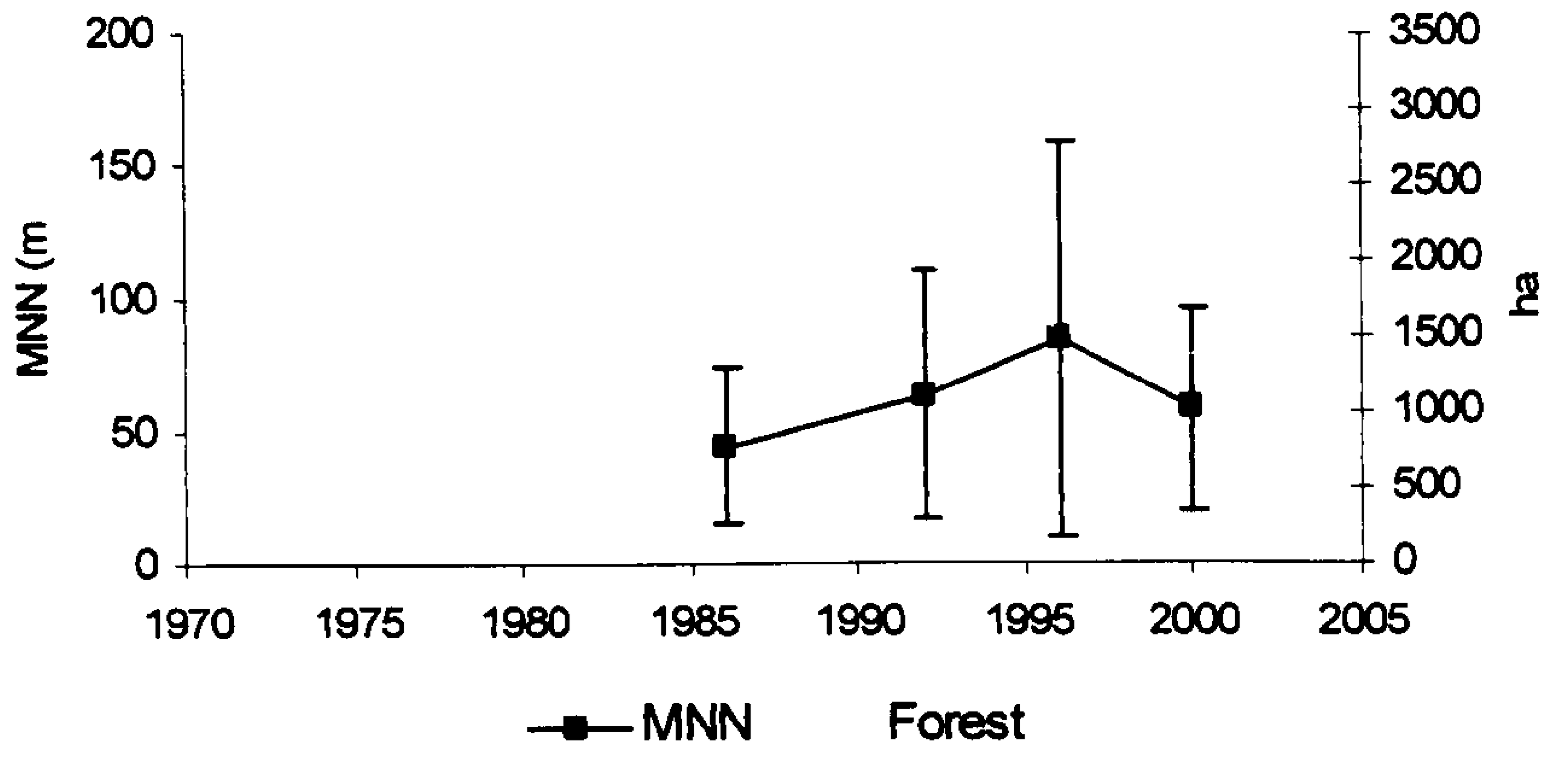


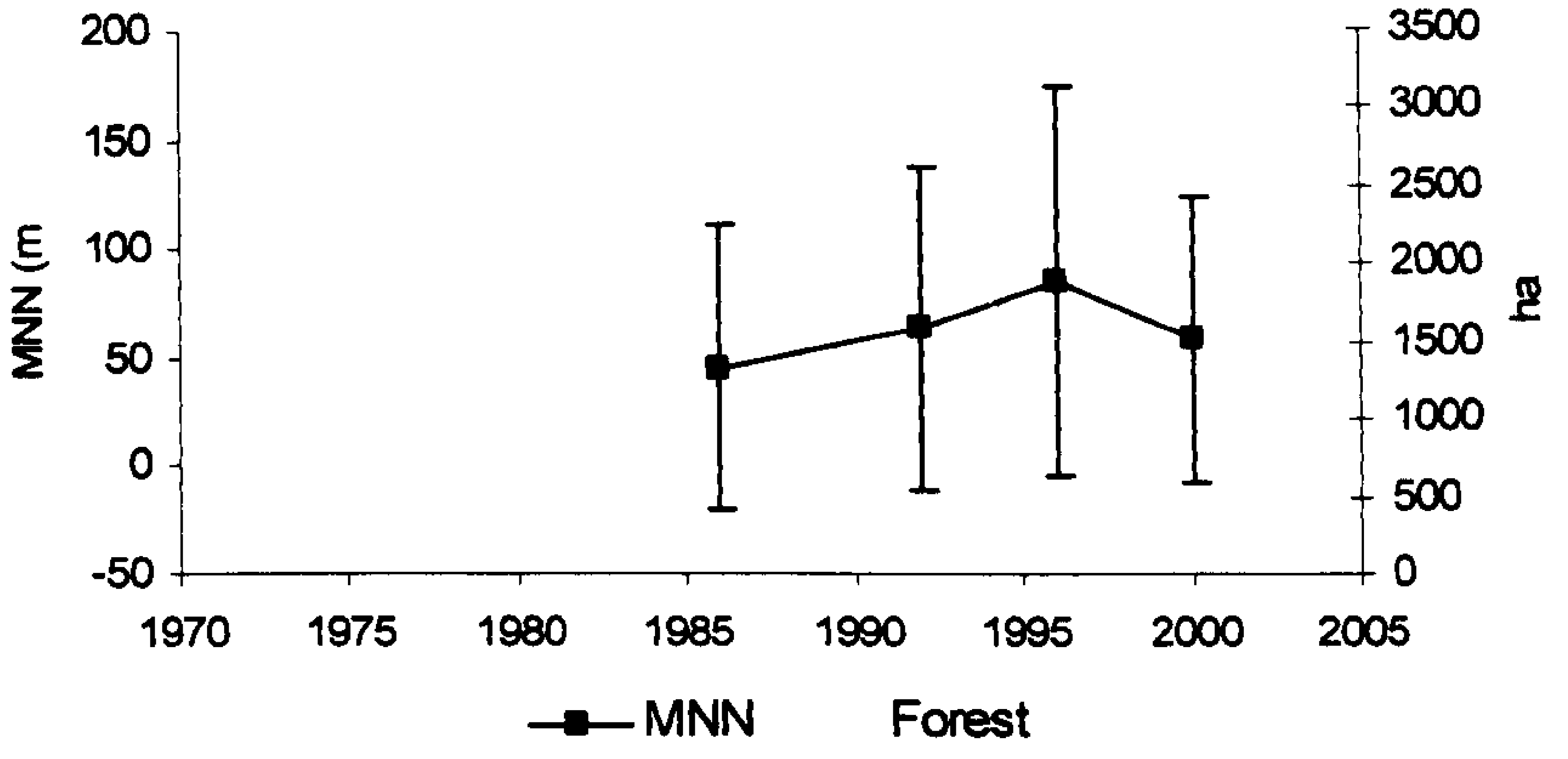
Figure 5.39: MPS (ha) and PSCV (error bars on MPS curve) of non-forest patches and increase in non-forest area (ha).



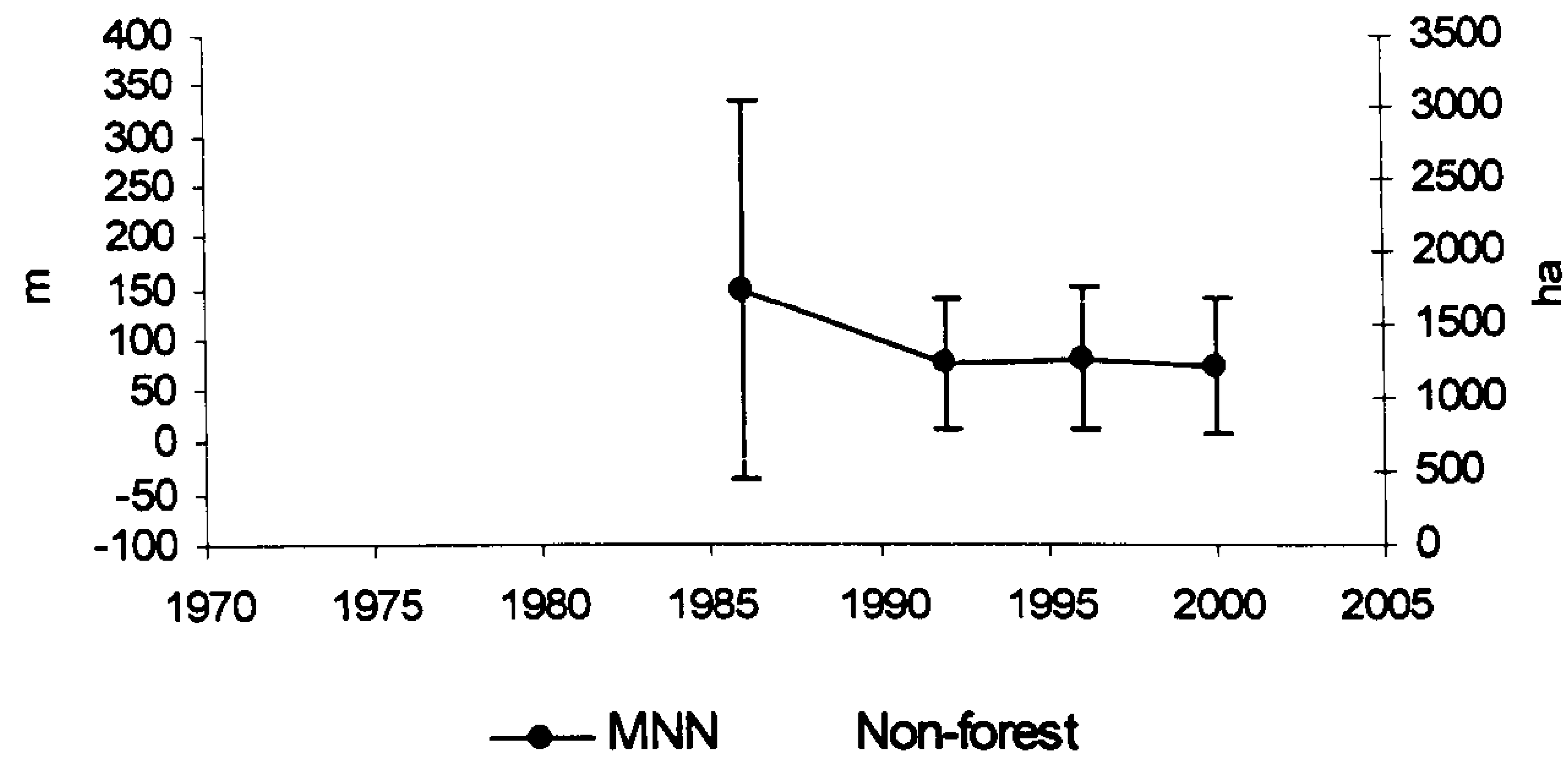
5.40: MNN (m) and NNSD (error bars on MNN curve) of forest patches and decrease in area of forest, Bogotá (ha).



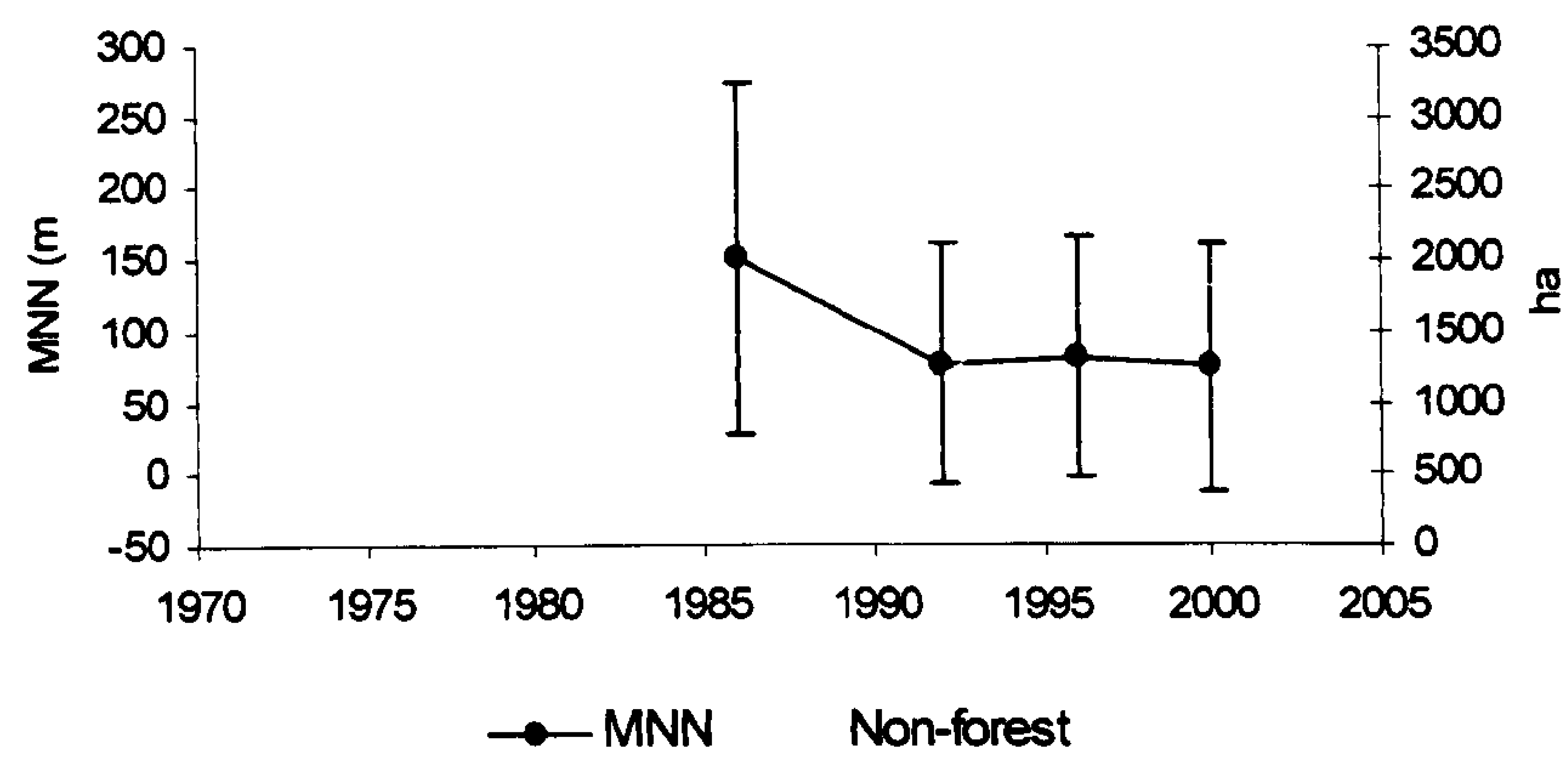
5.41: MNN (m) and NNCV (error bars on MNN curve) of forest patches and decrease in area of forest, Bogotá (ha).



5.42: MNN (m) and NNSD (error bars on MNN curve) of non-forest patches and increase in non-forest area, Bogotá (ha).



5.43: MNN (m) and NNCV (error bars on MNN curve) of non-forest patches and increase in non-forest area, Bogotá (ha).



Total Edge length (TEL)

In Bogotá, there was an increase in the TEL from 4,440 m in 1975 to 217,290 m in 2000 (Figure 5.44). Although there was an increase in TEL, there was little change between 1992 and 1996.

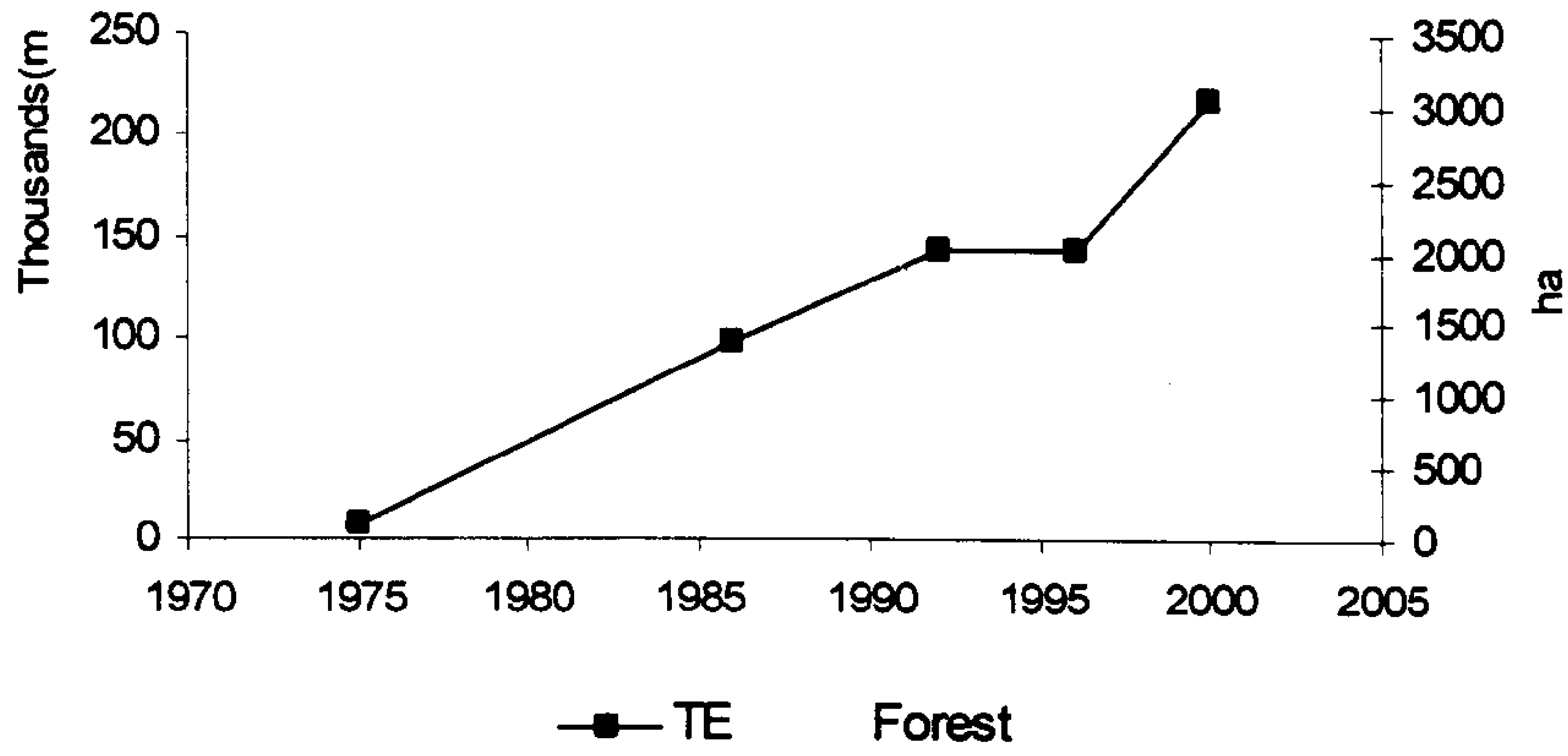
5.3.2 Average plot clearance characteristics

5.3.2.1 Average cleared area

In 1986 (Figure 5.45) an average 6.3 ha per plot had been cleared. This had doubled to 13.4 ha by 1993 and by 1996 had tripled 18.3 ha. By 2000 on average 20.2

ha each plot had been cleared. The standard deviation increased from 3.92 (1996) to 9.43 (2000), indicating the variability in clearance rates between the plots.

5.44: Total edge length (TEL) (m) between the forest and non-forest patches from 1986 to 2000, Bogotá (ha).



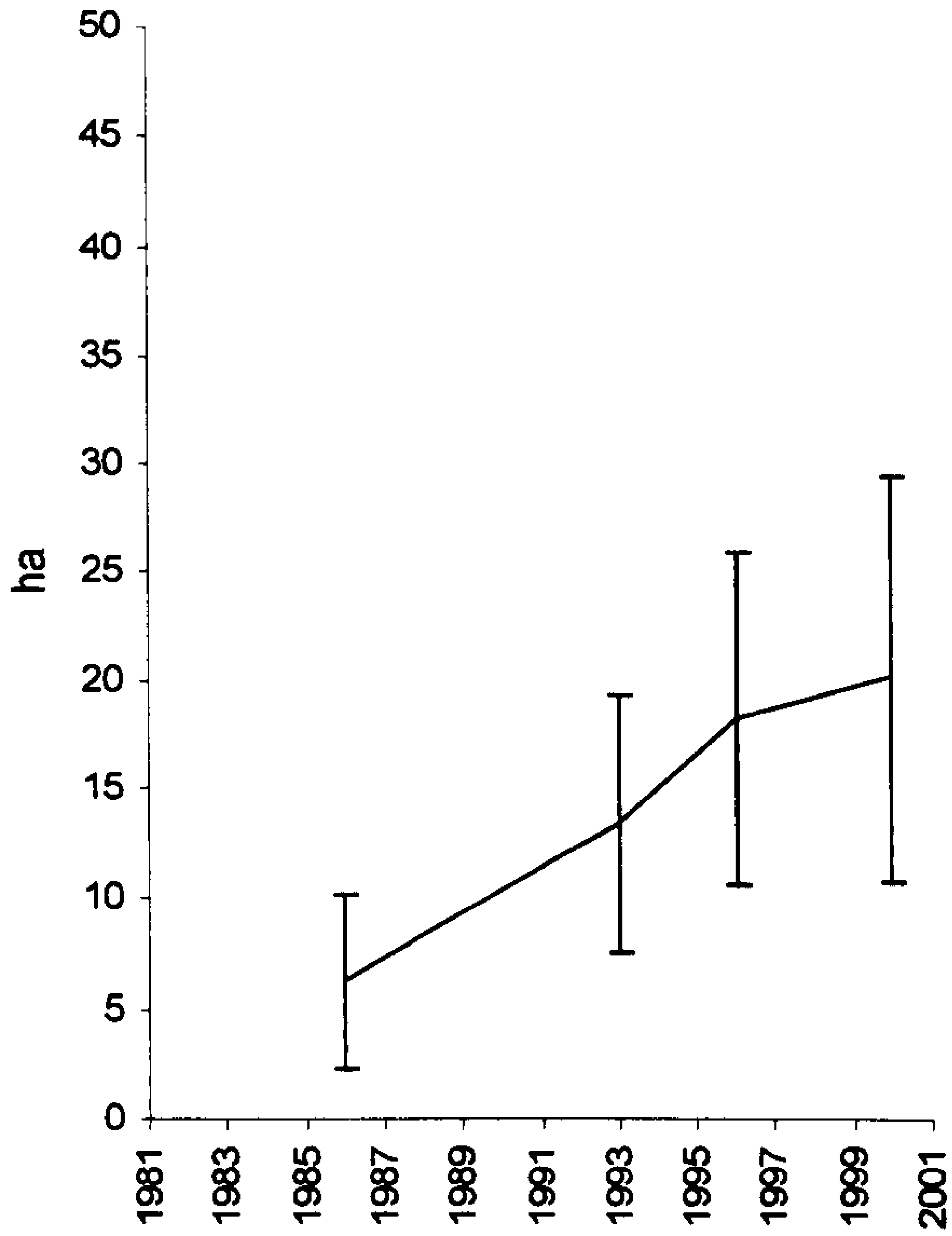
5.3.2.2 Average rates of clearance

Figure 5.46 show the average rates of clearance in Bogotá between 1975 and 2000. Some forest clearance had already begun by 1975, but the majority of settlers arrived in 1983 (INRA, 1986) and this has been taken as the first time point to calculate the rates of clearance. Rates of forest clearance were generally constant – 1.4 to 1.19 ha yr^{-1} – except for a decrease – 0.47 ha yr^{-1} – from 1996 to 2000. The standard deviation indicates that there was a wide variation in clearance rates between plots throughout the time sequence, which reached +/-1.45ha yr^{-1} by 2000.

5.3.3 Plot clearance typologies: Bogotá

Adopting the plot typology classification from Figure 5.20, Table 5.6 shows the numbers of different clearance typologies for each time point in the image sequence. In 1975 the typology is entirely Type II (7%) because the few plots that were occupied were cleared from the primary end. By 1986 most of the plots were Type II (57%) and

5.45: Average areas of non-forest land for individual plots between 1986 and 2000, Bogotá. Plot sizes are 13.5 - 50ha, the error bars are one standard deviation from the mean.



Type IV (33%) a majority of the farmers were clearing from one end of their plot and others were clearing in the central sections of their plots. In 1992 more farmers cleared from the secondary end of the plots increasing Type V, to 26% and a decrease in Type II plot to 24%. The high numbers of Type IV and the Type V increase indicated that farmers had cleared isolated patches. In 1996 there was a decrease in Type IV to 21% and an increase in Type II to 40%. By 2000 most farmers had cleared as Type IV (55%) and some farmers had completely cleared their plots, Type VI (6%).

5.3.4 Land-cover change at the plot level

The same criteria used in Section 5.2.4 are used to select the typical and atypical plots from the sample plots (Table 5.7). Plot B_H was closest to the mean at all time points, and plot B_N deviated the most from all the time points.

5.46: Average rates of clearance for individual plots between 1986 and 2000, Bogotá. Plot sizes are 13.5 to 50ha, the error bars are one standard deviation from the mean and indicate the variability in clearance rates. Between 1996 and 2000 the error bar goes below the *x*- axis because some plots experienced replacement of forest.

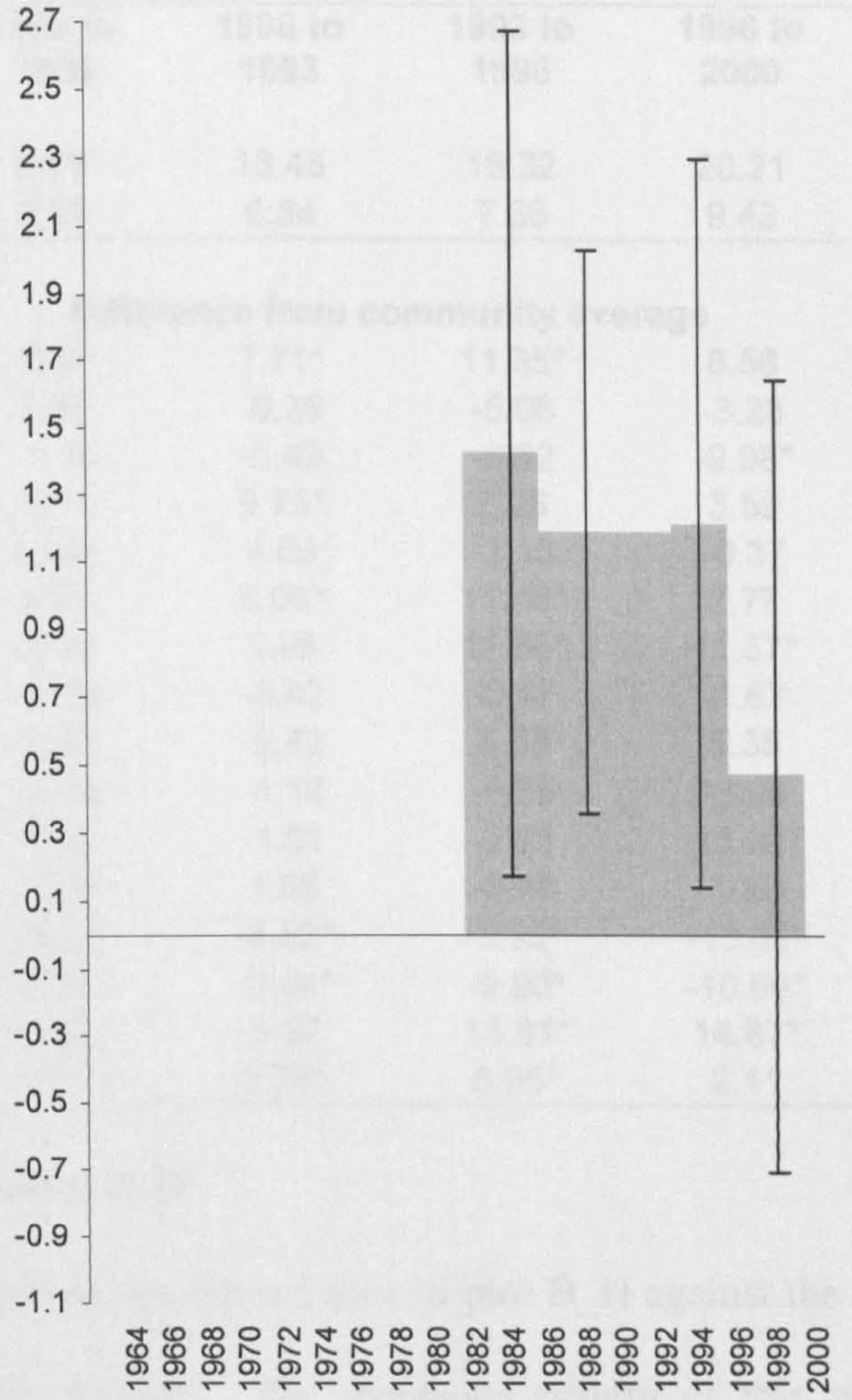


Table 5.6: Summary of total numbers of clearance typologies in Bogotá, 1975-2000 (n.b. four split plots have been excluded from the analysis).

Type	1975	1986	1992	1996	2000
I	80	0	0	0	0
II	6	49	21	34	25
III	0	3	10	10	3
IV	0	28	32	18	47
V	0	6	22	23	6
VI	0	0	1	1	5
Total numbers	86	86	86	86	86

Table 5.7: The difference between the average cleared area and area cleared in the sample plots: Bogotá. Where a plot falls outside +/- 1 standard deviation it is marked with an asterisk and the number of times the cleared area in a plot falls within 1 standard deviation of each time interval is shown in the final column. Where a plot falls outside 1 SD it is marked with an asterisk and the number of times the cleared area in a plot falls 1 SD of each time point is shown.

	1983 to 1986	1986 to 1993	1993 to 1996	1996 to 2000	
Average	6.29	13.45	18.32	20.21	
SD	3.97	5.84	7.66	9.43	
Plot	**Difference from community average**				**+/-1 standard deviation**
B_A	-0.91	7.71*	11.55*	8.56	2
B_B	3.85	-0.26	-5.06	-3.28	4
B_C	-1.44	-5.43	-6.92	-9.98*	3
B_D	0.10	9.75*	7.26	3.59	3
B_E	5.99*	4.06	-2.13	-0.37	3
B_F	3.61	6.08*	11.46*	7.77	2
B_G	-0.48	0.95	11.56*	11.57*	2
B_H	-3.16	-3.42	-0.47	-1.67	4
B_I	-2.76	-0.42	5.68	5.35	4
B_J	-2.76	-1.18	-6.35	-3.99	4
B_K	1.62	-1.01	-2.91	15.98*	3
B_L	6.06*	1.06	-0.49	1.80	3
B_M	-3.76	-8.52*	-9.92*	-15.62*	1
B_N	-4.67*	-6.54*	-9.80*	-10.66*	0
B_O	5.02*	5.57	13.81*	14.87*	1
B_P	3.71	8.76*	8.95*	2.11	2

Typical plot clearance: B_H

Figure 5.47 shows the cleared area of plot B_H against the average cleared area for the community of Bogotá. The clearance pattern of this plot was similar, but slightly lower than the average pattern of clearing. Plot B_H (200 by 1100 m) was first farmed in 1983 and in 1985, 2 ha of forest were cleared by the farmer, his spouse and three children who were under 7 years old (INRA, 1986). At this time the family had begun to cultivate bananas and citrus fruits. Figure 5.48 shows the directions of access into the plot, the markets and the location of the river. There was 'clearance' of the forest at the secondary end of the plot in 1986 (Figure 5.49), which might have partially been explained by disturbance from the nearby river channel encroaching into the

Figure 5.47: Plot B_H against the average cleared area for all plots in Bogotá.

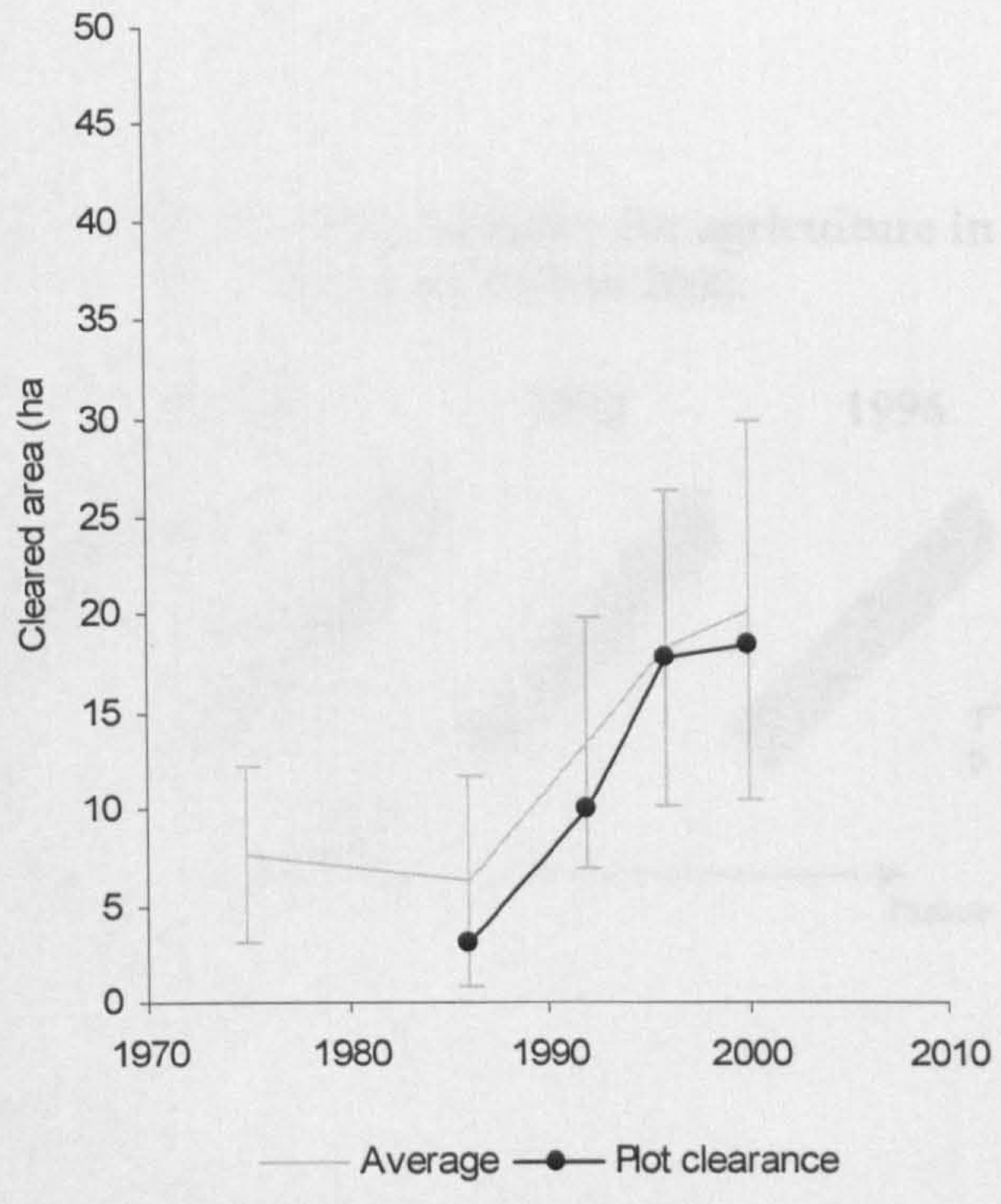
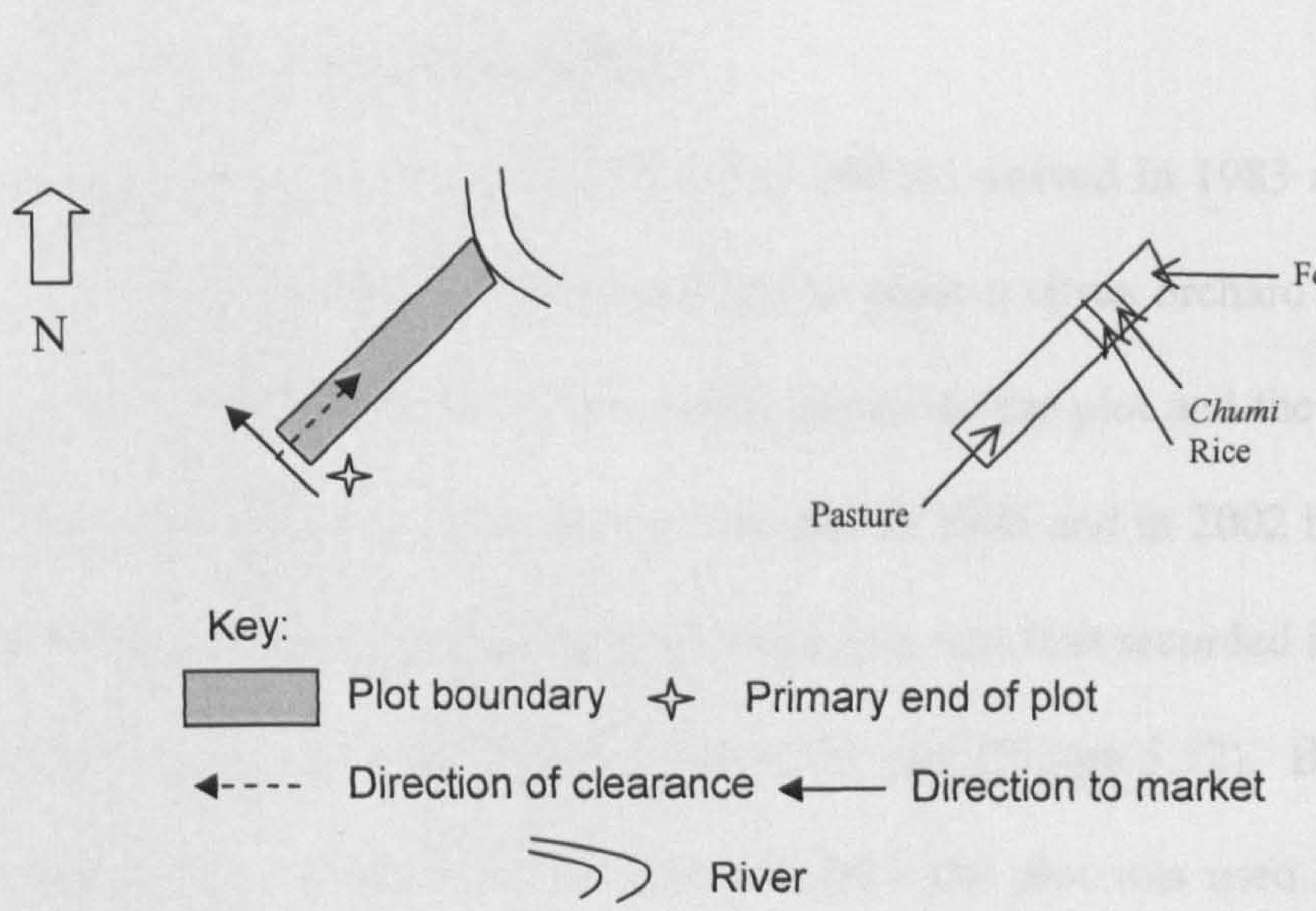


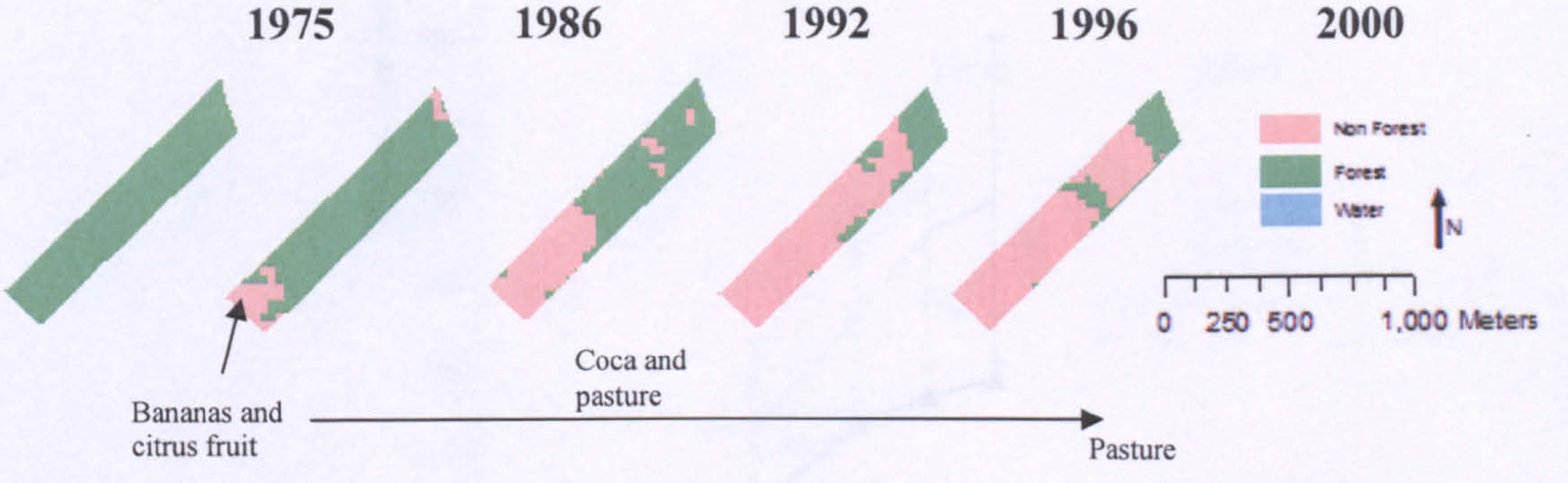
Figure 5.48: Schematic diagram of the plot of Eloy Campos, showing access and cultivation in 2002.



northern limits of the plot. In 1995 the plot was taken over by Eloy Campos and his wife (in 2002 they had one child under 5 years old).

When Eloy took over the plot it contained coca, but he decided to concentrate on rice production and cattle grazing. In 2002 with 40 cattle he produced meat and milk and sold to the local markets. Figure 5.48 shows the management of cultivation on the plot in 2002.

Figure 5.49: Progression of forest clearance for agriculture in the plot of Eloy Campos, 1975 to 2000.



Atypical clearance: B_N

Figure 5.50 shows how plot B_N deviates from the average cleared area of the community. The average cleared area of this plot was significantly lower than that of the community average for all time points.

The original owner of plot B_N (200 by 900 m) arrived in 1983 and cleared the plot from the primary end for subsistence and to grow a citrus orchard (INRA, 1985). Figure 5.51 shows the direction to the market, access to the plot and the location of the river. Miguel Robosio took possession of the plot in 1985 and in 2002 he had a spouse and a three year old child. On the imagery clearance was first recorded in 1986 and has continued to advance from the primary end of the plot (Figure 5.52). By 2000 a patch had been cleared in the centre of the plot. In 2002 the plot was used for pasture and included a citrus orchard. The citrus fruits were sold at the local market and in Yapacaní.

Figure 5.50: Plot B_N against the average cleared area for all plots in Bogotá

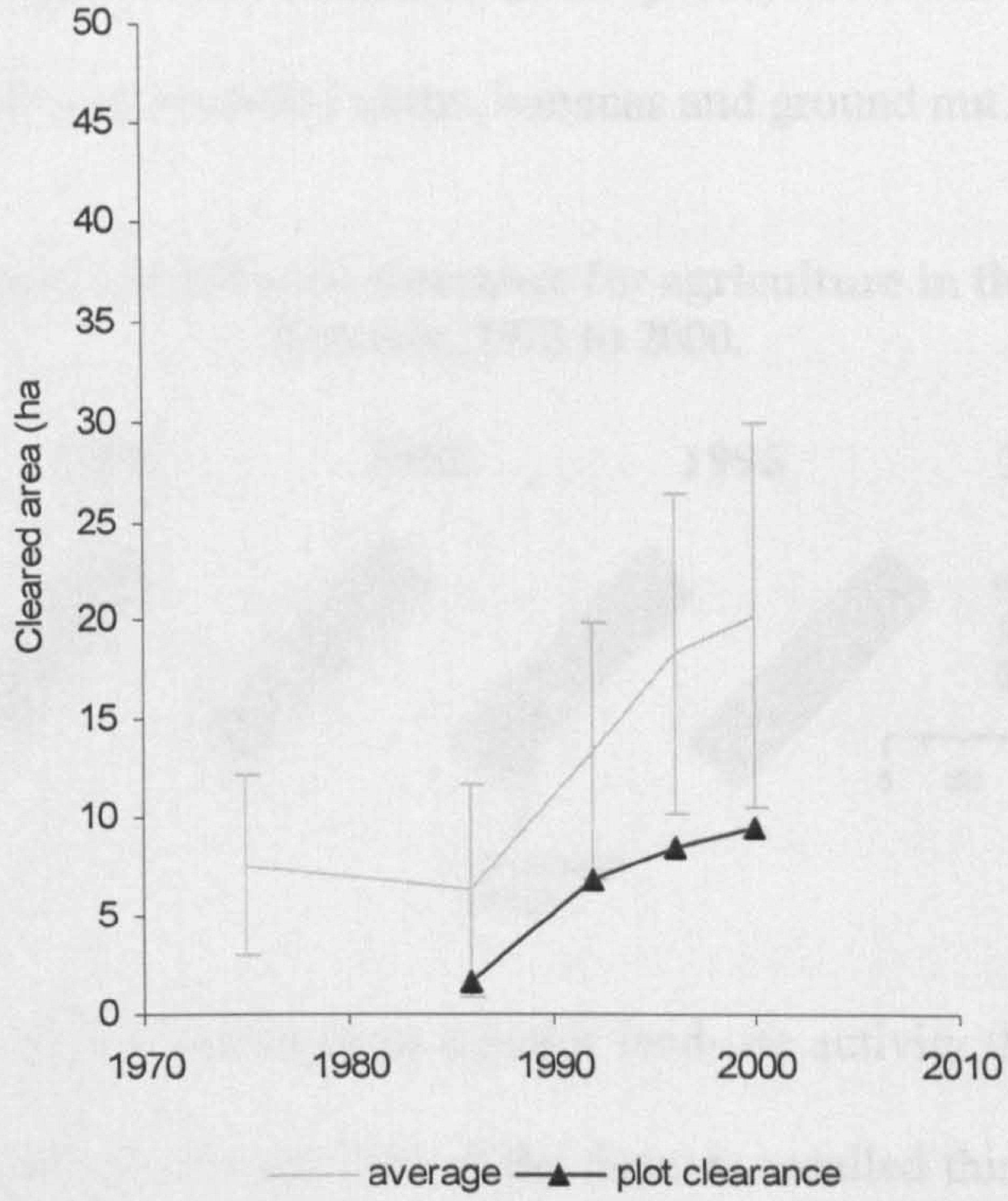
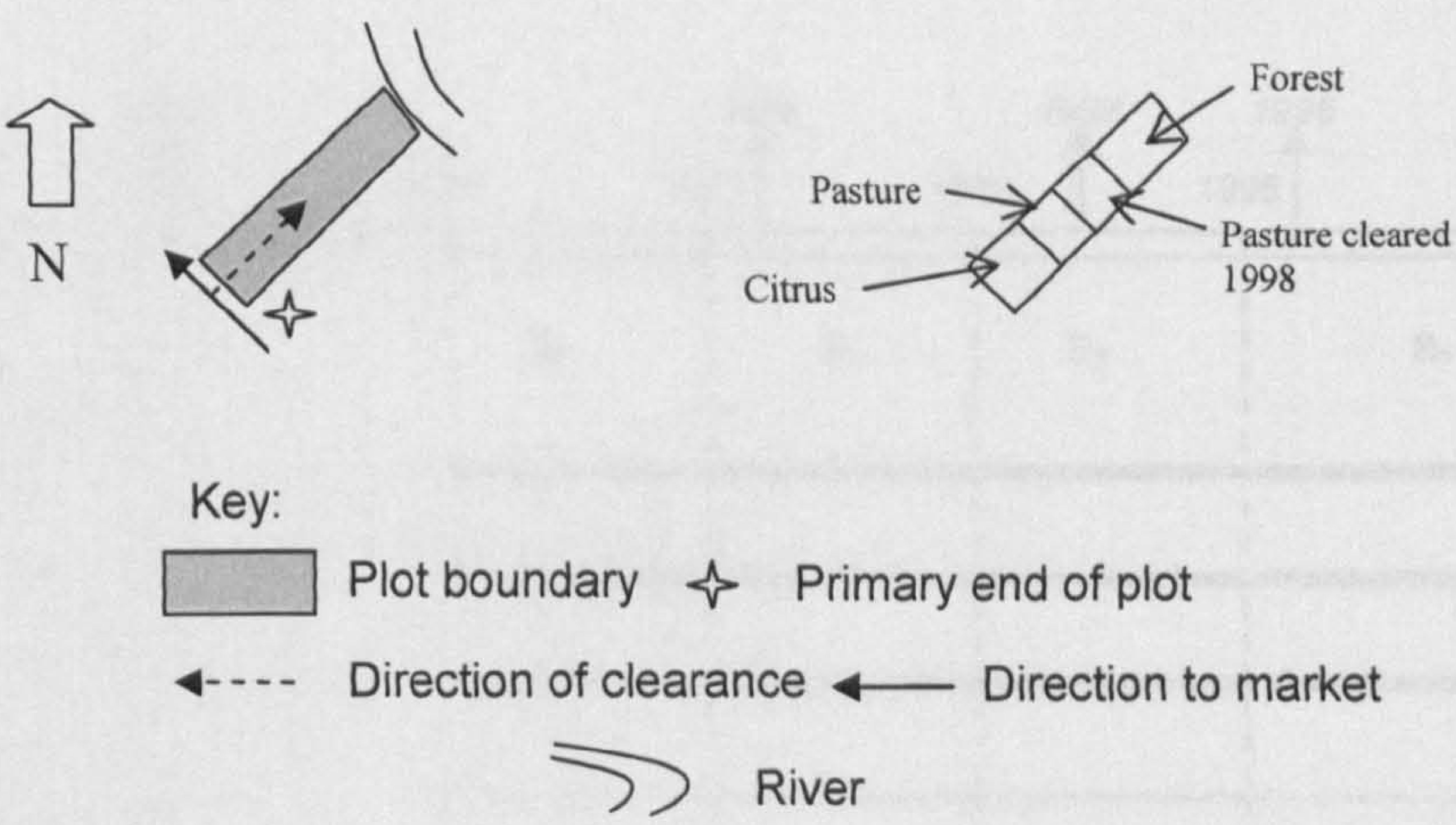


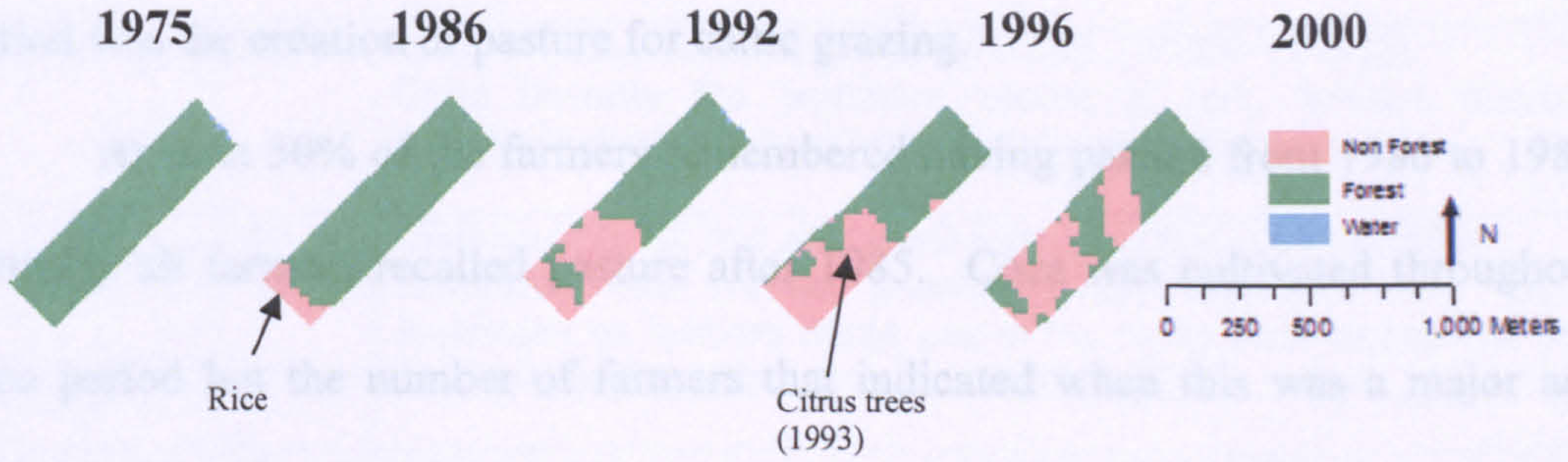
Figure 5.51: Schematic diagram of the plot of Miguel Rebosio showing access and cultivation in 2002.



5.3.5 Synopsis of land-use

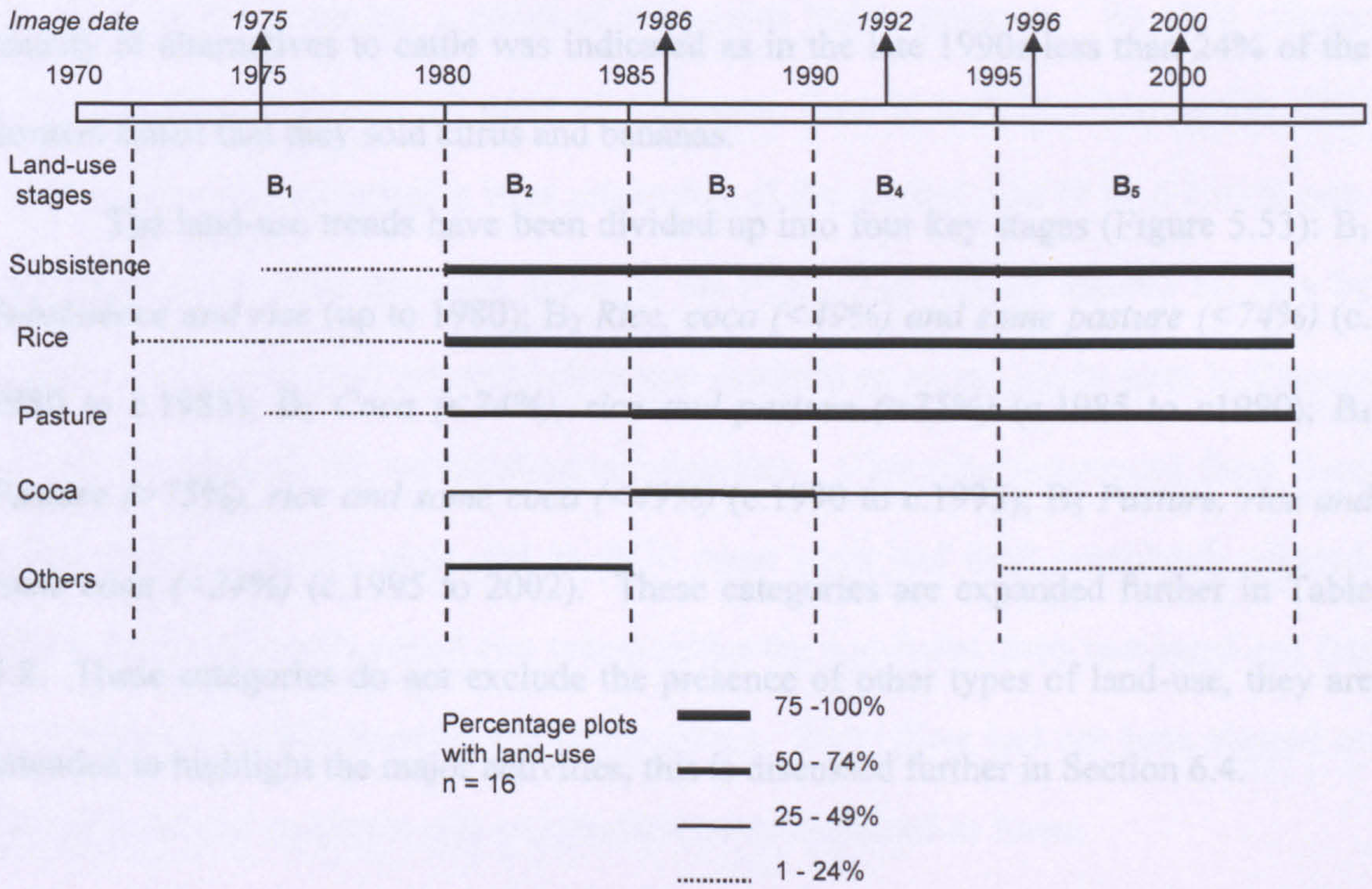
Figure 5.53 is a summary of the land-use activities determined from the questionnaires and INRA (1985) between the initial colonisation c.1972 and the interviews in 2002. The format is the same as for Figure 5.27. The major land-use activities found in Bogotá were subsistence (mainly rice, maize and manioc), coca, rice, pasture and other land-uses included citrus, bananas and ground nut.

Figure 5.52: Progression of forest clearance for agriculture in the plot of Miguel Rebosio, 1975 to 2000.



Subsistence cultivation has been a major land-use activity throughout the period of settlement of Bogotá, as at least 75% of the farmers recalled this (in the period up to 1983, there were fewer farmers, so low percentages are recorded).

Figure 5.53: Synopsis of activities in Bogotá. Source: INRA (1985) and interviews.



Rice was a major activity from the 1970s when the first colonists formed a cooperative. From the late 1970s (and into the early 1980s) despite the collapse of the rice co-operative and formation of the cattle rearing association, more then 75% of the farmers recalled cultivating rice crops between the time of the influx of colonists around 1983 to the interviews in 2003. The major land-use activity recalled throughout the period was the creation of pasture for cattle grazing.

At least 50% of the farmers remembered having pasture from 1980 to 1985 and virtually all farmers recalled pasture after 1985. Coca was cultivated throughout the time period but the number of farmers that indicated when this was a major activity varied. Fewer than 50% of the farmers interviewed recalled growing coca in the period before 1985, but more than 75% indicated that they grew coca between 1985 and 1990. Since then less than 24% of the farmers interviewed recalled that coca had been a major activity since 1995. Other crops have been grown but have seldom been relied upon as marketable products. Between 1980 and 1985 in the INRA documents at least 50% of the plots had a record of other crops and these were cultivated for subsistence. The paucity of alternatives to cattle was indicated as in the late 1990s less than 24% of the farmers stated that they sold citrus and bananas.

The land-use trends have been divided up into four key stages (Figure 5.53): B_1 *Subsistence and rice* (up to 1980); B_2 *Rice, coca (<49%) and some pasture (<74%)* (c. 1980 to c.1985); B_3 *Coca (<74%), rice and pasture (>75%)* (c.1985 to c1990); B_4 *Pasture (>75%), rice and some coca (<49%)* (c.1990 to c.1995); B_5 *Pasture, rice and some coca (<24%)* (c.1995 to 2002). These categories are expanded further in Table 5.8. These categories do not exclude the presence of other types of land-use, they are intended to highlight the major activities, this is discussed further in Section 6.4.

Table 5.8: Land-use stages in Bogotá

Community	Stage	Land-use description
Bogotá	B_1	*Subsistence and rice* before 1980. In this period there were only a few farmers working as a cooperative on the production of rice. It is likely that the rice land-use also included a subsistence element although only one farmer recalled this.
	B_2	*Rice, coca (<49%) and some pasture (<74%)* (c.1980 – c.1985). In this period rice and coca were the major land-use activities. Pasture was present but not much land had been cleared for this.
	B_3	*Coca (<74%), rice and pasture (>75%)* (c.1985 – c1990). Coca became the dominant source of rent, farmers placed less emphasis on rice cultivation and clearing for pasture.
	B_4	*Pasture (>75%), rice and some coca (<49%)* (c1990 – 1995). Emphasis had moved towards cattle rearing. Rice cultivation increased as farmers made use of the fertile soils cleared for pasture. The cultivation of coca was less dominant.
	B_5	*Pasture, rice and some coca(<24%)* (c.1995-2002). The major land-use was pasture (as cattle stock levels had increased) and this was the major source of rent. During this period a few farmers indicated that other crops (e.g. citrus and bananas) were grown but they were not as important as clearing forest for pasture.

5.4 LULCC development in Caracas

Originally humid tropical forest covered the area now occupied by Caracas and was used by the Yuracaré, a group of indigenous hunter-gatherers. By 1976 (Figure 5.54), after approximately 10 years of clearance, Caracas and the communities (OC) surrounding it had converted a large proportion of the original area (7 by 6 km) to non-forest land cover, pink and light green on the FCC. The farmers entered the area by following a planned road network which was designed to access all the plots in Caracas and all the plots in the surrounding communities. Clearance progressed from these access roads along the plots and in 1976 some plots had been completely cleared. Where the access roads joined two communities the non-forest areas coalesced and this created forest patches between the communities. Some plots had not been cleared on the northeast and southeast side and the land-cover remained as forest.

By 1986 (Figure 5.55) clearance had continued along the plots. Some farmers had reached the ends of their plots and this resulted in back-to-back clearance with other communities – causing non-forest patches to coalesce. Sometimes clearance progressed past the plot limits until farmers reached a geographical barrier such as a river. In a few cases farmers appeared to leave a small patch of forest within their plot. In the previously unoccupied plots to the northeast and southwest clearance had begun and where this allowed access to the ends of older plots clearing began (Figure 5.55).

By 1993 (Figure 5.56) forest clearance had continued from 1986 (Figure 5.55). There were areas where forest returned at the forest / non-forest margins. In the new plots in the northeast and southeast of the community clearance has advanced rapidly and double ended clearance progressed in the older plots. On the western side of the community clearance has not progressed much at all and there is return of forest around some of the forest / non-forest margins. Throughout the central parts of the community small islands of forest are becoming more widespread than previous years.

By 1996 (Figure 5.57) forest clearance was mainly in the new plots to the northeast and southwest and only small amounts of clearance had occurred elsewhere. Some of the forest patches (Figure 5.56) appeared to be increasing in size whilst others were continuing to fragment.

By 2000 (Figure 5.58) many of the plots had removed virtually all of the original forest. In the east side of the community clearance backed onto surrounding communities and up to the surrounding rivers but there were many small forest patches within the community. In the western side of the community the plots retained more of the original forest cover particularly at the community limits. Forest patches still remained in the areas around the access road and in central parts of the plots. The non-forest patch from 1996 had fragmented into smaller pieces.

Figure 5.54: Landsat MSS FCC bands 231 and land-cover map showing the extent of forest and progression of agriculture in the vicinity of Caracas, 1976

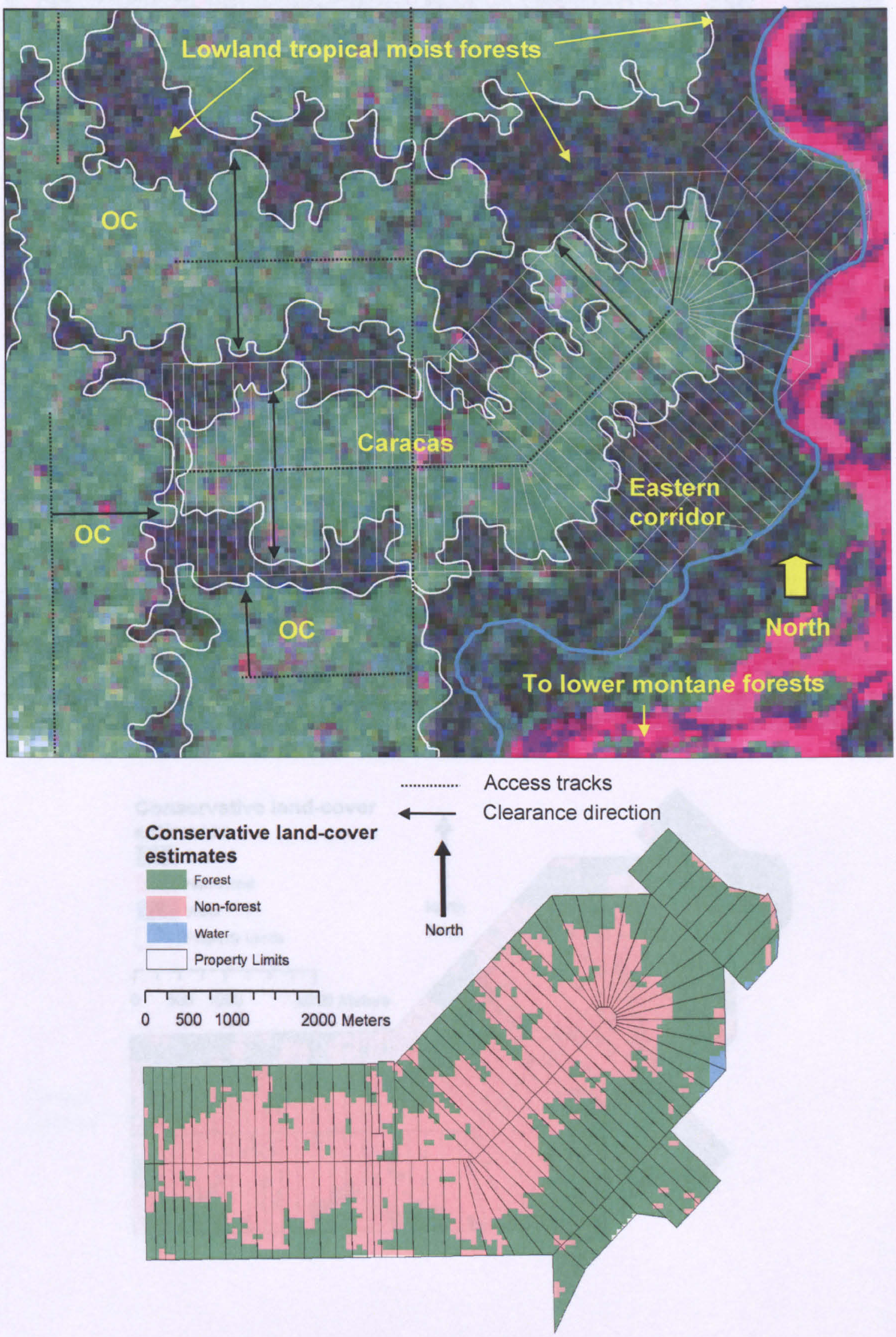


Figure 5.55: Landsat TM FCC bands 741 and land-cover map showing the extent of forest and progression of agriculture in the vicinity of Caracas, 1986

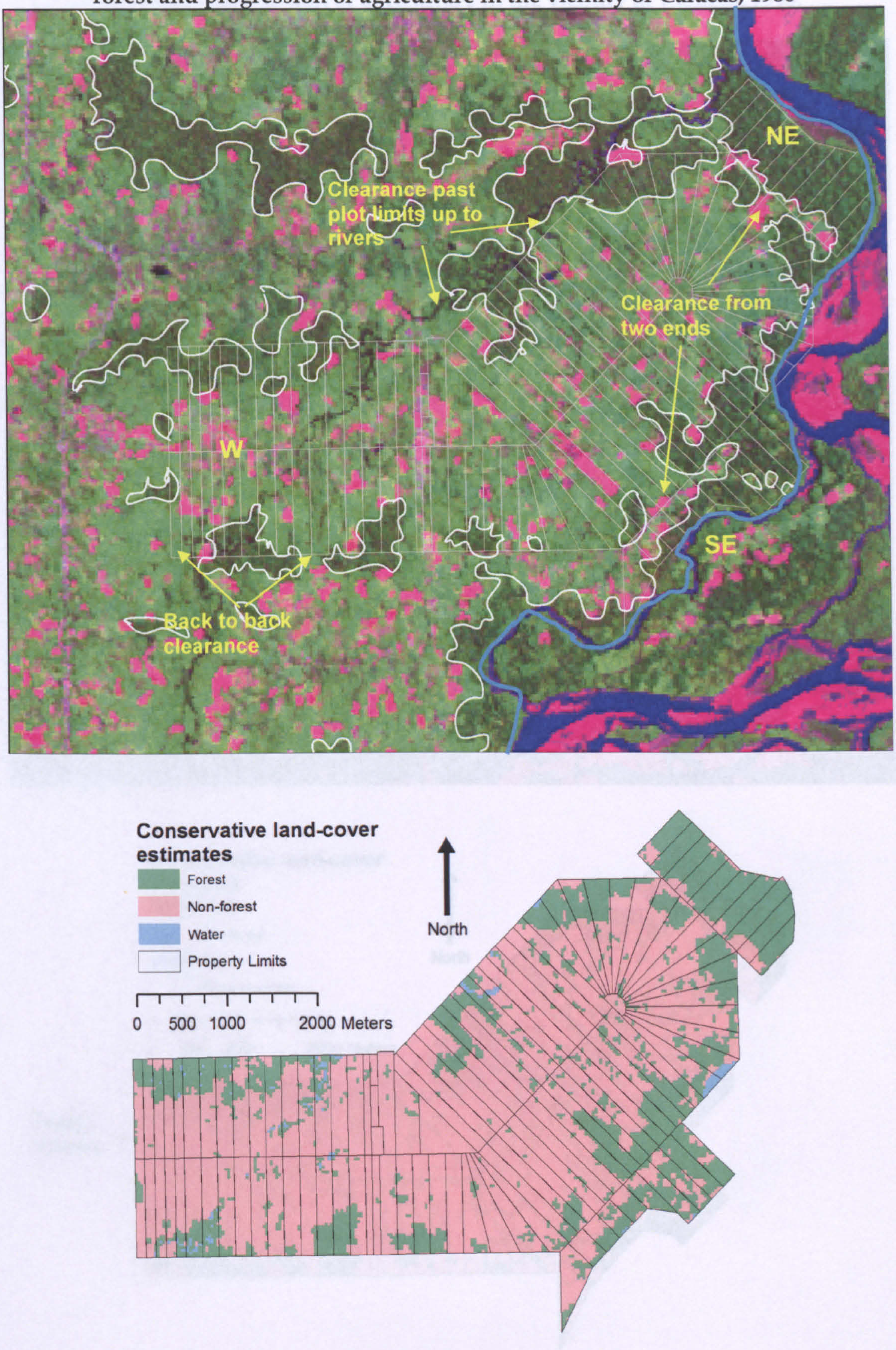
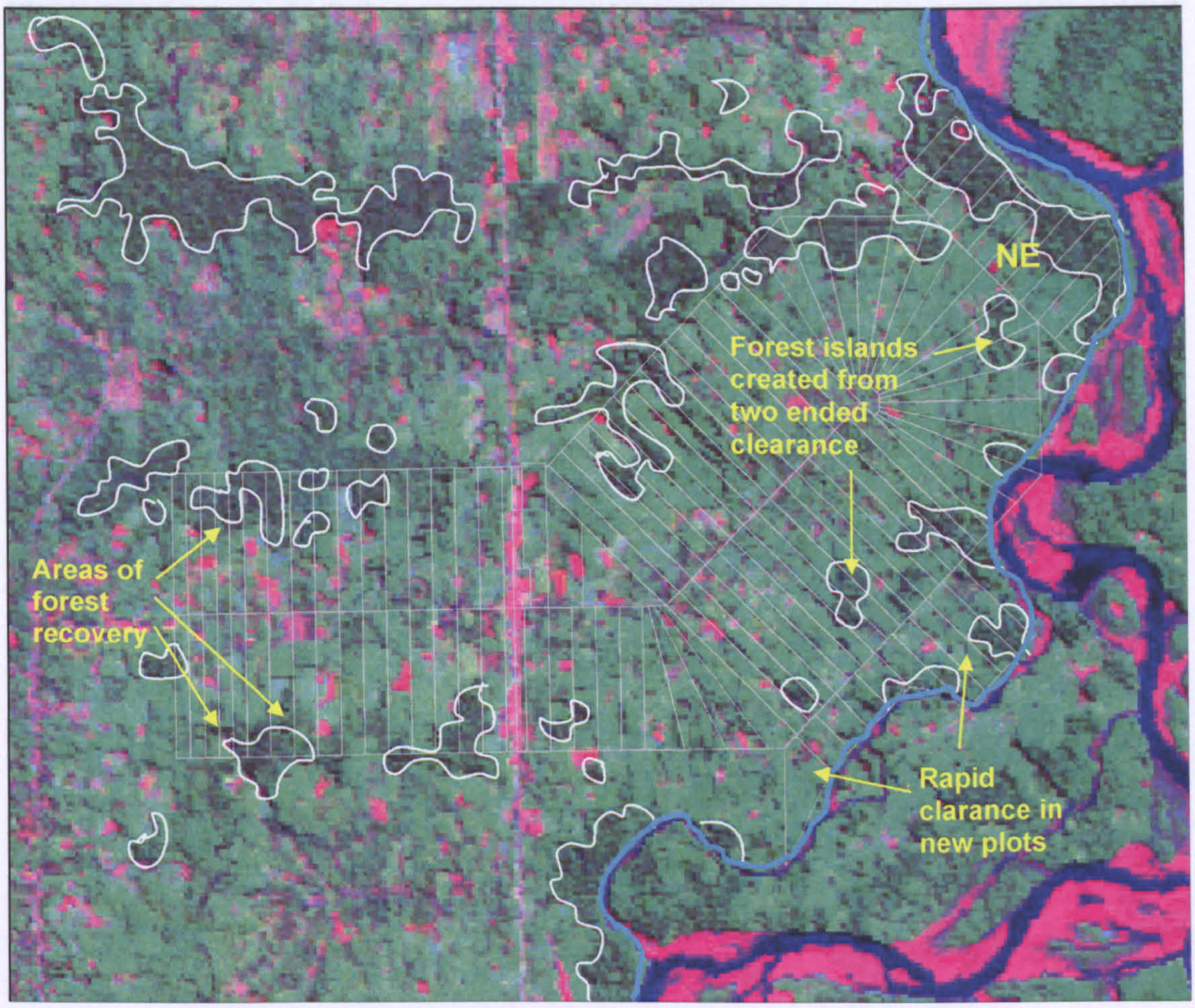


Figure 5.56: Landsat TM FCC bands 741 and land-cover map showing the extent of forest and progression of agriculture in the vicinity of Caracas, 1993.



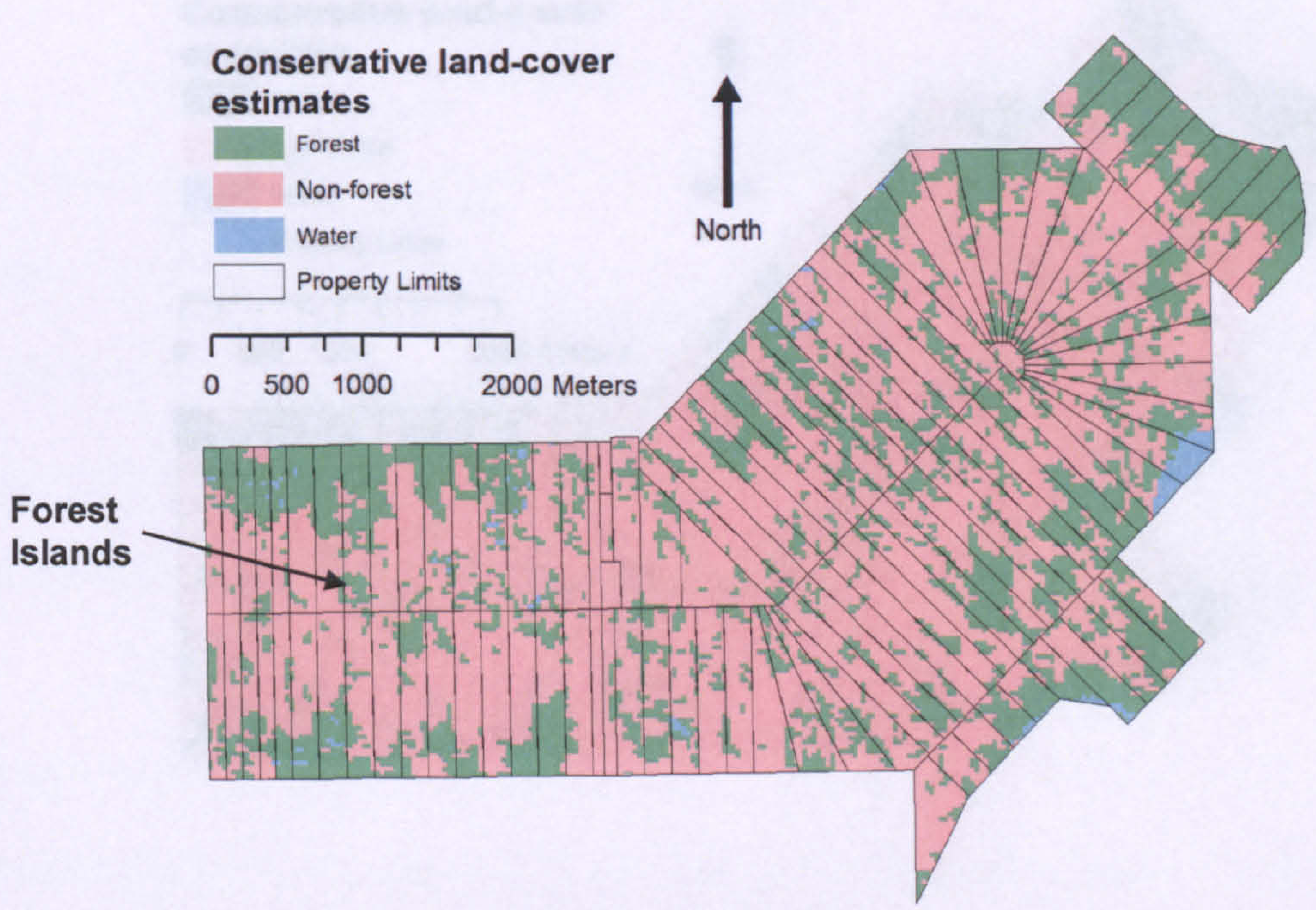
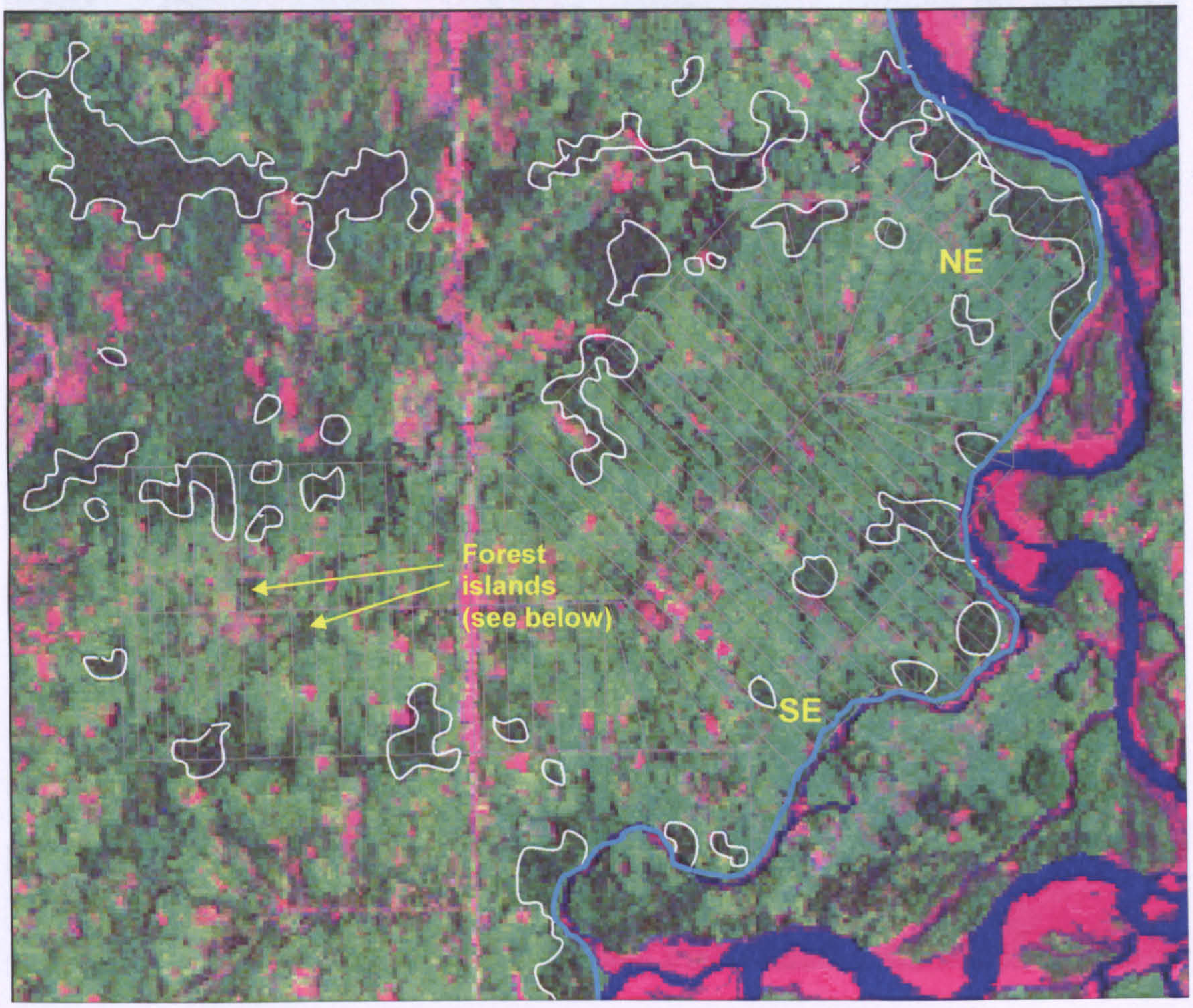


Figure 5.57: Landsat TM FCC bands 741 and land-cover map showing the extent of forest and progression of agriculture in the vicinity of Caracas, 1996



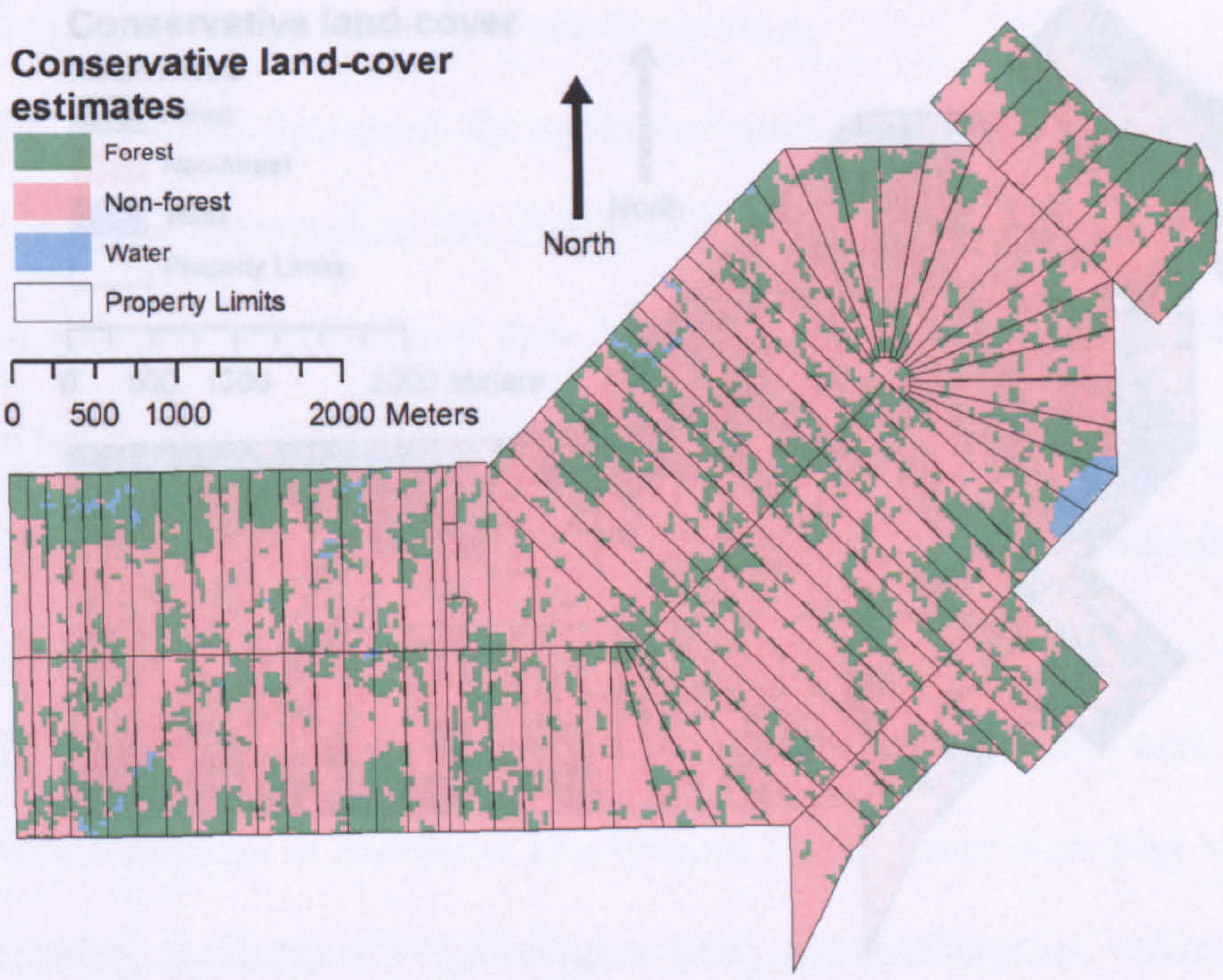
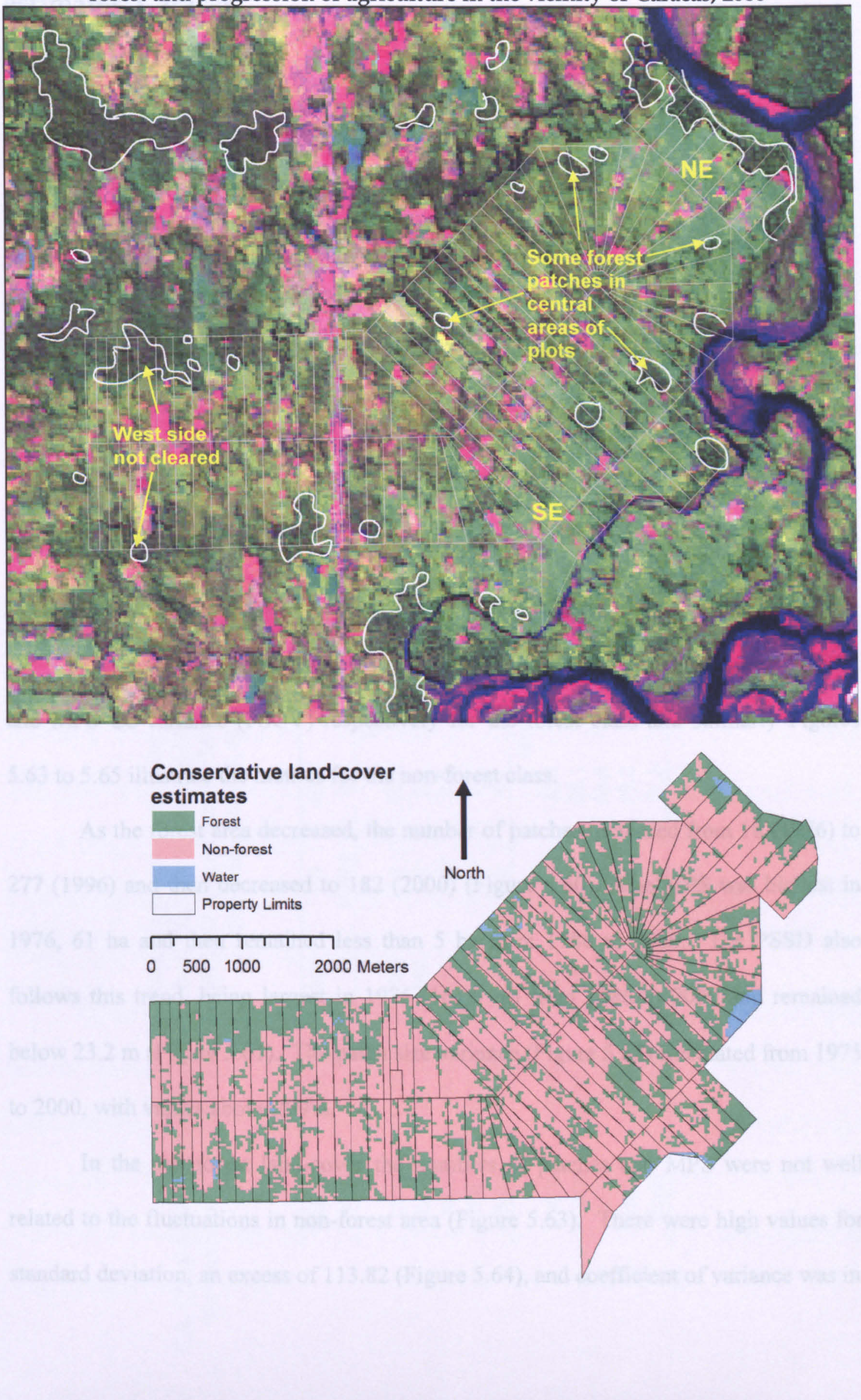


Figure 5.58: Landsat ETM FCC bands 741 and land-cover map showing the extent of forest and progression of agriculture in the vicinity of Caracas, 2000



5.4.1 Community level forest fragmentation and land-cover estimates: Caracas.

5.4.1.1 Class area: forest

Table 5.9 shows the results of the FRAGSTATS calculations. The estimate of forest between 1975 and 2000 is shown for Caracas in Figure 5.59. By the time the first image was acquired in 1976, 1,012 ha of the forest remained (58%) and in the next decade to 1986 there was a further decrease to 587.88 ha (34% of the original area). In the following period from 1986 to 1996 only 6 ha of forest was lost. For the final time period – 1996 to 2000 – the forest area had increased by 201 ha, to 44% of the original area.

5.4.1.2 Structural metrics

Number of Patches (NoP) and Mean Patch Size (MPS)

Figures 5.60 to 5.62 illustrate the NoP, MPS, MPS Standard Deviation (PSSD) and MPS Co-variance (PSCV) respectively for the forest class and similarly Figures 5.63 to 5.65 illustrate the metrics for the non-forest class.

As the forest area decreased, the number of patches increased from 18 (1976) to 277 (1996) and then decreased to 182 (2000) (Figure 5.60). The MPS was highest in 1976, 61 ha and then remained less than 5 ha from 1986 to 2000. The PSSD also follows this trend, being largest in 1976 (161.5 m) from 1986 to 2000 and remained below 23.2 m (Figure 5.61). The patch size variance (Figure 5.62) fluctuated from 1975 to 2000, with values above 299%.

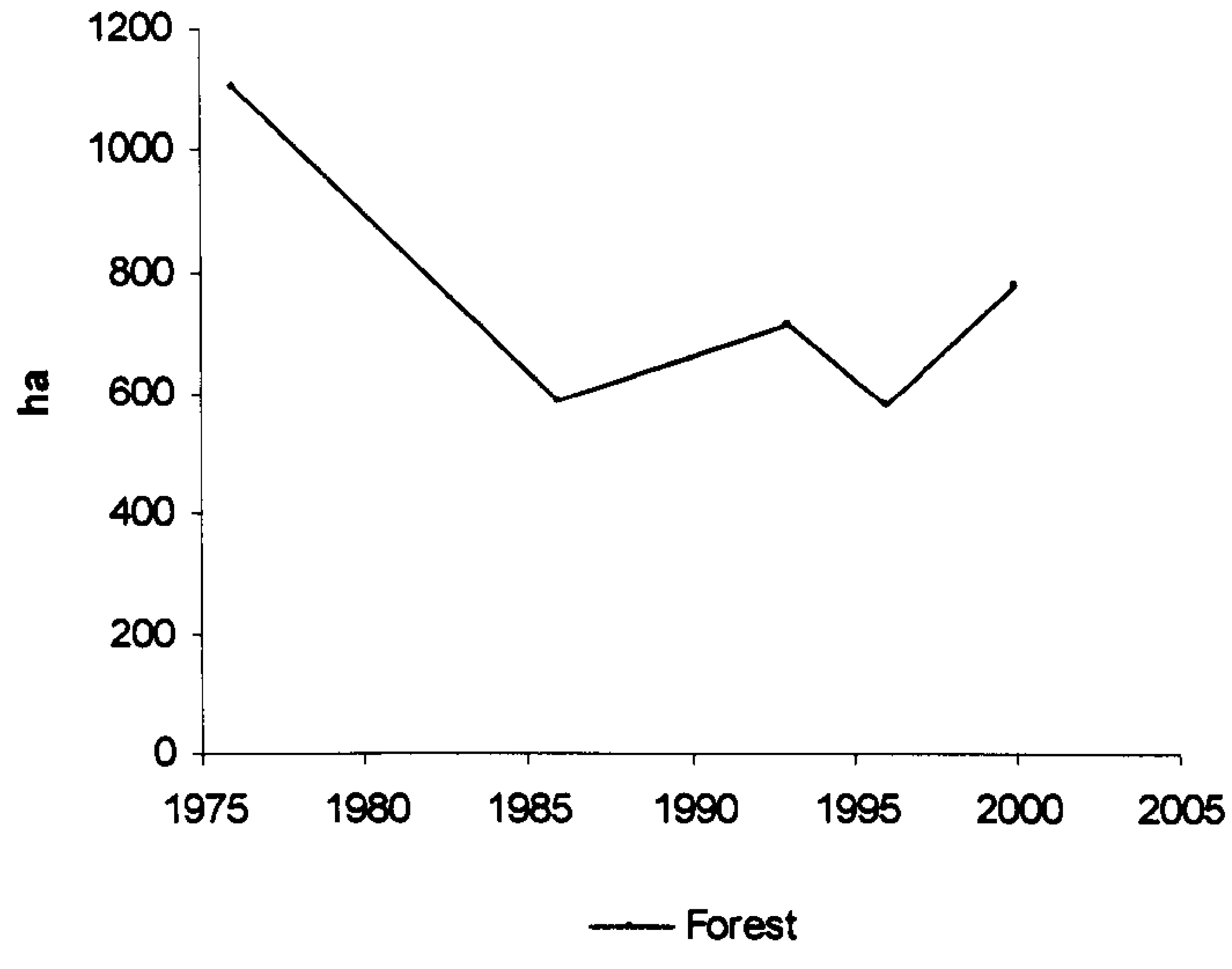
In the non-forest land-cover the numbers of patches and MPS were not well related to the fluctuations in non-forest area (Figure 5.63). There were high values for standard deviation, an excess of 113.82 (Figure 5.64), and coefficient of variance was in

Table 5.9: Selected landscape metrics for the forest and non-forest land-cover estimate in Caracas; CA, Class Area; NP, Number of Patches; PD, Patch Density; MPS, Mean Patch size; PSSD, Patch Size Standard Deviation; PSCV, Patch Size Co-variance; TEL, Total Edge length; ED, Edge Density; MNN, Mean Nearest Neighbour; MNSD, Mean Nearest Neighbour Standard Deviation; NNCV, Mean Nearest Neighbour Co-variance

Metric	CA	NP	PD	MPS	PSSD	PSCV	TEL	ED	MNN	NNSD	NNCV
Units	ha		NP/ha	ha	ha	%	m	m/ha	m	m	%
					Forest land-cover						
1976	1,102.0	18	0.9	61.2	161.5	263.8	66,780	32.6	119.8	63.7	53.2
1986	587.9	167	8.2	3.5	18.2	517.2	108,300	52.9	75.7	58.6	77.4
1993	716.6	245	12.0	2.9	10.3	352.1	236,400	115.5	40.9	19.3	47.3
1996	581.5	277	13.5	2.1	6.3	299.3	189,210	92.5	54.0	31.5	58.3
2000	782.3	182	8.9	4.3	23.2	540.4	265,350	129.6	45.9	44.3	96.5
					Non-forest land-cover						
1976	939.2	29	1.4	32.4	163.1	503.5	65,670	32.1	117.9	102.9	87.3
1986	1,444.9	48	2.4	30.1	201.3	668.7	106,200	51.9	55.9	26.4	47.3
1993	1,312.4	36	1.8	36.5	210.8	578.3	231,030	112.9	63.6	66.4	104.5
1996	1,449.4	49	2.4	29.6	201.4	680.8	187,110	91.4	54.1	33.1	61.3
2000	1,246.6	72	3.5	17.3	113.8	657.4	262,140	128.0	41.8	23.5	56.1

excess of 504%, (Figure 5.65). Patch sizes at each time point were highly variable and did not have a specific size range at any time between 1975 and 2000.

Figure 5.59: Forest area in Caracas from 1975 to 2000, the total area of Caracas is 1,745 ha.



Mean Nearest Neighbour (MNN) statistics

As the forest area decreased from 1976 to 1986, MNN decreased from 120 m (1976) to 76 m (1986) and the NNSD were approximately 60 (Figure 5.66). The forest area and MNN then fluctuated from 1993 to 2000, but did not follow the same trend. The NNSD ranges were narrow, less than 44 (Figure 5.66). The NNCV values did not relate to the non-forest area or exceed 97%, and were least in 1993 (47%) and 1996 (58%). The range of sizes and variability of the MNN was fairly low.

In the non-forest class as the area of non-forest increased the MNN of non-forest patches decreased from 103 m (1976) to 89 m (1986), but after these dates the forest class and the MNN did not follow the same trend (Figure 5.68). The NNSD were highest in 1976 (103) and fell to 25 for the other years, and 66 in 1993 (Figure 5.69). The NNCV were relatively low, had a narrow range (47 to 87%) with the exception of 1993 (104%) (Figure 5.69).

Figure 5.60: Number of forest patches (NoP) and decrease in area of forest, Caracas (ha).

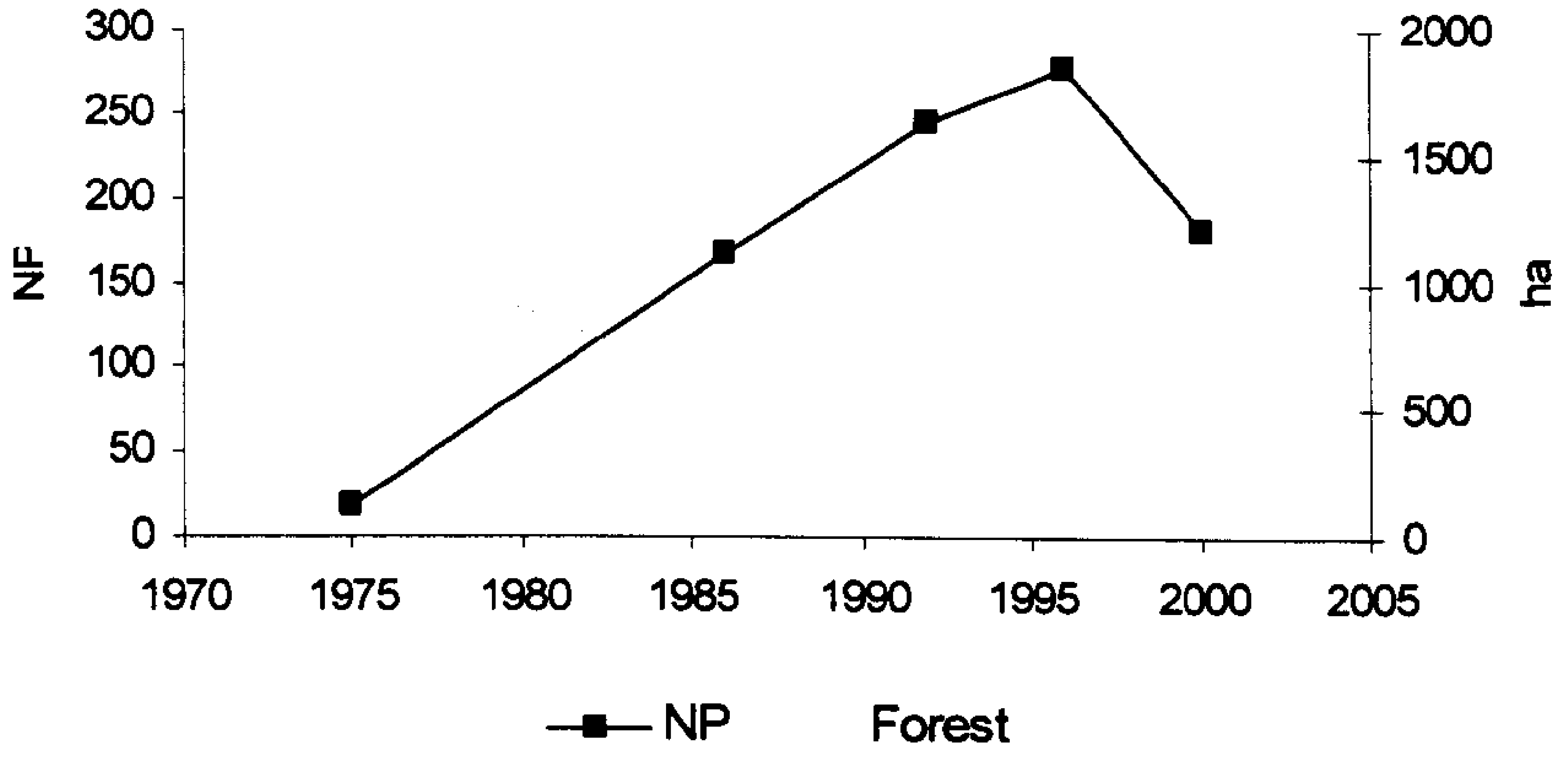


Figure 5.61: MPS (ha) and PSSD (error bars on MPS curve) of forest patches and decrease in area of forest, Caracas (ha).

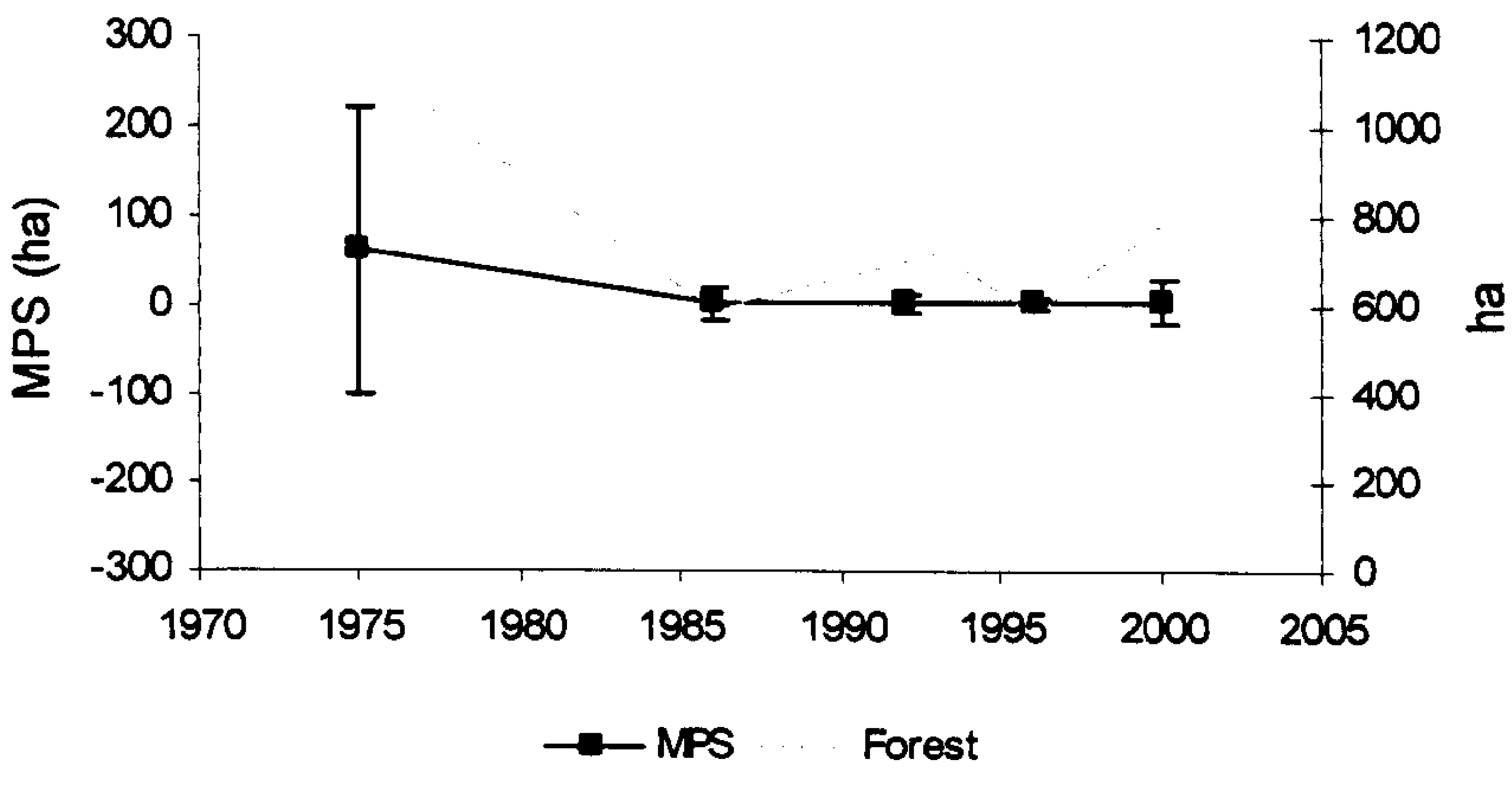


Figure 5.62: MPS (m) and PSCV (error bars on MPS curve) of forest patches and decrease in area of forest, Caracas (ha).

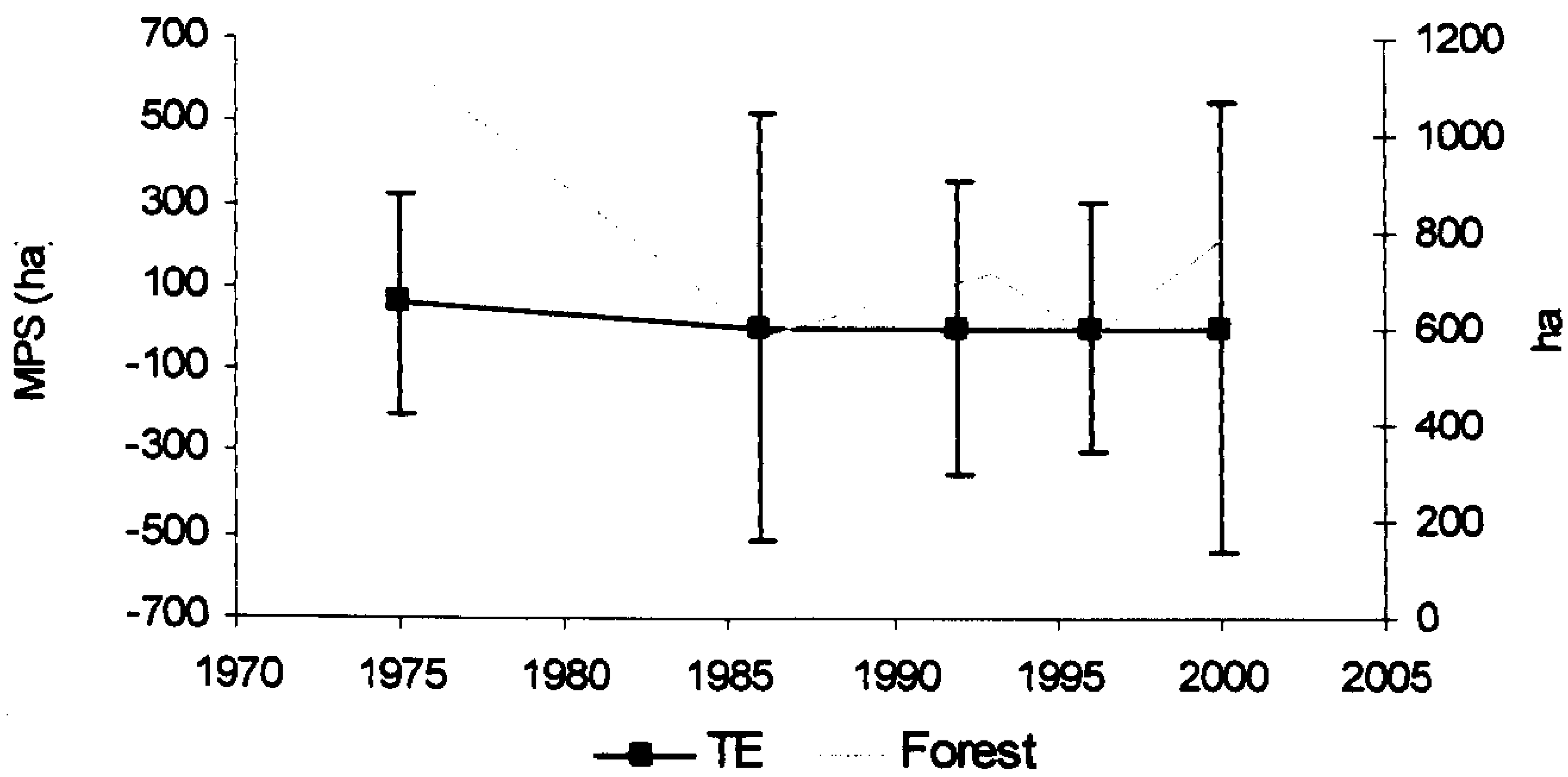


Figure 5.63: Number of non-forest patches and increase in non-forest area, Caracas (ha).

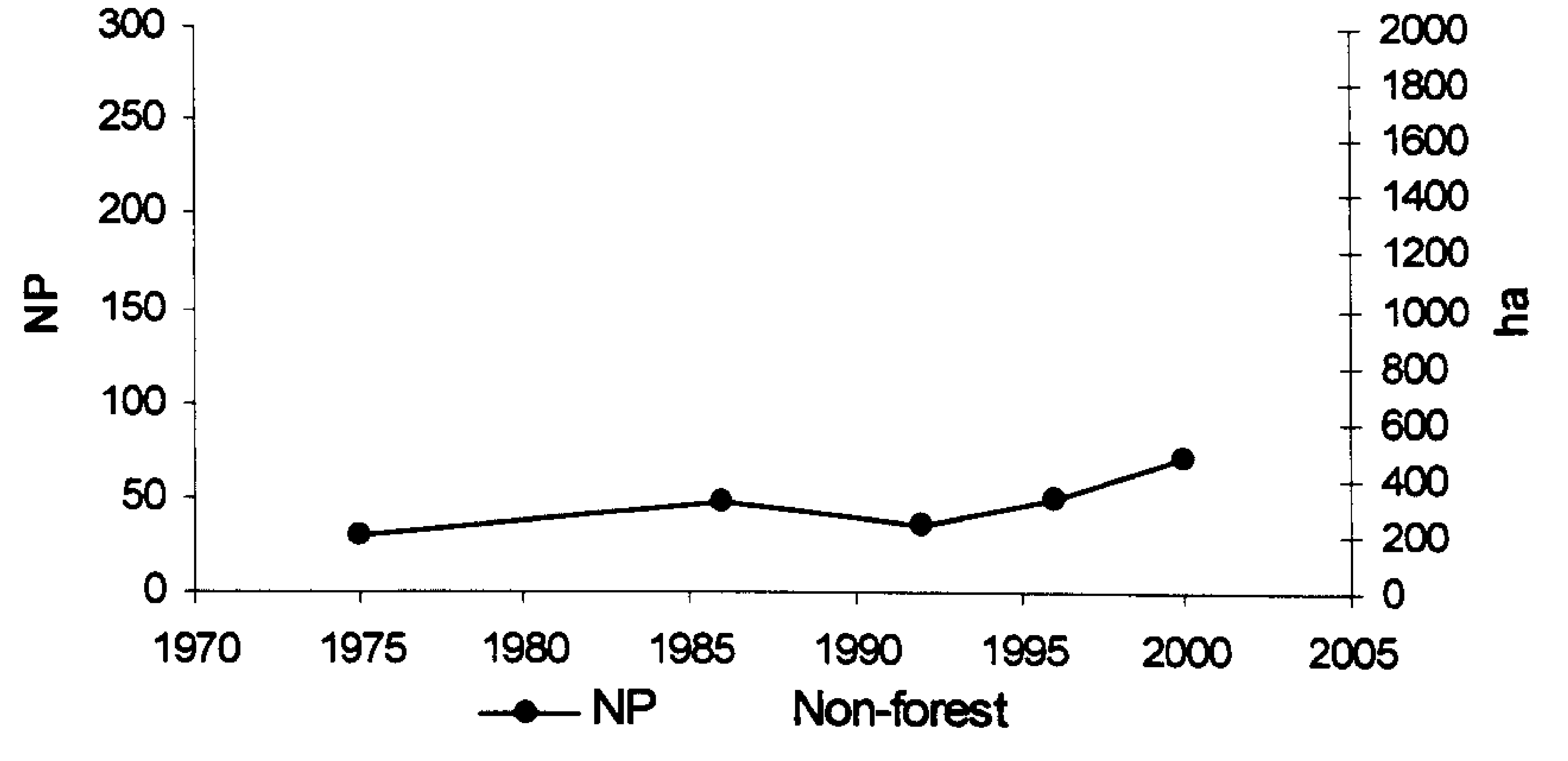


Figure 5.64: MPS (m) and PSSD (error bars on MPS curve) of non-forest patches and increase in non-forest area, Caracas (ha).

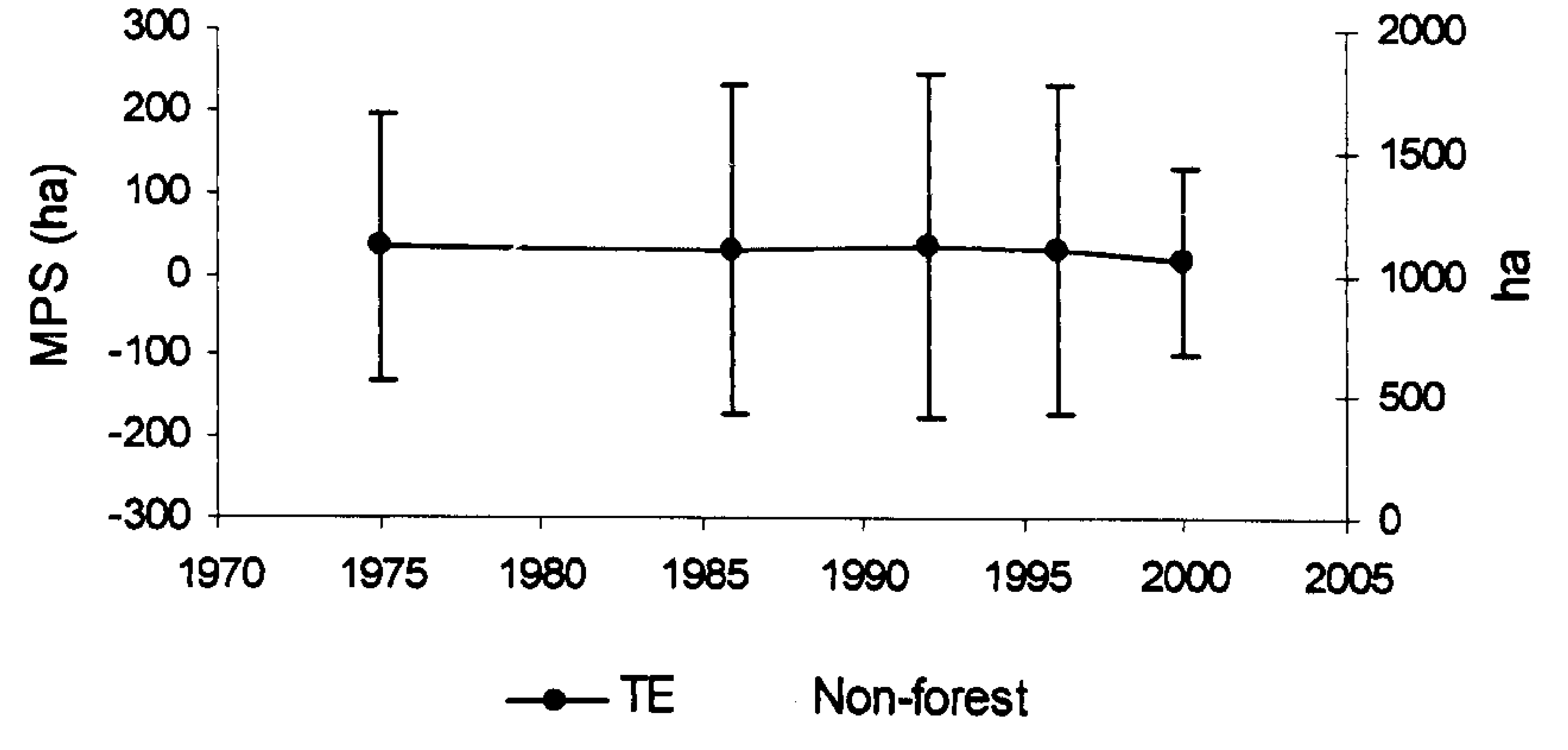


Figure 5.65: MPS (m) and PSCV (error bars on MPS curve) of non-forest patches and increase in non-forest area, Caracas (ha).

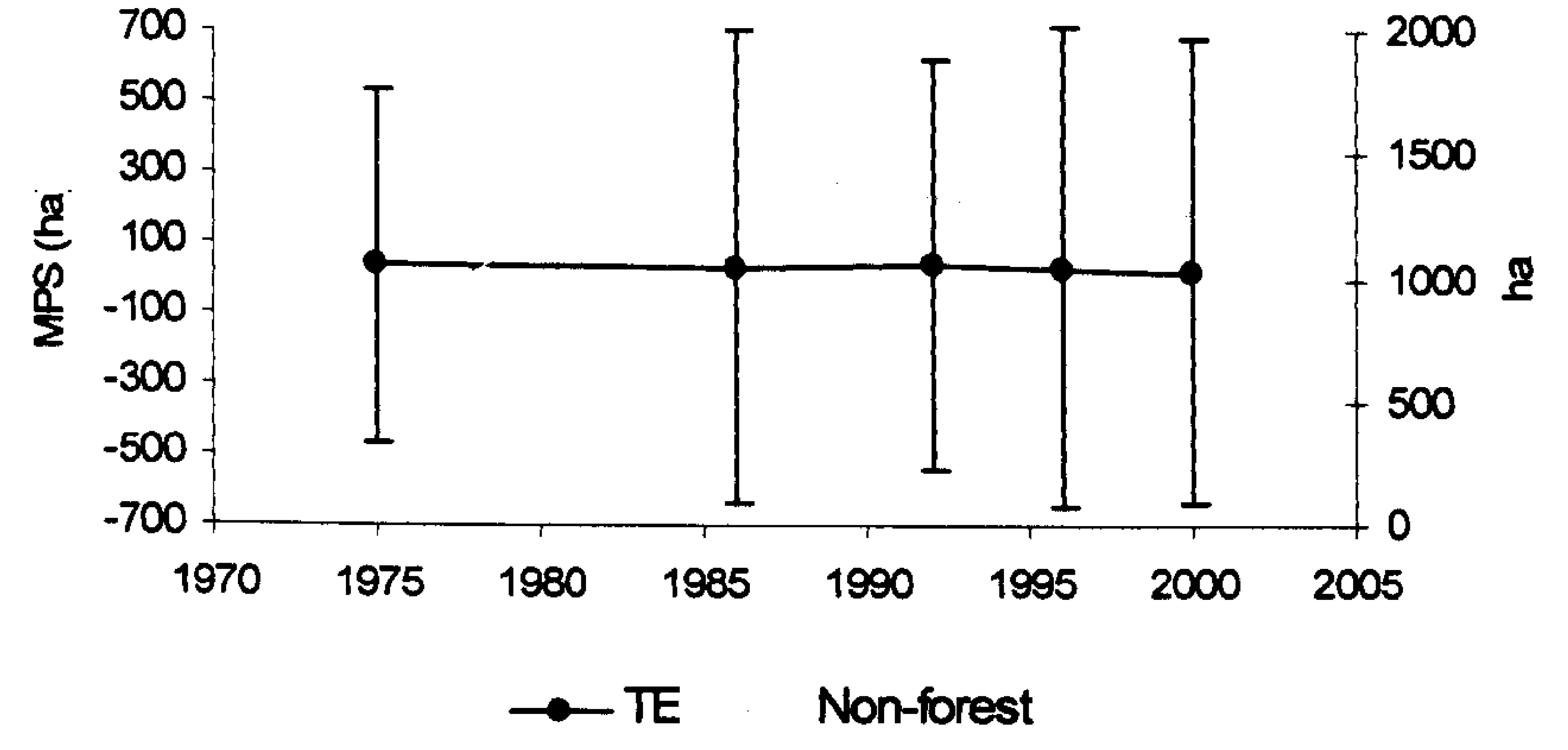


Figure 5.66: MNN (m) and NNSD (error bars on MNN curve) of forest patches and decrease in area of forest, Caracas (ha).

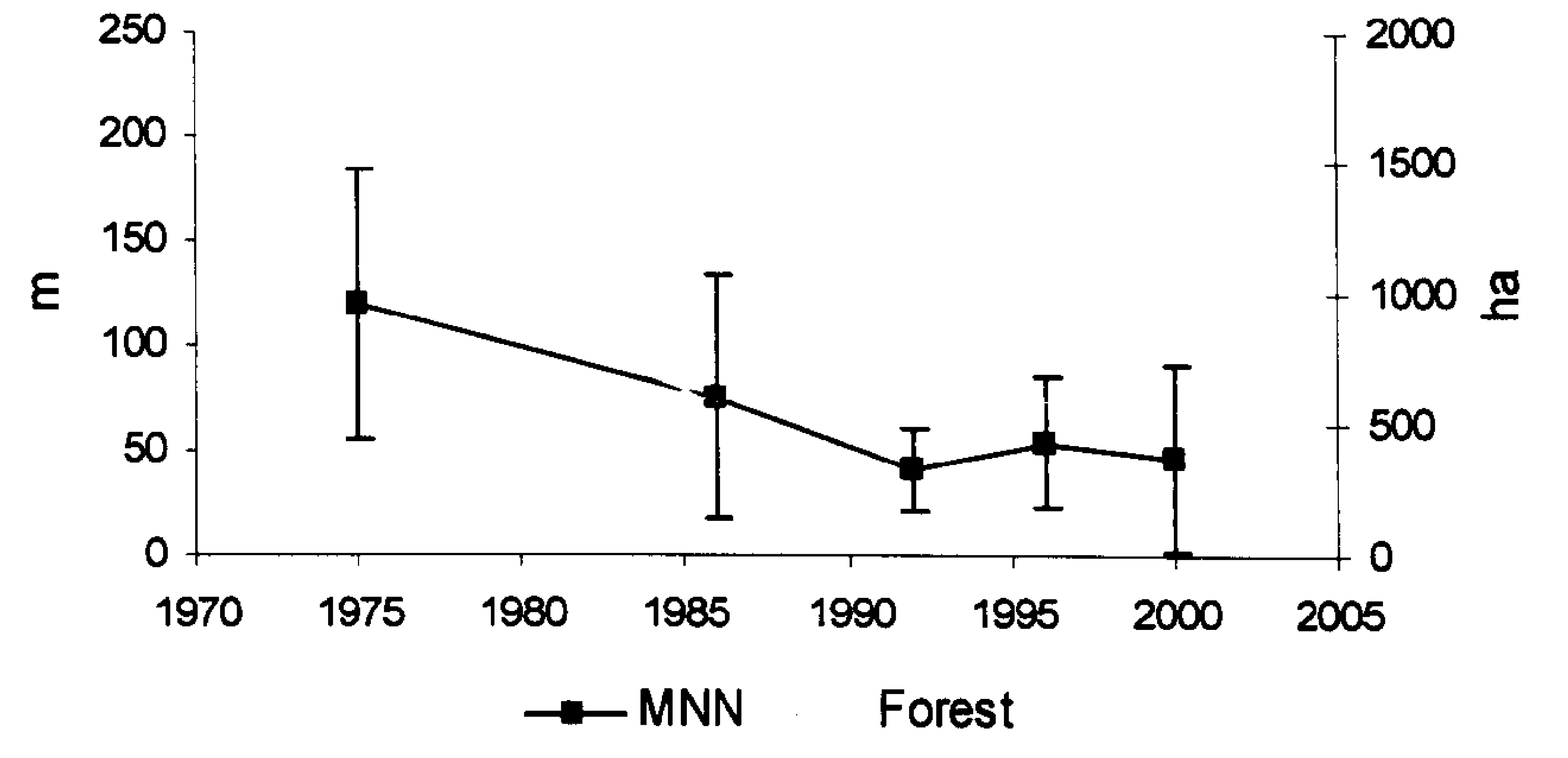


Figure 5.67: MNN (m) and NNCV (error bars on MNN curve) of forest patches and decrease in area of forest, Caracas (ha).

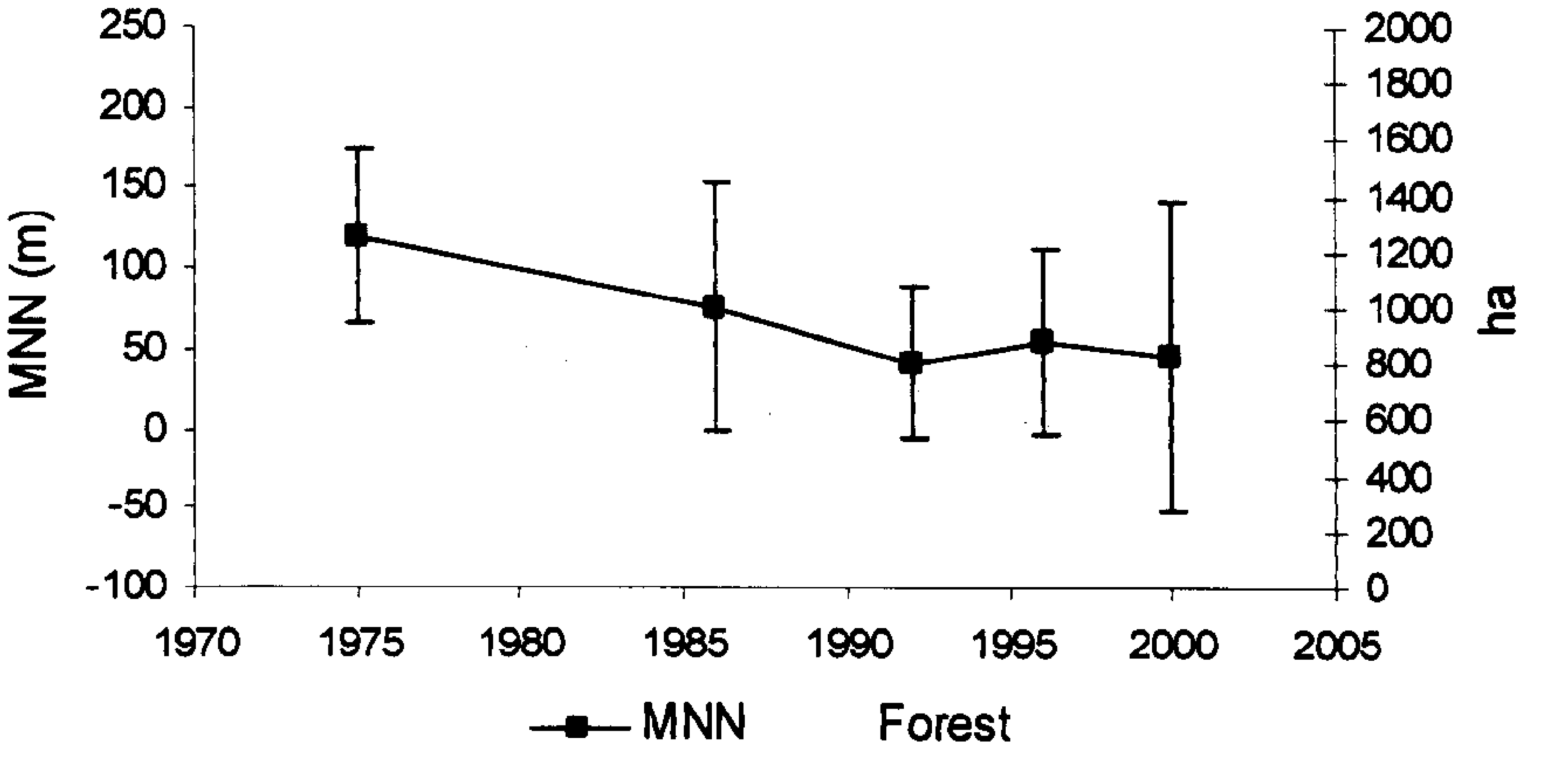


Figure 5.68: MNN (m) and NNSD (error bars on MNN curve) of non-forest patches and increase in non-forest area, Caracas (ha).

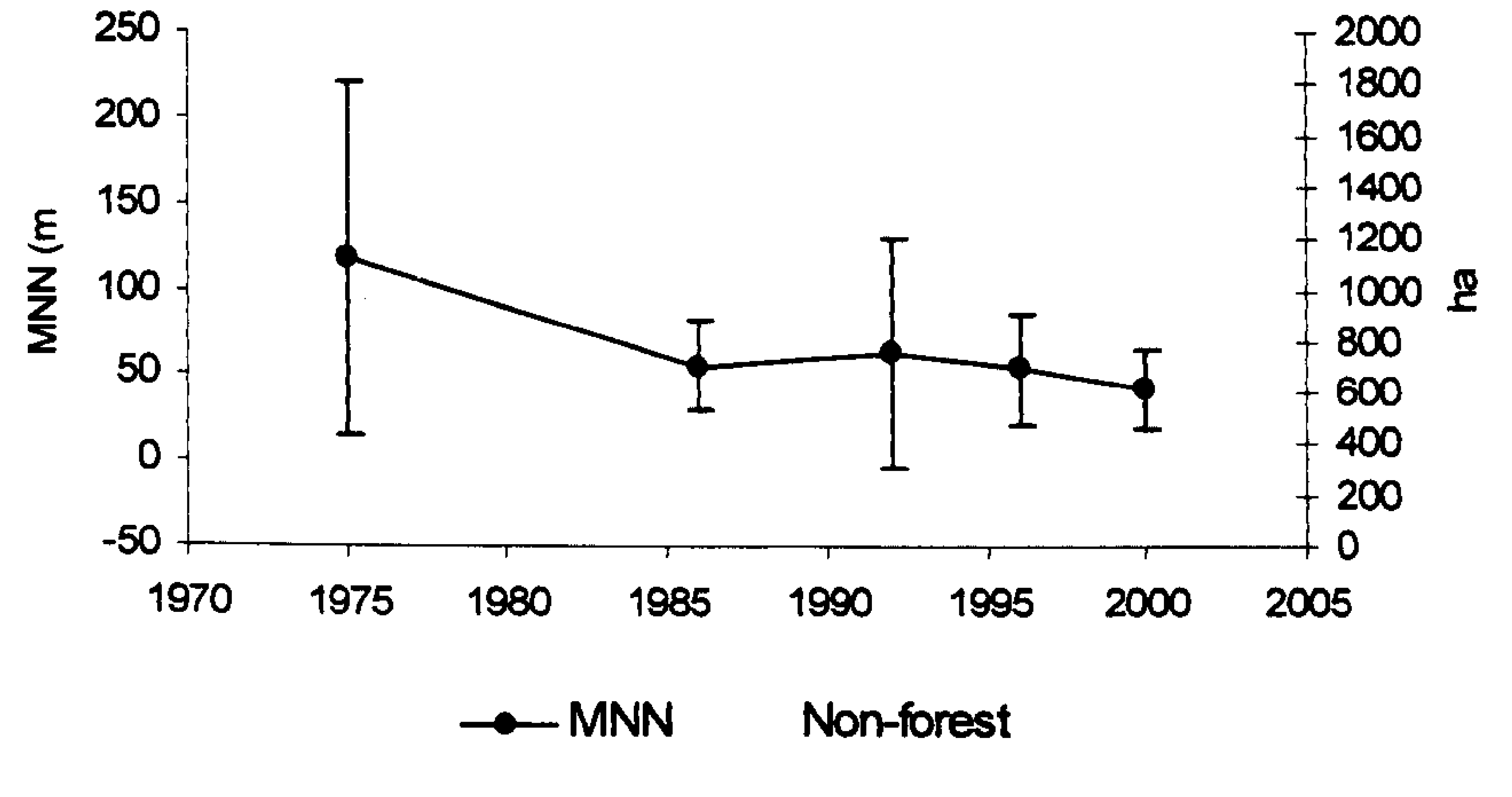
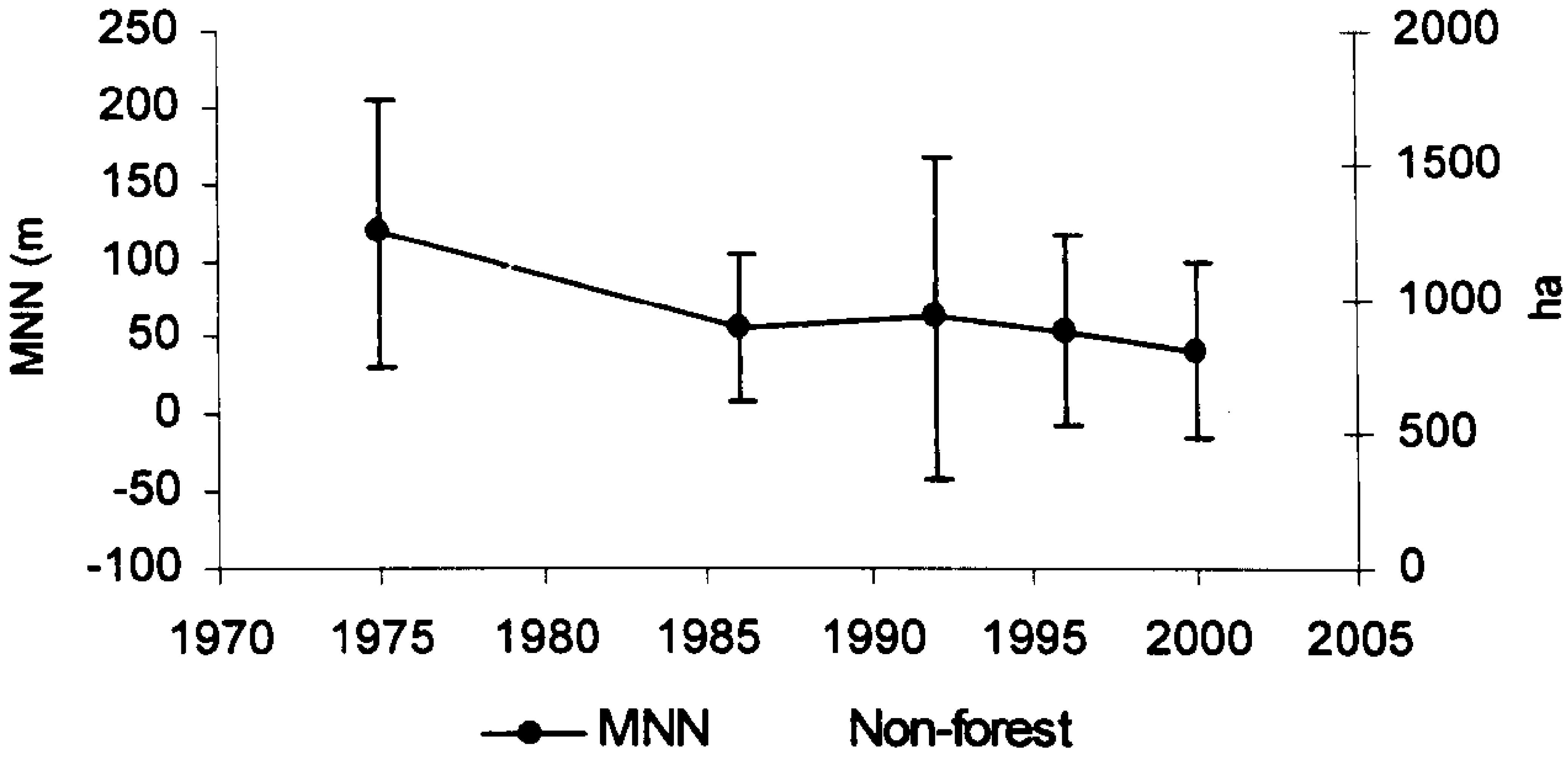


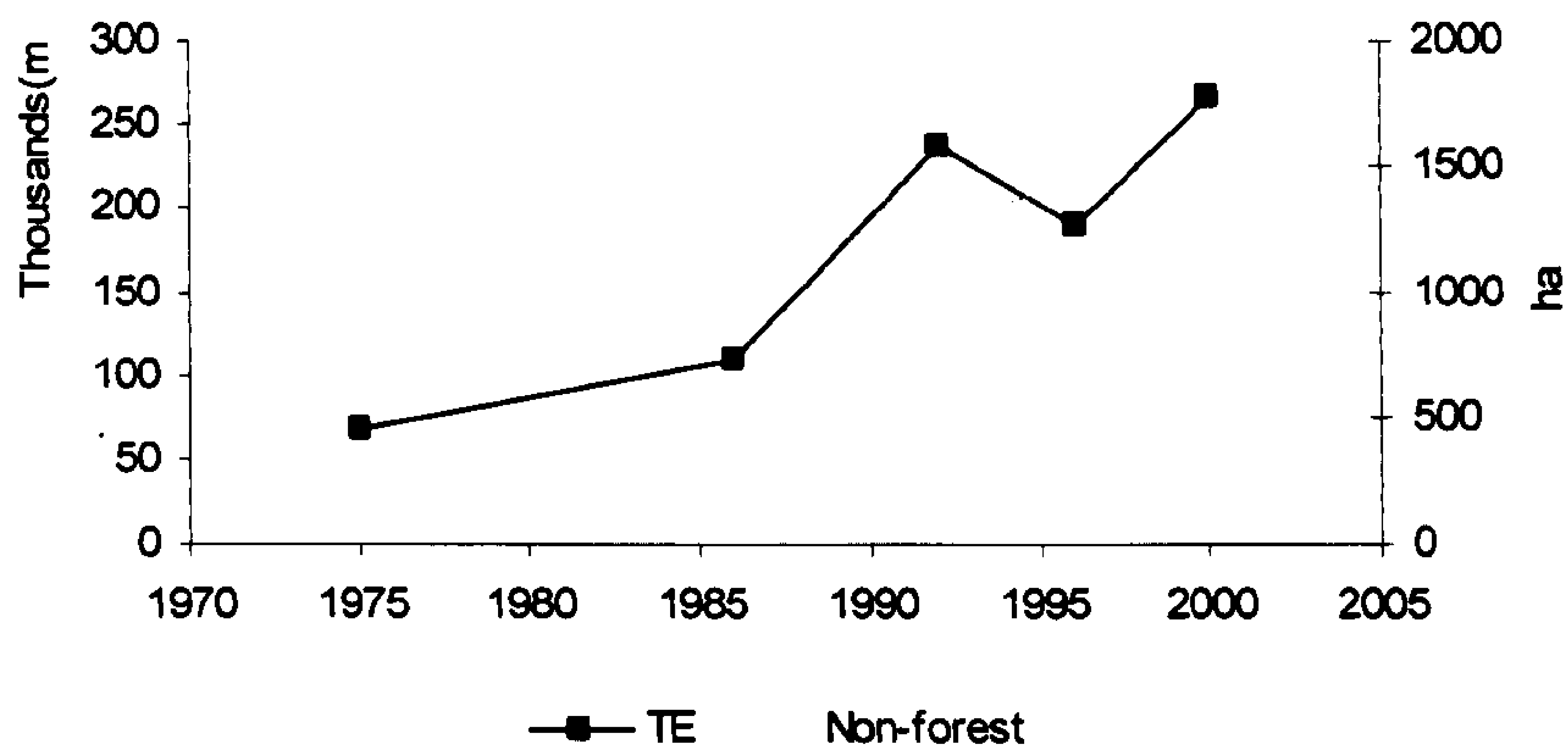
Figure 5.69: MNN and NNCV (error bars on MNN curve) of non-forest patches and increase in non-forest area, Caracas (ha).



Total Edge Length (TEL)

As the forest area increased the TEL increased, but when the forest area began to fluctuate the trend in TEL continued to increase from 66,780 to 265,350 m with an anomalous increase in 1996 (Figure 5.70).

Figure 5.70: Total edge length (TEL) (m) between the forest and non-forest patches from 1986 to 2000, Caracas.



5.4.2 Average plot clearance characteristics

5.4.2.1 Average cleared area

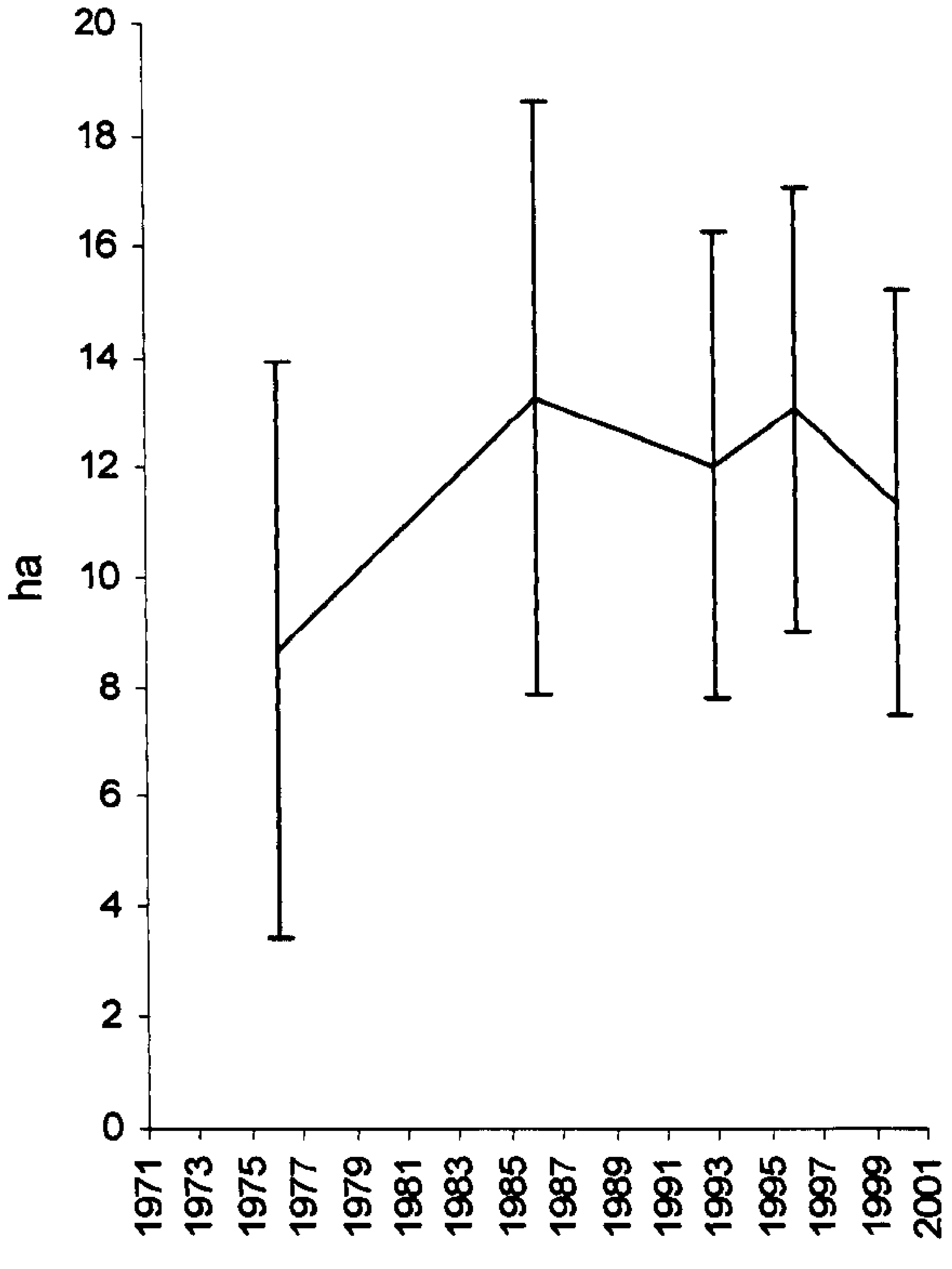
By 1976 (Figure 5.71) on average, 8.7 ha had been cleared and by 1986 an average of 13 ha was cleared. In 1993 there was a slight decrease in cleared area to 12.0

ha and in 1996 the cleared area increased 13.1 ha and by 2000 decreased to 11.4 ha. In both estimates the standard deviation had decreased, indicating that the area of forest cleared between plots had become less variable.

5.4.2.1 Average rates of clearance

The rate of deforestation (Figure 5.72) decreased through the time period from 0.67 ha yr^{-1} to an average of -0.43 ha yr^{-1}. These negative values indicated forest returned between 1986 and 1992 and 1996 to 2000. There was a slight increase in rate during the 1993 to 1996 interval to 0.34ha yr^{-1}.

Figure 5.71: Areas of non-forest land for individual plots between 1986 and 2000, Caracas. Plot sizes are 12.5 - 20ha, the error bars are one standard deviation from the mean.



5.4.3 Plot clearance typology

Adopting the clearance typologies described in Figure 5.20, Table 5.10 shows the number of different clearance typologies for each time point in the image sequence.

In 1976 all the typologies were represented but the most common ways farmers cleared plots were Type II (57%), and IV (18%). From 1986 to 2000 Type II plots gradually decreased from 33% to 14%. In 1986 more farmers cleared from two ends, Type III (21%) and 30% of the plots were cleared Type VI. From 1993 onwards Type IV, V and VI shows that the farmers cleared their plots from, one end, both ends and /or with isolated patches.

Figure 5.72: Average rates of clearance for individual plots between 1986 and 2000, Plot sizes are mostly 20ha, the error bars are one standard deviation from the mean and indicate the variability in clearance rates. From 1986 the error bars fall below the *x*- axis because some plots experienced replacement of forest.

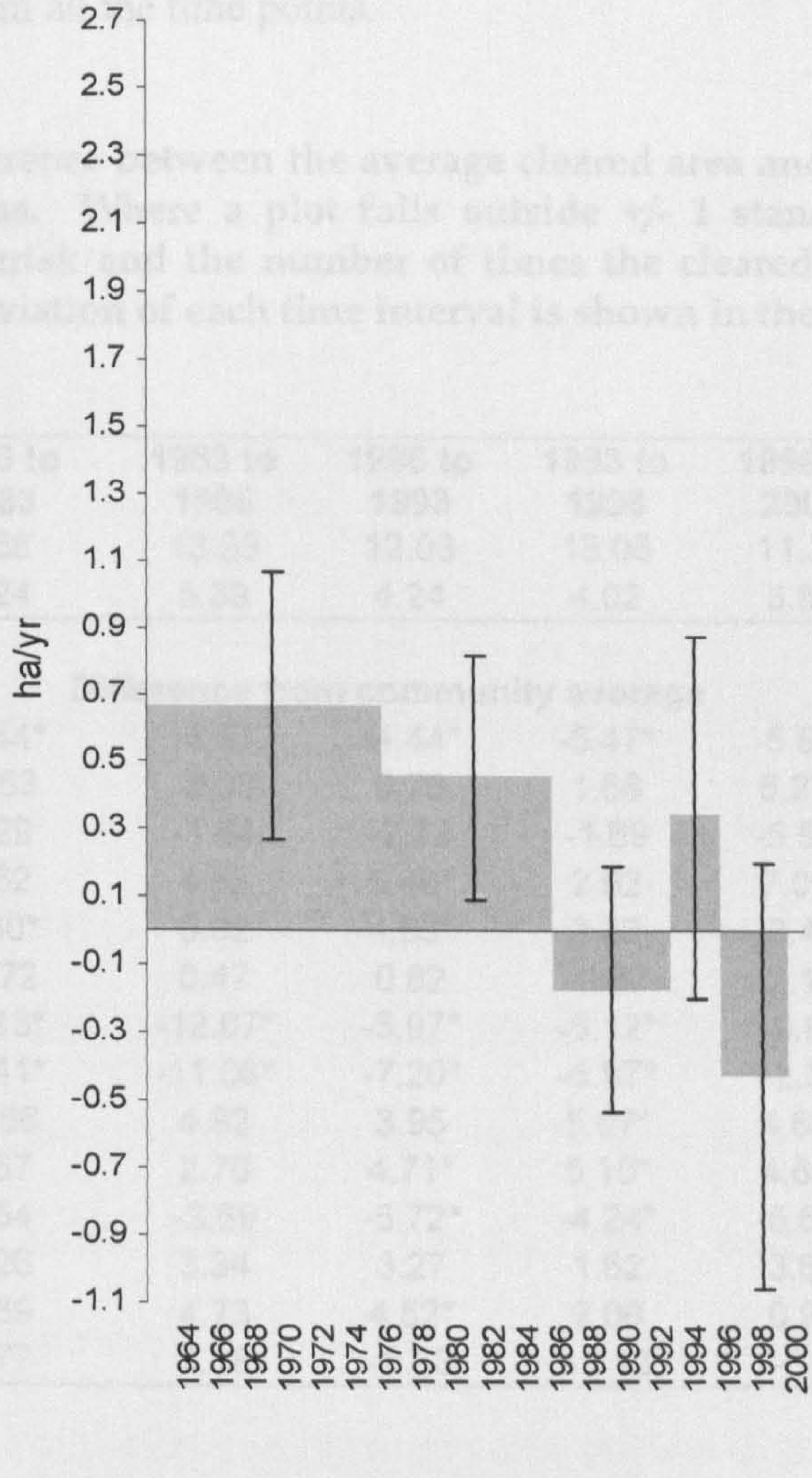


Table 5.10: Summary of clearance typologies for Caracas; 1976 to 2000 (n.b. eight plots have been removed from the analysis due to boundary uncertainties).

Type	1976	1986	1993	1996	2000
I	8	0	0	0	0
II	56	32	18	13	14
III	9	21	5	8	5
IV	18	11	26	17	34
V	1	5	25	24	29
VI	6	29	24	36	16
Total number	98	98	98	98	98

5.4.4 Land-cover change at the plot level

The criteria to select the average and non-average plots were applied from Section 5.2.4 (Table 5.11). Plot C_M was closest to the mean at all time points, and the plot C_G deviated from all the time points.

Table 5.11: The difference between the average cleared area and area cleared in the sample plots, Caracas. Where a plot falls outside +/- 1 standard deviation it is marked with an asterisk and the number of times the cleared area in a plot falls within 1 standard deviation of each time interval is shown in the final column.

	1976 to 1983	1983 to 1986	1986 to 1993	1993 to 1996	1996 to 2000	
Average	8.68	13.23	12.03	13.05	11.35	
SD	5.24	5.39	4.24	4.02	3.85	
Plot	**Difference from community average**					**+ / - 1 standard deviation**
C_A	-5.44*	-4.61	-4.44*	-5.47*	-5.59*	1
C_B	-3.63	-2.03	0.78	1.68	6.27*	4
C_C	0.29	-1.64	-2.73	-1.69	-5.50*	4
C_D	3.62	4.53	5.40*	2.62	7.09*	3
C_E	7.60*	5.02	4.96*	3.33	3.42	3
C_F	-0.72	0.47	0.82	-0.57	2.11	5
C_G	-8.13*	-12.07*	-5.97*	-5.12*	-0.80	1
C_H	-8.41*	-11.06*	-7.20*	-5.87*	-2.35	1
C_I	-3.66	4.82	3.95	5.07*	4.66*	4
C_J	1.87	2.70	4.71*	5.10*	4.65*	2
C_K	1.54	-3.59	-5.72*	-4.24*	-5.60*	2
C_L	4.26	3.34	3.27	1.62	3.63	5
C_M	4.69	4.73	4.52*	2.06	0.98	4
C_N	3.77	2.18	-0.33	-1.12	-0.3	5

Typical plot clearance: C_F

Figure 5.73 shows the average cleared area for the plot C_F which was closest to the average cleared area for the community. This plot (182 by 1100 m) was occupied from 1964 by Oscar Ibáñez. Oscar is now 86 and has managed the plot with his spouse (now 78 years) and their family.

Figure 5.73: Plot C_F against the average cleared area for all plots in Caracas.

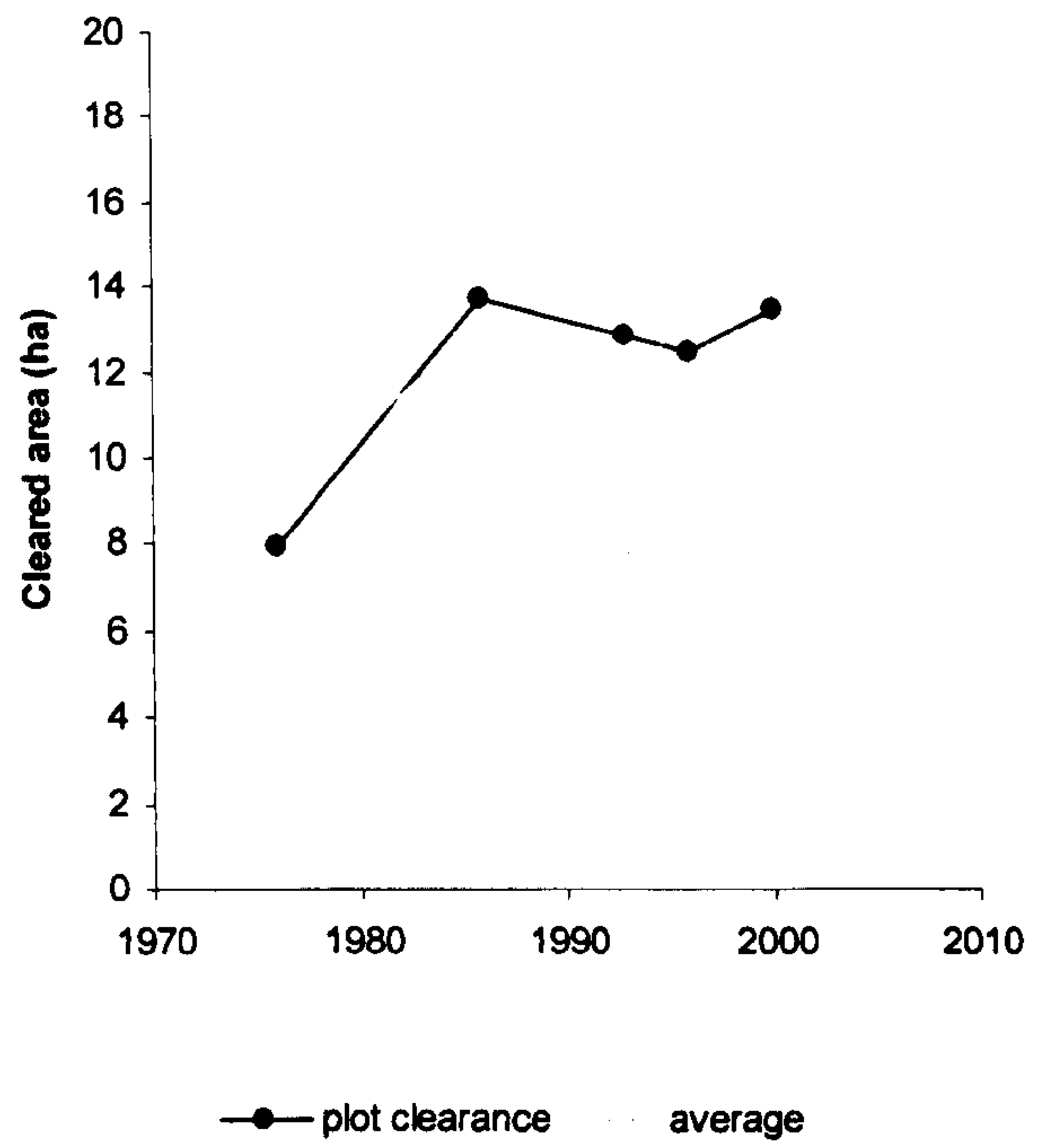


Figure 5.74 shows the access to the plot and market, the location of a small river running through the plot and the arrangement of crops as described by the farmer. Clearance progressed from the primary end of the plot throughout the sequence and in 1976 almost half the plot had been cleared (Figure 5.75). Most of the clearance occurred prior to 1986 as rice cultivation followed by the creation of pasture for cattle grazing. In 1988 one of his household members moved to another plot to support his own family and the labour force declined. In 1995 the rice crop became susceptible to disease and the farmer concentrated efforts on cattle grazing because the market prices were attractive.

Figure 5.74: Schematic diagram of the plot of Oscar Ibáñez, showing access and cultivation in 2002.

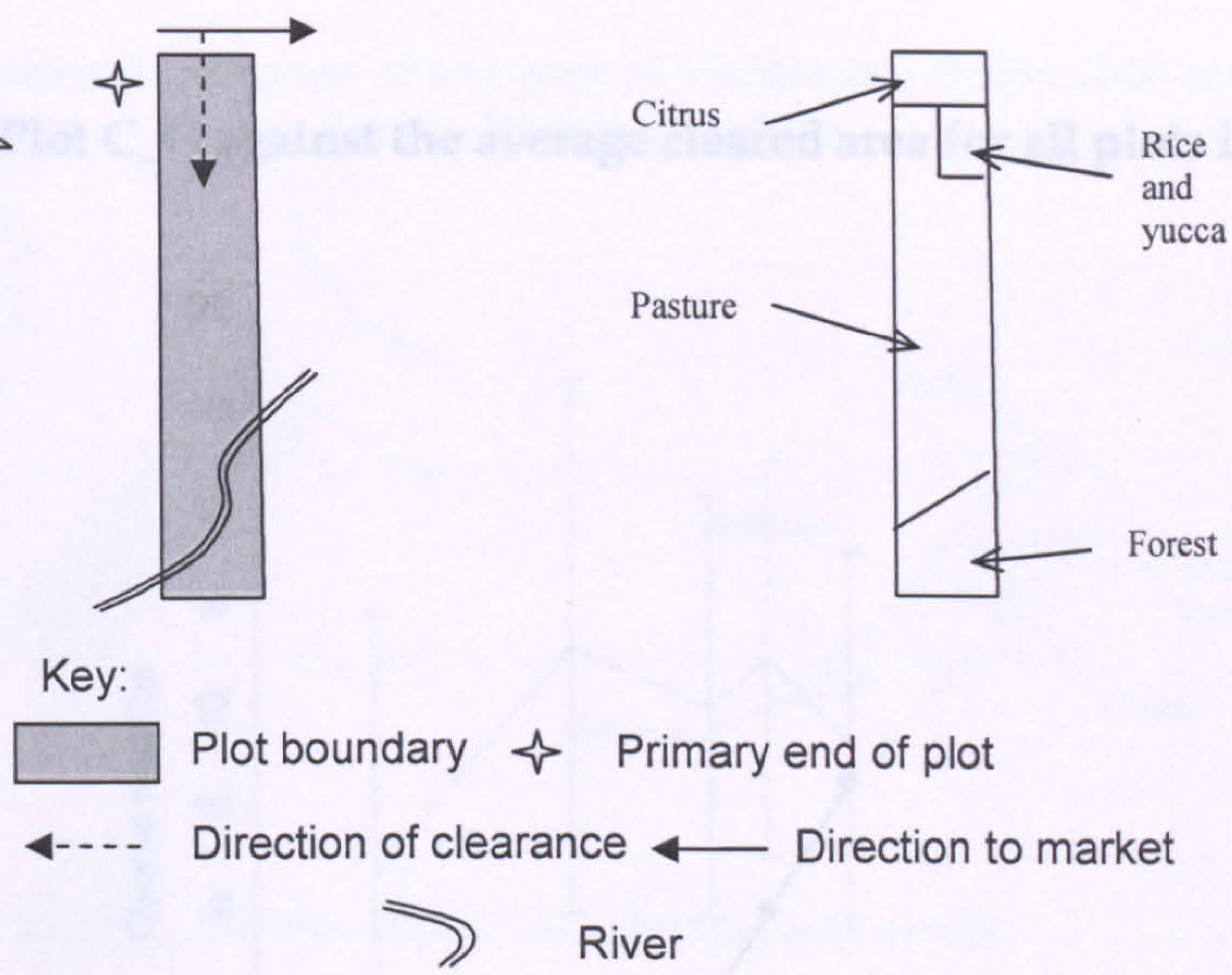
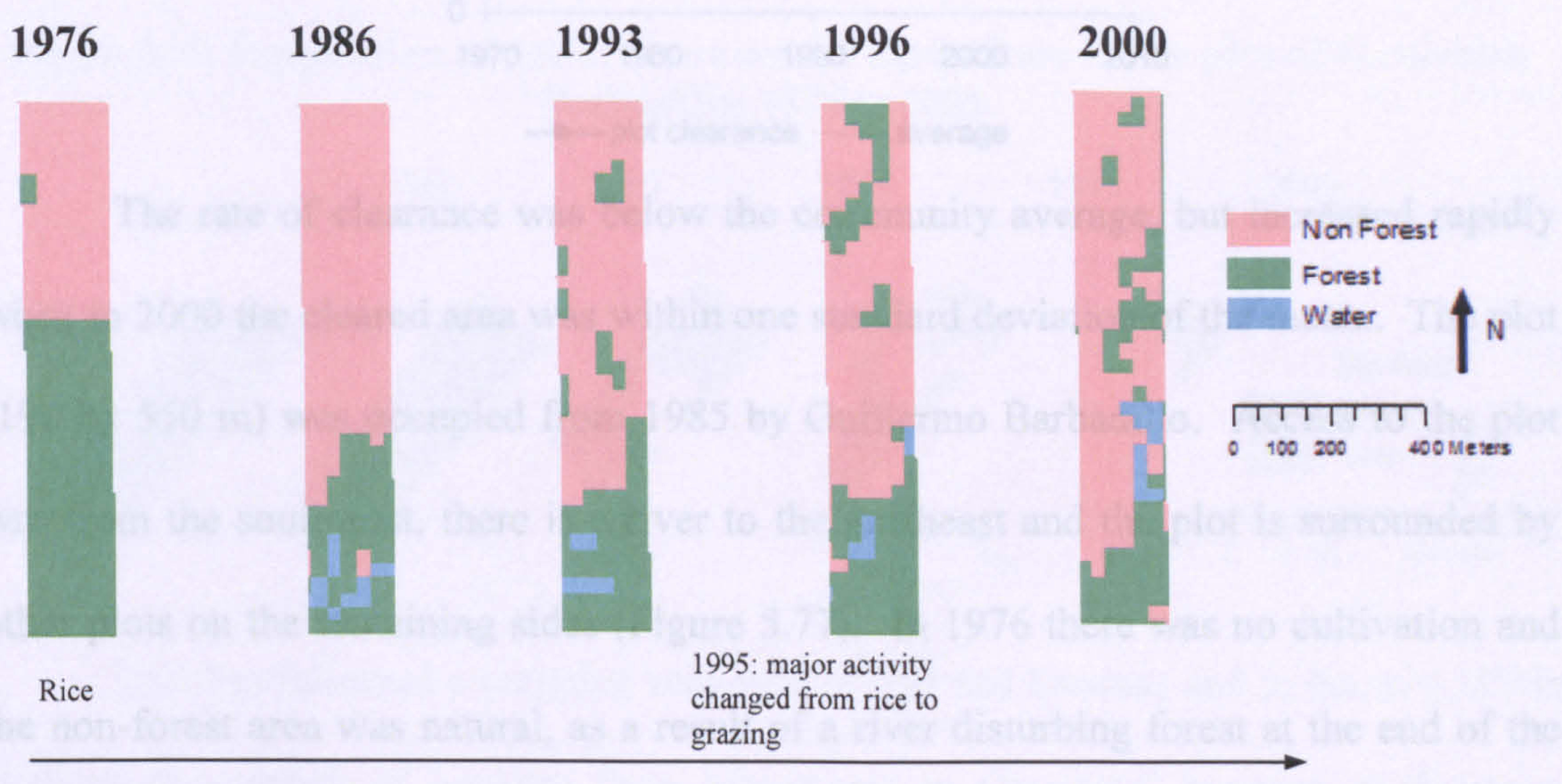


Figure 5.75: Progression of forest clearance for agriculture in the plot of Oscar Ibáñez, 1975 to 2000.

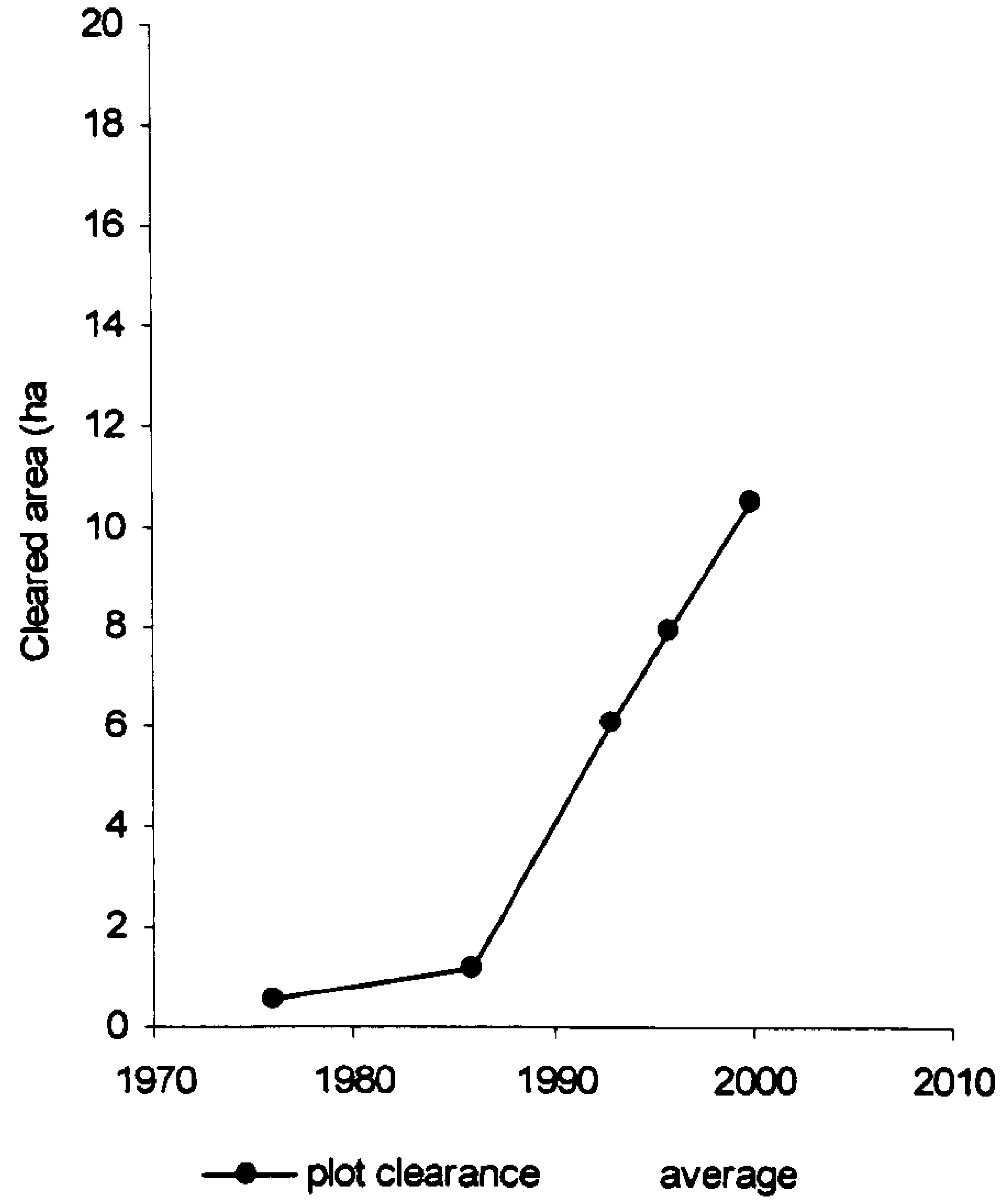


After 1986 when the farmer reached a small river, clearance did not progress much further, and patches of forest returned inside the plot. The return of forest coincides with the farmer discontinuing clearance of the plot, losing labour from the household ceasing rice cultivation. In 2002 the farmer had 25 cattle and sold to the local market milk, meat, cheese and small amounts of manioc and rice.

Aypical plot clearance: C_G

Figure 5.76 shows how plot C_G deviates from the average cleared area of the community.

Figure 5.76: Plot C_G against the average cleared area for all plots in Caracas.



The rate of clearance was below the community average, but increased rapidly when in 2000 the cleared area was within one standard deviation of the mean.. The plot (190 by 550 m) was occupied from 1985 by Guillermo Barbadillo. Access to the plot was from the southwest, there is a river to the northeast and the plot is surrounded by other plots on the remaining sides (Figure 5.77). In 1976 there was no cultivation and the non-forest area was natural, as a result of a river disturbing forest at the end of the plot before the land had been set aside for cultivation. The farmer and his spouse began clearance of this plot in 1985. Clearance began from one end with a small patch of forest clearance at the primary end of the plot in 1986. In 1993 and 1996 there was an isolated patch of non-forest in the middle of the plot (Figure 5.78). In 2000 the clearance had coalesced into one large patch and the plot was almost completely cleared.

Figure 5.77: Schematic diagram of the plot of Guillermo Barbadillo showing access and cultivation in 2002.

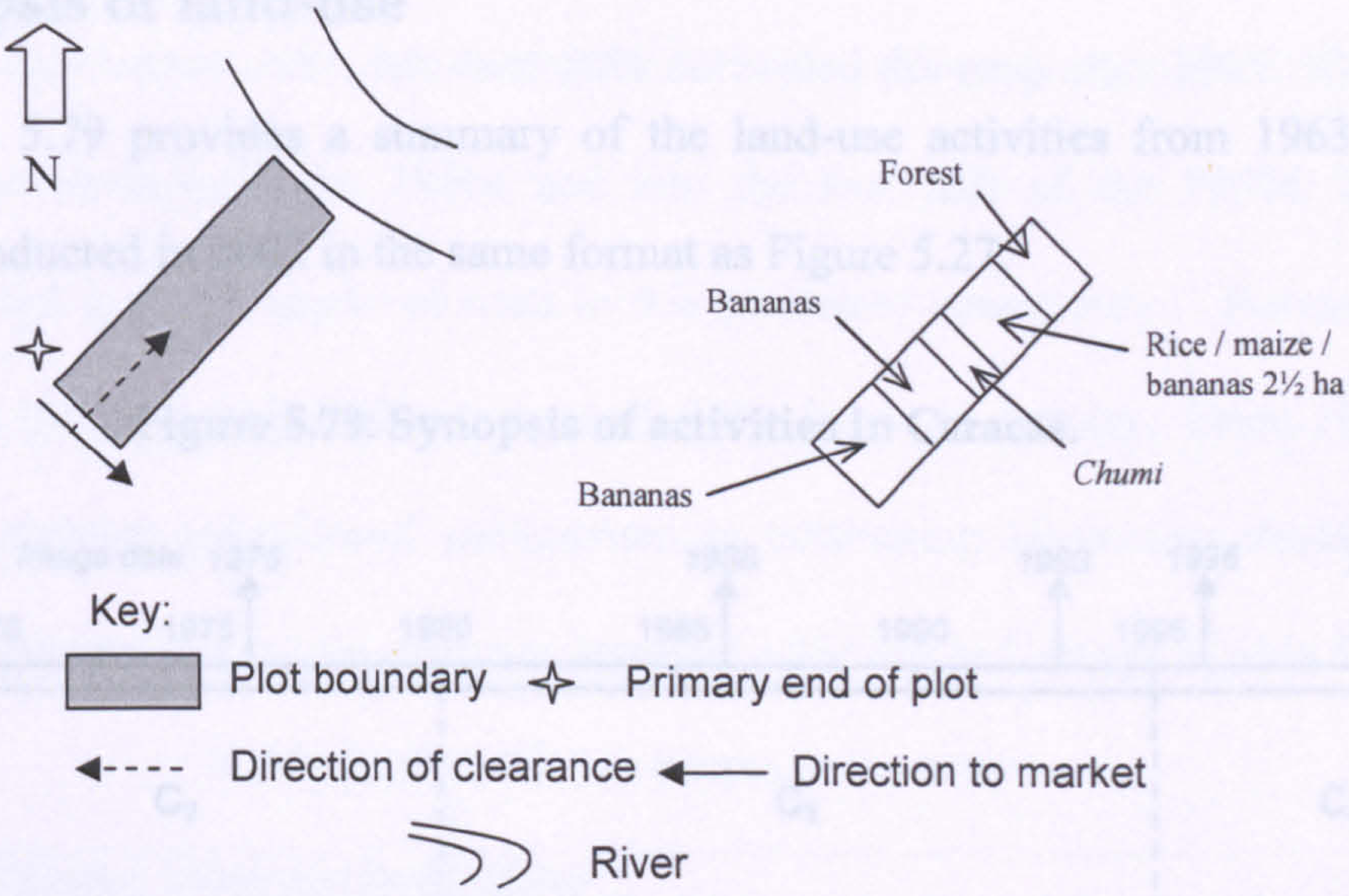
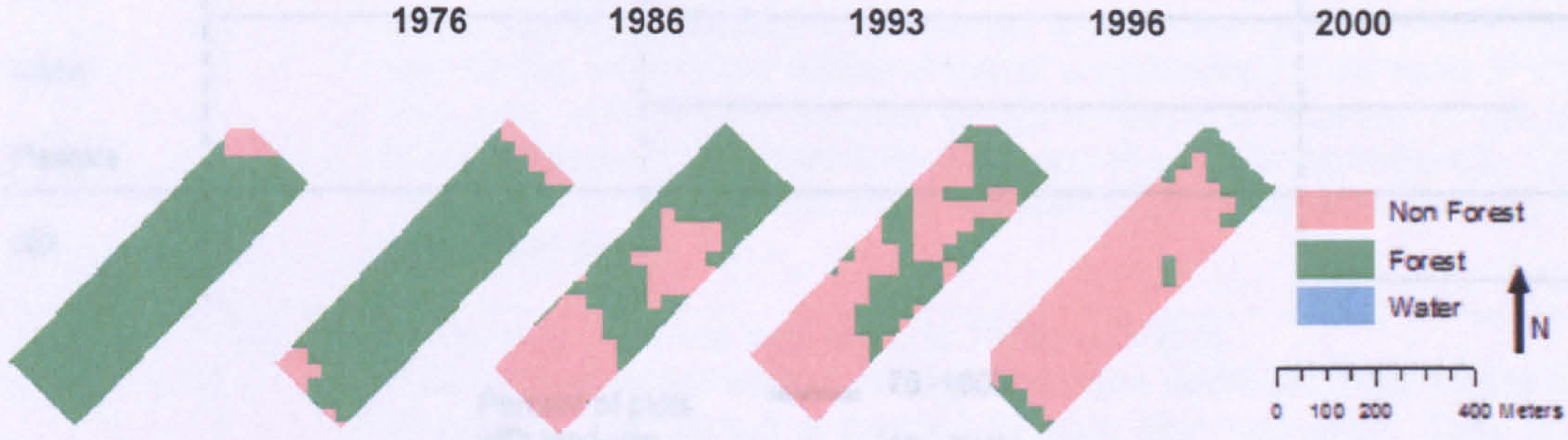


Figure 5.78: Progression of forest clearance for agriculture in the plot of Guillermo Barbadillo, 1975 to 2000.

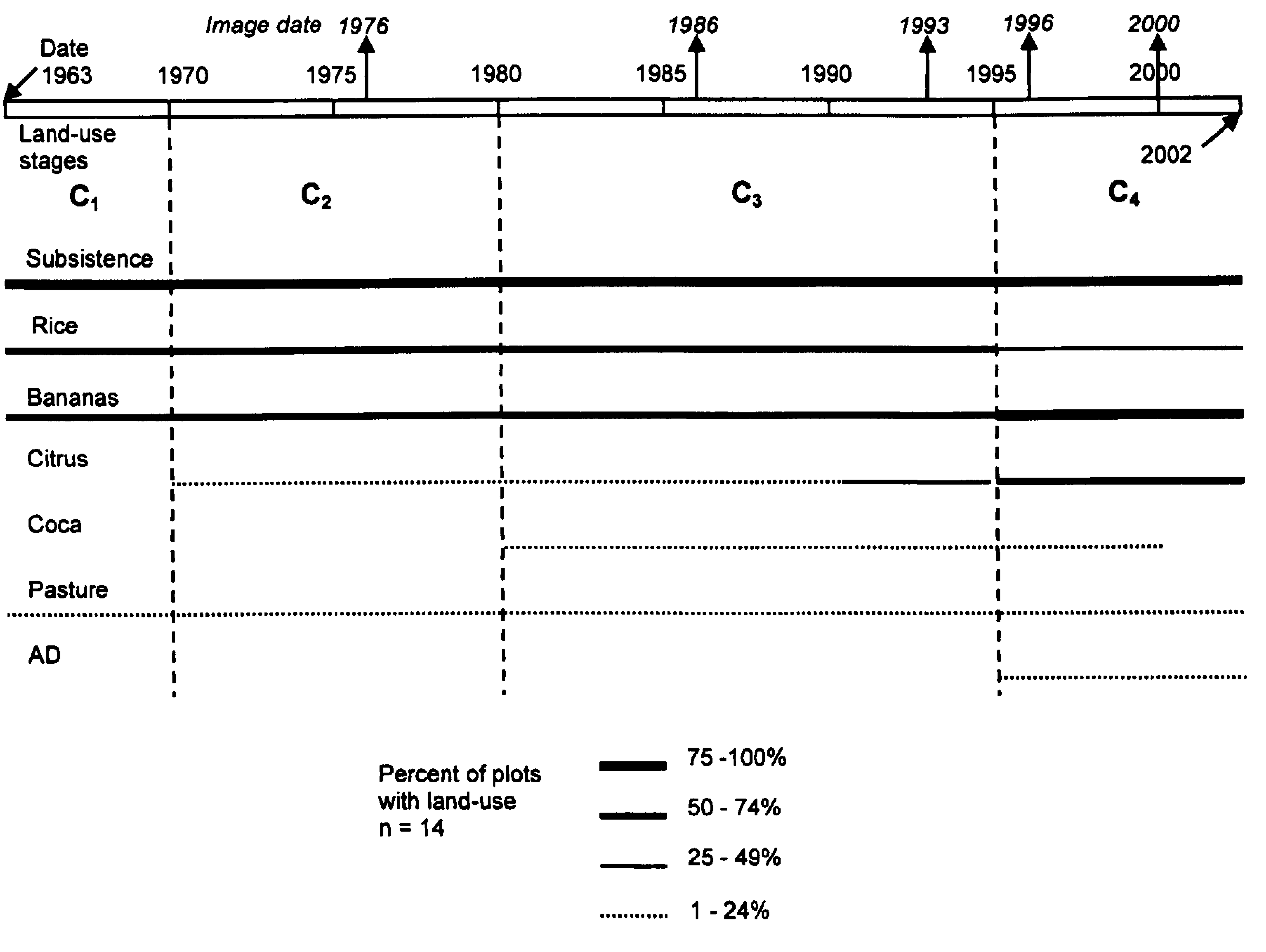


José has followed a cropping sequence of rice and bananas and in the mid 1990s changed the variety of bananas from Mogotoqui to Guayaguil because of Sigatoka Negra disease. By 2002 he had diversified his crops with the inclusion of citrus fruit and palm cultivated at the primary end of the plot for subsistence and for sale to the local market. The plot was managed with some rotation, the farmer allowed *chumi* to re-grow for up to 3 years, cut and burned the re-growth and then planted rice and bananas. The farmer, like a number of his neighbours, was a member of a banana grower association. As a member of this association he had an overhead rail to move his bananas to a nearby packing shed where bananas were sorted, boxed and packed for export.

5.4.5 Synopsis of land-use

Figure 5.79 provides a summary of the land-use activities from 1963 to the interviews conducted in 2002 in the same format as Figure 5.27.

Figure 5.79: Synopsis of activities in Caracas.



The major land-use activities in Caracas were subsistence (mainly rice, maize and manioc) cash crops cultivated were rice, banana, citrus, and some alternative development products. There was also pasture for cattle grazing. At least 75% of the farmers interviewed recalled subsistence as a major land-use activity since colonisation in 1963 and it has remained an important activity through 2002.

Rice has also been a major activity, but from 1995 less than 50% of the farmers recalled this activity. Bananas have been grown by at least 50% of the farmers throughout the time period, but more than 75% of the farmers noted bananas as an important crop after 1995. Citrus has been a relatively minor activity with less than 24% of the farmers recalling this crop before 1995, but over 50% cultivated the crop after 1995. Coca has been cultivated throughout the 1980s and into the first half of the 1990s, but few farmers admitted to the presence of coca in this particular community. Pasture is not widespread as less than 24% of farmers recalled this land-use activity. From 1995 less than 24% of farmers interviewed participated in cultivating alternative development crops. There are four key stages of major land-use activities in Caracas, (Table 5.12),

Table 5.12: Land-use stages in Caracas

Community	Stage	Land-use description
Caracas	C_1	*Subsistence, rice and bananas* (c.1963 – c.1970). In this period the major activities were the cultivation of rice and bananas accompanied by subsistence farming.
	C_2	*Rice and bananas* (c.1970 – c.1980). In this period cultivation of rice and bananas continued. A number of unsuccessful government sponsored crops were grown in this period e.g. cocoa, cotton and rubber (Henkel unpublished). This level of detail was only occasionally recalled by some farmers because of the time lapse between the fieldwork in 2002 and the period considered. Often farmers only recalled the more successful land-use activities e.g. rice and bananas.
	C_3	*Coca, rice, bananas and citrus* (c.1980 – c.1995). Rice and bananas were in reality much less dominant than Figure 5.79 suggests. This period is marked by coca leaf cultivation. Only a few respondents openly recalled growing coca on their plots (this was a particularly difficult topic to address in this community) but some individuals could recall eradication of coca in Caracas. Towards the end of the period there was an increase in the number of farmers growing citrus.
	C_4	*Bananas and citrus* (c.1995 – 2002). In this period the dominance of coca had been reduced and almost 75% of farmers recall that citrus cultivation increased as land-use. Bananas had increased in importance and over 75% of the farmers indicated this as an important land-use activity. Alternative development crops were cultivated but less than 25% of farmers indicated that they participated in this activity.

These stages have been divided up according to the major land-uses (Figure 5.79); C_1 *Subsistence, rice and bananas* (c.1963 – c.1970); C_2 *Rice and bananas* (c.1970 – c.1980); C_3 *Coca, rice, bananas and citrus* (c.1980 – c.1995); C_4 *Bananas and citrus* (c.1995 – 2002). The details of these stages have been expanded in Table 5.12. These stages do not exclude the presence of other land-use activities but serve to highlight the main land-use activities.

5.5 Summary

The main findings of this research are summarised below (their implications will be discussed in Chapters 6 and 7).

- **Forest clearance trajectories at the community level.**

Between 1983 and 2000 in Arequipa, 47% of the forest was lost; on average 9.2 ha had been cleared from each plot. The fastest rates of clearance were between 1983 and 1986 (0.93 ha yr^{-1}) and 1996 through to 2000 (0.92 ha yr^{-1}), with the slowest rates between 1986 and 1996 (0.14 ha yr^{-1}). Although most of the colonists in Bogotá arrived at the same time as in Arequipa, the timing of the clearance trajectories was dissimilar. Between 1983 and 2000, 57% of the forest was lost; on average 20.2 ha had been cleared from each plot in Bogotá. The fastest rates of clearance were between 1983 and 1986 (1.4 ha yr^{-1}), with the slowest rates between 1986 and 1996 (0.47ha yr^{-1}). The clearance trajectories in Caracas were quite different to both of the other communities. Between 1963 and 1986, 77% of the forest was lost but the rates then varied through the 1990s and by 2000, 55% of the area was under forest. In 1986, on average, 13.0 ha had been cleared from each plot but this fell to 11.4 ha by 2000. The fastest rate of clearance was from 1963 to 1986, (0.67 ha yr^{-1}) with the slowest rates between 1996 and 2000 (-0.43 ha yr^{-1}).

- **Structural metrics**

For the forest class, in Arequipa and Bogotá the number of forest patches increased from 1975 to 2000; the mean patch size decreased to values below 10 ha; the ranges in patch sizes decreased to below 100 m and the patch size variability always exceeded 294%. In Caracas the number of forest patches increased but then fell in 2000. The mean patch size decreased to below 5 ha after 1976 and the ranges in size were much lower than the other two communities; however, there was a high variability in patch sizes (~264 to 540%.) In all three communities the mean nearest neighbour statistics were similar (50-100 m) with a low range around the mean (< 75) and low variability (< 97%).

Concerning the non-forest class, in Arequipa and Bogotá the number of non-forest patches increased from 1975 to 2000; and the mean patch sizes increased but remained below 26 ha, except in Bogotá in 1976, (54 ha). The ranges in patch sizes increased to 64 m in Arequipa and 205 m in Bogotá and the patch size variability was always high, exceeding 499%. In Caracas the number of non-forest patches also increased over the period of study. The non-forest patch sizes were variable (between 17 and 36 ha) as was the range in sizes (114 to 211 m). Patch size variability was high (504 to 681%).

In all three communities the mean nearest neighbour statistics decreased slightly over the period of study (~150-70 m), but in Caracas after the decrease from 1976 to 1986 the values varied between 42 and 64 m. The range of values decreased from ~ 200 to 50 m and the variability of sizes fell below 100%, but again in Caracas the variability was inconsistent after the decrease in 1976.

- **Plot clearance typologies**

As farmers cleared their plots the typologies reflected the progression of different land-use management patterns. In Arequipa and Bogotá plots tended to be cleared from one end at first and this was shown by the high proportion of Type II clearance. But some farmers also cleared isolated patches deeper into their plots early on, and this was shown by the high proportion of Type IV plots. However, two ended clearance then became more common, shown by the increase in Type V clearance. The timing of these patterns was not synchronous between the two communities. The proportions of two ended clearance began earlier in Bogotá (1992) than in Arequipa (2000) and by 2000 the proportion of one ended clearance increased again in Bogotá but this was not the case in Arequipa. In Caracas trends in land-use patterns tended to go from one ended to two ended (between 1976 and 1996), with a high proportion of completely cleared plots (Type VI). However the number of completely cleared plots fell between 1996 and 2000, and the proportion of two ended clearance with isolated patches increased.

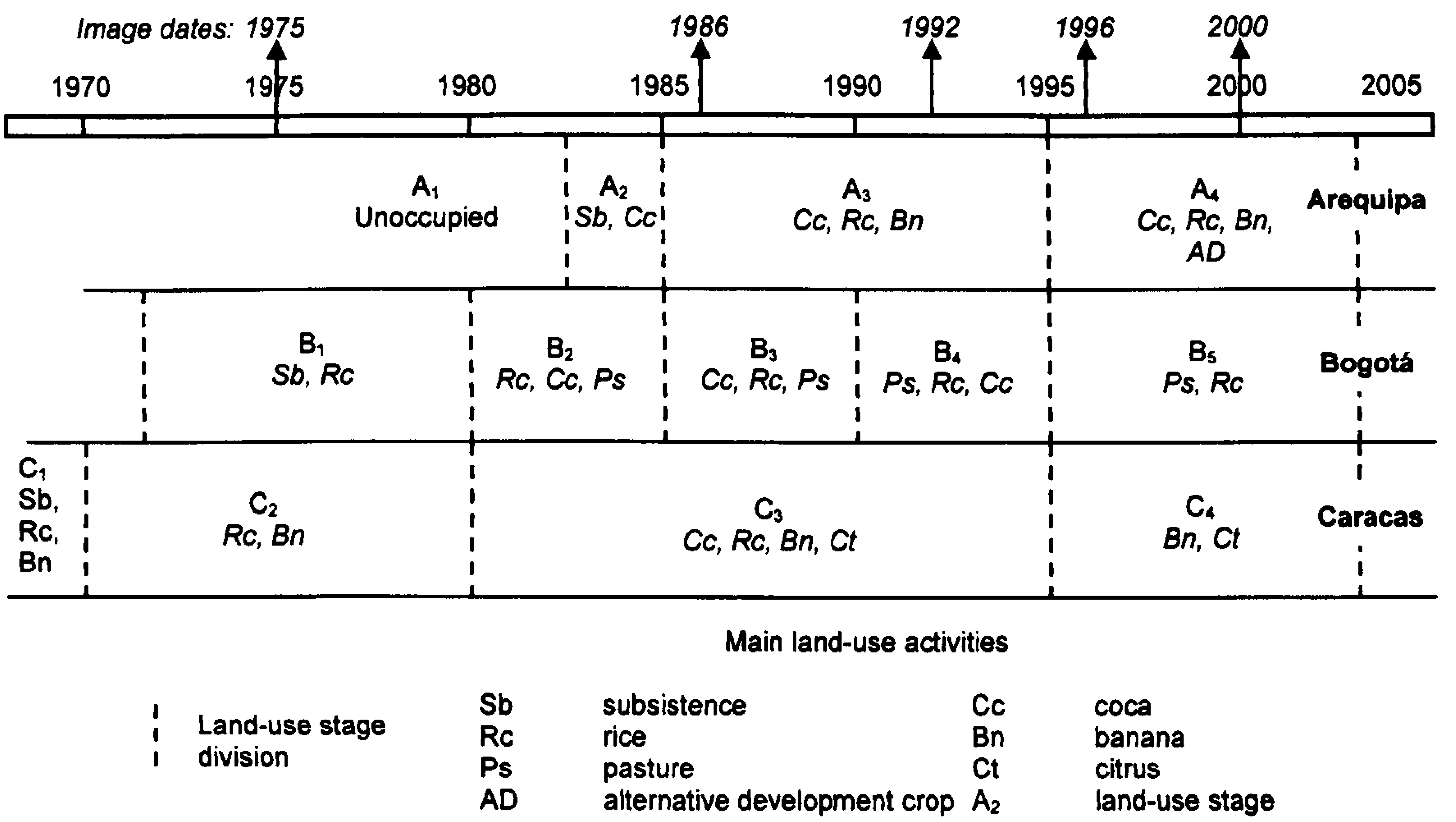
- **Land-cover change at the plot level**

The classified images, the error bars on the average cleared area and rates of clearance values illustrate that there was variability in clearance trajectories between the plots within each community. The sampled plots from the interviews showed that the land-cover variation was caused by the diversity of land management activities. In Arequipa a typical plot showed diversification from coca to other crops and led to the high average rates of clearance found in this study. The atypical plot analysed showed how a farmer had always cultivated coca and this activity resulted in lower clearance rates. In Bogotá a typical plot with average clearance rates, was found to be a result of expansion of pasture. The atypical plot studied was a more diversely cultivated plot with fruits and pasture, which led to low clearance rates. In Caracas there was less distinction between typical and atypical plots. The interview data indicated a high diversity of land-uses for both plots. However the atypical plot that was studied was more recently settled and found to be related to the rapid expansion of a single activity, in this case banana cultivation.

- **Synopses**

The sampled plots showed the diversity of land-use management both between and within individual plots. However, a retrospective analysis of the community as a whole (using the interview data) enabled the identification of periods when certain land-use activities had become dominant or were favoured over other activities in each community. In general the major activities were different between the communities but at certain times there is some correspondence in activities (Figure 5.80), this is discussed further in Section 6.5.

Figure 5.80: Synopsis of the land-use activities for the three communities



The causes in the trends of rates, fragmentation statistics, typologies and land-use between the three communities will be related to the economic and policy drivers in both the temporal and spatial context of land-cover change (this forms the basis for the discussion in Chapter 6 and Chapter 7).

Chapter 6

Explaining land-use and land-cover change (LULCC) over time

Chapter 6

Explaining land-use and land-cover change (LULCC)

6.1 Introduction

This chapter explains the main drivers of deforestation in Chapare and the changes in these drivers over time. The drivers are then used to explain the causes of LULCC in the three communities since the farmers settled in Chapare. The drivers can also be used to explain the spatial patterns of deforestation and this will be the subject of Chapter 7.

The first two sections consider the variations in the economic and policy drivers acting on the area during the period of the imagery. Much of the detail for the economic and policy drivers has been recovered from secondary data sources and they have also helped validate information gathered in the field. Next the information from the RRA and documentary evidence used to make the individual synopses of land-use for the three communities (Figure 5.27, 5.53, 5.79) are compared. The main land-use trends for the three communities are explained by the temporal variations in economic and political drivers of LULCC in the communities. The progression of deforestation is then tested against an existing model of deforestation developed in Brazil, the 'colonist footprint' model of Brondizio *et al.* (2002). Finally the drivers are then ordered at different scales to provide a conceptual framework for LULCC in the Chapare region, which is considered more appropriate for the area than the BioAndes model (Figure 1.1).

6.2 Economic drivers

6.2.1 Supply to local, national and international markets

The markets for agricultural outputs from Chapare have a range of scales, and this section will describe the different scales and market networks. Produce may be sold to the customer as fresh produce or preserved following some form of industrial process (e.g. juicing factories). Value is added as the product moves along the supply chain. The local markets (e.g. Chimoré, Ivirgasama, and Siniahota) are accessible to all farmers in the area, but accessing the national and international markets is more difficult without getting produce to the regional markets (Cochabamba and Santa Cruz). The difficulties arise because:

- goods are perishable and must reach the market quickly;
- goods are bulky and cannot easily be transported by farmers;
- the distances to Cochabamba and Santa Cruz are in excess of 100 km and most farmers do not own their own vehicles; and
- the small number of industrial processing plants that do exist in the study area do not have a high enough production capacity to satisfy demand on an international scale (Castañeda, 2002).

Consequently farmers have had to rely on transport contracted by networks of wholesalers but more recently farmers have formed and joined grower associations to transport and sell produce to the markets. These networks are described for the most common products which are various fruits, meat and milk, and also for the illicit coca leaf economy which is a characteristic of the area.

Fruit Crops

Discussions with farmers indicated that there are several ways that fruit is brought to market, and this information was verified by and used to elaborate flow diagrams of agricultural networks for Chapare (CEDES, 2002). Figure 6.1 shows four of the major pathways:

(i) farmers were observed transporting their own produce on foot, in sacks, over short distances to a local retailer in the nearest town;

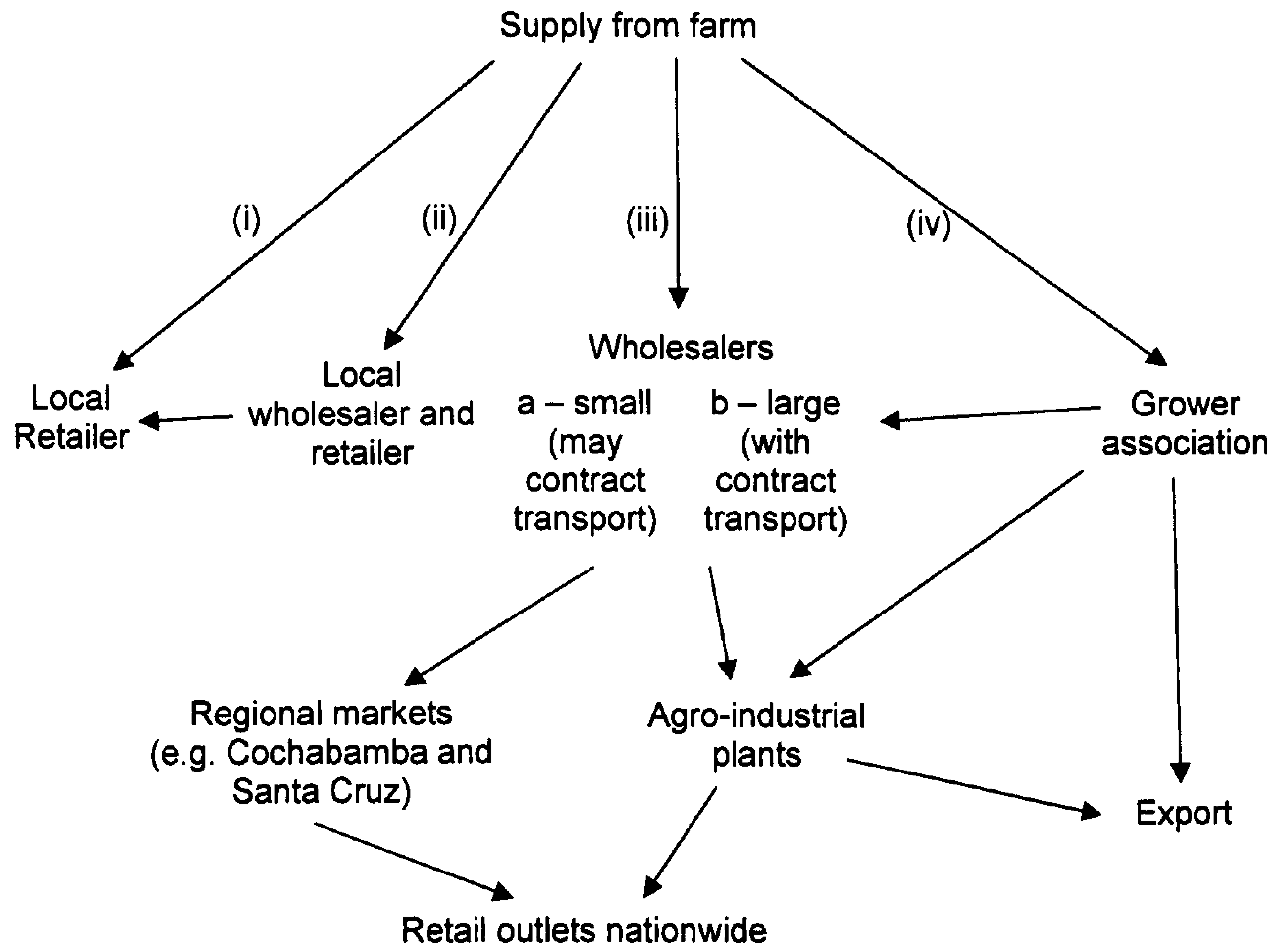
(ii) a middleman may purchase the goods directly from the farmer and then sell on to a local retailer or wholesaler;

(iii) produce may be sold directly to a wholesaler who either deals with small quantities of goods (*rescatista*) (Figure 6.1 pathway (iii) a) or large quantities of goods (*majorista*) (Figure 6.1 pathway (iii) b). In both these cases hauliers (*transportistas)* contracted by the wholesalers drive a truck along the access roads of the communities and pick up produce at the ends of the plots. The hauliers then transport goods to the markets such as those in Cochabamba and Santa Cruz;

(iv) produce is sold through a growers association. In this case produce is selected, cleaned and packed on site and loaded on to trucks. One example I came across was the growers association ASPROBAN in Caracas. This group are affiliated to UNABANA the export agency who supply the resources to prepare the bananas and refrigerated trucks to transport bananas to Argentina.

After the farmers have sold the goods there may be trade in produce between the small wholesalers (*rescatistas*) and large wholesalers (*majoristas*) (CEDES, 2002). In addition produce of inferior quality may be sold to either type of wholesaler by the grower's associations. For example the members of ASPROBAN explained how they rejected the undersized bananas that do not meet export requirements and put them in crates that would be transported to juicing factories in Cochabamba. The wholesalers, mainly the *majorista*s, contract the hauliers who distribute the produce to agro-industries and retailers in the national markets (CEDES, 2002).

Figure 6.1: The supply network for fruit crops produced in Chapare (modified from CEDES 2002).

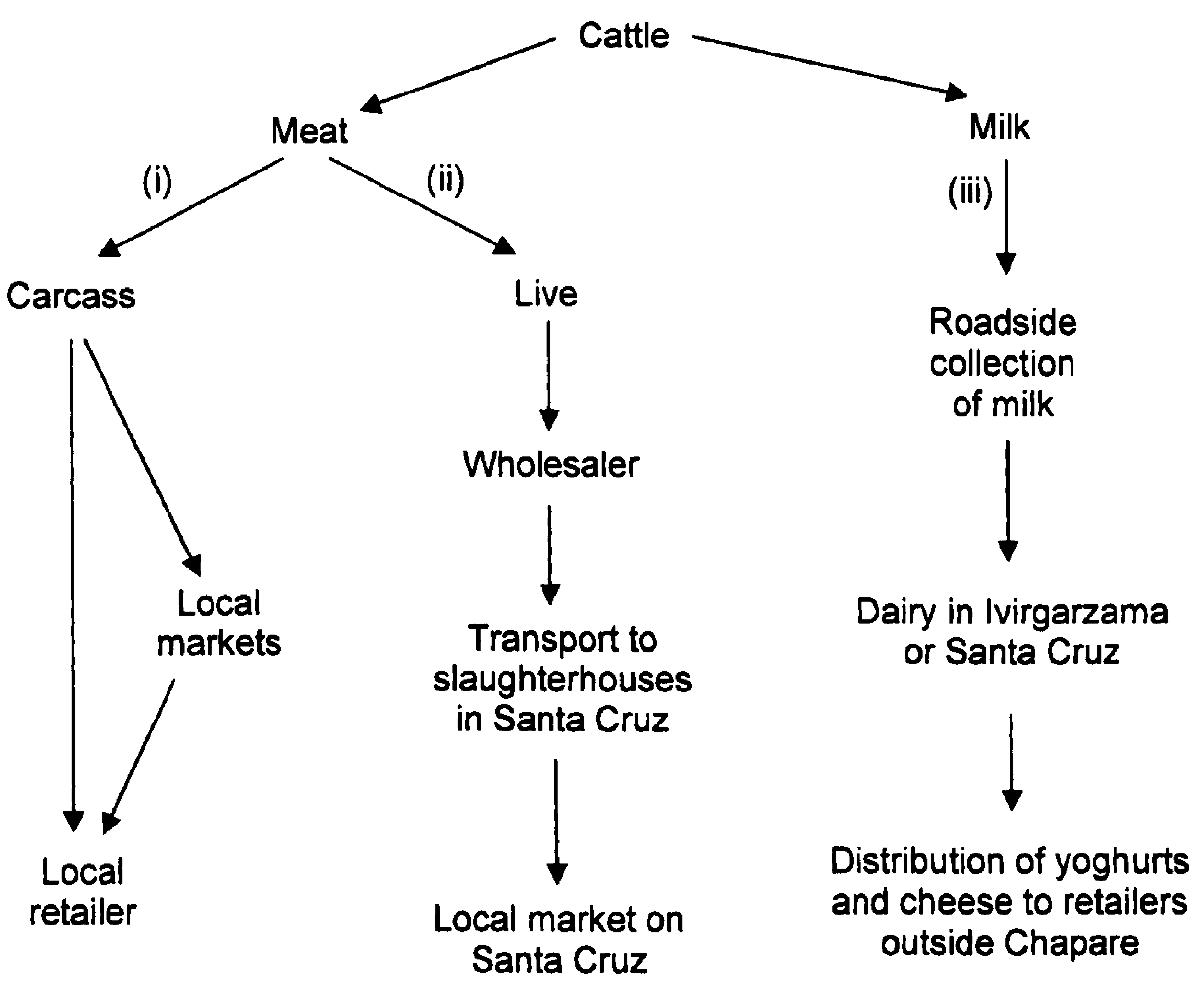


Farmers explained that unless they were a member of a grower's association it was difficult to sell direct to the market without using the wholesalers because of the costs of getting produce to the regional markets. A common complaint of the farmers was that the supply chain has developed in favour of the wholesalers who have an upper hand in the price negotiations because they are in control of the supply of produce to the regional markets such as Cochabamba and Santa Cruz. However there are other factors that determine wholesale prices and this is related to the product variety, quality, size, origin (i.e. which agricultural zone of Chapare), demand for the product and the time of year. This information had been documented at the coca check points since 2000 by CONCADE/DAI, (Lourdes O'Campo, USAID, personal communication, 2003). The supply structure has virtually been dominated by the wholesalers, but since the 1990s alternative development projects have attempted to broaden market opportunities with the creation of export markets which support grower associations. Examples of fruits which are cultivated in growers associations are bananas and pineapple, and their export potentials are discussed in Section 6.2.2.

Cattle rearing: Meat and milk supply

Cattle rearing in Chapare provides both meat and milk. The pathways of the markets are shown in Figure 6.2.

Figure 6.2: The supply of milk and meat to the markets.



Farmers in the communities I studied sold meat either as whole carcasses or as live cattle. The carcasses (Figure 6.2 pathway (i)), come from cattle slaughtered on the farm and are normally transported on the roof of a taxi to the local market. The meat is bought by weight and contributes to the local demand for meat, and is usually sold by butchers in the local towns. The sale of live cattle, (Figure 6.2 pathway (ii)) is to wholesalers who negotiate prices for cattle with community members in one of the local town (e.g. Ivirgarsama) centres. Interviews with farmers showed that prices normally depend on the breed of cattle (Table 3.1). The day after a deal has been concluded a haulier drives into each community and collects the live cattle from the farms. Some of the cattle are sold locally, but bulk sales go to slaughterhouses, which are mainly in Santa Cruz, of the three slaughterhouses I contacted in Cochabamba none received meat directly from Chapare. Along pathway (iii) farmers use their cattle to produce milk (Figure 6.2). Farmers leave urns or plastic containers of milk by the roadside which are then picked up and taken to dairies in nearby Ivirgazama or Santa Cruz. The milk is then processed and some is made into yoghurt and cheese for distribution to retailers in Cochabamba and Santa Cruz. As with fruit, farmers rely on these networks because they cannot meet the transport costs to move cattle and milk individually. In the 1990s cattle rearing was encouraged through alternative development programs supported by the United Nations and a Swedish NGO. The dairy in Iviragzama in the eastern part of the study area was built through one of these programs.

Coca leaf supply

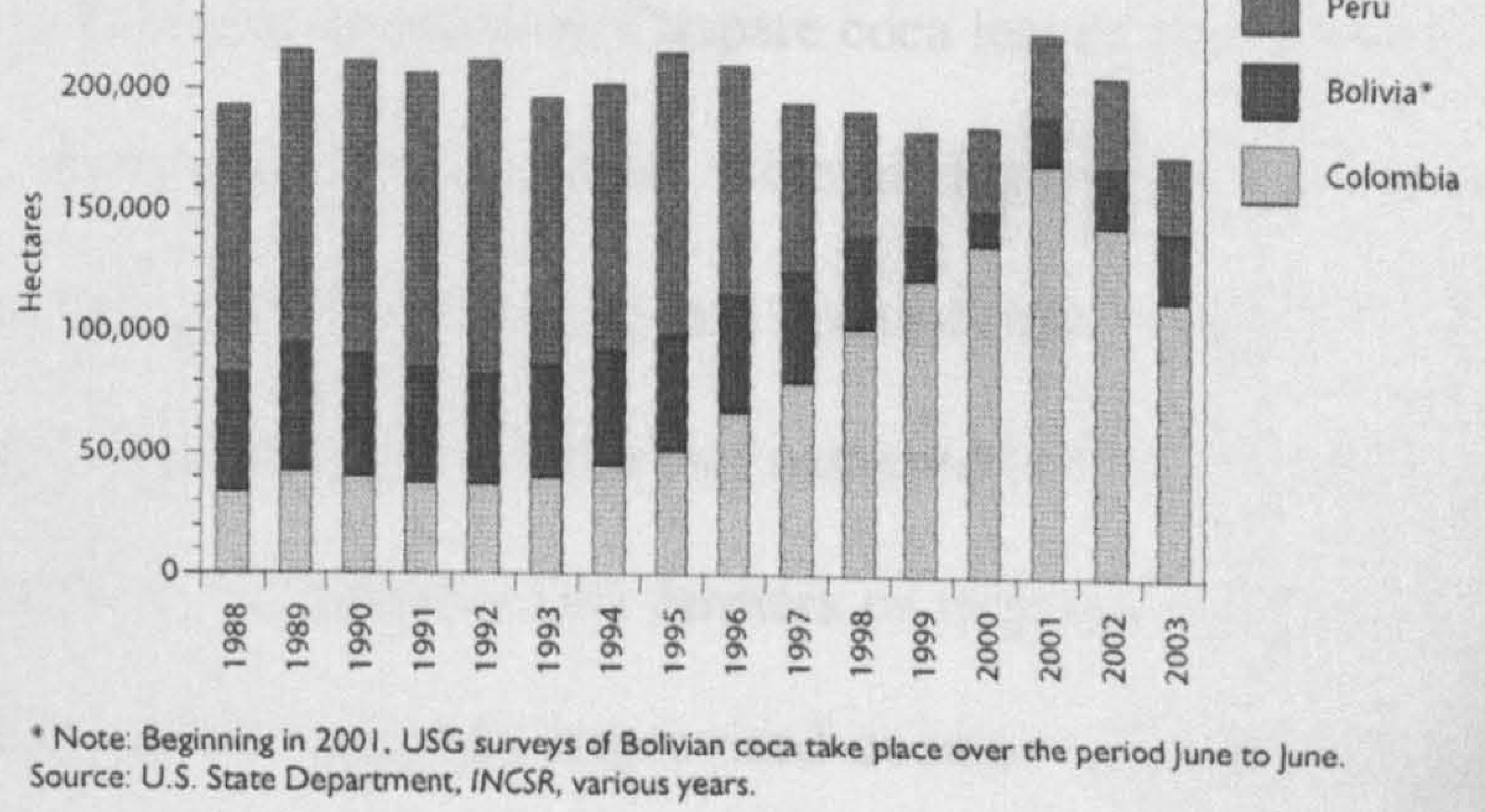
The traditional use of coca stretches back to the rule of the Incas when coca was used in ceremonies and chewed by the Inca rulers and the elite (Meruvia, 2000). After the Spanish conquest and during colonial times, coca leaves were used as tribute from Indians in the yungas of La Paz and Cochabamba. Most of the coca leaf was originally cultivated in the yungas of La Paz and to a lesser degree in the Yungas of Cochabamba (Mervia, 2000). In Cochabamba Department coca was supplied from the Yungas around Vandiola, Arepucho and Chuquioma and passed as tribute to the encomiendas and, later haciendas, in the Cochabamba highlands to the major markets such as Cochabamba, Punata and Colomi. The coca leaves were then used to pay the miners on the Altiplano. The miners would chew the coca to stave off hunger during long working hours and to overcome fear in the mines. The market for coca leaves was related to the strength of the mining industry and if there was a collapse in the mining industry the coca market would also suffer (MacGregor, 1993). This history of coca use has fortified a culturally driven demand for coca leaves and formed a licit trade network across Bolivia.

In the early stages of colonisation in Chapare it was discovered that the climatic conditions on the lowland plains suited the cultivation of coca bushes (Rodríguez, 1997). As colonisation developed in Chapare, coca from the area is likely to have filtered into the market network via the transport connections to the highland towns on the road to Cochabamba. However, in the 1960s and 1970s the coca leaf was increasingly being purchased for processing into cocaine paste to supply world demand for cocaine, and because of the social problems created by cocaine international attention centred on the supply countries. In 1981 the Government of Bolivia attempted to control the market by insisting all coca leaf was sold to collection points of the Anti-Drug Traffic Council, but these centres became corrupt and the leaves were traded back onto the black market (*balsa negra*) (MacGragor, 1993). As a result the market of coca leaf was becoming increasingly more clandestine. Because Chapare was a frontier zone it was difficult to govern, and the illicit market for coca expanded. Moreover, the variety of coca that flourished in the lowlands (*Erythroxylum coca* variety *ipandu*) was better for processing into cocaine paste than the variety grown in the Yungas (*Erythroxylum coca* variety *coca*) (Negrete, 1992) and farmers noted that *ipandu* was not considered a good variety for chewing. Networks of coca leaf trading, processing and trafficking of cocaine paste developed.

Since the 1980s, international efforts to reduce the illicit supply and movement of coca leaf in Chapare (Section 6.3) have reduced the strength of the illicit market. For example, in 1988, 12,000 ha of coca were designated for legal coca leaf farming in traditional cultivation locations in the yungas of La Paz, enabling the destruction of coca crops in Chapare. Coca control checkpoints have been positioned on the roads from Chapare to Cochabamba, Santa Cruz and the road to Todos Santos near Villa Tunari to stop the transport of coca leaf to the regional markets, for example Colomi. Bolivia now supplies a much smaller proportion of coca leaf to the international cocaine market as a result of the policies against coca leaf cultivation (Walsh, 2004) (Figure 6.3). Coca leaf cultivation for chewing and production of coca tea is currently limited to legal areas in the yungas of La Paz and a recent addition included the area of Vandiola in the yungas of Cochabamba inside Parque Nacional Carrasco (Figure 1.3) because of the historical origins of production of coca leaf in this area.

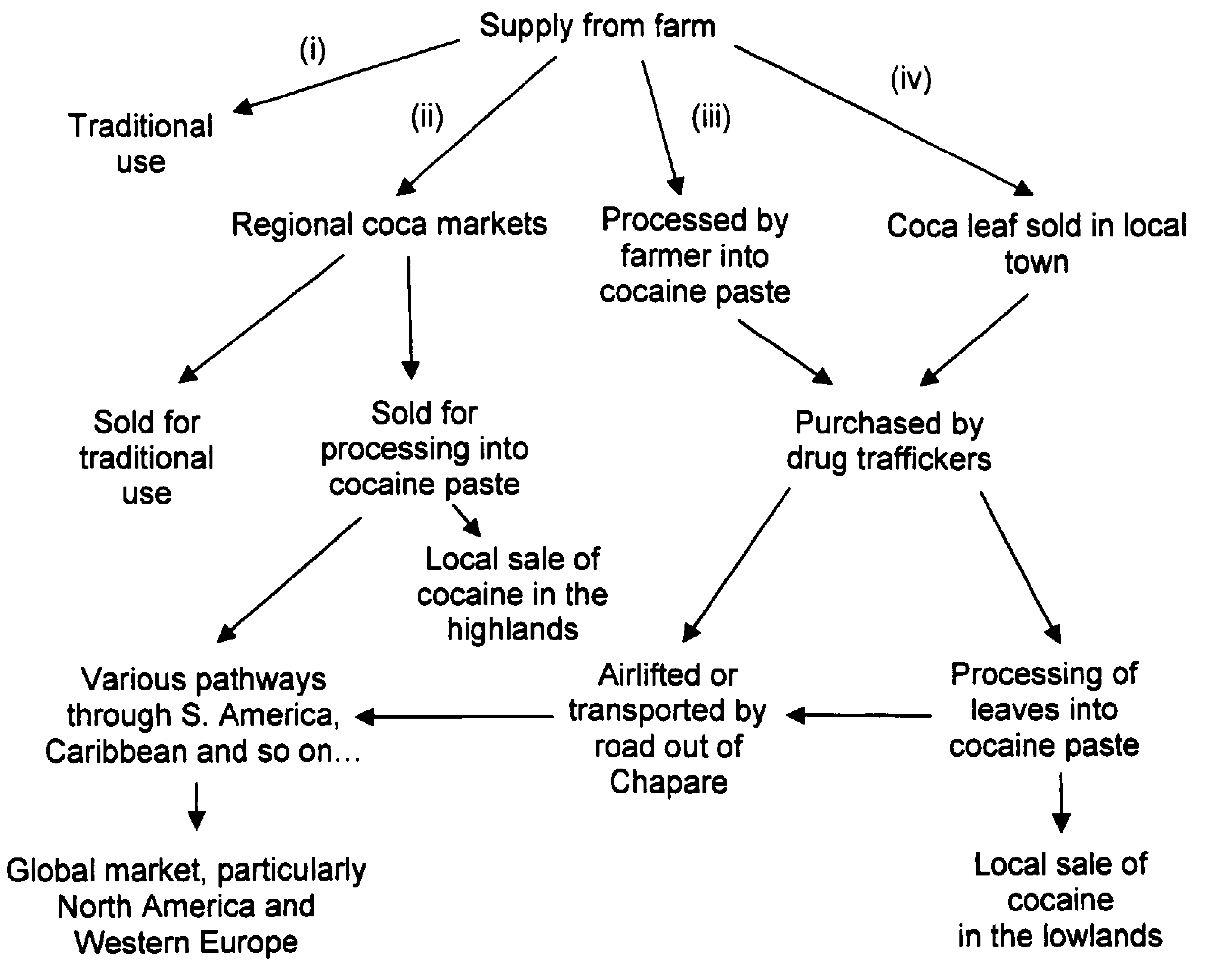
The supply pathways of coca leaf from Chapare into the cocaine market are outlined in Figure 6.4. This is a snapshot in time because the cultivation of coca leaf is

Figure 6.3: Coca cultivation in the Andes. Source: Walsh (2004).



* Note: Beginning in 2001, USG surveys of Bolivian coca take place over the period June to June.
Source: U.S. State Department, *INCSR*, various years.

Figure 6.4: The supply of coca leaf into the national and global cocaine trade.



illegal and, as described above, there have been a number of policies employed to stop the movement of leaves out of the region. Coca leaf can be cultivated and consumed directly by the farmer to satisfy the cultural needs of a household, (Figure 6.4 pathway (i)). Before restrictions were imposed on Chapare coca leaves were transported to legal markets in the Cochabamba department i.e. Colomi, Figure 6.4 pathway (ii). There most of the leaves were sold for processing into cocaine rather than for chewing. In the 1980s and 1990s much of the trade in coca leaf occurred in Chapare and took pathways similar to (iii) and (iv). In pathway (iii) farmers or migrants (searching for cocaine-related employment) would establish improvised cocaine producing laboratories and process coca leaf into cocaine paste, which was easier to transport and fetched a higher price than coca leaves, and was supplied to the drug traffickers (Negrete, 1992). In pathway (iv) which was probably the commonest in the 1980s and 1990s large 100lb sacks (*cargas*) of coca leaves were sold directly from the farm to storehouses in local towns such as Vueltadero, Shinahota, Ivirgazama and Eterzama. The buyers would assess the quality of the *cargas* of coca leaves to determine the price. Once purchased the good and bad leaves were blended together, processed locally into cocaine paste, and then dispatched to the drug-traffickers to be airlifted or transported by road from Chapare (Rivera, 1990) then on into the international drug trafficking networks who supply the North American and Western European markets. The interviews indicated that coca was still grown in Chapare as some farmers clearly relied on an income from a coca crop (small quantities were also illegally cultivated for household consumption). Because of the sensitive nature of the subject I did not inquire about the current trade network for illicit coca as I would have wished and no opportunities arose for me to do so.

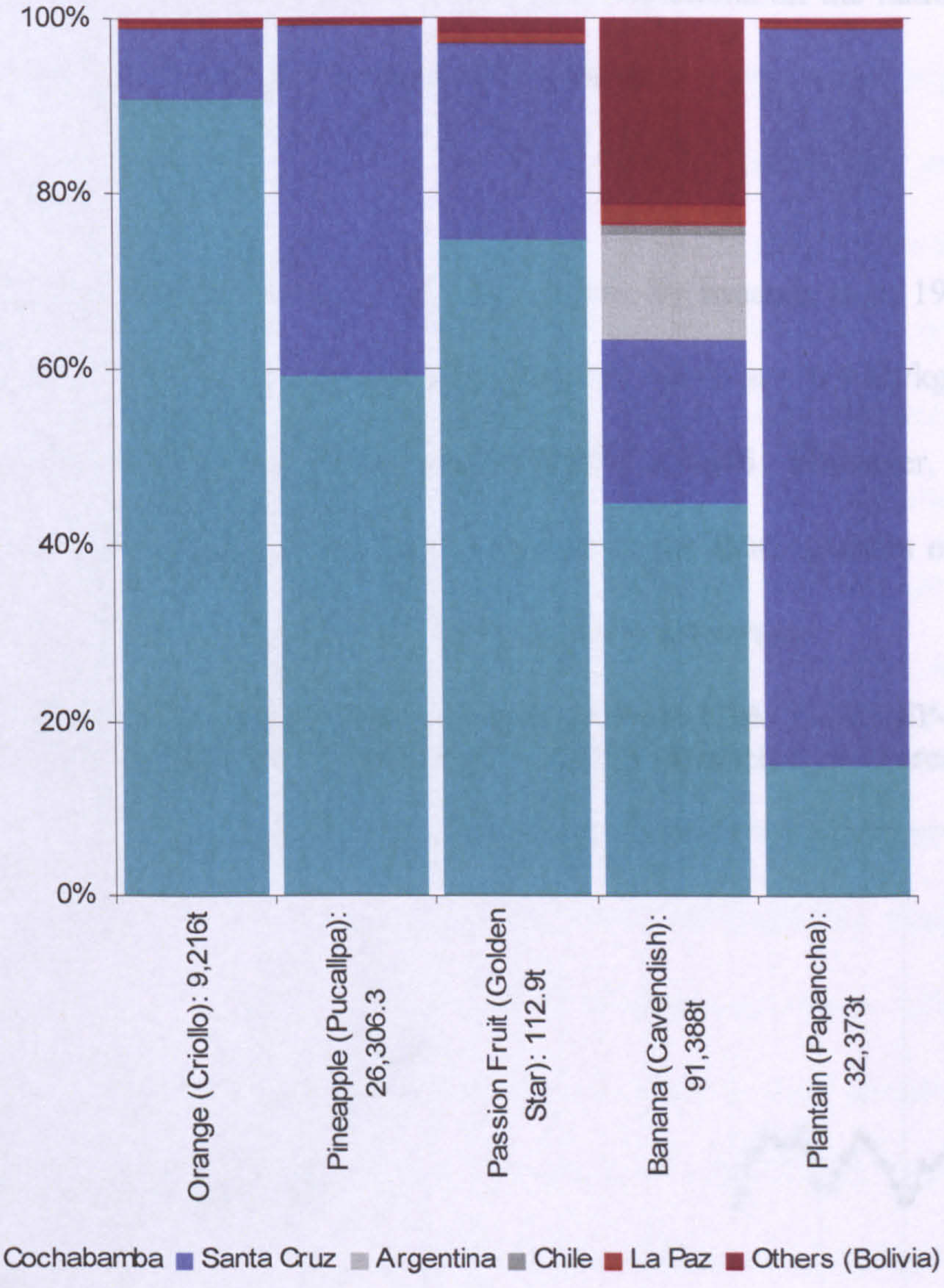
6.2.2 Variation in national and international markets

I obtained details on prices and markets for products in Chapare from the main offices of USAID in Cochabamba. During project CONCADE, USAID began to archive these data from 2000 in their marketing office, logging the weights, origins and destinations of the crops. A sample of these data has been used to show the market destinations and distribution routes to these markets reached for selected Chapare fruit crops (Figures 6.5). USAID staff compiled these data from hauliers as they left Chapare and passed through the coca check points (Figure 1.3) the data refers to the destinations and volumes of produce transported out of Chapare. These figures represent data for 2001 (though it is 2002 for plantains), but data available from 2000 and 2002 show similar patterns. Continuous monitoring of data on fruit and cattle prices in Chapare had rarely been done before 2000 which means documented data of continuous time series are rare. This is not helped by the repatriation of USAID data to the US at the end of different alternative development programmes which has made this kind of documentation scarce in Bolivia.

The major national markets for oranges, pineapples, passion fruit, bananas and plantain were dominated by the departments of Cochabamba and Santa Cruz (Figure 6.5). Within Cochabamba Department most of the produce is sold in the city of Cochabamba though there are secondary markets in Colomi, Punata, Quillacollo, Sacaba and Tarata. In Santa Cruz Department, the major market is in the city of Santa Cruz, but some produce is sold 'en route' from Chapare to Santa Cruz at Yapacaní, Montero and Warnes. Other departments 'import' small amounts of produce from Chapare these are: Oruro, La Paz, Potosí and Chiquisaca (Figure 1.2).

Figure 6.5 indicates that the sale of legal produce from Chapare is heavily dependent on the regional markets in Cochabamba Department. This was integral to the the colonisation policies and plans for Chapare. Eastern Chapare has always had a strong market focus on Cochabamba city, but the regional market for this part of Chapare has broadened to include Santa Cruz since the completion of the Cochabamba to Santa Cruz highway in the late 1980s. Additionally the colonisation zone to the east of Chapare in Santa Cruz now has better access to Cochabamba city, the northern and western parts of Bolivia. Distribution of produce to the other main centres of population in other departments of and to Bolivia's main urban centre of La Paz – El Alto – is proportionally much lower mainly because the poor state of the transport network in Bolivia means it is difficult to distribute perishable produce. Furthermore, La Paz – El Alto – is supplied by another, closer tropical colonisation zone known as Alto Beni. For the main varieties of oranges (*criollo*), pineapple (*pucallpa*), passion fruit (*Golden Star*), bananas (*Cavendish*) and plantains (*Papancha*) there is a strong national

Figure 6.5: National and international destinations of major fruit crops grown in Chapare in 2001, the data for plantain is from 2002. For each crop the variety which was most widely grown is shown and total amounts for all crops produced are provided on the x- axis. Source: 2000-2002 Projecto CONCADE, Oficina de Informacíon de Mercados.

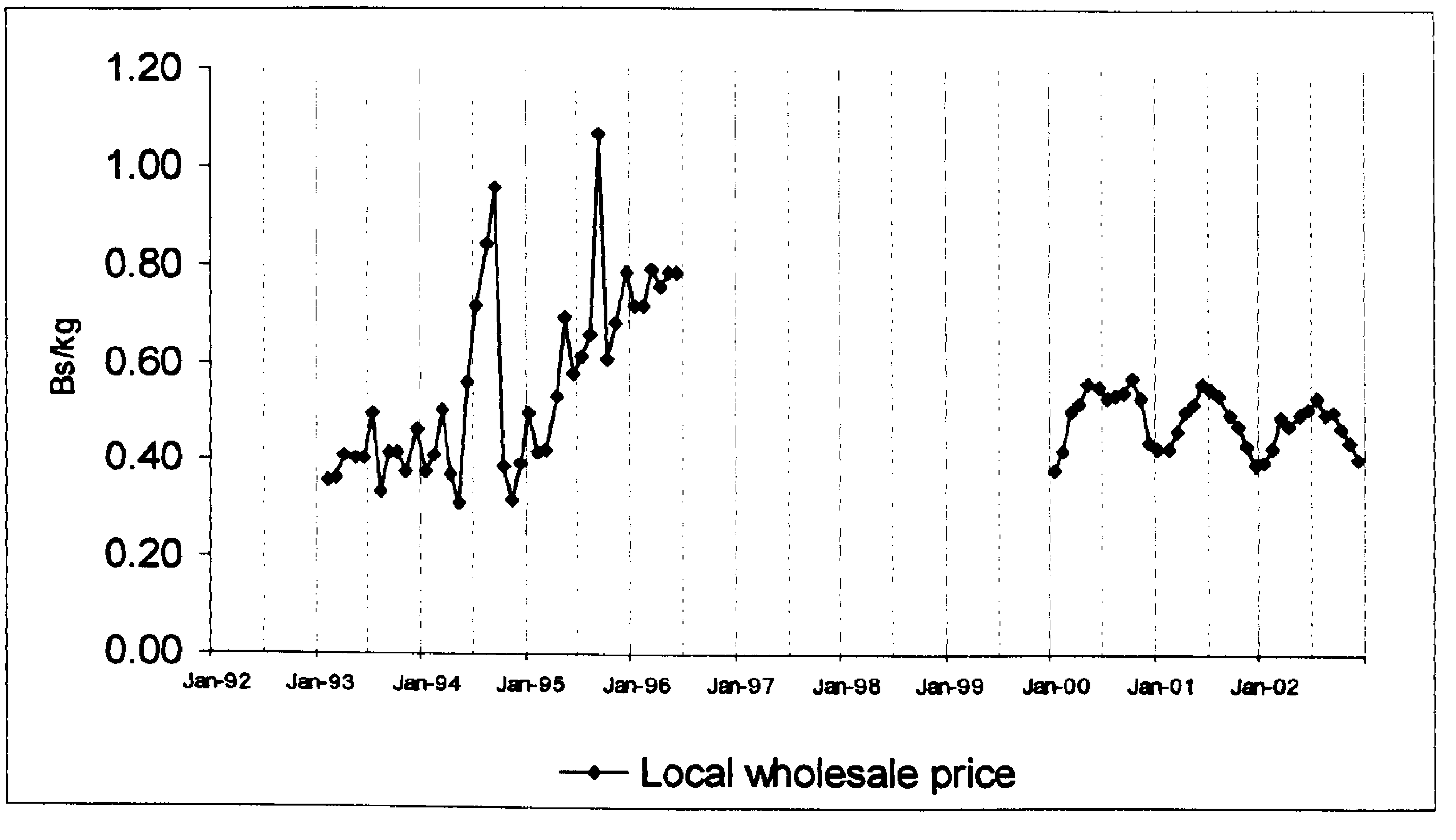


market for Chapare produce because the majority of produce goes to the regional markets of Cochabamba and Santa Cruz. This did and still does cause difficulties for farmers because they need to sell their produce to the regional markets but to do so they must use the wholesale network described in Figure 6.1. However, alternative development programmes in the 1990s provided another option to this wholesale network. Provided farmers joined a growers association they could export fruits (e.g. bananas and pineapple) directly from their farms to neighbouring countries (e.g. Argentina). The following sections illustrate typical products which are grown in Chapare. The section considers the wholesale price variations on the national market and the state of their potential export market if one exists.

6.2.2.1 Bananas

An incomplete set of monthly wholesale prices for bananas from 1993 to 2000 are shown in Figure 6.6. Banana prices were relatively stable at ~ 0.4 Bs/kg until early 1995 and then increased to ~ 0.8Bs/kg by the middle of 1996. However, this rise in prices was interrupted by two sharp peaks in prices in the third quarters of 1994 and September 1995. The exact cause for these price rises is not certain.

Figure 6.6: Wholesale prices of bananas. Sources: 1993 to 1996 - CORDEP-DAI 1996; 2000 to 2002 - Projecto CONCADE, Oficina de Informacíon de Mercados.



Farmers recalled the spread of *Sigatoka Negra* through Chapare from 1995/6 and several of the farmers I interviewed suggested their crops had been affected by the disease and they experienced a decline in yields, furthermore since this outbreak is recorded to have occurred in 1997 the farmers have had to invest into anti-fungicides to treat the crops (Hellin, 2001). It is therefore likely that the outbreak of the fungus affected the supply and prices of bananas from 1995 (if the farmer recall is accurate) and may have contributed to the general rise in banana prices up to 1997. The 1993 to 1996 price data and the 2000 to 2003 data show a strong seasonal pattern in prices. The highest prices have generally been in the second and third quarters; they are lower by about 1 Bs/kg in the first and fourth quarters. Apart from the peak prices in 1994 and 1995 it appears that the market has been quite stable and the farmer has a better chance to predict the price. Unlike many other crops, the distribution data for bananas (Figure 6.5) shows that this fruit was not as reliant on the markets in Cochabamba and Santa Cruz Departments, as there is a significant country-wide distribution and also exports to Argentina and Chile. Approximately 12% of the crop was exported to Argentina in 2001.

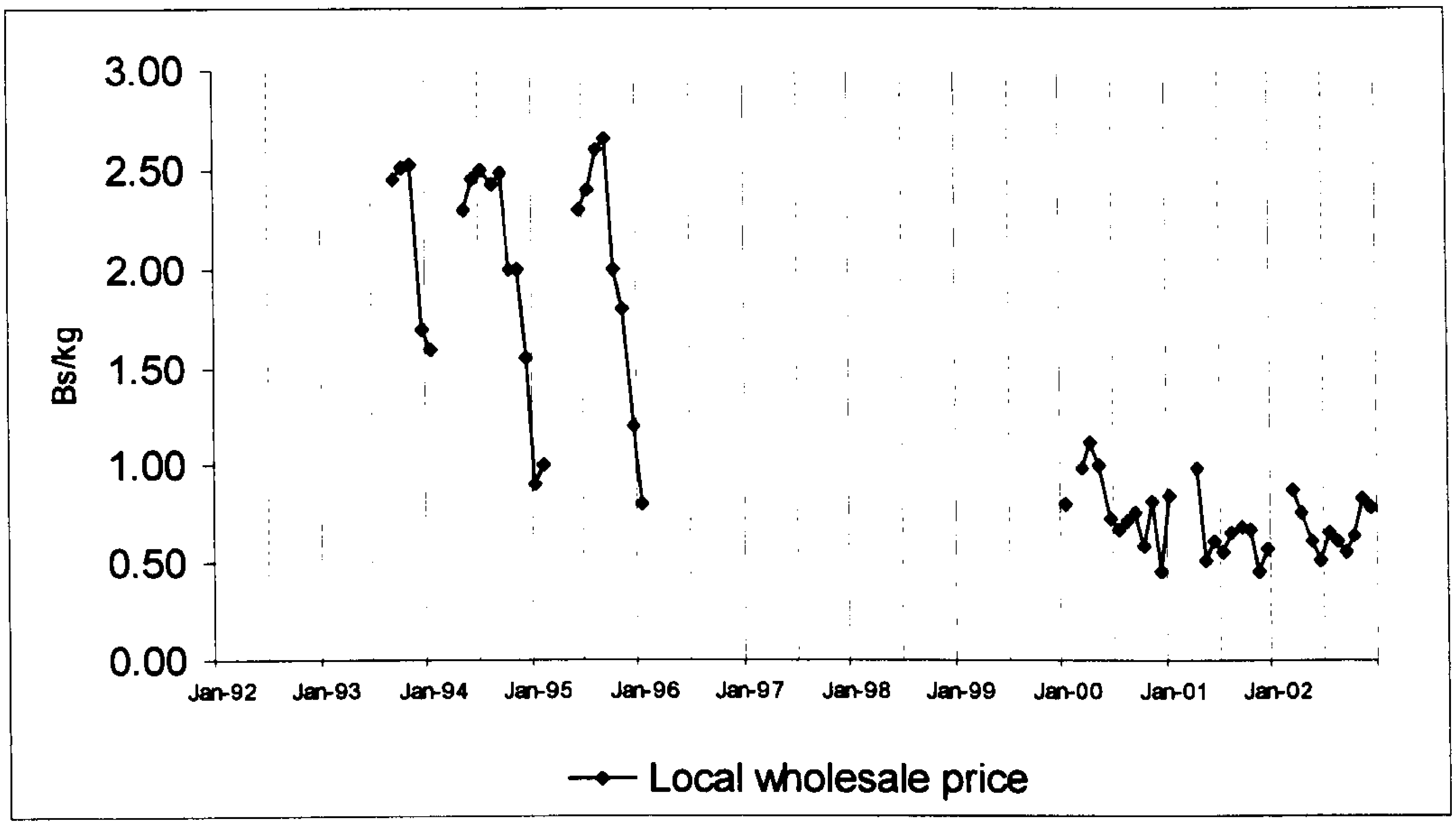
From 1991 varieties that were suitable for the export market were introduced (Hellin, 2001). Some varieties of bananas are now cultivated by banana grower associations who are affiliated to a national union of banana growers – UNABANA – who export the bananas directly from Chapare. There are also three private companies who have been involved in the export of bananas – BANECO, WINNEX and CORFRUT (CORDEP/DAI, 1996), USAID offered subsidies of USD 0.25 per box of bananas to the private companies (who had their own plantations) if they bought and exported bananas from the growers associations (Hellin, 2001). USAID documents provide details on the progress of the fruit exports and show that exports of bananas from Chapare increased from 57,942 tonnes in 1993 to 157,900 tonnes in 1997 (CORDEP/DAI, 1999), but this is still a small proportion of the total exports from Bolivia. Between 1993 and 1996 total Bolivian banana exports increased from 303.592 tonnes to 2,837.918 tonnes (CORDEP/DAI, 1996). The export markets were Argentina, Brazil, Chile and Paraguay, although the latter two markets had diminished by 1996 as there was strong competition in these countries from Ecuador. The exports to Argentina only form 1% of the Argentine market and when the currency devaluation occurred in Ecuador Argentina increased imports of cheap Ecuadorian bananas (Hellin, 2001). Paradoxically, Bolivia does not satisfy its domestic demand internally and, banana imports to Bolivia increased from 110,000 tonnes in 1984 to 465,000 tonnes in 1994. Even more paradoxically imported bananas came mainly from the adjacent countries that were export destinations – Chile and Argentina, with small quantities from Paraguay and Uruguay. At present poor transport links from Chapare (in the centre of the country) to other regions in Bolivia (that were well connected to neighbouring countries) means that imports are cheaper and it is difficult to get large volumes of exports out the country (Hellin, 2001).

6.2.2.3 Pineapple

Figure 6.7 shows the prices for the variety *Pucallpa*. From 1993 to 1996 prices were, at times, five times higher than those between 2000 and 2002. In both time periods strong seasonal signals in the wholesale prices are evident. In the period from 1993 to 1996, high prices ~2.5Bs/kg were mainly restricted to the second and third quarters (June to September), and decreased to ~1Bs/kg at the end of the season in January / February. From 2000 to 2002 the highest prices were in the first and second quarters but the range of the wholesale prices – 0.5-1.0 Bs/kg – were much lower than for the 1993 to 1996 prices. 2001 data from CONCADE indicates that the seasonal price signal is determined by the availability of pineapple. In the early part of the year –

January to April – the total supply of pineapples is as low as a 100 tonnes pineapples fetch the best prices around 1 Bs/kg in these months.

Figure 6.7: Wholesale prices of pineapples. Source: 1993 to 1996 - CORDEP-DAI 1996; 2000 to 2002 - Projecto CONCADE, Oficina de Informacíon de Mercados.

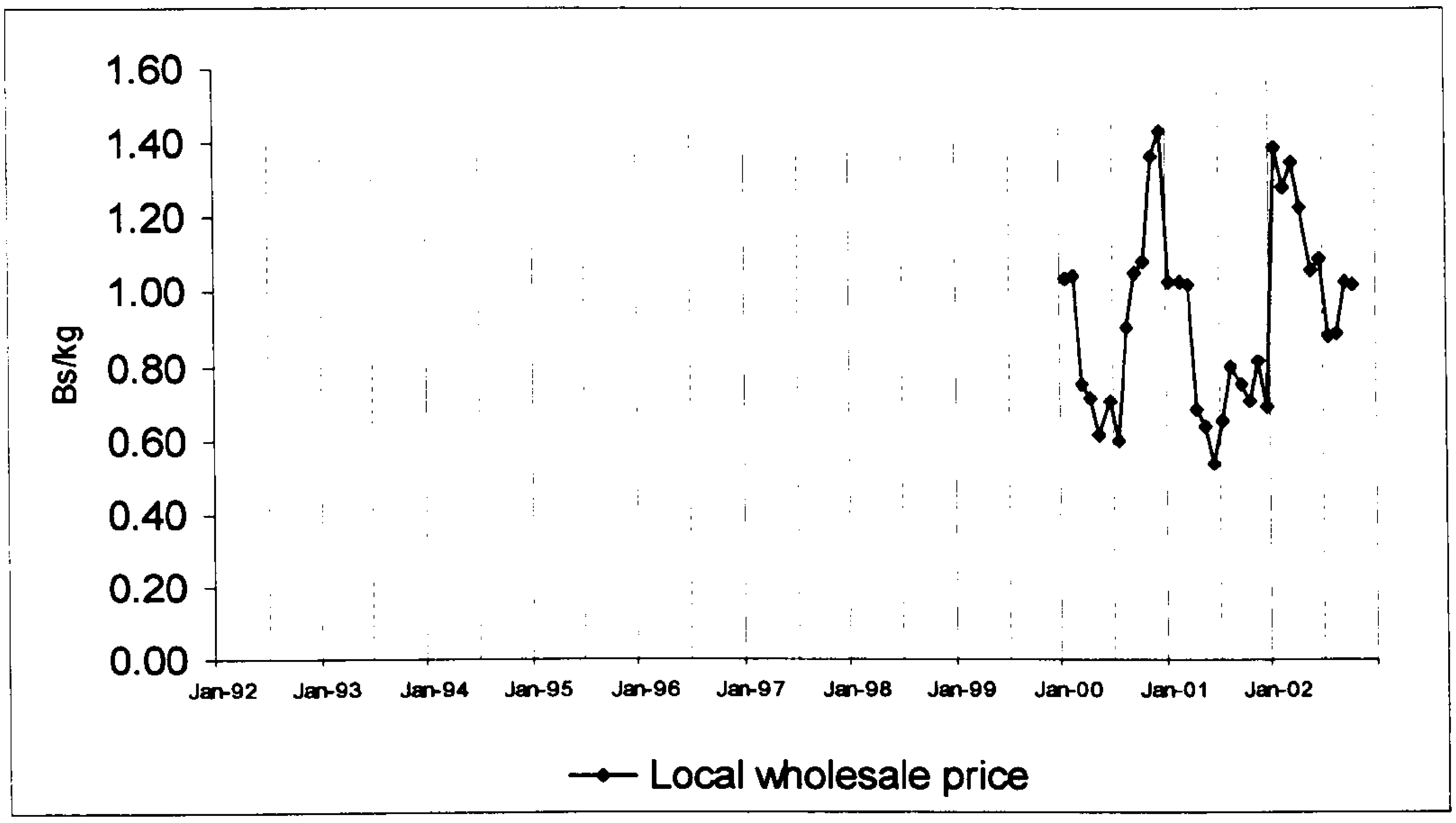


As the supply increases to a maximum of around 4,500 tonnes and in October, prices fall to between 0.75 and 0.5 Bs/kg. Supply data was not available for the first time period (1993 to 1996) so the reasons for this seasonal variation remain at this time uncertain. Figure 6.7 demonstrates that prices of pineapple have fallen overall since the 1990s and the seasonal variations in prices are now less extreme. The data presented in 6.7 is for the variety *Pucallpa* which has a national market. The variation in prices through the decade are because in the early 1990s there was a stable market for pineapple, however promotion through the alternative development program increased the number of hectares of pineapple from 338 ha in 1987 to 3,804 hectares in 1997. This resulted in an over supply of pineapple to the national market and the price crashed (Hellin, 2001). However there is another variety called *Cayena Lisa* that is preferred on the export market. Documentation from USAID shows that in the early 1990s Bolivia exported pineapples to Chile and Argentina. Exports to Chile decreased from 489,932 tonnes in 1990 to 92,000 tonnes in 1993 (CORDEP/DAI, 1996) and after this, in 1994, the main export market switched to Argentina mainly because Chile imposed phytosanitary requirements on the Bolivian exports (Hellin, 2001). The quantities exported between 1994 and 1995 fell from 1,352.310 to 673.490 tonnes. By 1999 the export markets had diversified to include Uruguay and Paraguay (CORDEP/DAI, 1999). The export markets for *Cayena Lisa* are not stable despite the fact that there were three grower's associations – ASPROCUT, ASPROPI and APAMI – exporting pineapples (CORDEP/DAI, 1996, 1999). Although the prices for *Cayena Lisa* are better than *Pucallpa* (in 2002 a 1.5kg pineapple of each variety will fetch ~ 2.11 and ~ 0.77Bs respectively), the majority of growers cultivated *Pucallpa*. As is the case with bananas, Bolivia also imports pineapples. From 1991 to 1994 Argentina was the principal source of pineapple imports and were maintained at over 10,000 tonnes/yr. This amount began to decrease after 1994 due to the economic crises in Argentina. Because of the boom bust scenario and the strict controls on the exports to Chile the area of cultivation fell to 1,660 ha in 1999 (Hellin, 2001).

6.2.2.4 Oranges

Wholesale prices of *Criollo* oranges were found at the marketing office of USAID, but were only available for 2000 to 2002. The prices vary seasonally (Figure 6.8) with the lowest prices being experienced during the harvest season (~0.6 to 0.8Bs/kg, May to August). In these months about 7,000 to 10,000 tonnes of *criollo* oranges were harvested in Chapare. The highest prices, up to 1.4Bs kg, occurred when the crop was out of season and, again, a comparison with the supply indicates that a little over 500 tonnes and produced in these months. Citrus fruits are not exported in any significant amounts.

Figure 6.8: Wholesale prices of oranges (*Criollo*) in Cochabamba. Source: Projecto CONCADE, Oficina de Informacíon de Mercados.



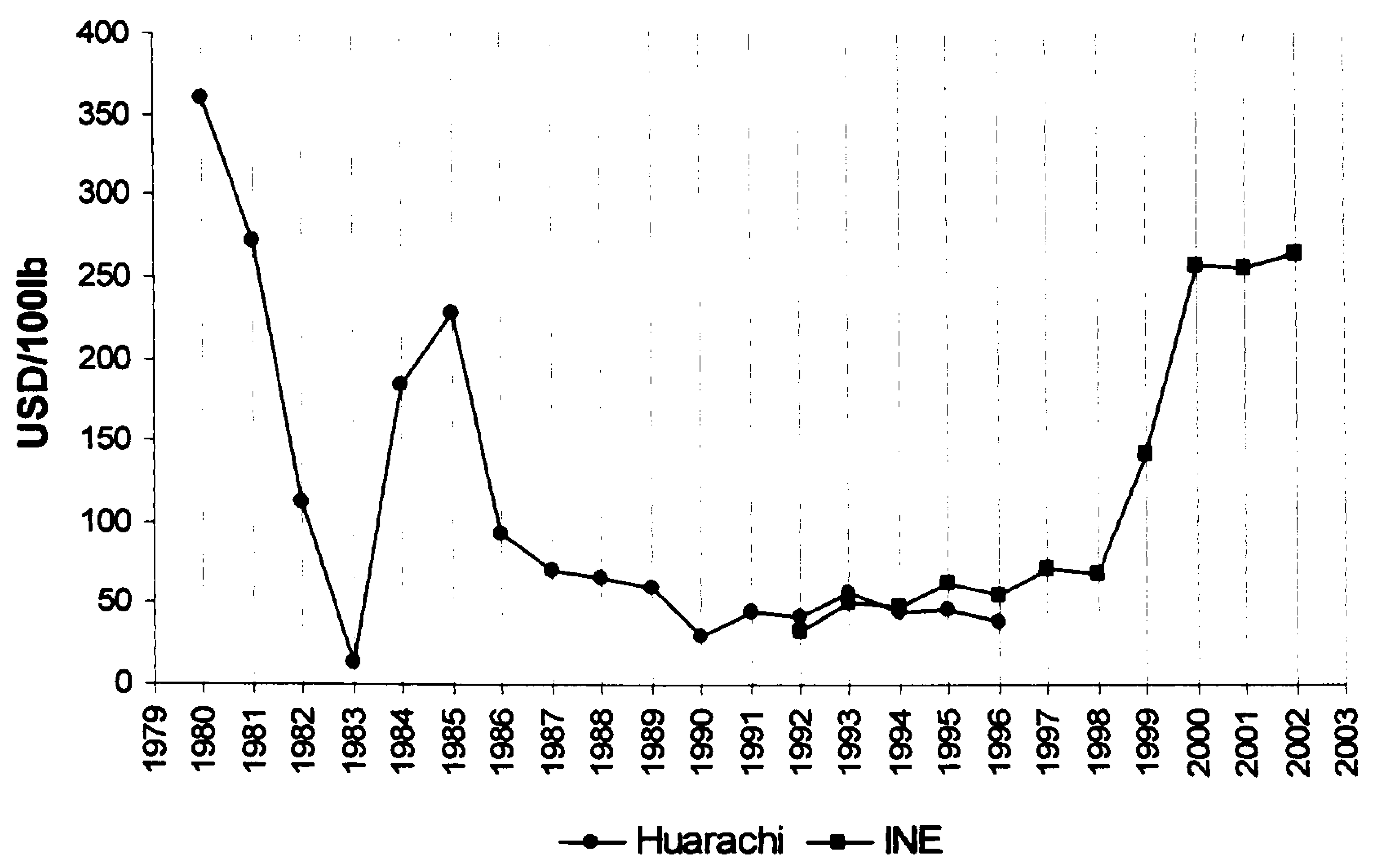
6.2.2.5 Heart of palm

Despite the increase in the area of heart of palm cultivated in Chapare from 51 ha in 1993 to 4,149 ha in 1998 (CORDEP/DAI, 1999) there has been little promotion of the crop so heart of palm from Chapare had not appeared on the domestic market to any great extent by 1999 (CORDEP/DAI, 1999). By 1996 potential markets for heart of palm had been identified in France, Japan, Argentina, Chile, and Brazil, but they had not been exploited (CORDEP/DAI, 1996). Marketing of heart of palm is made difficult because production in Chapare has internal competition from Beni and Santa Cruz Departments and international competition with Brazil, Costa Rica, Columbia, Ecuador and Venezuela. These countries supply the US and European markets with 70, 12, 8, 4 and 3 percent of the combined market respectively (CORDEP/DAI, 1999). There was no market for heart of palm in 2002 according to some of the farmers I interviewed, and stacks of *tallos* left at the end of farmers plots were fetching low prices (0.6 to 1.0 Bs each). These low prices had occurred because of currency devaluations in Brazil and Ecuador, and were in fact half the price that the alternative development programmes had promised (Hellin, 2001). However, by 2003 SPANIBOL had built a heart of palm processing plant near Chimoré and the indications were that the product would be exported to Europe in the near future.

6.2.2.6 Coca

Prices for dry coca leaf from two different sources (Hurachi, 1997; INE[1]) were combined to complete a time series from 1979 to 2002. Figure 6.9 shows the market prices for 100lb sacks (*cargas*) of coca leaves from 1979 to 2002. The data from 1980 to 1996 (Hurachi, 1979) was in USD. The data from 1992 to 2002 (INE[1]) was in Bolivianos and I converted this to USD using an annual average of the exchange rate between Bolivianos and USD for the period 1992 to 2002. The trends in these prices can be analysed by reference to documented trends in coca leaf prices. The price of coca leaf was high at the end of the 1970s, because few farmers were cultivating the coca bushes; the area of coca in Chapare had reached only 12,300 ha by 1978

Figure 6.9: Coca leaf prices from 1979 to 2002. USD per 100lbs (*carga*)
Sources: Huarachi, 1997; from Lazcano, 2002 for data between 1979 to 1997 and INE[1] for data between 1992 to 2002.



[1] www.ine.gov.bo

(Morales, 2004). The supply of coca leaf was relatively low and a high price could be obtained for the harvested leaves (Bostwick *et al.*, 1990). The high prices for coca leaf attracted many migrants to Chapare to grow coca and / or process cocaine paste (Rivera, 1990) but after 1980 there was a rapid fall in prices from over 360 USD per *carga* to 13 USD per *carga* in 1983. This crash in prices coincided with a rapid expansion in the area of coca cultivation, this reached 20,000 ha in Chapare (CIDRE, 2002) and 31,500 ha for the whole of Bolivia (Morales, 2004). The over supply of coca leaf resulted in the price crash (Bostwick *et al.*, 1990). However, prices increased sharply again in 1984 and 1985 to around 200 USD; this was caused by the increased demand for cocaine on the international market (Bostwick *et al.*, 1990). A comparison with the retail price of cocaine (Walsh, 2004) shows that between 1982 and 1992 prices in the US decreased from ~600 USD / g to ~150 USD / g and remained around ~150 USD / g up to 2003. The low price of cocaine has contributed to the low prices of coca leaf which fell to 38 USD / *carga* between 1990 and 1996. Price data archived by the INE starts in 1992 and from 1992 to 1996 (the period in which the two data sets overlap). Both data sets show that prices were low and showed similar minor fluctuations. Low price levels (<69 USD / *carga*) were maintained until 1999 after which coca leaf prices increased and since 2000 have maintained a price above 250 USD /*carga*. The explanation for the recent rise in prices has been due to the effectiveness of 'Plan Dignidad' which was introduced to remove all coca bushes from Chapare between 1998 and 2000. The reduction in the supply of coca leaf caused an indirect and unforeseen effect in pushing up the prices of coca leaf (Jackson *et al.*, 2003). I saw coca still being grown in some relatively isolated parts of Chapare in 2003.

6.2.3 The market strength of coca

Using data published by GOA (1991) I have been able to demonstrate the economic strength of coca as a crop in comparison to the most common alternatives to coca leaf grown in Chapare. In Table 6.1, column one shows the profits from the equivalent of a 1 ha plot of selected crops against 1 ha of coca.

Table 6.1: Comparison of the profit of a hectare of coca and selected substitute crops. The comparison is made for varying prices for a 100lb *carga* of coca leaf against the profits for a hectare of alternative crops (*1991 price data from GOA, 1991).

	Profit	Coca price (USD/*carga*)				
	USD/ha	100	75	60	50	40
Coca profit USD/ha	**17,714***	**17,714***	**11,387***	**7,589***	**5,059***	**2,530***
Pineapples	**10,022***	1.8	1.1	0.8	0.5	0.3
Black Pepper	**5,162***	3.4	2.2	1.5	1.0	0.5
Heart of Palm	**4,782***	3.7	2.4	1.6	1.1	0.5
Oranges	**4,280***	4.1	2.7	1.8	1.2	0.6
Bananas	**2,622***	6.8	4.3	2.9	1.9	1.0

For example, the economic return on 1 ha of pineapple was estimated to be 10,022 USD/ha, whilst that of bananas is 2,622 USD/ha when the price of a *carga* of coca is 100 USD / *carga*. The data in Table 6.2 also demonstrates that provided the alternative crops maintain the same price the only way all of the alternatives could out compete with coca is if the profit on 1ha of coca falls to 2,530 USD which, given the 1991 price data used, would happen when the price of coca leaf fell to 40 USD / *carga*. The figures in Table 6.1 show that it is rarely more profitable to cultivate a hectare of an alternative crop and in the 1980s the reason farmers chose coca cultivation was that the high prices of the coca leaf gave an excellent return on their investments (Bostwick *et al.*, 1990) which included high inputs of labour for weeding, spraying and harvesting the coca crop (Perira, 1990). If alternative crops decrease in price as happened to pineapples (Figure 6.7) this strengthens a farmers investment in coca so much so that they continue to grow coca despite the risks of losing a coca leaf crop due to eradication measures (which occurred commonly through the second half of the 1980s and into the 1990s) or a decrease in coca leaf prices, as also happened in the 1990s (Figure 6.9).

An important implication of these price variations for LULCC studies was that if farmers were forced to give up coca cultivation (as did happen during eradication campaigns) they had to cultivate much more land in order to match the returns on coca from the alternative crops. In Table 6.1 the numbers of hectares of alternative crops required to be cultivated to equal the same returns of that a hectare of coca bushes would give, are provided. For example, when coca prices are 100 USD/ *carga,* 1.8 ha of pineapples or 6.8 ha of bananas, need to be cultivated to provide the same returns as a hectare of coca. When the coca leaf price is as low as 40 USD/ *carga,* only 0.3 ha of pineapple or 1.0 ha of bananas need to be cultivated to produce the equivalent returns. The shaded part of Table 6.1 shows the economic conditions in which alternative development crops become more profitable than coca leaf. In reality coca prices have rarely fallen to 40 USD/*carga* since it was grown in Chapare (Figure 6.9). Farmers are unlikely to switch to cultivating other crops if the alternative crop prices remained at 1991 levels. In these calculations made by USAID the profits on the alternative crops included an investment of 2,000 USD and they also assume this is paid to the farmer as compensation of coca eradication. In reality corruption in the compensation system has resulted in many part payments (Sage, 1994). If this payment was not received or only received in part, profits would have been reduced and the competitiveness of the alternative crops would have fallen further. It is worth noting that, as demonstrated by the price data in Section 6.2, the prices for alternative crops have been subject to change and this will have affects on the per hectare profitability in the same way fluctuations in coca leaf may have. In particular, the large decrease in pineapple prices (Figure 6.7) will have had negative impacts on the competitiveness of pineapple as alternatives to coca, and this will have been accentuated by the increase in the price of coca leaf during the same time period.

Another advantage of cultivating coca leaf is the possibility of a regular income for a household because two to four harvests are possible each year. Comparing the data for fruit products such as pineapples (Figure 6.7) and oranges (Figure 6.8) this overcomes the problem of a seasonal income. However, heart of palm has a comparable number of harvests per year. I questioned farmers over the competitiveness of heart of palm with coca leaf production and the findings are summarised in Table 6.2.

Table 6.2: Comparison of prices between heart of palm and coca. Source: interviews 2002.

Crop	Potential number of harvests per year	Quantity and price USD (2000 prices)	Potential crop	Selling price per hectare of crop at 2002 prices
Coca	3	*100 lbs*: 98USD	4 *cargas* per *cato* (1/6ha)	2,352 USD
Heart of palm	3	*Unit*: 0.10 USD	1,500 *tallos* per ha	150 USD

There were two important findings of this research: (i) despite the same number of harvests the returns on a hectare of heart of palm are much lower than for coca leaf; and (ii) the comparison was between a *cato* of coca a sixth of a hectare, and a hectare of heart of palm so farmers need to cultivate more land (and possibly clear more forest) if they give up coca leaf and cultivate heart of palm if they are to maintain their incomes.

Even in the case of heart of palm, the attraction of a crop with multiple harvests still cannot compete with coca leaf. Over 15 ha of heart of palm would have to be cultivated in order to match the returns of one sixth of a hectare of coca. It holds true for all the crops promoted under alternative development in Chapare that they yield lower profits per unit and require more land to sustain a reasonable farm income. This has implications for the rates of forest clearance, as when alternative crops are encouraged more land is likely to be cleared: a clear case of policy driven variations in land conversion rates.

6.3 Policy drivers

The description of changes in Bolivian politics and economic policies (Chapter 1) showed how, in the 1960s, the country aimed to broaden from its narrow mining base by diversifying into petrochemicals and agriculture, and releasing pressures on farmland on the altiplano (Pacheco, 1998). The military governments of the 1970s and early 1980s accumulated huge debts whilst continuing with the plans for economic diversification which eventually led to an economic crisis (Morales, 2004). This situation was controlled in the mid 1980s by structural adjustment of the economy (Kaimowitz *et al.*, 1996). Colonisation of tropical lowland areas like Chapare began as part of the economic plans of the 1960s (Henkel, 1973) but in the early 1980s a number of push-pull factors increased the number of migrants to Chapare (Painter *et al.*, 1991).

International concern had already been vented on the narcotic supply countries at the Convention of Narcotics in 1961 (Negrete, 1996) and, driven by US interests, Bolivian President Víctor Paz Estenssoro (1960 to 1964) installed a new commission to eradicate and substitute coca and in 1962 proposed that coca chewing and growing would cease in 25 years i.e. by 1987 (Cardozo, 1999). In 1973 President Hugo Bánzer Suárez's government (1971 to 1978) recognised the cultural importance of chewing coca leaves and replaced total eradication policies with policies to control the production of coca leaf through the 'Law of Dangerous Substances' (Law 11254). Alternative development programmes were launched by the Bolivian government with

Proyecto de Desarollo Chapare – Yungas (PRODES) whereby technical and financial assistance was provided for coca alternatives. PRODES lasted from 1975-1980.

Coca leaf cultivation increased from 4,450ha in 1970 to 27,707ha in 1980 (Salazar, 2002) during the period of unstable and corrupt military governments. In a one-year term, President Luis García Meza (July 1980 to August 1981), directly managed paramilitary groups and 'blatantly' negotiated with the drug cartels (Morales, 2004). Presidential involvement with the drugs cartels put the Bolivian government in an uncompromising position with the administrations of Jimmy Carter, and Ronald Reagan, and other Latin American and European governments. Consequently the Carter administration (1977 to 1981) suspended USD 26 million of foreign aid to Bolivia (Morales 2004). After the overthrowing of President Meza, in return for foreign loans the new Bolivian government was obliged to combat coca leaf cultivation and work closely with the US Government and aid agencies. The Bolivian government introduced several coca reduction policies and laws as conditions for the receipt of foreign loans, and they enforced them in Chapare with the aid of Bolivian military personnel (Table 6.3).

Table 6.3: Significant policies to combat coca cultivation in Bolivia since 1981
Sources: Jackson *et al.*, (2003); Ortuño, (2002); Cardozo (1999).

Act / Policy	Year	Aims
Law 18264	1981	The gradual reduction of coca with the possibility of compensation leading to collective benefits and diversification of crops.
Law 18714	1981	With US pressure Law 18254 was modified to maintain coca eradication through force or voluntary means, the voluntary option included US$2,000 as compensation for the destruction of the farmers coca. All coca was to be sold to the collection points of the Anti-drug Traffic Council establishing a state monopoly on the sale of coca.
Operation Blast Furnace	15/07/86 to 15/11/86	The US Government made a *convenio* with the government of Bolivia to send a small military force supported by helicopters to Chapare to eradicate coca bushes in order to influence prices of coca leaf. The intention was to make prices fluctuate daily over small areas by concentrating eradication of coca bushes in concentrated areas.
Plan Trienal	1986 to 1989	This three year plan was intended to remove 50,000ha of coca bushes in the first twelve months (Márquez (no date)) but was halted after less than a year because of the civil rights violations and the social unrest that resulted.
Law 1008	1988	This law legalised 12,000ha of coca bushes in traditional coca areas (Yungas of La Paz) to satisfy the traditional demand for coca leaf chewing. The remaining coca was thus illegal and had to be substituted with legal crops. This came into immediate effect in the Yapacaní colonisation area, but Chapare was declared a transition zone and coca bushes were to be removed within 8 years.
Plan Dignidad	1998 to 2003	A five year plan to reduce the amount of coca outside legal areas to zero. Hailed a success as all coca was reportedly eradicated in 2000, this figure is however doubtful.

The Bolivian government was also assisted with aid programs, mainly co-ordinated by United States Agency for International Development (USAID), to provide support to farmers with crop substitution to replace their coca leaf crops (Table 6.4).

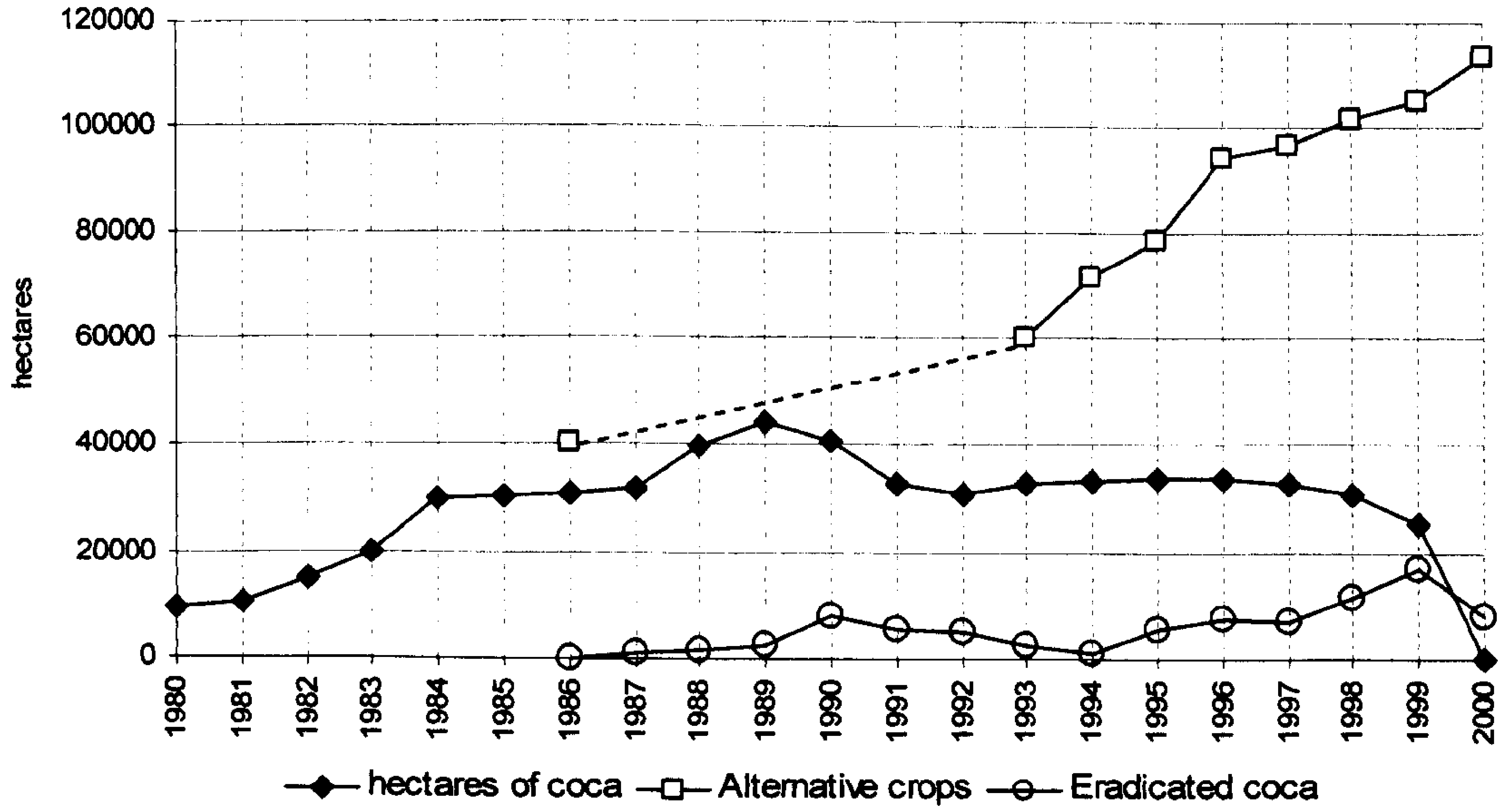
Table 6.4: Development projects aimed at reducing coca cultivation in Bolivia since 1981. Source: Jackson (2003); Ortuño, (2002).

Duration	Project	Aims
1984 to 1987	Cochabamba Regional Development Project (CDRP)	This project aimed to broaden the area of distribution for coca alternatives, and use the Bolivian Institute for Agricultural Technology (IBTA) to research into the alternative crops. This was to be supervised and inspected by a US agency USAID. IBTA divided Chapare into seven sub-regions considered to have different agricultural conditions, developed and introduced new products along with technical expertise to cultivate the new crops. The project was criticised because, although experimentation with new crops was occurring no economists were employed to investigate the market potential of the products. Project resources were also channelled towards solving problems in the Cochabamba highland valleys which was the source of many of the migrants. (Bostwick *et al.*, 1990)
1987 to 1990	Amendment to Chapare Regional Development Program (CRDP)	USAID made an amendment to the existing CRDP to take the emphasis away from the high valleys of Cochabamba. The policies were now intended to 'reduce coca production in Bolivia' and to develop alternative sources of income for the people who were engaged or could be engaged in the production, processing and marketing of coca. Credit was given for substitution of coca. This was known as 'crop substitution'.
1991 to 1999	Cochabamba Regional Development Project (CORDEP)	The project aimed to increase investment, production and employment in licit activities away from coca. 'Crop substitution' was replaced with 'economy substitution'. The project concentrated on marketing selected agricultural commodities, developing infrastructure and sustainable production for small farmers. There was also co-ordination with the FAO on sustainable forestry.
1999 to 2003	Counter-Narcotics Consolidation of Alternative Development (CONCADE)	This project was implemented to support the alternative development side of Plan Dignidad and involved the Drug Enforcement Agency (DEA) and Narcotics Affairs Section (NAS) of the US Government. The latter two agencies being in charge of coca eradication, prevention of new planting and increasing the risks of coca production and marketing. USAID was to sustain farm level productivity, market linkages and market demand.

6.4 Temporal impacts of economic and policy drivers

If Chapare operated under a free market economy the economic drivers (Section 6.2) show that coca leaf cultivation would be the farmers choice. However farms in Chapare are currently not dominated by coca so the policy drivers (Section 6.3) and the tools used to implement the policy must have overridden the economic drivers. Farmers have been encouraged and coerced to stop growing coca and to cultivate alternative crops. This has implications on the variations in the rates of LULCC because the area of land required for alternative crops is far greater than that for coca bushes (Section 6.2.3). This section examines the evidence that an economy based on coca cultivation is more conservative in terms of forest conversion than an economy which is not based on coca. Three data sets have been used to illustrate this argument: (i) the area of coca bushes (CIDRE, 2000); (ii) the amount of coca eradicated (UNODC, 2004); (iii) and the area of crop substitutes (CIDRE, 2000) for the whole of Chapare.

Figure 6.10: The area of coca, eradicated coca and substitute crops in Chapare between 1980 and 2000, dotted line indicates extrapolation. Sources: Lazcano *et al.* (2002); CIDRE (2000); eradication data UNODC (2004)[2].



[2] The value of zero coca in 2000 is a little optimistic given the responses given by farmers during the BioAndes survey and are likely to have been released to support the 'success' of Plan Diginidad (Mario Lazcano, UMSS-CBG, personal communication).

Figure 6.10 shows that the area of coca in Chapare increased from 9,300 ha in 1980 to 30,000 ha in 1984. It then gradually increased until 1989 when the area of coca cultivation reached 44,300 ha. The area of coca then fell and maintained levels of around 30,000 ha from 1991 until 1998. In 1999 there was a slight decrease in the area of coca and by 2000 there was apparently no coca (which is unlikely). The latter estimate may have been released to support the progress of Plan Dignidad, which aimed to reduce the area of illegal coca cultivation to zero. The area of coca that was eradicated is much less than the area of coca cultivated (Figure 6.10). This data set did not begin until 1986; although farmers were being encouraged to substitute coca prior to 1986 by the Bolivian government with compensation, and coca crops were being destroyed. Less than 2,500ha of coca were eradicated up to 1989 and this even coincided with an increase in the area of coca cultivated. It was not until the period between 1990 to 1993 that larger amounts of coca (between 5,000 and 8,000 ha yr^{-1}) were eradicated that there was a decrease in the area of coca cultivated (there is a lag of one year between the dates). This did not reduce coca cultivation significantly and farmers continued to plant more coca than was eradicated even though there was steady increase of area eradicated (1,064 ha to 7,026 ha from 1994 to 1997). From 1998 the rise in the area of coca eradicated did appear to reduce coca below 30,000 ha for the first time since the mid 1980s. The fact that in 2000 7,900 ha were eradicated when there was apparently no coca brings the zero value for 2000 into question. Figure 6.10 shows that for most of the period considered new plantations of coca were replaced faster than they were eradicated. What remains uncertain is whether new coca plantings were at the expense of forest or existing agricultural land. These data also show the area of alternative crops for the same time period. From 1986 to 1993 there was no data but there was an increase from 40,000 to 59,800 ha of alternative crops in this time

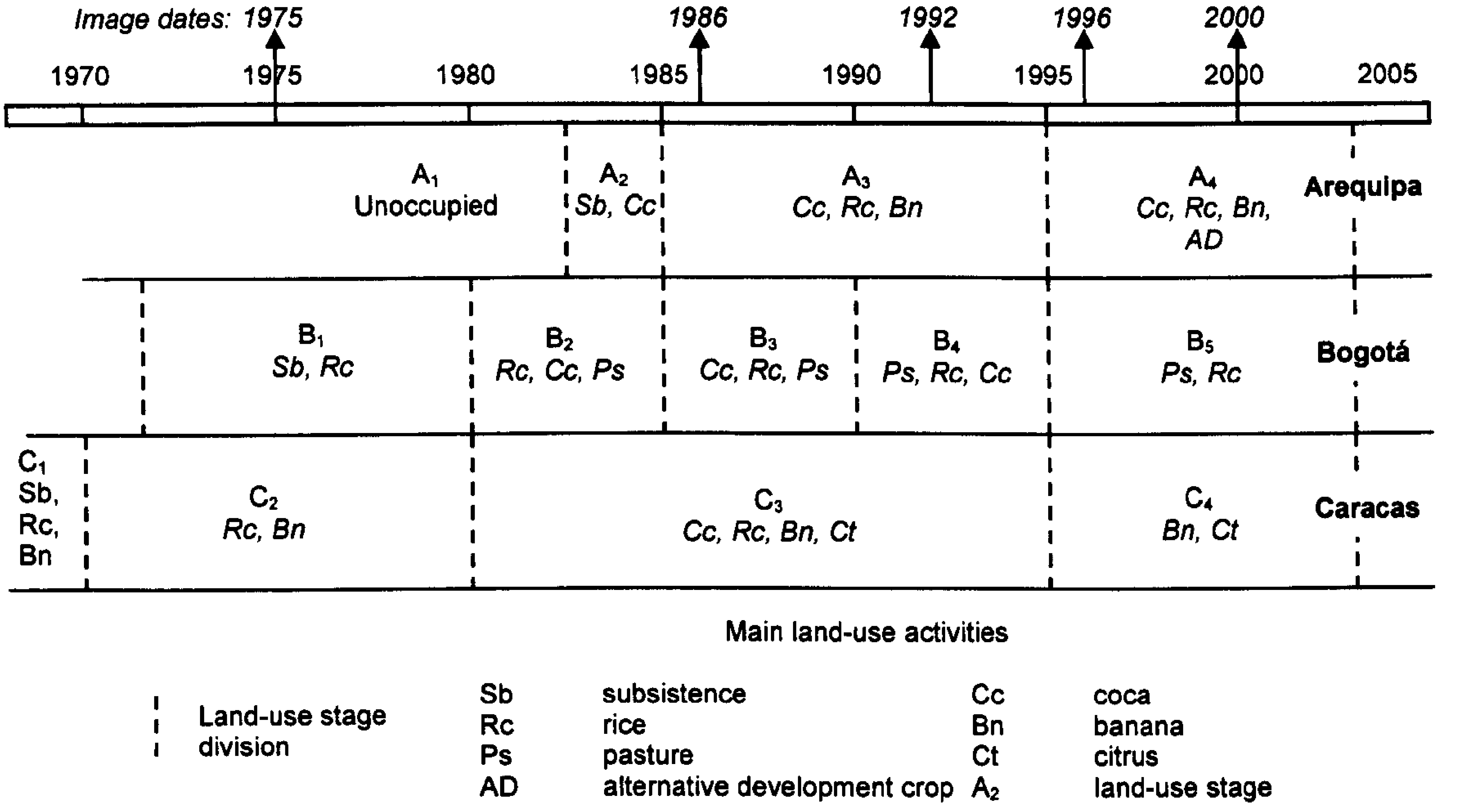
(Figure 6.10). It is likely that the greatest increase in alternative crop area occurred after the large decline in coca between 1989 and 1991 when farmers were encouraged to cultivate alternative crops. After 1993 there is a more-or-less steady increase in the area cleared of roughly 11,000 ha yr, which then decreases to approximately 5,000 ha yr between 1996 and 2000. Thus throughout the 1990s the area under alternative crops has increased, and since this is not at the expense of the area of coca, which has maintained the similar levels over the same period, a vast majority of the area used for alternative crops has to be at the expense of the forest. The decrease in the accumulation of alternative crops area between 1999 and 2000 may be because the markets have improved and less fewer alternative crops are being abandoned.

The temporal behaviour of these drivers can now be assessed in relation to the increase in cultivation shown in Figure 6.10. From 1981 to 1984 there is an increase in the area of coca, yet under Laws 18264 and 18741 farmers were offered a USD 2,000 incentive for the reduction of each hectare of coca. Although there are no data that showed an increase in substitute crops at this time, the area of coca increased and it was later discovered that those who had received the compensation had often reinvested the money back into coca (Sage, 1991). At the same time the overall failure of CDRP (1984 to 1987) did not have an impact on the replacement of coca with substitute crops due to the mis-direction of resources to the Cochabamba high valleys (Bostwick *et al.*, 1990). In 1986 the US Government's war on drugs which initiated Plan Trienal was quickly aborted after less than a year because of the civil unrest the programme triggered (Jackson *et al.*, 2003) This plan did not affect the area of coca cultivation between 1987 and 1989 when coca cultivation actually increased. The amended CRDP project between 1987 and 1990 offered credit for substitution of coca which was again often reinvested into coca cultivation. The CDRP project was most likely to have brought about an increase in substitute crops at this time. In 1988 the cash for coca policy was overridden by Law 1008 and this essentially made all coca cultivation illegal in Chapare. Coca cultivation did not instantly disappear however, as Chapare was declared a transition zone and had eight years to eradicate all its coca bushes. There was a slight increase in 1989 but in the next three years there was a decrease of around 10,000 ha of coca. In 1993 the area of alternative products increased, which shows the influence of CORDEP (1991 to 1999). CORDEP built on the progress of CDRP by concentrating on the marketing of specific alternative development crops through grower's associations, and improving the transport and market infrastructure. Beginning in 1994 the area of coca eradicated increased. The driver for this may relate to the change in government policy; but until Plan Dignidad came into effect it was not obvious which policy influenced this increase. Plan Dignidad had an affect on the area of coca in 1999 but is unlikely to have reduced coca to the value of zero as the data suggests (see footnote 2). Meanwhile project CONCADE (1999 to 2003) encouraged a further increase in alternative development crops, with the intention of supporting Plan Dignidad and the offer of alternative development based on concessions for whole communities. These policies however did not prevent further planting of coca bushes in Chapare. This section has illustrated how policy drivers affected the Chapare region as a whole; the next section discusses how clearance rates of forest varied at the community level in response to the changes in policies and markets.

6.5 Local level responses to the LULCC drivers

The synopses of land-use activities in the three communities studied were summarised in Figure 5.80 which is reproduced below as Figure 6.11. The land use stages A_1 to A_4, B_1 to B_5 and C_1 to C_4 were described in Tables 5.5, 5.8, and 5.12.

Figure 6.11: Synopsis of the land-use activities for the three communities.



The following sections – 6.4.1 to 6.4.3 – use the information from Figure 6.11 to synthesise the land-use activities for all the three communities. This synthesis is then related to the variations in rates of land-cover change (Figure 6.12). Using the data in Figure 6.11 the land-use stages have been divided into three-over arching land-use periods which are related to the amount of coca cultivation in the area, these are: the pre-coca dominance period (1960 to 1979); the coca dominant period (1980 to 1995); and the post-coca period (1996 to 2000).

6.4.1 The pre-coca dominant period (1960 to 1979)

During this time period, 1960 – 1979, forest clearance was well underway in Caracas, there was some clearance in Bogotá and there was no clearance in Arequipa. In Caracas the highest rates of forest clearance (0.66 ha yr^{-1}) (Figure 6.12) were calculated for the period 1963 to 1975. This then decreased between 1975 and 1986 to 0.45ha yr^{-1}, a time when there was a general increase in coca; however only four years of the 1975 to 1986 time period fall in the pre-coca dominance period.

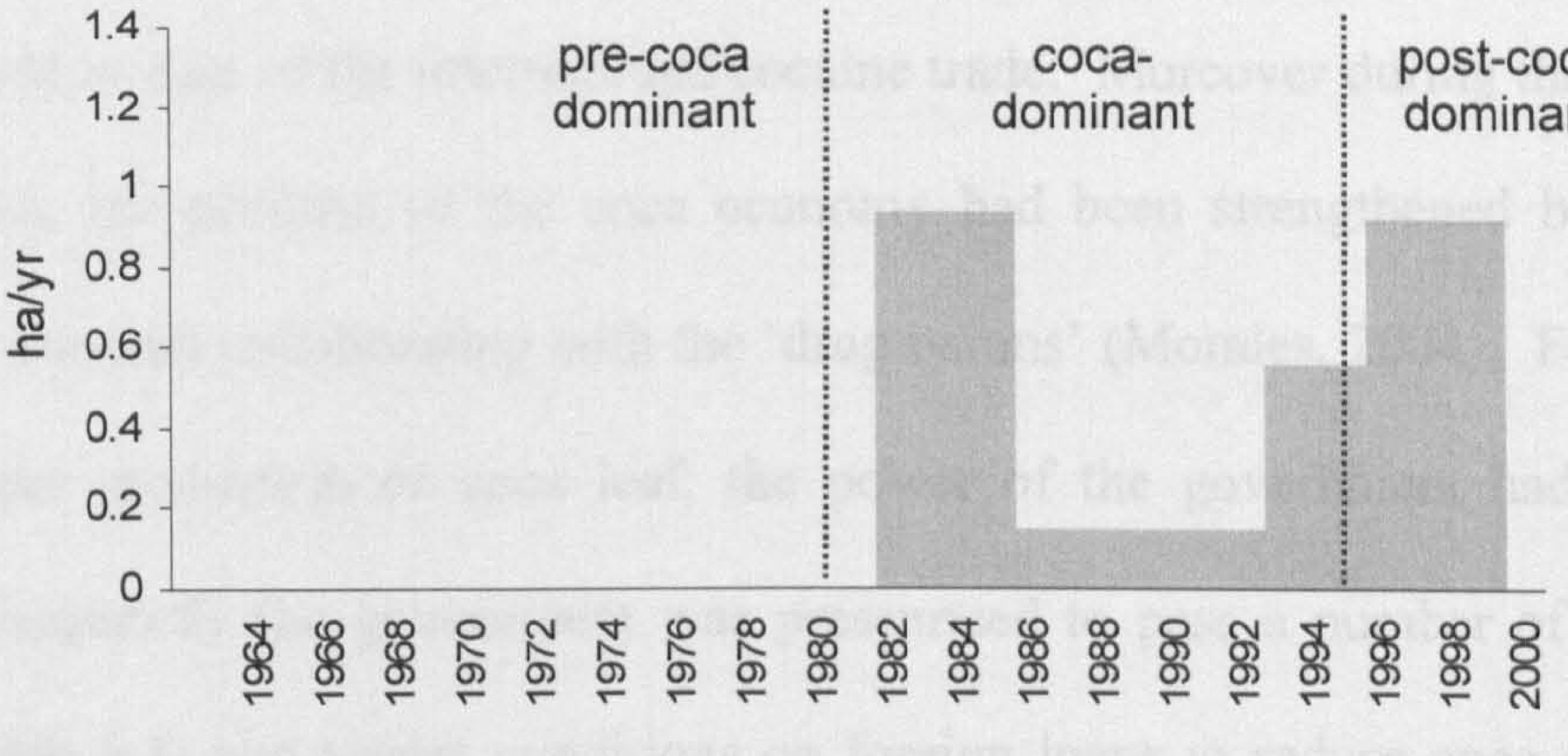
LULCC in Chapare in this period was driven by the demographic (migration) and economic policies of the various Bolivian governments. The general thrust of these policies was to open up Bolivia's tropical lowlands to broaden the country's macroeconomic base, to increase import substitution (thereby avoiding economic dependence on the mining industry) and to alleviate the post-agrarian reform impoverishment of the highland people by stimulating migration to areas like Chapare (Henkel, 1995; Rodríguez, 1997; Pacheco, 1998, 2002; Morales, 2004).

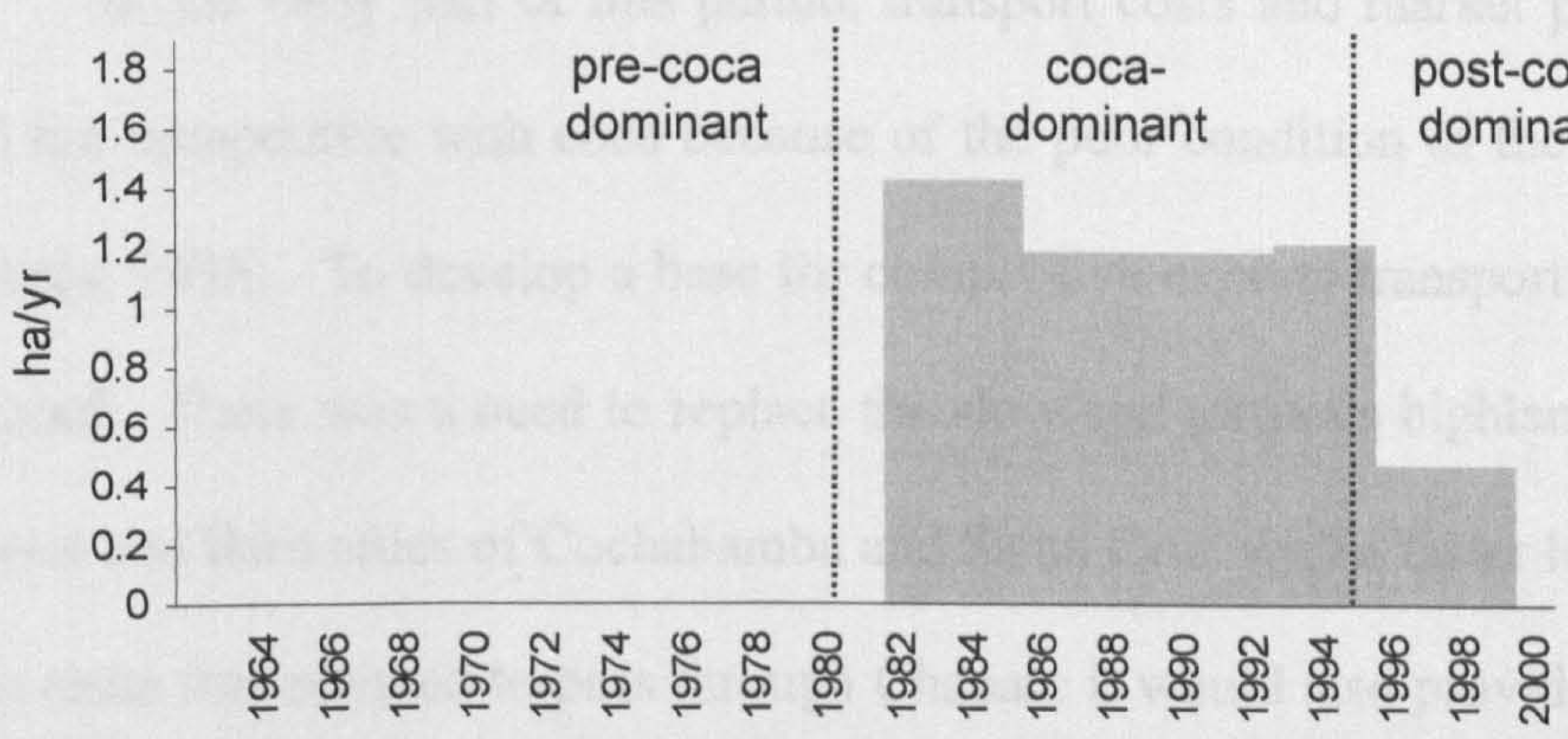
As part of Plan Decinal in 1961, government colonisation was funded by an IDB loan to provide support to colonists in Chapare (and other tropical lowland areas) to cultivate a variety of crops including coffee, rubber and tropical fruits (Henkel, unpublished). Caracas was colonised by groups of highland people arriving from Cochabamba and a decade later colonisation of Bogotá began from the Santa Cruz colonisation area, Yapacaní. The two areas were yet to be linked by the Cochabamba to Santa Cruz highway. Prior economic development had been directed towards linking Beni to Cochabamba *via* river ports including Todos Santos, and Puerto Villarroel (Rodríguez, 1997), and colonising the lowland areas close to the three major Bolivian population centres of La Paz, Cochabamba and Santa Cruz (Henkel, unpublished). A decline in the hydrocarbon reserves in the early 1970s temporarily halted further colonisation because external borrowing was injected into that industry rather than into colonisation projects (Pacheco, 1998). The location of the future community of Arequipa was not yet accessible by roads and so was disconnected from the modern transport infrastructure.

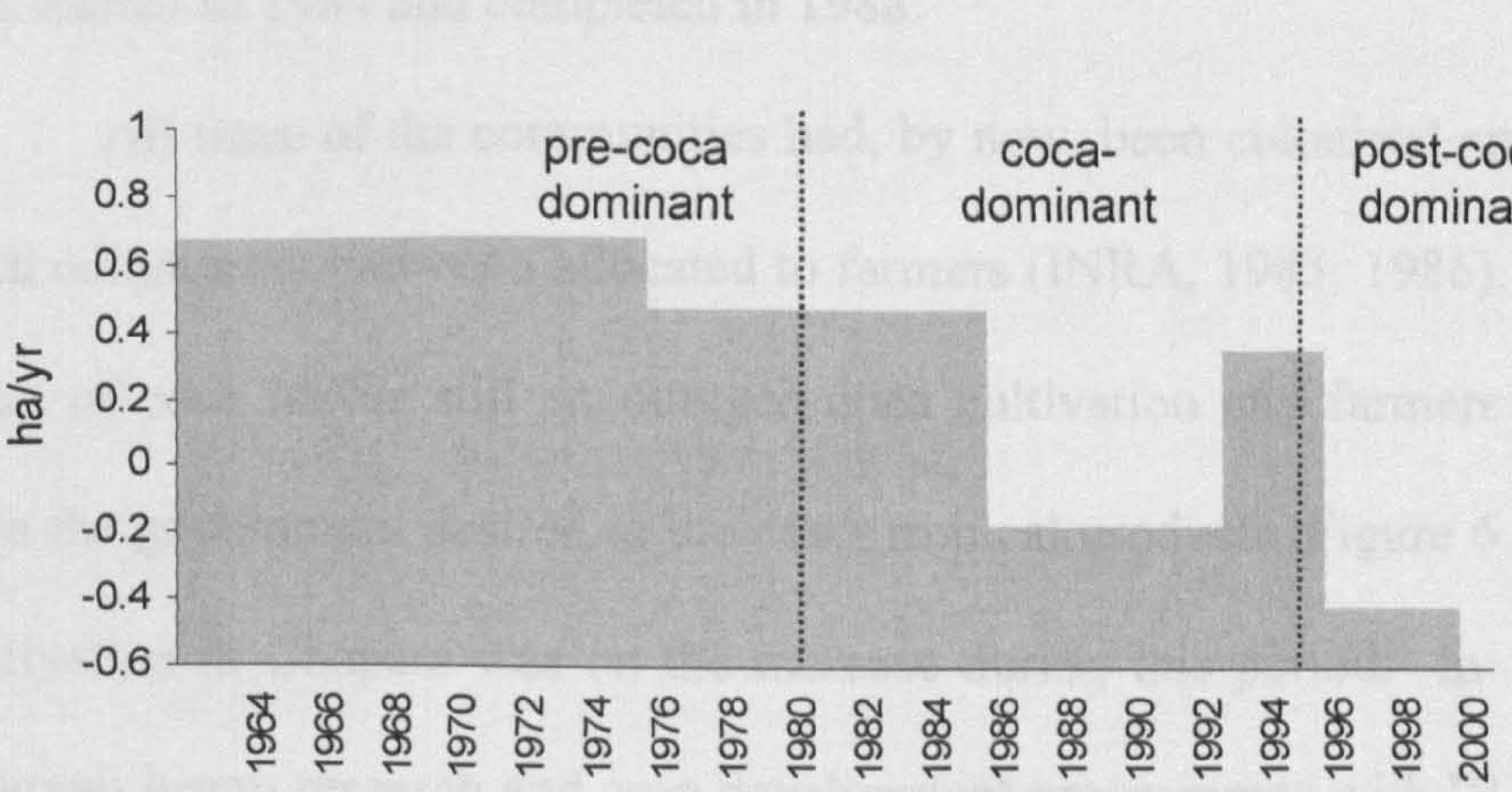
Caracas had high rates of forest clearance at this time because the government supported programs were frequently failing due to the lack of technical knowledge on the tropical environment and farmers were experimenting with new crops. This experimentation included attempts to cultivate unsuitable crops like coffee and cocoa (Henkel, unpublished). Some forest was cleared for long term projects such as stands of rubber trees which would not yield crops for at least twelve years, which meant that, farmers still needed to clear forest to generate an income from a cash crop (Rivera, 1990). These small rubber plantations could still be observed in the field as part of the cultivation mosaic in 2003. The disadvantage for some crops was that because the transport connections to Cochabamba had been poorly planned and under-invested, it was difficult for farmers to transport perishable goods to markets in the city. The combination of these problems led to a change in the major choices of crops to cultivate and helps to explain the switch to coca at the end of this period. The ease of transport of sacks of coca and non-perishable rice under these conditions initiated the growth of a coca and rice economy, which was seen by many farmers as a better alternative to tropical fruit cultivation (Rivera, 1990). The increase in coca production was contrary to any policies in the 25-year plan of coca elimination introduced by President Estenssoro following the Single Convention of Narcotic Drugs (1961) and controls on coca leaf production (Law 11254). This led to the formation of PRODES, which existed from 1975 to 1980 and gave technical assistance to farmers through the first crop substitution programmes (Cordozo *et al.*, 1999; Salazar, 2002).

By 1979 the military governments of the 1970s had accrued large external debts as they had continued to borrow heavily for economic development. This was beginning to put future Bolivian governments at a disadvantage with international aid donors (Hellin, 2001; Morales, 2004).

Figure 6.12 Comparison of the rates of clearance for Arequipa (top), Bogotá (middle) and Caracas (bottom).







6.4.2 The coca dominant period (1980 to 1995)

Coca cultivation as a land-use activity was more attractive than the cultivation of tropical fruits at this time because of the high demand and assured market for coca leaves as part of the international cocaine trade. Moreover during the term of President Mesa, the position of the coca economy had been strengthened by members of the government collaborating with the 'drug barons' (Morales, 2004). Following the boom in the production of coca leaf, the power of the government had been eroded and consequently the government was pressurised to pass a number of coca control laws (Table 6.3) and accept conditions on foreign loans to reduce coca cultivation and co-operate over alternative development projects (Hellin, 1994).

In the early part of this period, transport costs and market prices of fruit were still not competitive with coca because of the poor condition of the Cochabamba road (Rivera, 1990). To develop a base for competitive exports transport costs needed to be reduced. There was a need to replace the slow and tortuous highland route linking the second and third cities of Cochabamba and Santa Cruz with a faster lowland route. As a new route was planned to pass through Chapare it would also provide lower cost access to markets in Cochabamba and Santa Cruz for produce cultivated in Chapare. This route was started in 1984 and completed in 1988.

All three of the communities had, by now, been colonised and all of the plots in each community had been allocated to farmers (INRA, 1985; 1986). However the high price of coca leaves still encouraged coca cultivation and farmers paid less attention than the government desired to the other tropical products. Figure 6.10 shows that coca cultivation in Chapare was on the increase during this period. In 1984 the CORDEP program began research and crop development programmes with IBTA (Cardozo *et al.*, 1999; Salzar, 2002). One of the major outcomes was the zoning of Chapare into agro-ecological regions (Kornfeld *et al.*, 1979) each of which would be targeted with specific substitute crops and, furthermore, a market centre was planned in each zone and located on the Cochabamba to Santa Cruz highway (Rivera, 1990).

The actual rates of clearance vary in each community, but follow a broadly similar pattern. The highest rates of clearance in this period occurred up to 1986. The most rapid rates of clearance occurred in Arequipa (0.93 ha yr^{-1}) and Bogotá (1.42 ha yr^{-1}) (Figure 6.12) where farmers were both concentrating on clearance for subsistence between 1983 and 1986 and entering into the coca economy. In Arequipa there was no previous history of cultivation so coca had been the first choice as the income-generating crop; the cultivation of tropical fruits was mainly for subsistence although some farmers did cultivate bananas because they were encouraged by good prices. After the breakdown of the rice cooperative in Bogotá (because of the poor market for rice reported at that time), subsistence cultivation and cattle rearing were the intended direction of many farmers, but the high demand and prices for coca leaf stimulated the planting of coca bushes. Coca also provided a lower risk than having small cattle herds and it provided a reliable alternative source of income while farmers expanded their area(s) of pasture and increased their herd sizes. In Caracas there had been almost two decades of bananas and citrus cultivation, as well as other failed crops (e.g. cocoa and coffee) under government direction (Rivera, 1999; Henkel unpublished). Prior to the major phase of coca in Caracas, some plots had been almost completely cleared and the mean rate of clearance in the community had declined to 0.46 ha yr^{-1}. As it was an established activity, fruit cultivation continued in the background whilst coca increased in importance as a source of income. Overall, many farmers in Chapare switched their land-use from fruit to coca which meant that the supply of bananas to the departmental market (Cochabamaba) declined. The prices of bananas however, remained relatively buoyant and this encouraged some farmers to continue with the cultivation of bananas.

Rates of forest clearance decreased from 1986 to 1992/1993, to below that recorded prior to 1986. The most dramatic was in Arequipa, a decline from 0.93 to 0.14 ha yr^{-1}, Bogotá decreased from 1.42 to 1.19 ha yr^{-1}. In Caracas the rates declined from 0.45 to -0.17 ha yr^{-1} because some citrus orchards were maturing, thereby reducing the necessity for further land clearance, and several plots had been totally cleared so there was no more forest left to clear. One factor that contributed to the decline in forest clearance rates in all three communities was much effort was being expended on coca cultivation which required less land than fruit production and cattle pasture. Coca cultivation was at its peak between 1986 and 1992/3 (Figure 6.10).

Throughout the coca dominant period the pressure on the communities to stop growing coca increased. The US government had pressured the Bolivian government to pass Law 1008 which made coca cultivation illegal in undesignated areas. This effectively gave the authorities all the powers they required to eradicate coca in Chapare. Policies were directed at eradicating coca and did not consider the importance of alternative crops to divert farmer's attention away from coca leaf cultivation. In 1990 (following the Declaration of Cartegena) the US government released 300 million USD to the Andean countries in the war against drugs. However only 16% was designated to alternative development programmes; the rest was to support in eradication (Cardozo *et al.*, 1999; Salzer 2002). At the same time, the impacts of some of the possible substitute crops which could have potentially been imported from Bolivia (e.g. oranges and soya) were being investigated by the US Office of Accounting regarding their impacts on the US internal market. Support for these products was therefore suspended while a report was complied (GAO, 1991). In the early 1980s farmers were offered USD 2,000 per hectare in compensation for their coca crops. It was later discovered that a large proportion of the compensation was reinvested by the farmers into coca cultivation rather than on purchasing substitute crops (Sage, 1994).

The impact of alternative development programs on LULCC in the three communities was relatively minor at this time. In Arequipa, banana cultivation and alternative development crops increased towards the end of the time period and coca still dominated (Figure 5.27), and clearance rates were at their lowest (0.14 ha yr^{-1}). Forest clearance rates had also fallen slightly in Bogotá (1.19 ha yr^{-1}), but were the highest of the three communities. Clearance for rice and pasture continued in Bogotá but this period coincided with the highest recollection of coca cultivation by farmers interviewed (Figure 5.53). In Caracas the clearance rates became negative (-0.17 ha yr^{-1}), and this period again coincided with the highest recall of farmers for cultivation of coca. Although established banana plantations were present farmers were more inclined to set aside and / or to clear small areas for coca.

In 1991, when a new CORDEP programme began the alternative development emphasis changed from crop substitution to economy substitution, and the range of alternative development crops had been narrowed down to bananas, pineapples, passion fruit, black pepper and heart of palm, from the 40 being considered at the beginning of the 1980s. These crops were selected because of the commitment and long term investment required by a farmer (Jackson *et al.*, 2003). Many of the other crops had failed because there were no markets, e.g. ginger in 1989 and tea and turmeric in 1990 (Sage, 1994). The CORDEP project also included research and development into markets for alternative crops. The price of coca was relatively low at this time (Figure 6.9) but coca cultivation was still considered a more lucrative activity by many farmers than growing other crops.

The rates of forest clearance between 1992/3 to 1996 (Figure 6.12) increased into the post coca period (which began in 1995) in response to eradication and alternative development projects. In Arequipa and Caracas rates increased to 0.55 ha yr^{-1} and 0.33 ha yr^{-1} respectively, but in Bogotá remained similar (1.26 ha yr^{-1}) in the period from 1986 to 1992/3. The pressure to substitute alternative crops for coca had its greatest impact on the forest clearance rates in Arequipa where land-hungry bananas were substituted for land-conservative coca and rates increased from 0.14 ha yr^{-1} to 0.55 ha yr^{-1}. There was now strong evidence that the alternative development programmes were beginning to make a significant negative impact on conversion of forest to agriculture in the region (Figure 6.10).

6.4.3 The post-coca dominant period (1996 to 2000)

Around the mid 1990s the transition of land-use activities from coca dependence to the existing fruit crops and new alternative development crops began. In Caracas, citrus and bananas rose in importance again, along with new alternative development crops. In Bogotá farmers continued to clear forest to expand their areas of pasture whilst at the same time reducing coca production. In Arequipa the cultivation of bananas and alternative development crops increased, but several farmers still continued to cultivate coca leaves. Alternative development programmes were now meeting their goal of developing and searching for new markets to make the alternative development products more stable options for farmers. In 1996 CORDEP reviewed its policy on substitution and offered conditions to whole communities, such as road improvements in return for the destruction of all coca crops. This strategy occurred after it had become obvious that farmers accepting coca compensation were re-investing their money into the cultivation of more coca. Plan Dignidad implemented by the Government of Bolivia in 1998, planned to eliminate all coca by 2000 (Salzer, 2002;

Jackson *et al.*, 2003; Morales, 2004). CONCADE was established one year later and one of its aims was to support Plan Dignidad with crop substitution. However, the rate of crop substitution did not keep pace with the rate of reduction of coca, and coca prices rose to their highest since the early 1980s; making coca a highly lucrative crop yet again (Jackson *et al.*, 2003).

In the post-coca period between 1996 and 2000 clearance rates fell in Bogotá from 1.21 to 0.47 ha yr^{-1}, and in Caracas from 0.33 to -0.42 ha yr^{-1}. But the rates increased in Arequipa from 0.55 to 0.92 ha yr^{-1}. In the first two cases land clearance continued but because some of the plots in Bogotá are less than 20 ha they were virtually cleared by this time and have reduced the community average rate of clearance. In Caracas some plots were completely or virtually cleared and farmers had no choice but to allow forest regrowth and rotate crops. In Arequipa the rates of clearance were still high because forest was still available to clear.

By the end of the CONCADE project in 1999, alternative development programmes chosen had been more thoroughly researched, internal and export markets had strengthened and support from grower's associations helped with technical and marketing support for the major products. Rates of forest clearance rose in Arequipa as a response to the substitution of coca with alternative development crops. In Caracas rates of forest clearance in some plots increased because of the increase in banana cultivation but were offset by crop rotation and the regrowth of forest in some plots. Although coca prices have risen since 1998 farmers have resisted growing the crop in large quantities. This reduction in coca cultivation may have been helped by encouraging whole communities to co-operate in return for improved transport connections (i.e. converting from a dirt track to an unsealed or cobbled road) to the Cochabama to Santa Cruz highway. Overall, cultivation of coca was being discouraged and land-hungry alternative development crops including banana cultivation and heart of palm encouraged. The increase of production of alternative crops for the whole of Chapare at this time is evident in Figure 6.10.

6.6 Comparing clearance with other colonisation zones

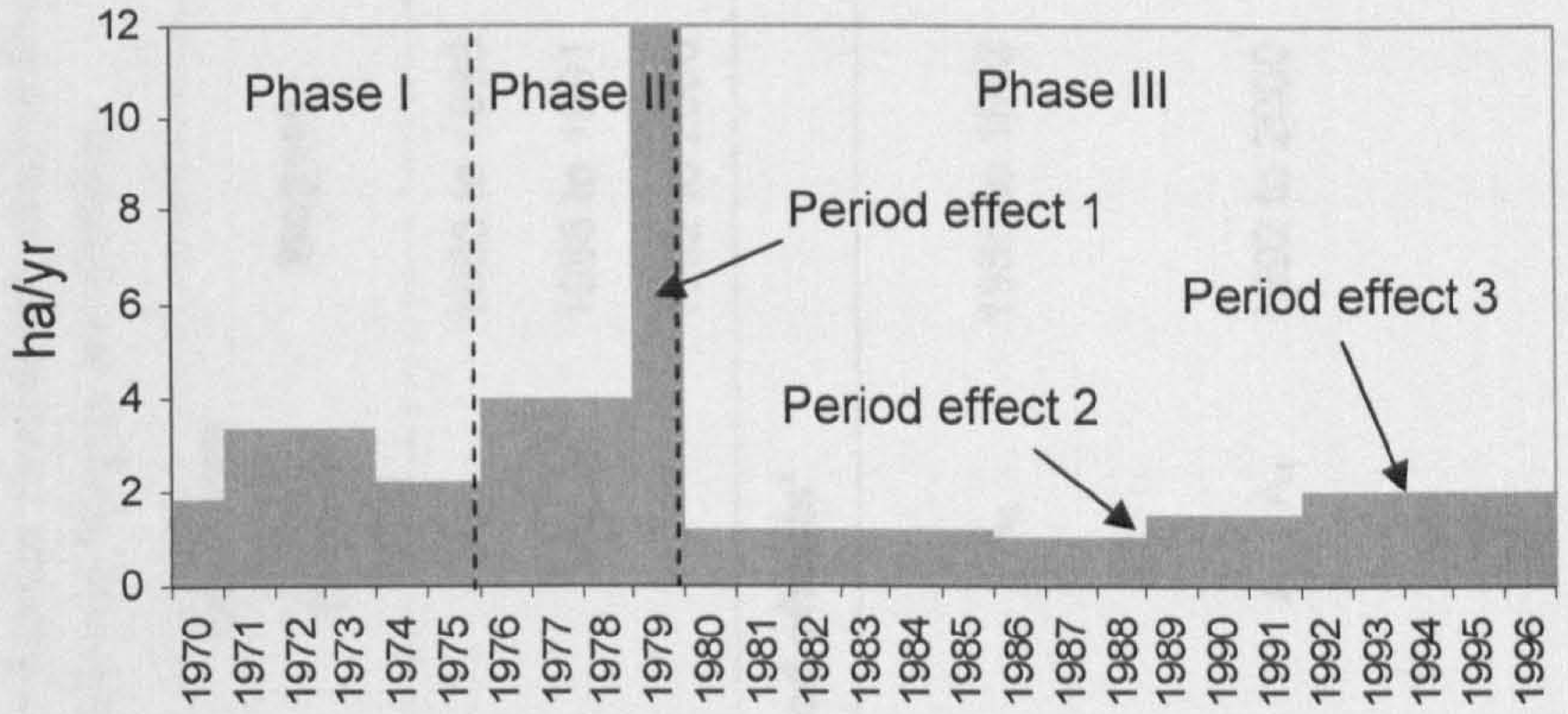
The variations in drivers identified in this research have caused the LULCC in Chapare to progress at different rates producing a particular deforestation trajectory or trajectories (Figure 6.12). It is possible to compare the findings of this research with deforestation trajectories that have been studied and described in detail in Altamira, Brazil, described by the 'colonist footprint' model (Brondizio *et al.*, 2002). For the ease of comparison the descriptions of age effects in Brondizio *et al.*'s (2002) 'colonist footprint' model have been assigned to three phases:

- Phase I – Opening up of farms, causing a rapid increase in the rates of forest clearance followed by a decrease in rates of forest clearance;
- Phase II – Investment in a perennial crop (s), resulting in another rapid rise in rates of clearance;
- Phase III – Consolidation of perennial crop(s) with secondary succession management. Rates of forest clearance decline.

Brondizio *et al.* (2002) describe these phases in terms of the percentage clearance of plots between times of image acquisition where 3,288 plots averaged 100 ha. The comparisons between the Chapare communities and the Brondizio work are made in ha yr^{-1} because some plots are different sizes and the number of plots in Arequipa, Bogotá and Caracas are 59, 86 and 98 respectively. In this calculation the rates between image dates are assumed to be consistent. Figure 6.13 shows an example of the 'colonist footprint' in Altamira for Cohort 1 as described by Brondizio *et al.*

(2002) the phases are noted on the diagram. Brondizio *et al.* (2002) also described 'period effects' which are events that happen at a specific time and become superimposed on the trajectory e.g. subsidies for cattle ranching may lead to an increase in deforestation. The 'colonist footprint' of the three communities in Chapare is illustrated in Figure 6.12. The age and 'period effects' for cohort 1 (Altamira) and Arequipa, Bogotá and Caracas (Chapare) have been summarized in Table 6.5.

Figure 6.13: Cohort 1 Altamira, 'colonist footprint' model showing age and where 'period effects' are postulated to have contributed to clearance rates. 'Period effects' explained in Table 6.9. Source: Brondizio *et al.* (2002).



The land-use stages in Chapare can be compared to Brondizio *et al.'s* (2002) model. However, the deforestation trajectories (Figure 6.10) show that the three communities do not always conform to the phases the 'colonist footprint' in Altamira. Phase I, the opening of farms, has occurred in all three communities in Chapare. There were high rates of clearance from 1982 to 1986 in both Arequipa and Bogotá which were then followed by decreased deforestation rates from 1986 to 1992. These two trajectories are comparable to the period when subsistence was being established in the Altamira footprint model, A_1 and the early stages of B_1. In Caracas there was no imagery for the equivalent phase, but interviews and documentation suggested that farmers began with subsistence so this is a good indication that Phase I occurred there

Table 6.5: Comparison of the 'colonist footprint' model with the land-use trajectories of the communities in Chapare. The three Phases of the 'colonist footprint' for Cohort 1 in Altamira are shown in the first two columns and the 'period effects' superimposed on the footprint are explained (refer to Figure 6.13). The similarities and differences to this model are shown for Arequipa, Bogotá and Caracas in Chapare, their equivalent land-use stages are shown.

'colonist footprint' Brondizio *et al.* (2002)	Cohort 1 (pre 1973) Altamira	Comparison of 'colonist footprint'	Arequipa	Land-use stage (Figure 6.11)	Bogotá	Land-use stage (Figure 6.11)	Caracas	Land-use stage (Figure 6.11)
Phase I	1970 to 1975	Phase I	1983 to 1985	A_2	1983 to 1985	B_2	1963 to ?	C_1
Phase II	1976 to 1979	Phase II	1986 to 1992	A_3	1986 to 1991	B_3/B_4	? to 1986	$C_1/C_2/C_3$
Phase III	1980 to 1991	Phase III	-	-	1992 to 2000	B_5	1986 to 2000	C_3/C_4
				'Period effects'				
1. No explanation	1979	Coca prices	1986 to 1992	A_3	1986 to 1992	B_3 / B_4	1986 to 1992	C_3
2. Withdrawal of cattle ranching incentives, late 1980s	1988 to 1991	Coca eradication and AD policy	1992 to 2000	A_3 / A_4	1992 to 2000	B_4 / B_5	1992 to 2000	C_3 / C_4
3. Credit incentives in 1994	1992 to 1996							

as well, although there is no quantifiable evidence for this because the deforestation rate calculation between 1963 and 1976 smoothed out any increases or decreases within deforestation, which may last for up to three to five years (Brondizio *et al.*, 2002).

The deforestation trajectories for the three communities then deviate from the 'colonist footprint' model in Altamira. In Arequipa Phase II (investment in perennial crops) occurred during land-use stages A_2 to A_3 (the cultivation of coca and bananas); yet from 1986 to 1993 the deforestation rates were at their lowest and the community did not conform to the 'colonist footprint' model. The rates are lower in Arequipa for two reasons: first, because the coca crop does not require large areas of land; and, secondly, although bananas would normally require a large area of land, at this time the market price was high and it was unnecessary to clear large amounts of forest. The deforestation rates in Bogotá differed from those at Arequipa. Although in land-use stages B_3 and B_4 a perennial crop (coca leaf) was being cultivated at Bogotá, at this time, the farmers were also clearing land for pasture. This pattern of land clearance fits into phase II of Brondizio *et al.*'s (2002) model. However, pasture and cattle herd expansion was often funded by money from coca substitution, so this investment could arguably be seen as a localised response to a 'period effect' superimposed upon the deforestation trajectory. In the region of Caracas documentation referring to the government sponsored programs (Henkel, unpublished) and interviews in 2002 indicate that perennial crops were invested in between 1963 and 1976 and excessive clearance would have taken place because of the lack of technical knowledge on the cultivation of suitable crops in this new colonisation zone. The original colonisers in Altamira have also been recorded as having removed greater areas of forest than necessary because of their lack of understanding of the conditions in the area (Brondizio *et al.*, 2002).

Brondizio *et al.*'s (2002) model indicates that by Phase III there should be a decline in rates of deforestation after the investment in perennial crops. However in Arequipa the opposite occurred and there was an increase in rates of forest clearance. As most of the plots still had about half of their plots available to clear at this time, farmers continued clearing forest as there was no pressure to move into the management of secondary succession. In Bogotá there was a decline in the rate of deforestation between 1996 and 2000 (land-use stages B_4 and B_5). At this time pasture expanded following two or three years of rice cultivation. Although the rates of land clearance were low and forest conversion declined overall, some farmers were still expanding their pasture areas whilst other plots have been completely cleared and turned over to pasture. In Caracas the equivalent of Phase III was reached between 1986 and 2000 (land-use stages C_3 and C_4). Here investment of several perennial crops, rather than just one was occurring, e.g. bananas, citrus fruit and, in some cases, tea and other alternative development crops. Management of secondary succession was occurring because many farmers had completely cleared their plots and had reverted to crop rotation. There was a general decline in deforestation rates through the period in Caracas, but this did fluctuate and was probably the result of 'period effects' being superimposed on the trajectory, for example some farmers in the newer plots were clearing the forest for bananas.

There are two main 'period effects' which have contributed to variations in trajectories for the three communities: (i) high coca prices from 1986 to 1992; (ii) attempts at coca eradication and the encouragement of alternative development from 1993 to 2000 (Table 6.3). In Arequipa during land-use stage A_3, a perennial crop (coca) was being cultivated and this resulted in low rates of forest clearance because of the high selling returns from small land areas. The effects of high coca prices are less clear in Bogotá because it was not possible to determine if the clearance rates decreased at the end of Phase I. The land-use Phase changed from B_3 to B_4 and farmers generally moved from coca cultivation to pasture. The interviews suggest that some farmers had invested in coca cultivation at this time because of the high coca prices but other farmers accepted subsidies for reducing coca cultivation and invested this in expanding their cattle herds which caused forest clearance rates to increase. Between 1986 and 1992 the land-use stage in Caracas was C_3 and there was a fall in clearance rates. There were a number of reasons for this. First, high coca leaf prices discouraged the need to clear large areas of forest; secondly, many of the plots are totally or almost cleared; and thirdly, secondary succession management was occurring. All of which accords with Phase III of the Brondizio *et al.* (2002) model. The effect of attempts at coca eradication and encouragement of alternative development ('period effect' ii) had different responses in each of the communities. In Arequipa there was a pulse of clearance from 1993 and this corresponded to the land-use stages A_3 and A_4 when farmers were beginning to move away from dependence on coca and starting to cultivate alternatives to coca. Alternatives, such as bananas and heart of palm are less conservative in their land requirements (Table 6.1) and rates of forest clearance increased. Therefore instead of complying with Phase III it can be argued that Arequipa at this time had returned to a Phase II-type situation with investment in perennial crops. The effect of coca eradication and the encouragement into alternative development was not evident in Bogotá as there was a general fall in deforestation rates. Most of the incentives to remove coca in Bogotá resulted in cattle expansion (land-use stages B_4 and B_5). In Caracas there was an increase in clearance rates between 1993 and 1996, but these had declined by 2000 because the community had reached Phase III of the 'colonist footprint' model. At this time a number of farmers had been encouraged to expand or begin to cultivate bananas for export. The new plots to the northeast and southeast of the community were evidence of this, these plots were only partially cleared and the clearance rates increased between 1993 and 1996 (Figure 5.7).

Although the 'colonist footprint' model of Brondizio *et al.*, (2002) goes some way to explaining the clearance patterns in the three Chapare communities studied for this research, the model does not always work. The Phase I in the communities in the Chapare communities has similar characteristics to Phase I in Altamira, i.e. initially high forest clearance rates followed by a period in which the rates slacken off, is found in Arequipa and Bogotá. This Phase probably occurred at Caracas before the acquisition of the first image in the sequence. The biggest variations between Chapare and Altamiria occur in Phase II. On the one hand in both areas farmers generally switched to perennial crops, but on the other hand the effects of this switch on clearance rates was different. Because farmers in Arequipa chose coca, a crop with conservative land requirements, during Phase II, clearance rates were low. However, in Bogotá and Caracas the trajectories more-or-less corresponded to the increased clearance rates seen in Altamira because of the perennial agricultural land-use type chosen was pasture and bananas respectively. Elements of Phase III management of secondary forest regrowth can be seen in Bogota and Caracas, but this has been complicated by the 'period effects' associated with the coca economy. These have had even greater effects at Arequipa. The main differences in the application of the 'colonist footprint' model lie in the fact that (i) perennial crops require different amounts of forest to be cleared (and coca is at the lower end of this range); and (ii) the timing of local 'period effects' and, maybe, more widespread policy shifts and market fluctuations compared to the time of initial colonisation and the demographic growth of communities.

6.7 A conceptual framework for LULCC in Chapare

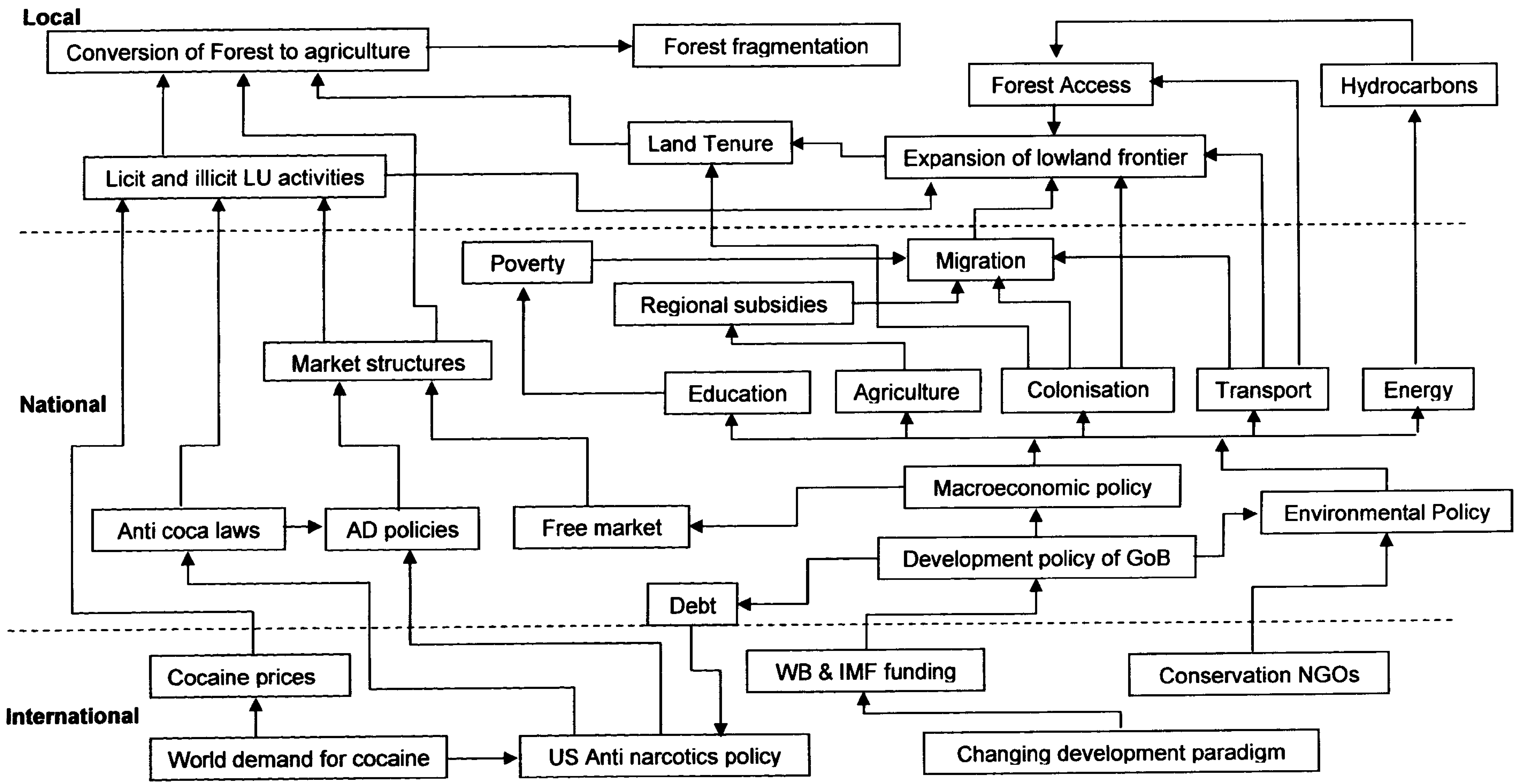
In Chapter 1 the conceptual framework of driving forces of LULCC and biodiversity change for Parque Nacional Carassco was introduced (Figure 1.1). In this model the driving forces of LULCC and biodiversity were described for the highlands and lowlands of the study area. The driving forces acting on the lowland area can be applied to the forests in Chapare and these components of the model have been elaborated on. The model in Figure 6.14 excludes environmental impacts in the region, drivers acting on the highland region, and the details on biodiversity loss have been removed.

This research has enabled expansion of the details of the coca cycle and market structures in the model which are present in Chapare, and it has been changed to include economic and policy drivers at the national level. The policy drivers relate to criminalisation of the cultivation of coca and alternative development programmes to substitute for coca. The economic drivers are expanded upon by the inclusion of market structures for the main agricultural activities in the Chapare. The model divides the driving forces discussed in Section 6.5 in local, national and international scales. These drivers are not equally dominant as the components of the model are time dependent, i.e. some parts of the model may have operated with greater influence than others at particular times.

The Government of Bolivia's policies operate at the national level and policies are generally applied country-wide. Since the 1950s, macroeconomic policy has developed to diversify the economy from the dependence on the mining industry, by broadening the economy into agriculture, by opening areas of lowland forest to farming, encouraging colonisation and improving transport linkages between the lowlands to the highlands. Highland poverty needed to be relieved and the national policies stimulated migration into new agricultural zones in the tropical lowlands. Chapare was one of these areas and this is an example of where national level drivers have influenced local level drivers. After unsuccessful colonisation prior to the 1960s, government directed colonisation planned communities, divided these into plots which could supply agricultural produce to the national market while sustaining the needs of a family (Plan Decinal, 1961 to 1971). The programme sponsored colonists to grow particular crops, while the land tenure patterns determined the extent and spatial patterns of future LULCC. Investment in the transport network was initially directed at linking the cattle-rearing regions of Beni to Cochabamba which is why roads to Todos Santos and Puerto Villarroel were developed in the 1940s and the 1970s respectively. However, there was an expanding agricultural area in Santa Cruz which also needed to be integrated with the rest of Bolivia. The old highland route linking Cochabamba and Santa Cruz was slow and arduous and a national programme to develop exportation corridors to transport agricultural products across the country replaced the existing Cochabamba to Santa Cruz road with a faster route through Chapare. Funding for these developments were secured, in part because of interest and investment from foreign oil companies prospecting for hydrocarbon reserves during the 1970s. Prior to road building in Chapare it is unclear what impacts hydrocarbon prospecting had on LULCC but access roads to gas installations has subsequently encouraged spontaneous colonisation. Agricultural policies have also stimulated growth in certain areas of Bolivia, but Chapare has often been overlooked and subsidies have been directed towards the soya bean cultivation zone in Santa Cruz Department.

National policies have been supported by lending through international sources such as the World Bank, International Monetary Fund and Inter-American Development Bank, European Union.

Figure 6.14 Conceptual model of the driving forces of LULCC leading to forest fragmentation in Chapare.



The conditions for foreign lending to developing countries have changed as development paradigms have changed.

In the 1960s and 1970s lending tended to be based on the building of national economies through national development plans. In the 1980s, the Washington Consensus favoured strengthening of the economy by opening up markets through structural adjustment policies in the beginning of the modern era of globalisation. In the 1990s the Washington Consensus favoured sustainable human development and decentralisation while the Southern Consensus argued for strategic market integration and technology transfer from the north (Gore, 2003). Not surprisingly then, international lending has driven policies of national development in Bolivia, along the lines outlined above, but there have been particular riders to lending to Bolivia related to the eradication of coca which have been referred to earlier in the thesis. Structural Adjustment Policies in the 1980s led to widespread unemployment of former state employees which fuelled migration to Chapare (amongst other regions). This is just one example of how development programs formulated in response to the macroeconomic policies have affected the 'local scale' in Chapare. Such cases illustrate how international drivers are linked to the local level.

Economic policy drivers have also been inept and, at the international level the world demand and price of cocaine has had a major impact on the land-use activities at the local level in Chapare. High prices of coca leaf, relative to the other crops, has not only encouraged preferential coca cultivation but encouraged migration to Chapare. The development of other crops has been hindered by a national level obstacle the structure of the supply routes to market. Coca cultivation, which dominated through the 1980s and 1990s in Chapare, slowed LULCC. The national and international supply structures and cocaine market undermined national development policies in the Chapare region and also concentrated international drivers on the area. The US Government anti-narcotics and allied policies more-or-less by passed the national level and linked directly to local level drivers of LULCC. For example, anti-coca policies dictated a change in land-use towards tropical fruits and cattle grazing when the economy was more reliant and economically favourable to coca leaf cultivation, and clearance rates increased. Because of the level of foreign debt incurred by Bolivia through lending to support national level development policies and the country's involvement, with the cocaine trade, the US government have been able to impose *their* solutions on Bolivia and this has in part led to the direct international-local linkages in Chapare. Though of course, the nature of the coca trade meant that Chapare was always directly linked to a particular global economy once farmers began to cultivate coca.

6.8 Summary

- **Economic drivers**

In Chapare farmers produced bulky, perishable goods which they could not transport to markets easily by themselves because of the high costs of moving these goods to market. The markets for fruits, meat and dairy produce were all outside Chapare in the major cities of Bolivia (mainly Cochabamba and Santa Cruz) with export markets (e.g. Argentina) for some fruits (Section 6.2.2). Markets were reached through the supply chains using middlemen who transported the goods for the farmers however, this gave them the capacity to control the market supply and prices (Section 6.2.1). The sale of meat was to the local market, and farmers could easily transport a single carcass there, but in order to reach the slaughterhouses of the national market farmers had to use the supply chain and sell to the wholesalers. The fruit crops discussed showed that prices had seasonal and inter-annual variations. Bananas prices (Section 6.2.2.1) in the early 1990s showed boom-bust scenarios and prices gradually increased, and decreased to

2000. In the 1990s, alternative development projects created grower associations where overheads and transport costs were shared this was designed to supply the export market. The situation was similar for pineapple (Section 6.2.2.3) and prices also showed seasonal variations. These variations were more pronounced in the early 1990s when prices were five times lower than 2002 to 2003. As with bananas growers associations were created, but a producer had to commit to an export variety not favoured on the national market. The market for oranges (Section 6.2.2.4) is almost entirely based on selling to the national markets through the wholesale supply chain and highest prices for oranges were when the crop was out of season. Heart of palm can produce up to three crops a year, but in 2002 and 2003 prices were disappointingly low often less than a Boliviano for a stem, there was little demand on the national market and export potential is low (Section 6.2.2.5).

- **Policy drivers**

The colonisation of Chapare began through national policies designed for economic diversification and import substitution. These policies were implemented in the 1960s and led to colonisation of tropical forest for agriculture (including Chapare) but the government incurred national debts in the 1970s and an economic crisis in the 1980s which was countered with structural adjustment policies. Because of the events in the 1970s and the 1980s, aid money came at a price as a result of the expansion of coca leaf production. International support demanded the implementation of policies towards the reduction of coca cultivation and this led to a focus on internationally-led policies in Chapare from the 1980s (Section 6.3). Limited success of national policies was related to the reduction in coca cultivation and encouragement of substitute crops (Section 6.4). Anti-coca policies included: compensation for voluntary or forced coca bush eradication (1981); an attempt to control the coca leaf market (1981); aggressive programmes of coca bush removal (1986 and 1998); and legalisation of areas to cultivate coca (1988). The focus of alternative development policies have also changed: encouraging the cultivation of coca bush alternatives, later with compensation for 'crop substitution' (CDRP 1984 to 1990); and 'economy substitution' (CORDEP 1991 to 1999) plus better support and promotion to farmers in Chapare following actions of anti coca policies (CONCADE 1999 to 2003). The limited success of coca bush reduction is illustrated (Table 6.10), whilst the area of alternative crops increased from 1985 to 2000 areas of coca cultivation from 1991 to 1999 were still relatively high.

- **The illicit coca economy**

The expansion of coca cultivation since the 1970s changed the focus of the coca leaf market from supplying the traditional national markets to the illegal international cocaine trade. Furthermore the high prices, high demand, multiple harvests, relatively stable market and ease of transporting sacks of coca leaf for sale made this activity far more attractive to farmers than totally relying on fruit and cattle. Prices of coca were affected by national level events, e.g. a boom-bust scenario in the early 1980s (Figure 6.9) led to the relatively low coca leaf prices, and the eradication of bushes in Plan Dignidad (1998 to 2002) increased the price of coca leaf. At the international level falling prices of cocaine in North America contributed to the low price of coca leaf. Despite these price fluctuations the financial reward of cultivating coca leaf was better than legal activities in Chapare. One significant aspect of LULCC in Chapare was that even if a farmer choose an alternative to coca he must clear a larger area of land in order to make the same financial returns, thus in terms of land clearance, coca cultivation out competes other crops on a hectare-by-hectare basis, paradoxically this means that illicit coca cultivation is more conservative on land requirements in comparison to alternative crops.

- **LULCC responses to the drivers**

In the communities the synopsis of land-use management illustrated three stages of land-use; pre-coca dominance (1960 – 1979), coca-dominance (1980 to 1995) and post-coca dominance (1995 to 2000), (Section 6.5). The clearance rates in each stage were related to land use management decisions as a response to the driving forces acting on the area. In the pre-coca dominance (1960 – 1979) stage, national level policy drivers to expand the economy drove the forest clearance, but land-use management problems at the local level led to high clearance rates in Caracas. The coca-dominance (1980 to 1995) period was driven by the continuing failure of the national level economic policies to adequately connect Chapare to the national market, whilst at the same time there was an expanding market for coca leaf driven by the international market for cocaine. However, rather than increase rates of deforestation through the expansion of coca cultivation there were different rates of clearance in the communities, depending on their existing land-management systems. Toward the end of the coca dominant period national policies encouraged alternatives to coca, such as selected crops and encouraged pasture expansion, this contributed to the higher clearance rates at the end of the period. This process continued into the post-coca dominance (1995 to 2000) period, but where plots of land had been completely cleared rates of forest clearance had fallen as the forest was cleared during the previous period. For example, in the older community of Caracas and in Bogotá where there was a mixture of plot sizes, clearance rates fell because some plots were virtually cleared of forest, but where land was still available to clear, deforestation was continuing, this was most evident from the clearance rates in Bogotá.

- **Changes in LULCC drivers**

In the 1960s economic drivers (Section 6.2) were largely responsible for LULCC in Chapare through national level policies. The plan was to make Chapare into an agricultural zone farmed by the migrants from the highlands. However, the constraints of implementing this model allowed the illegal coca market to expand particularly through the 1980s and early 1990s, as the market conditions favoured this activity. The 'free market' conditions were then overridden in the mid 1990s with the implementation of policies from the international level designed to stop the cultivation of coca (Section 6.3). These policies had gradually forced farmers in Chapare to enter markets with alternative development products or concentrate on their original activities where the access to and returns on the national market were constrained. As the economic drivers were overridden by the policy drivers the rates of LULCC were affected and the clearance rates increased, particularly in communities where forest was available to clear.

- **The difference in clearance trajectories to the 'colonist footprint' model**

The clearance trajectories prior to 1986 showed all the hallmarks of Phase I in the 'colonist footprint' model of Brondizio *et al.* (2002) when the communities were first settled (Section 6.6). However, Phase II was more difficult to apply because the perennial crops which were chosen were not always land-hungry options, and this was clear when coca leaf cultivation was selected in Arequipa. In Bogotá and Caracas the communities showed Phase II characteristics as a major land-use activity had been selected before the coca boom, this was production of fruits (Caracas) and expansion of pasture (Bogotá) although coca was also selected, the impacts on LULCC rates were less obvious. Because of the progression of clearance in the plots of Caracas and Bogotá, Phase III was evident because many plots had exhausted their land area, and in

Arequipa this phase was not evident because there was available land. In fact in Arequipa the anti-coca and alternative development policies had rejuvenated a Phase II scenario. The difficulty of applying this model in the three communities is that the area was complicated by the coca economy, policy shifts to counter coca cultivation and market fluctuations in comparison to the time of colonisation.

- **Scales of drivers**

Drivers of LULCC exist at the local, national and international levels (Section 6.7). At the international level LULCC activities have been affected directly by the economics of the international cocaine market. The international drivers have also affected the economic policies of the governments of Bolivia as the paradigm of international lending has shifted from supporting national expansion to free market economies. The international support for development obliged the Government of Bolivia to implement policies against coca cultivation in Chapare in response to international pressure against narcotics.

At the national level the timing of macroeconomic policy shifts are responsible for the colonisation of the region and periods of agricultural expansion, in turn the national policies have driven the land-use management patterns and expansion into the forest by creating access and distributing land to migrants at the local scale.

Also at the local level, clearance of the forest is a response to the licit (national markets) and illicit (international markets) where the combinations of land-use activities lead to forest fragmentation and differential rates of clearance, (discussed in Chapter 7). As indicated above the economic drivers were then overridden by policy drivers which criminalised coca cultivation in Chapare and encouraged activities with a national market accompanied by the creation of small scale export markets.

Chapter 7

Explaining forest fragmentation in the context of LULCC

Chapter 7

Explaining forest fragmentation in the context of LULCC.

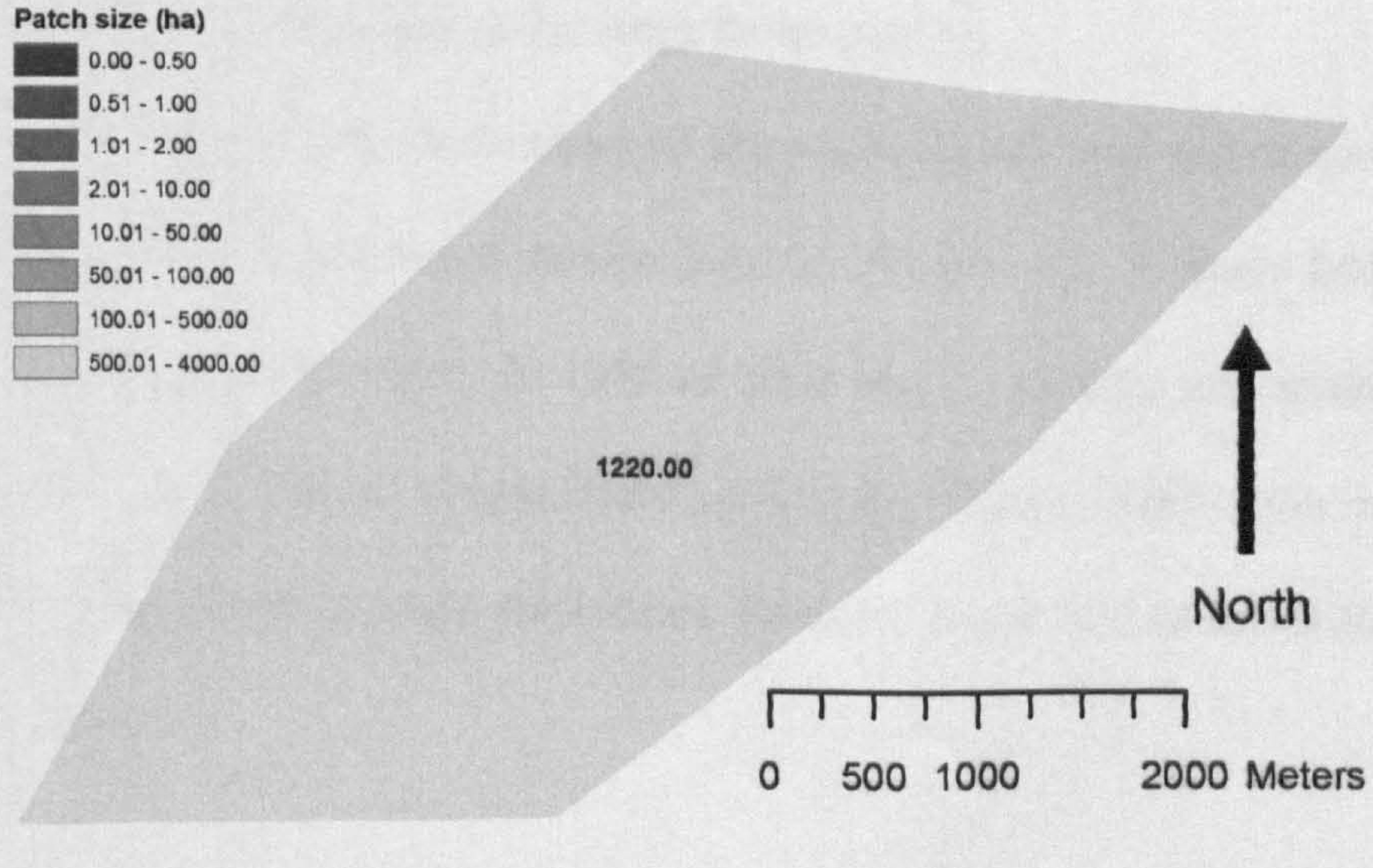
7.1 Introduction

In this chapter the evolution of fragmentation patterns of the three communities in Chapare in the context of the drivers of LULCC and key spatial attributes of the communities are analysed. The trends in fragmentation patterns for each community are then compared to Lambin's (1997) fragmentation model parameterised with metrics from Trani *et al*. (1997). Finally, the findings of this research are used to construct an explanatory model of deforestation at the community level in Chapare.

7.2 Arequipa

In 1976 the land-use stage at Arequipa was A_1 *pre colonisation* (Section 5.2.5). Therefore all of the plots were Type I typology (Table 5.2) and there was no evident anthropogenic fragmentation of the forest (Table 5.1, Figure 7.1). The entire area was forest.

Figure 7.1: Forest at Arequipa in 1976



By 1986 the community had passed through land-use stage; A_2 – *subsistence cultivation* (c.1983 – c.1985), and was in the early stages of stage A_3 – *coca, rice and bananas* (c.1985 – c.1995) (Figure 5.27). The average cleared area for each plot was 2.8 ha. The major clearance typologies were Type II (47%) and Type IV (41%) (Table 5.2). The impact of this clearance was a large 160 hectare of non-forest area in the centre of the community and numerous small irregular non-forest patches (Figures 7.2 and 7.3). The MPS (4.17 ha) was low reflecting the high number of patches below 2 ha (Figure 7.2) and the skewed distribution led to a high PSCV (555%). The MNN (176.3 m) shows that patches were on average quite far apart but there was wide range of distances in non-forest indicated by the NNSD of 198.9 m and the NNCV of 113%.

The clearance that had taken place by 1986 had created two large forest patches – one each to the north and south of the large non-forest patch – with 17 small patches of no more than a hectare each (Figure 7.4); thereby producing a bimodal distribution of forest patch sizes (Figure 7.5). The MPS (54.9 ha) had fallen between the extremes and the PSSD (161.7 ha) and PSCV (294%) were high. However, the MNN (49.1 m) was low, as were the NNSD (28.5 m) and NNCV (58%) because the small forest patches in the non-forest area were close to the edges of the large forest patches.

The large cleared area had formed because of the original INC plan which had located all the plots next to each other with access from a central road. Farmers had cleared from the primary ends of the plots. In 1984 all plots had on average just under 1ha of coca (DAI, 1994). Over 70% of the *sindicato* participated in coca eradication in 1984, so some farmers had turned to coca substitutes, however many had returned to coca by land-use stage A_3.

Figure 7.2: Non-forest fragments in Arequipa 1986.

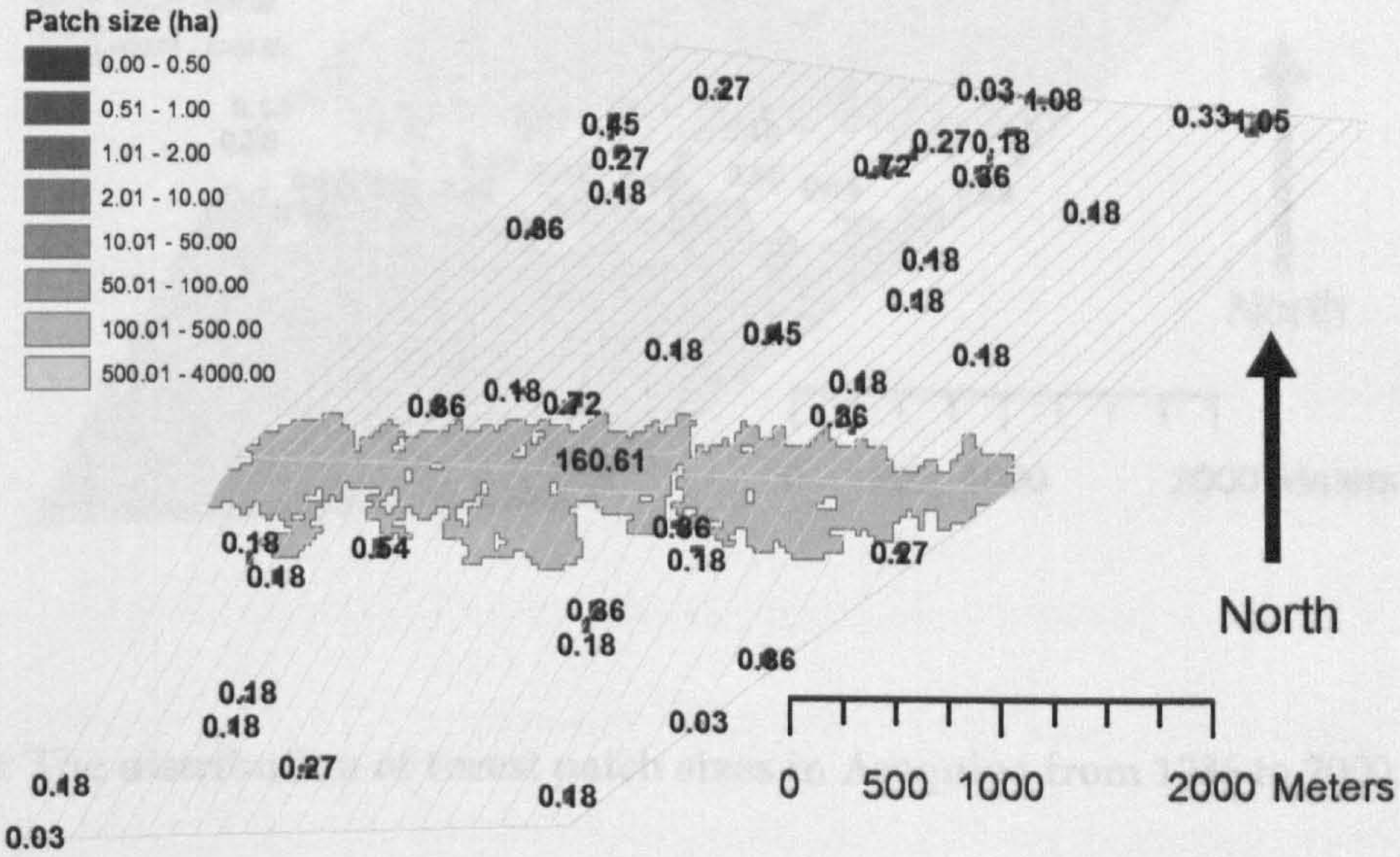


Figure 7.3: The distribution of non-forest patch sizes in Arequipa from 1986 to 2000.

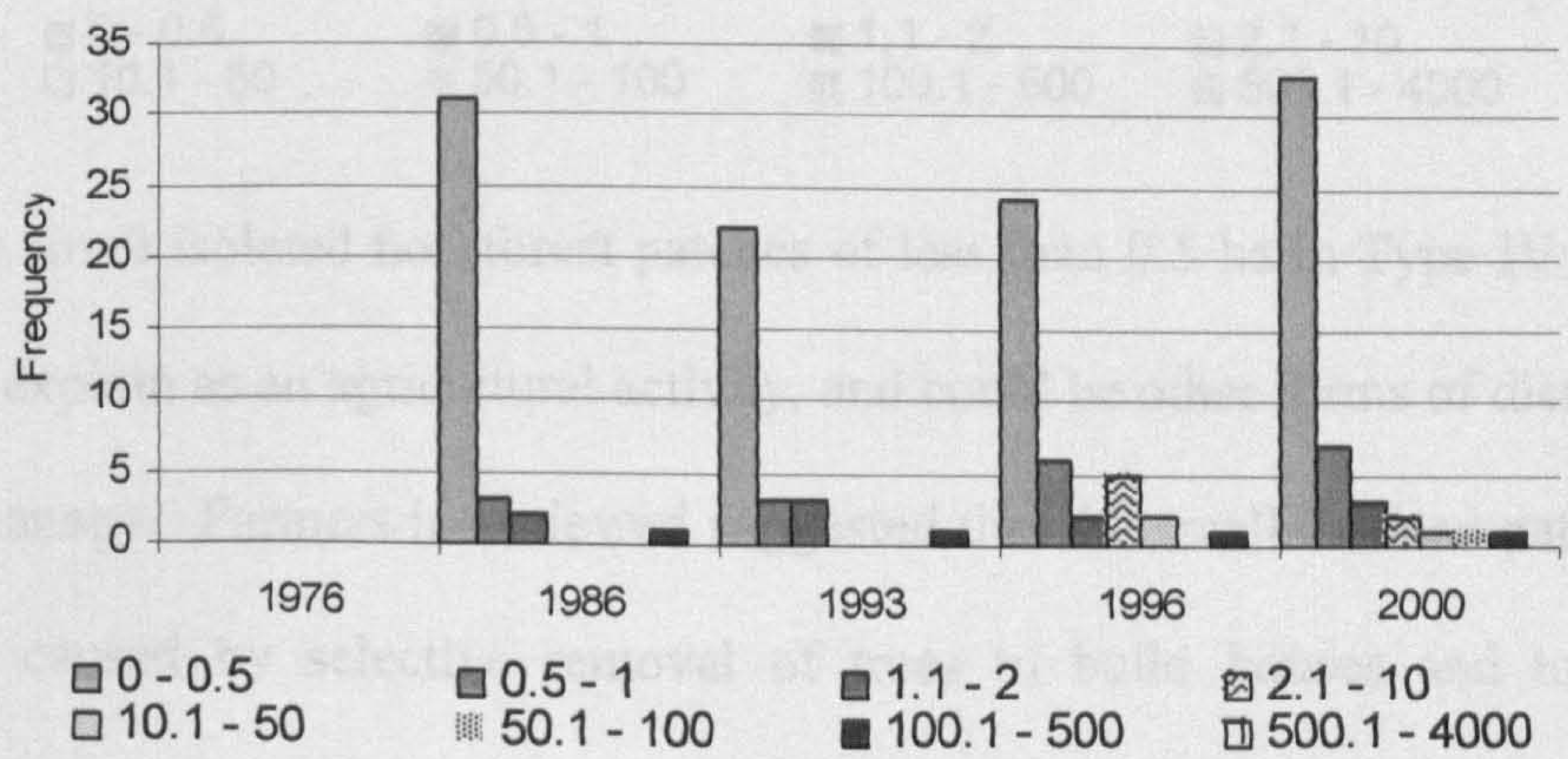


Figure 7.4: Forest fragments in Arequipa 1986.

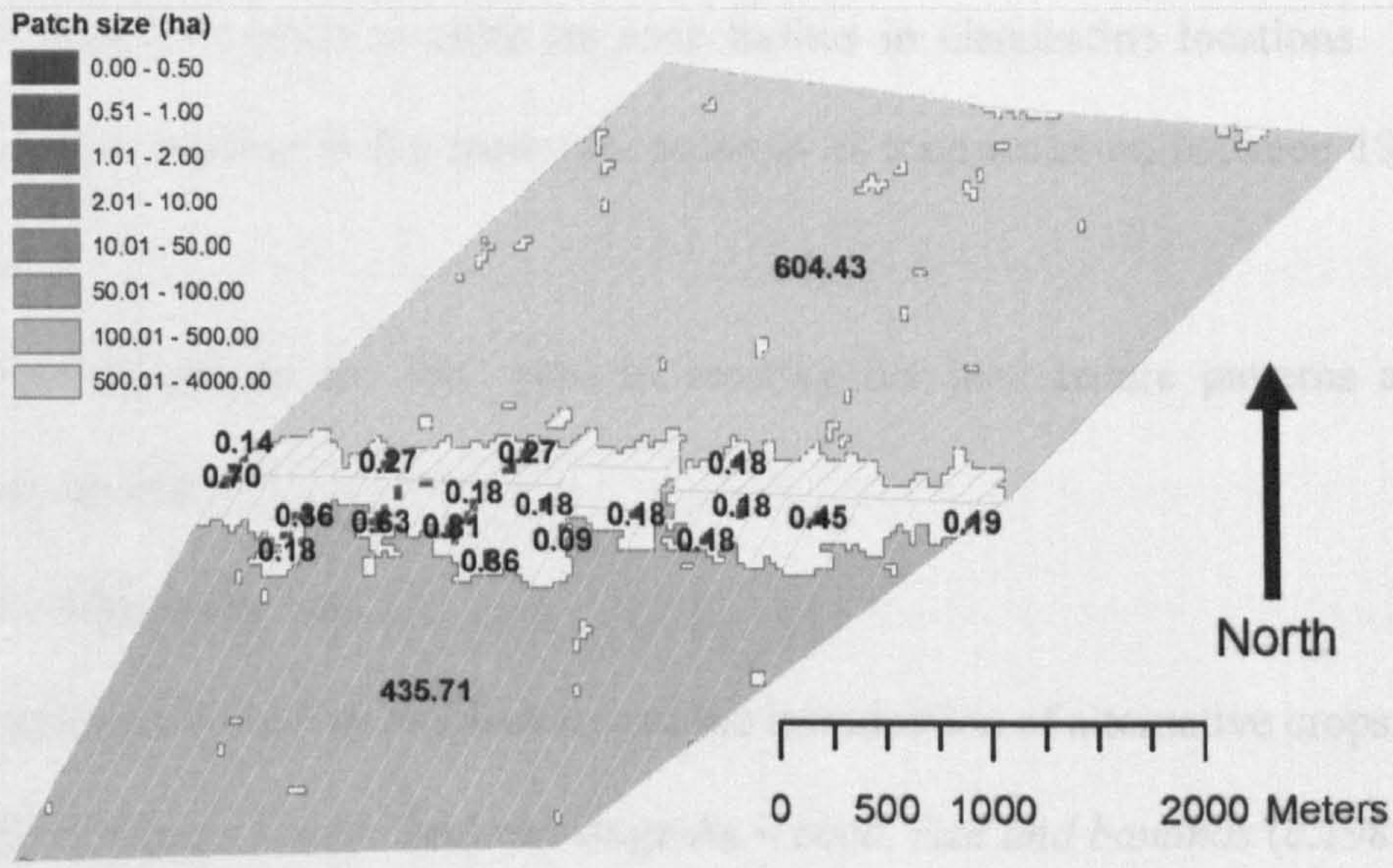
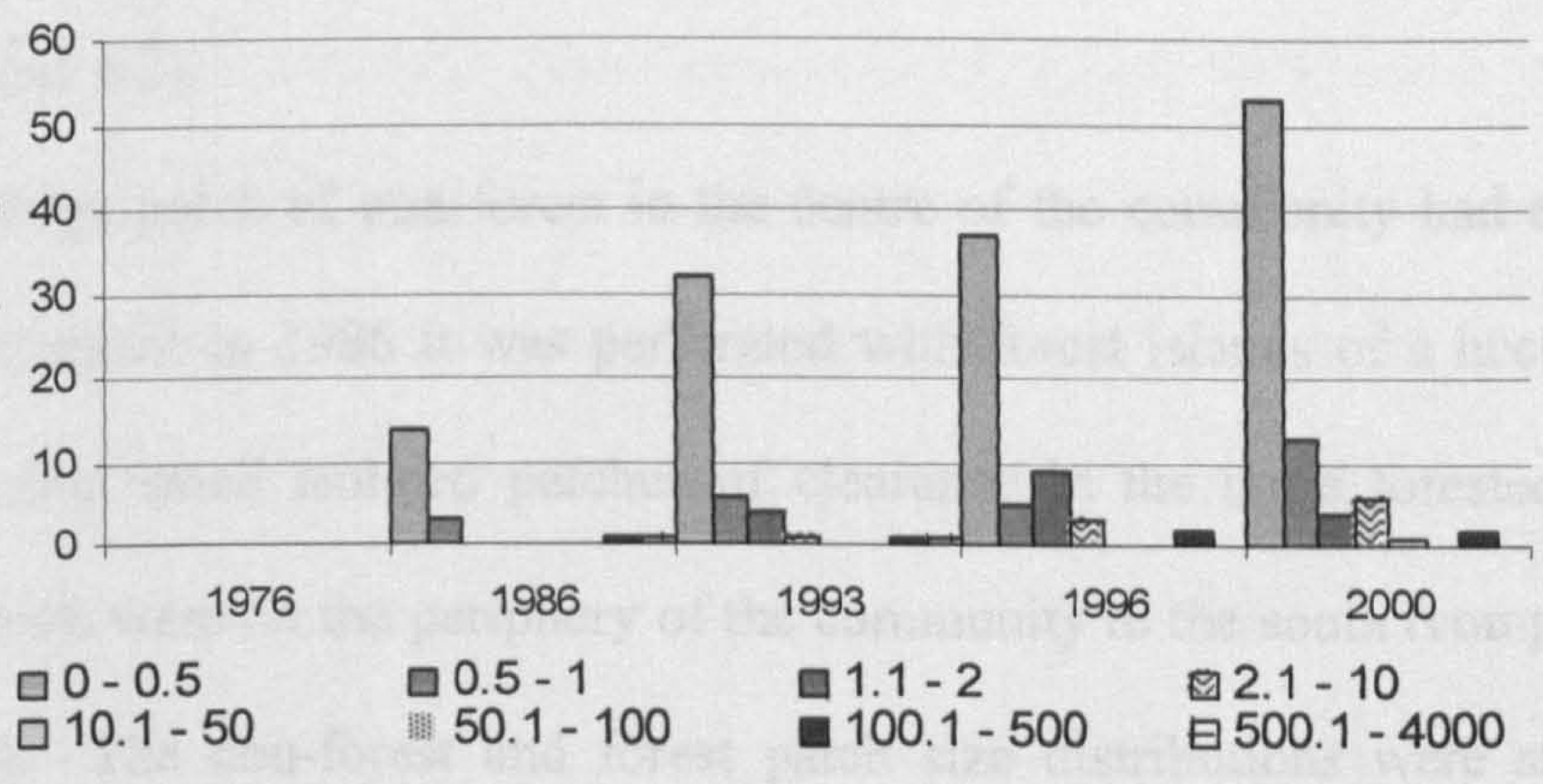


Figure 7.5: The distribution of forest patch sizes in Arequipa from 1986 to 2000.



The small isolated non-forest patches of less than 0.5 ha in Type IV plots were difficult to explain as an agricultural activity, and could be other forms of disturbance of the forest canopy. Farmers interviewed suggested that the small isolated patches could have been caused by selective removal of trees to build houses and to construct furniture which was a priority in the early stages of settlement. The larger, 0.5 to 2.0 ha, isolated patches of non-forest were likely to be agriculture and not tree fall. Some non-forest patches were because farmers had encountered physical barriers, for example a river or a short steep slope but it was possible that eradication of coca had driven some farmers further into their plots to cultivate coca bushes in clandestine locations. In summary the drivers leading to the particular patterns of fragmentation between 1976 and 1986 were:

- the spatial attributes of the INC plan in creating the land tenure patterns and determining access;
- subsistence cultivation; and,
- coca cultivation followed by eradication and the introduction of alternative crops.

By 1993 Arequipa was in land-use stage A_3 – *coca, rice and bananas* (c.1985 – c.1995). The average area cleared in each plot had increased to between 3 and 4 ha, but the rate of clearance (0.14 ha yr^{-1}) over seven years prior to 1993 was lower than prior to 1986 (0.93 ha yr^{-1}). Type IV was the major clearance typology, comprising 64% of the plots (Table 5.2).

The large patch of non-forest in the centre of the community had expanded to 205.3 ha but unlike in 1986 it was perforated with forest islands of a hectare or less. There were also small isolated patches of clearance in the large forested areas, the largest of which were on the periphery of the community to the south (compare Figures 7.4 and 7.6). The non-forest and forest patch size distributions were still bimodal (Figures 7.3 and 7.5). The number of small (< 5 ha) forest patches had increased and the number of small non-forest patches had decreased slightly. The MPS (8.0 ha) for non-forest areas increased because a group of patches of about 1-5 ha had been created. The PSSD (40.1) had also increased because the large non-forest patch had increased in area and the PSCV (499%) remained large. The MNN (145.9 m) of non-forest patches decreased because the patches were larger and closer together than in 1986, but the high NNSD (182.3 m) reflected the fact that some patches were still a long way from the main non-forest patch and the high NNCV (125%) indicates that these distances were not constant.

The distribution pattern of forest patches in 1993 was similar to 1986. There were two large patches and quite a few 0 to 2 ha size patches in the non-forest area. The metrics indicate that there was an increase in forest patches, but the MPS had decreased (55 to 22 ha) from 1986 to 1993. The NNSD had fallen in this time (161.7 to 100.4 m) because the forest patches had reduced in size, but an increase in PSCV (294 to 458%) showed that the patches were not of regular size. Because the patches were close to each other the MNN was low (42.1 m), the NNSD (16.86 m) was small and the consistency (NNCV) in this distance was high (40%). The total edge length of the forest had increased from 31,380 m in 1986 to 56,460 m in 1993.

Farmers continued to clear from the primary ends of their plots for rice then cultivate either bananas or coca. Many farmers had had their coca bushes eradicated by 1986 and their response was to clear more forest and cultivate more coca, bananas or both. Bananas were a good coca substitute particularly with the prices of around 20Bs per *chipa* (source: interviews). Prices were reported to have crashed to 6Bs per *chipa* in the early 1990s as the market became saturated. There was a trend towards farmers clearing at the periphery of the community, rather than in the centres of their plots as farmers were gaining access from the track around the boundary of the community. Clearance rates were, however, generally low because the good returns on coca and banana reduced the need to clear much forest. In the event of a price crash the response was to clear more forest and cultivate coca or to expand the area of banana cultivation to make up the income deficit.

Farmers in Arequipa recalled that three years of logging began around 1988. The loggers created a north-south track through the community creating a direct link to the Cochabamba to Santa Cruz highway which meant access to the market for produce grown in the community. Farmers with plots close to the road cleared forest because of improved access to their plots as they were then able to carry heavy produce (e.g. *chipas* of bananas, sacks of rice) shorter distances to the pick up points for hauliers along the new road. A large linear extension of non-forest was created from the large central non-forest patch to the new road (Figure 7.4). The farmers also suggested that logging activities may have disturbed the forest canopy with selective logging contributing to the additional small isolated non-forest patches on the imagery. There was also a potential threat of other communities clearing inside the limits of Arequipa which encouraged farmers to secure plot limits at the periphery of the community which led to some Type III and IV plot typologies. Some forest clearance towards the end of plots was identified as clandestine coca out of sight of the authorities and the other community members.

The drivers that created the particular fragmentation patterns between 1986 and 1993 were:

- spatial attributes of the INC plan in creating land tenure patterns and determining access.
- high coca leaf prices which kept forest clearance rates low;
- high banana prices which meant that large areas did not need to be cultivated;
- and clandestine coca cultivation;
- logging which created a new linear access of clearance and created non-forest patches by selective logging;
- improvements in transport infrastructure; and
- securing land claims at the community limits.

Figure 7.6: Non-forest fragments in Arequipa 1993.

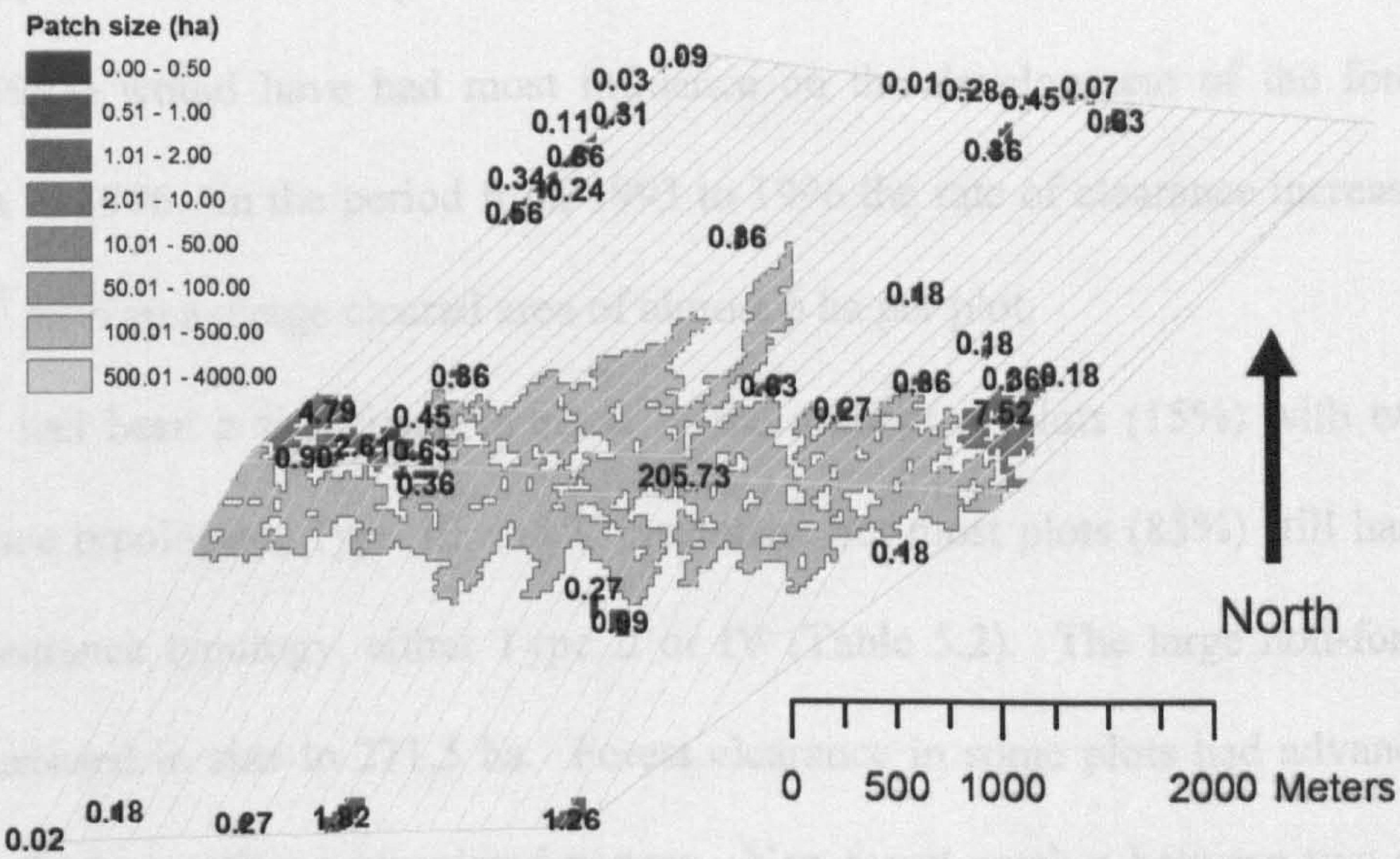
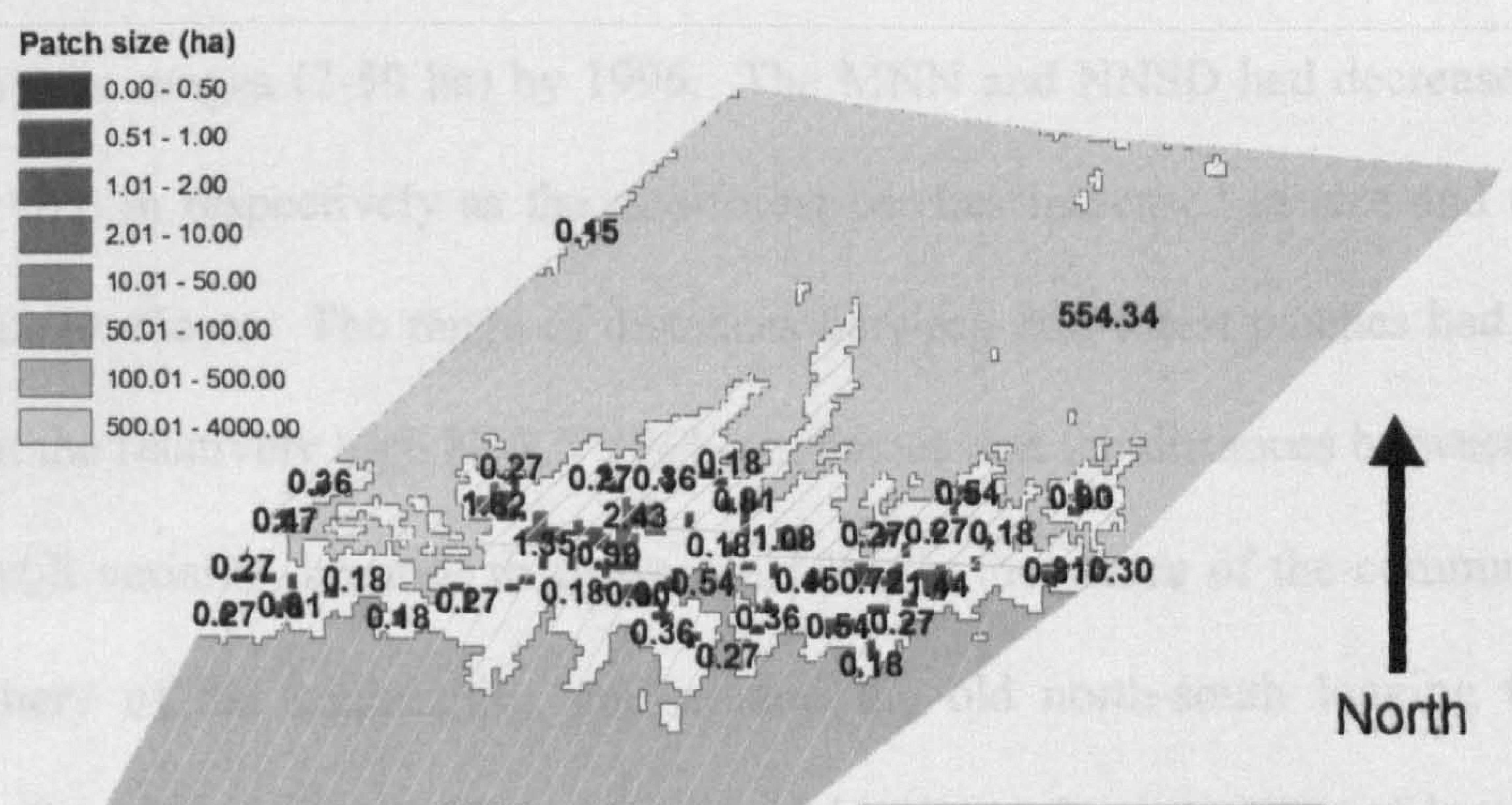


Figure 7.7: Forest fragments in Arequipa 1993.



By 1996 the land-use stage was A_4 – *coca, rice, bananas and alternative development crops* (c.1995 – c.2002) but because there had only been one year of A_4 land-use stage, the events in the previous land-use stage A_3 – *coca, rice and bananas* (c.1985 – c.1995) would have had most influence on the development of the forest fragmentation in 1996. In the period from 1993 to 1996 the rate of clearance increased to 0.56 ha yr^{-1} with an average cleared area of almost 6 ha per plot.

There had been a significant increase in the number of plots (15%) with two-ended clearance typologies, Type III and V clearance, but most plots (85%) still had a one-ended clearance typology, either Type II or IV (Table 5.2). The large non-forest patch had increased in size to 271.5 ha. Forest clearance in some plots had advanced further than others, creating a crenulated pattern. Non-forest patches between two and twenty hectares had formed, most of which were coalesced areas of clearance between neighbouring plots. The number of patches increased accordingly, the MPS (8.4 ha) had a high PSSD (42.5 ha), and the sizes were highly variable (PSCV, 504%). Figure 7.3 shows how the bimodal patch size distribution of non-forest patches had spread to include the middle ranges (2-50 ha) by 1996. The MNN and NNSD had decreased to 102.2 m and 96.6 m respectively as the non-forest patches increased in size and their edges had become closer. The range of distances between non-forest patches had also decreased, but the relatively high NNCV (94%) indicates that the distances between the patches was still variable, because there were patches in the centre of the community, on the periphery of the community, and around the old north-south logging track (Figure 7.8). In addition, there were still some isolated non-forest patches of less than 1.0 ha but they were fewer in number than 1986 and 1993.

From 1993 to 1996 there had been an increase in forest patches from 45 to 56 which was accompanied by decreases in the MPS (21.9 to 15.8 ha) and the PSSD (100

Figure 7.8: Non-forest fragments in Arequipa 1996.

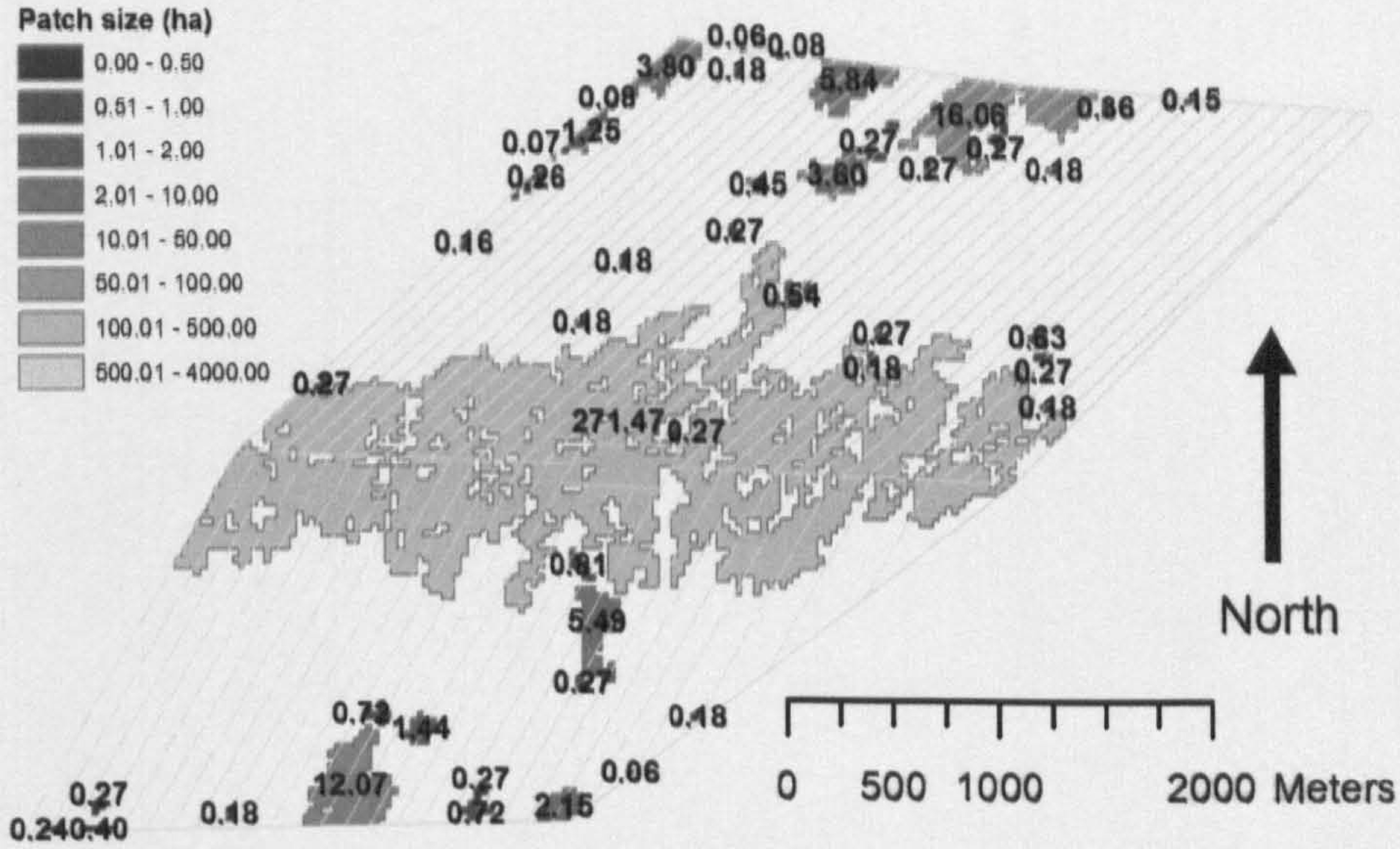
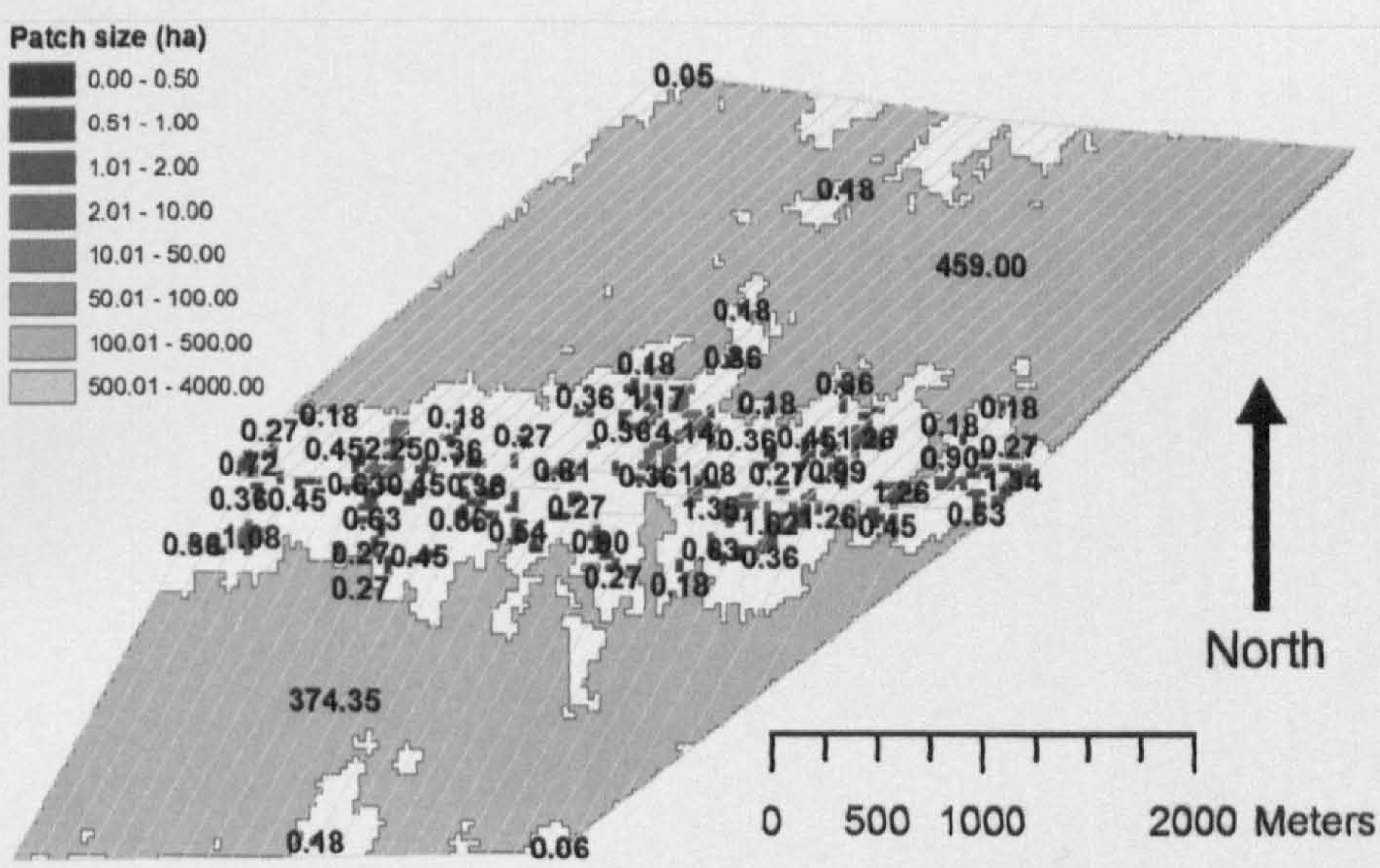


Figure 7.9: Forest fragments in Arequipa 1996.



to 78.8 ha). The PSCV (500%) indicates that the variability in sizes was still large. This was because the forest was still mainly in two large patches, but these had decreased in size to 459 ha (to the north) and 374.4 ha (to the south) as forest was cleared increasing the numbers of forest islands remaining in the large non-forest patch (Figure 7.8). Consequently most patches were under 10 ha (Figure 7.5). Some of the small forest patches represented remaining stands of forest that had never been cleared along streams, trees left to provide shade for livestock and close to dwellings and locations where forest re-growth (*chumi*) has occurred. Total edge length had increased from 56,460 to 76,460 m between 1993 and 1996.

There was limited diversification from the coca and banana economy in stage A_3. Farmers were encouraged by the government to cultivate bananas because of continued pressure to stop growing coca and the high prices for bananas (Figure 6.6). Access roads, to neighbouring communities to the northwest and south, improved and enabled access to the secondary ends of many plots and markets. By 1996 there were a number of isolated non-forest patches not connected to these lines of access. It is likely that these were being used for clandestine coca cultivation. The drivers of fragmentation between 1993 and 1996 were:

- spatial attributes of the INC plan in creating land tenure patterns and determining access;
- coca eradication policies and the introduction of some alternative development crops;
- banana cultivation;
- improvements in transport infrastructure within the community; and
- household demography, some farmers indicated that their household was increasing in size and they needed to increase the output of their farm to support their family.

From 1996 to 2000 the community was under land-use stage A_4 – *coca, rice, bananas and alternative development crops* (c.1995 – c.2002). The average annual rate of clearance had risen to 0.92 ha yr^{-1}, which was similar to the 1983 to 1985 values. Average cleared area was now almost 10 ha (i.e. half of each plot). The main clearance typology in 2000 was Type V (59%) (Table 5.2), i.e. two ended clearance. The main non-forest patch had expanded to 433.3 ha. A second large non-forest patch (65.3 ha) had developed because old plots in the north end of the community had coalesced (Figure 7.10). These large patches extended the distribution of non-forest patches in the 10 to 500 ha range and the distance of non-forest patch size was now skewed rather than bimodal (Figure 7.3). The non-forest metrics showed that there was a continued increase in the number of non-forest patches from 1996 to 2000 and the MPS had increased from 8.4 to 11.7 ha with a wider range of sizes PSSD 64.2 ha. However, the mean patch size still varied widely (PSCV, 547%). The MNN had decreased to 68.4 m, indicating that the patches were closer together and there was a smaller range of distances (NNSD, 51.6 m) and they were less variable than in previous years (NNCV 73%). Comparison of Figures 7.9 and 7.11 shows that the fragmentation of the two large forest patches in Arequipa into a series of smaller forest fragments was quite advanced by 2000. The again metrics again reflect this process. There was an increase in the number of forest patches (56 in 1996 to 79 in 2000) and the mean size had decreased (MPS, 8.3 m). However, patch sizes still showed high variability (PSCV, 554%). The MNN remained low (47.0 m) with a narrow range of values (NNSD, 26.2 m) and a low variability (NNCV, 56%) reflecting the close proximity of the forest patches. The length of the forest non-forest boundary had increased from was increasing from 76,740 m in 1996 to 101,730 m in 2000.

Figure 7.10: Non-forest fragments in Arequipa 2000.

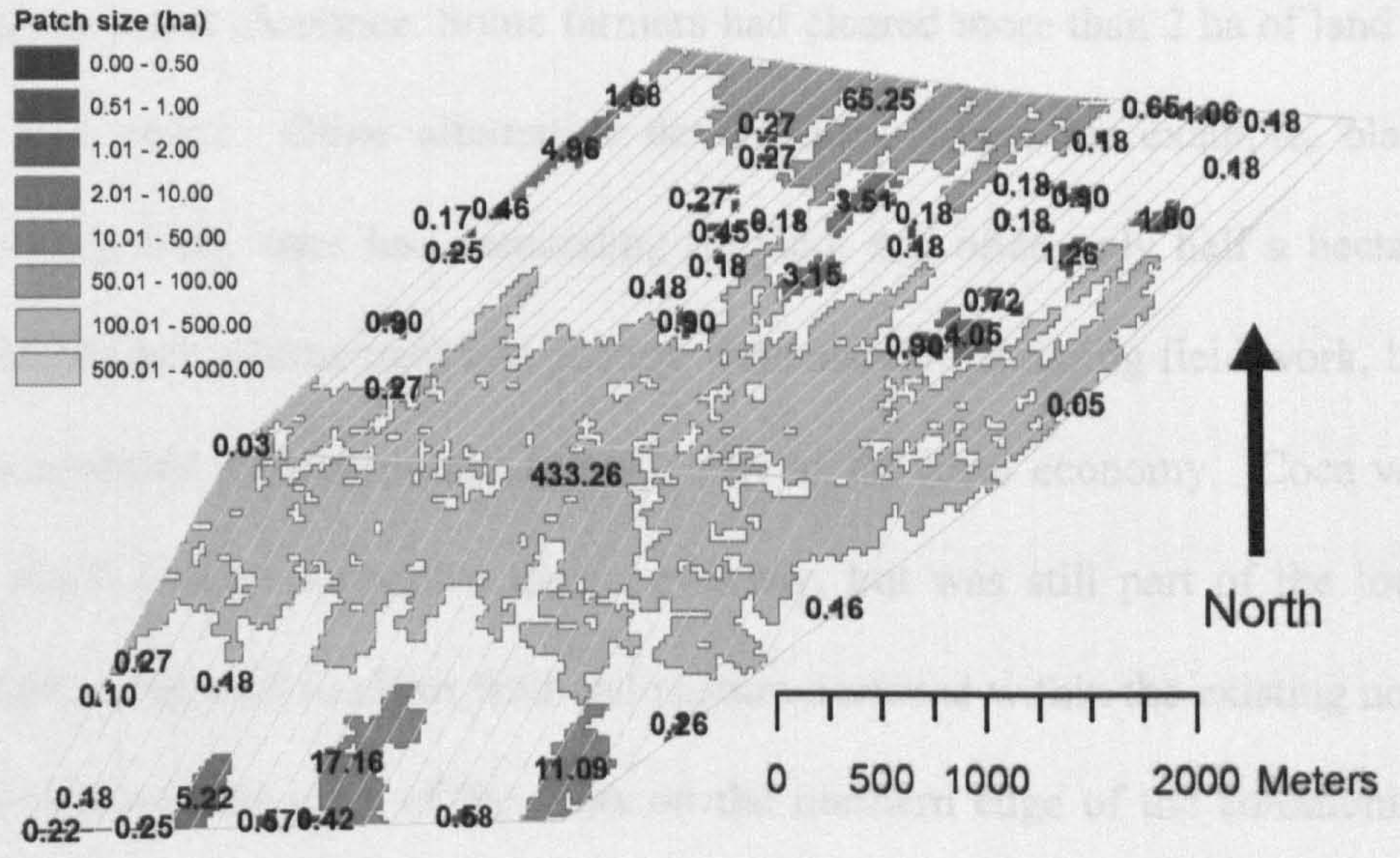
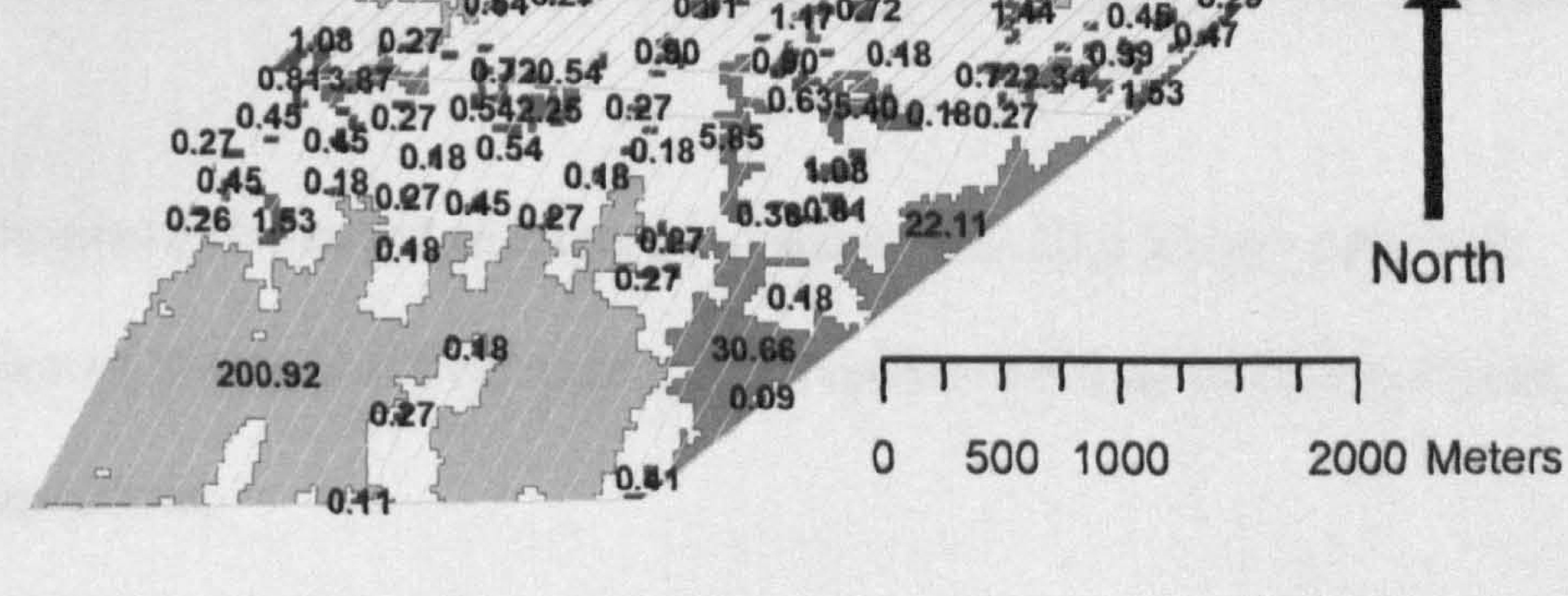


Figure 7.11: Forest fragments in Arequipa 2000.



The range of activities driving forest fragmentation had increased since 1996. Increased cultivation of bananas and alternative crops, in particular heart of palm, were clearly driving the forest clearance. Some farmers had cleared more than 2 ha of land in the previous four years. Other alternative development crops, for example, black pepper and passion fruit, were less demanding on land, and often only half a hectare needed to be cultivated. Citrus trees and pasture were also noted during field work, but the interviews revealed these were not a major part of the local economy. Coca was cultivated in much smaller quantities than previously, but was still part of the local economy in 2003. The shift to citrus fruit and pasture occurred within the existing non-forest cover at the primary ends of the plots on the northern edge of the community, where farmers exploited the advantage of the access road, and the impact from these two activities on forest clearance was minimal.

Fragmentation of forest mainly continued because of pressures to find substitutes for coca cultivation through the promotion of alternative development products. Low prices for bananas and the absence of a market for heart of palm had resulted in excessive forest clearance. The main driving forces influencing the fragmentation patterns between 1996 and 2000 were:

- spatial attributes of the INC plan in creating land tenure patterns and determining access;
- coca eradication policies had encouraged to adopt more land-hungry activities;
- the adoption of alternative development crops such as bananas and heart of palm;
- low banana prices;
- absence of a market for heart of palm; and
- improved access.

7.2.1 Characteristics of fragmentation in Arequipa

By 1986 bimodal distributions of patch sizes had developed for both non-forest and forest patches (Figures 7.3 and 7.5). In the non-forest category a large central patch increased in size from 1986 to 2000. Smaller non-forest patches were of variable size and distances between them. By 1996 larger non-forest patches (2 to 50 ha) had formed by: (i) the merging of isolated small patches (< 2 ha) when clearance had advanced from the secondary ends of the plots, and (ii) areas of clearance in adjacent plots that had coalesced. The main forest patches in 1986 gradually fragmented into smaller patches through to 2000 and the range of forest patch sizes decreased and with intermediate (2 to 50 ha) and small patches (< 2 ha) increasing in number. The small forest patches were mainly those left in the non-forested areas and were relatively consistent in spacing. The variation in forest patch sizes and its distribution indicates that the 'landscape texture' had tended to become more uniform whilst the non-forest landscape had become less uniform.

7.2.2 Evolution of landscape metrics in Arequipa

The 'fragmentation parabolic' postulated for LULCC in humid forest presented in Lambin (1997) was tested against the fragmentation patterns in the three communities. However, because no metrics were used by Lambin (1997) to parameterise this parabolic, data from Trani *et al.* (1996) was used. Trani *et al.* (1999) demonstrated how metrics vary as forest loss increases from 0 to 100% and this can be used to paramaterise the Lambin (1997) model. Additionally, this provides a test of Trani *et al.*'s (1996) research findings. The metrics in this research that were also evaluated by Trani *et al.* (1996) are NoP, MNN, TEL, MPS (Figures 2.15 to 2.18). The NoP, TEL and MNN metrics follow a parabolic curve from 1986 to 2000, although the peak of each metric varies with the % forest cover. However MPS begins with high values and then shows a gradual decline in the form of a logarithmic curve. The metrics are for forest cover and are compared with the forest cover in Arequipa.

In Arequipa fragmentation metrics can only be compared with Trani *et al.*'s (1996) curves up to the level of 47% forest loss over the time period from 1986 to 2000. These data are graphed in Figures 7.12 to 7.15.

Figure 7.12: Arequipa: number of patches and proportion of forest loss. Inset to the right is the comparison of Trani *et al.*'s (1996) curve. The unit for the x and y axis are the same for the main graph.

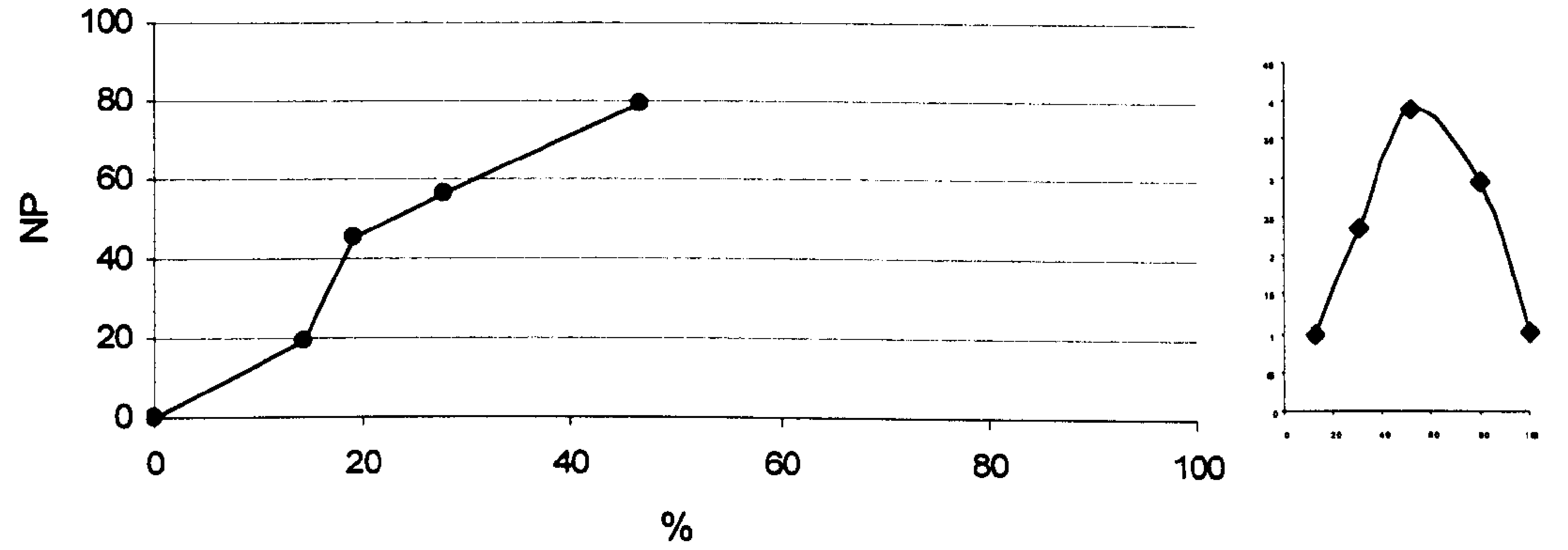


Figure 7.13: Arequipa: total edge length and proportion of forest loss. Inset to the right is the comparison of Trani *et al.*'s (1996) curve.. The unit for the x and y axis are the same for the main graph.

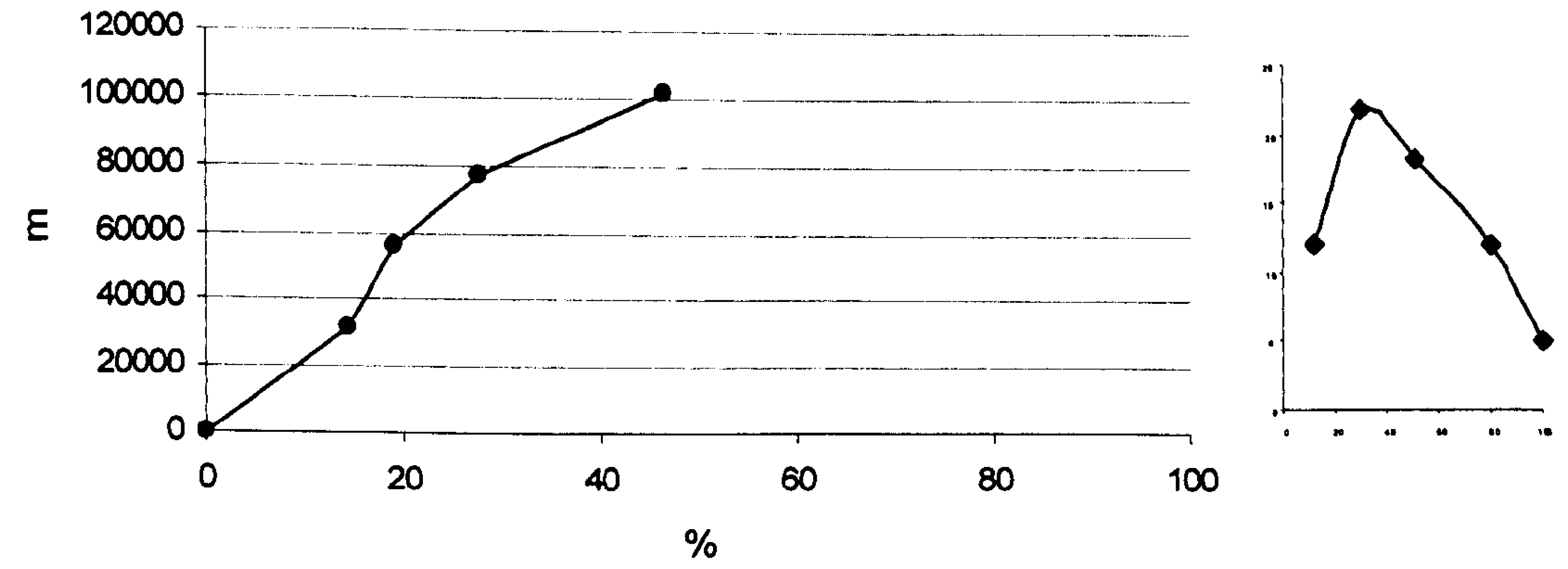


Figure 7.14: Arequipa: mean patch size and proportion of forest loss. Inset to the right is the comparison of Trani *et al.*'s (1996) curve. The unit for the x and y axis are the same for the main graph.

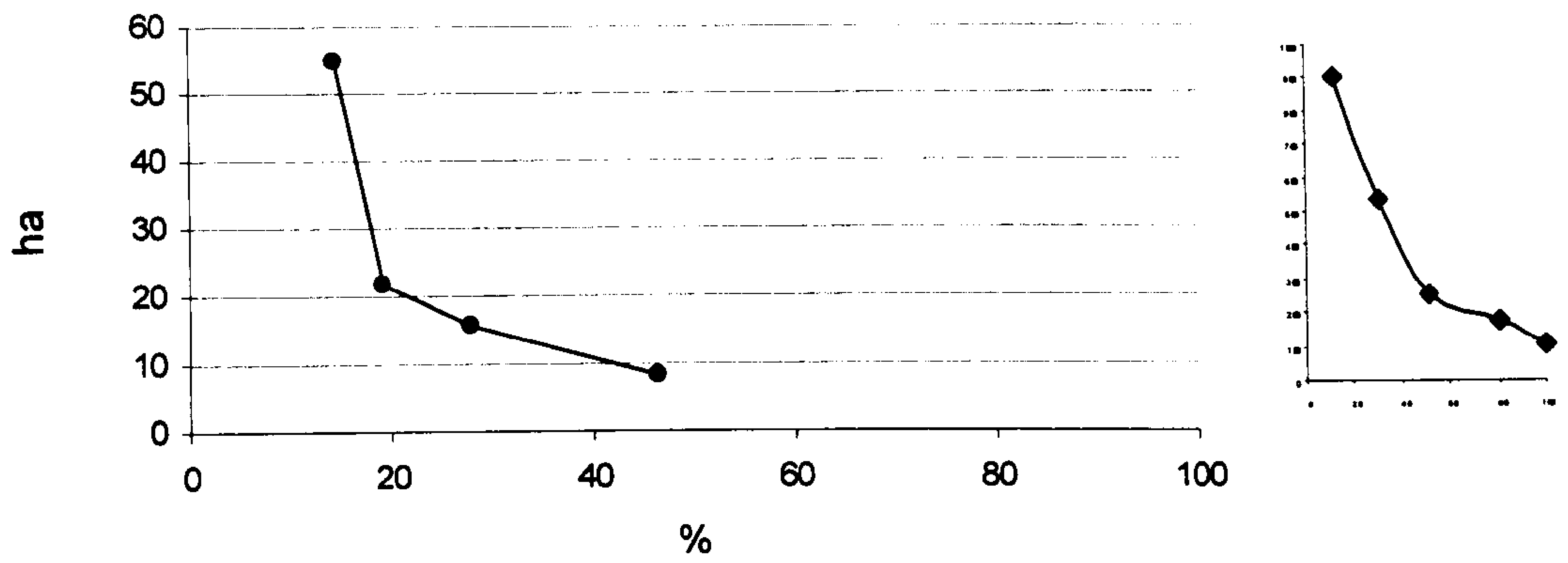
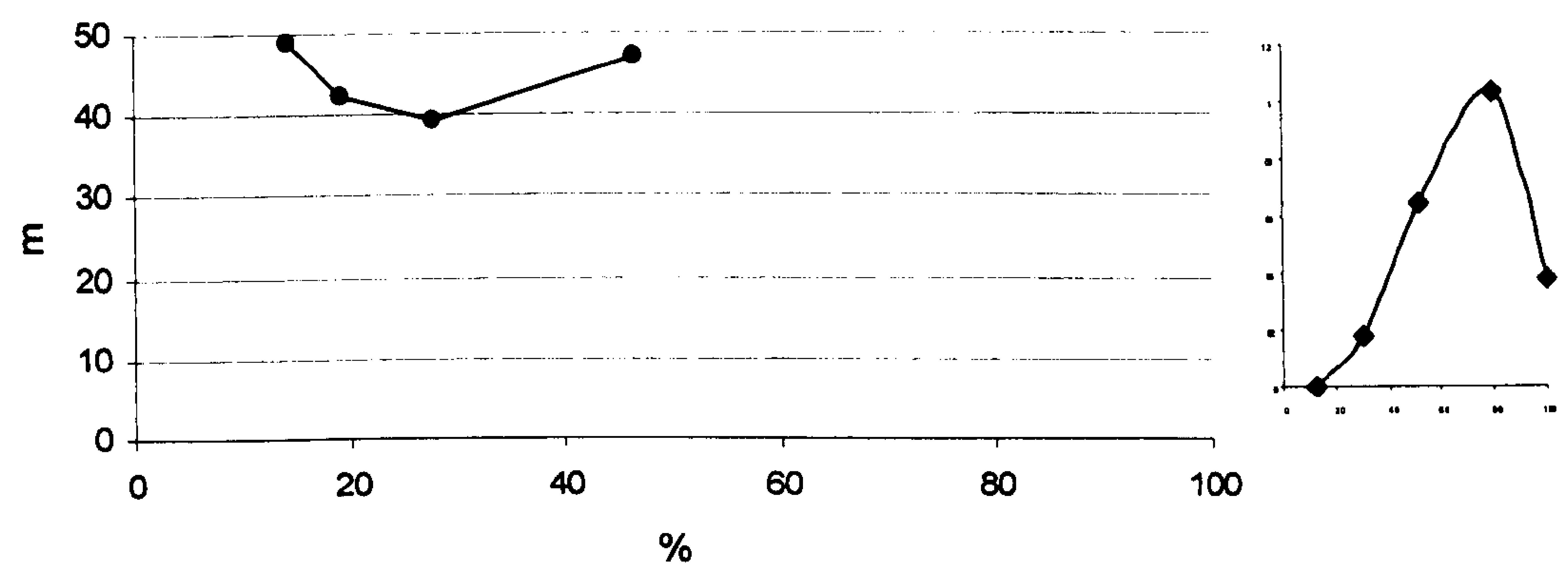


Figure 7.15: Arequipa: mean nearest neighbour and proportion of forest loss. Inset to the right is the comparison of Trani *et al.*'s (1996) curve. The unit for the x and y axis are the same for the main graph.



The NoP forest loss curve (Figure 7.12) corresponded to Trani *et al.*'s (1996) observations because the forest is increasingly fragmented over time and there is no spatial dependency to this metric. It can be postulated that the downward limb of Trani *et al.*'s (1996) curve has not yet been reached at Arequipa. The same may hold for the TEL – forest loss curve (Figure 7.13), though in Trani *et al.*'s (1996) curve TEL began to decrease at relatively high forest covers. The fact that at Arequipa TEL continues to increase until lower forest covers, is thought to be related to the increasing edge length around the growing number of small patches and the decrease in size of the large forest patches and is a function of the style of forest clearance in this (type of) community. The MPS (Figure 7.14) became smaller as forest cover decreased as predicted by Trani *et al.* (1996) because the forest was fragmenting into smaller patches. The behaviour of MNN did not conform to the model at all (Figure 7.15). This is because as the main forest areas were cleared they were not progressively divided up into smaller and smaller patches. Rather the losses were along a 'frontier' determined by the main and peripheral access roads. Furthermore, as the forest area decreased, small forest islands were left in the non-forest area and because they were close to the main forest patches MNN remained low.

7.3 Bogotá

Only six of the plots in Bogotá had started clearance by 1975. These were towards the southern end of the community, creating a non-forest patch of approximately 55 ha (Figure 7.16) surrounded by a large forest patch (Figure 7.17). The land-use stage for this year was early in stage of B_1 *Subsistence and rice* (up to 1980).

All of the cleared plots had Type II clearance typologies (Table 5.6), because clearance had only progressed from the primary ends of the plots adjacent to the main access road. From 1975 to 1986 the community had been in land-use stage B_2 *Rice, coca (<49%) and some pasture (<74%)* (c. 1980 to c.1985) and B_3 *Coca (<74%), rice and pasture (>75%)* (c.1985 to c.1990); although the second land-use stage had only been existed for about one year. Most of the plots had been cleared with Type II typologies by 1986 (57%) (Table 5.6). At the end of this period farmers had cleared, on average, 6.3 ha and the community had maintained clearance rates of 1.42 ha yr^{-1} (if an average settlement date of 1983 can be assumed). Because all the plots were now occupied and cleared

Figure 7.16: Non-forest fragments in Bogotá, 1975.

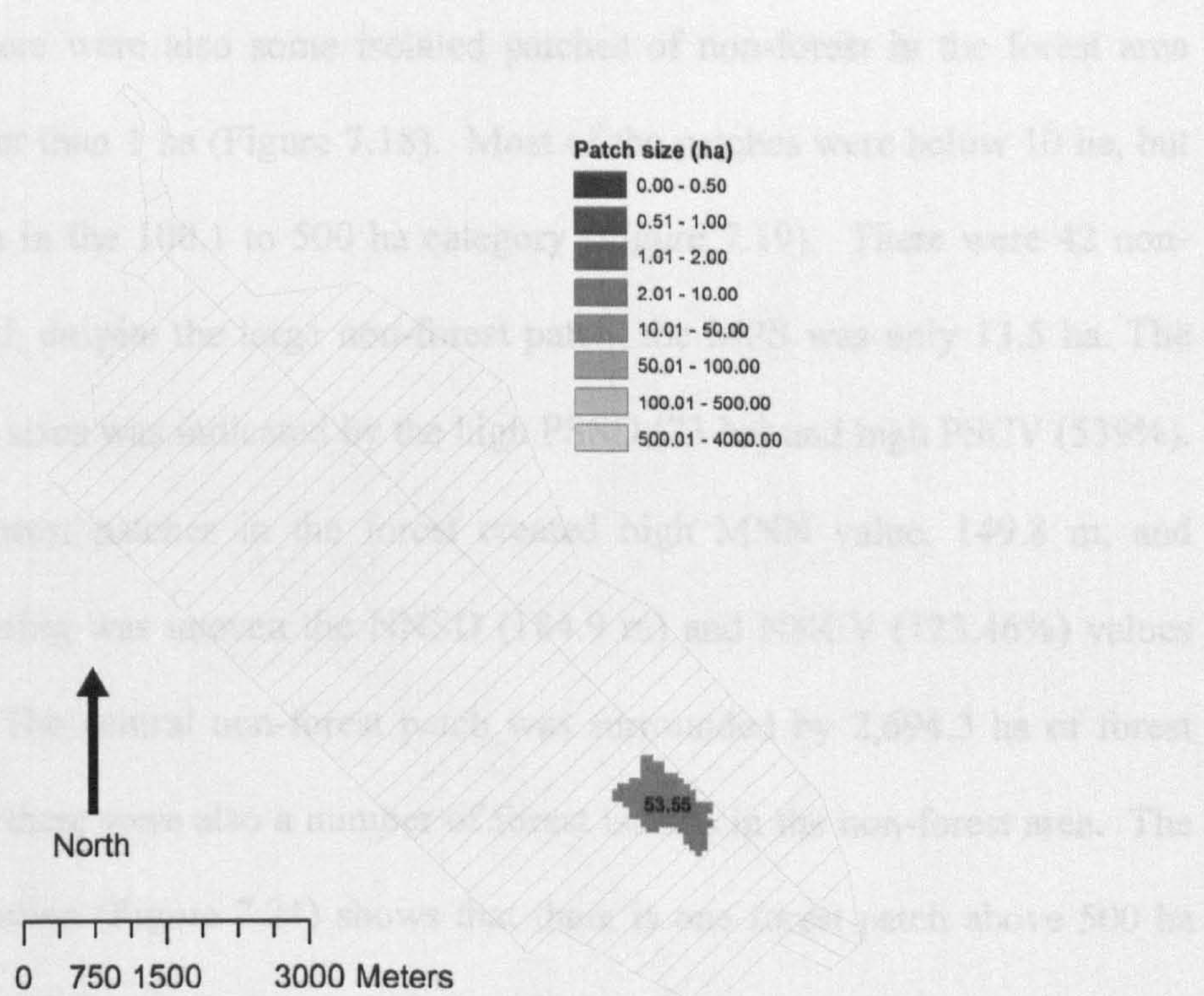
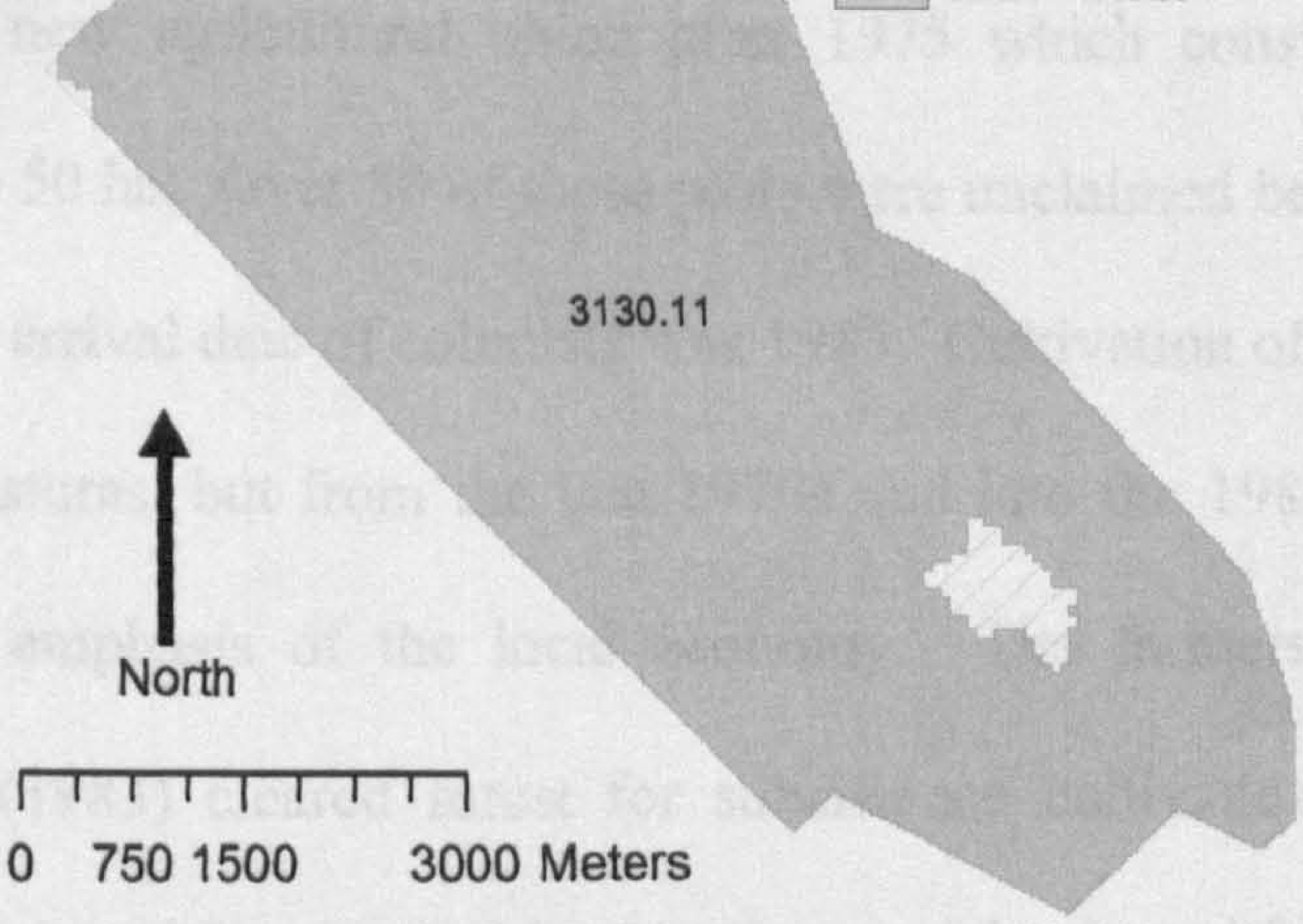


Figure 7.17: Forest fragments in Bogotá, 1975.



from the same end the impact on the land-cover was to create a narrow non-forest strip of 478.3 ha. There were also some isolated patches of non-forest in the forest area which were greater than 1 ha (Figure 7.18). Most of the patches were below 10 ha, but there was a patch in the 100.1 to 500 ha category (Figure 7.19). There were 42 non-forest patches and, despite the large non-forest patch, the MPS was only 13.5 ha. The disparity in patch sizes was indicated by the high PSSD (73 ha) and high PSCV (539%). The small non-forest patches in the forest created high MNN value, 149.8 m, and because their spacing was uneven the NNSD (184.9 m) and NNCV (123.46%) values were also high. The central non-forest patch was surrounded by 2,694.3 ha of forest (Figure 7.20) but there were also a number of forest islands in the non-forest area. The patch size distribution (Figure 7.21) shows that there is one forest patch above 500 ha and the remainder of forest patches were below 50 ha. There were 62 forest patches in total, with a MPS of 42.3 ha, because of the one large patch and many small patches the PSSD (324.2 ha) and PSCV (766%) were high. The MNN (45 m) was quite low because all the forest patches, except for the largest one were confined to the non-forest area. Consequentially the NNSD (29.6 m) and NNCV (69.5%) have relatively low values. TEL was 6,690 m in 1975 to 99,180 m in 1986.

The interviews indicated that the original settlers re-organised the rice growing co-operative into a new agricultural union after 1975 which consisted of 90 plots ranging from 13.5 to 50 ha. Over 80 of these plots were unclaimed before 1980 (INRA 1985) and the modal arrival date of colonists was 1983. Cultivation of rice preceded the creation of cattle pastures, but from the late 1970s and into the 1980s high coca leaf prices changed the emphasis of the local economy. The farmers who joined the community around (1983) cleared forest for subsistence cultivation and also began growing coca. The original farmers and later settlers mostly cleared from the primary

Figure 7.18: Non-forest fragments in Bogotá, 1986.

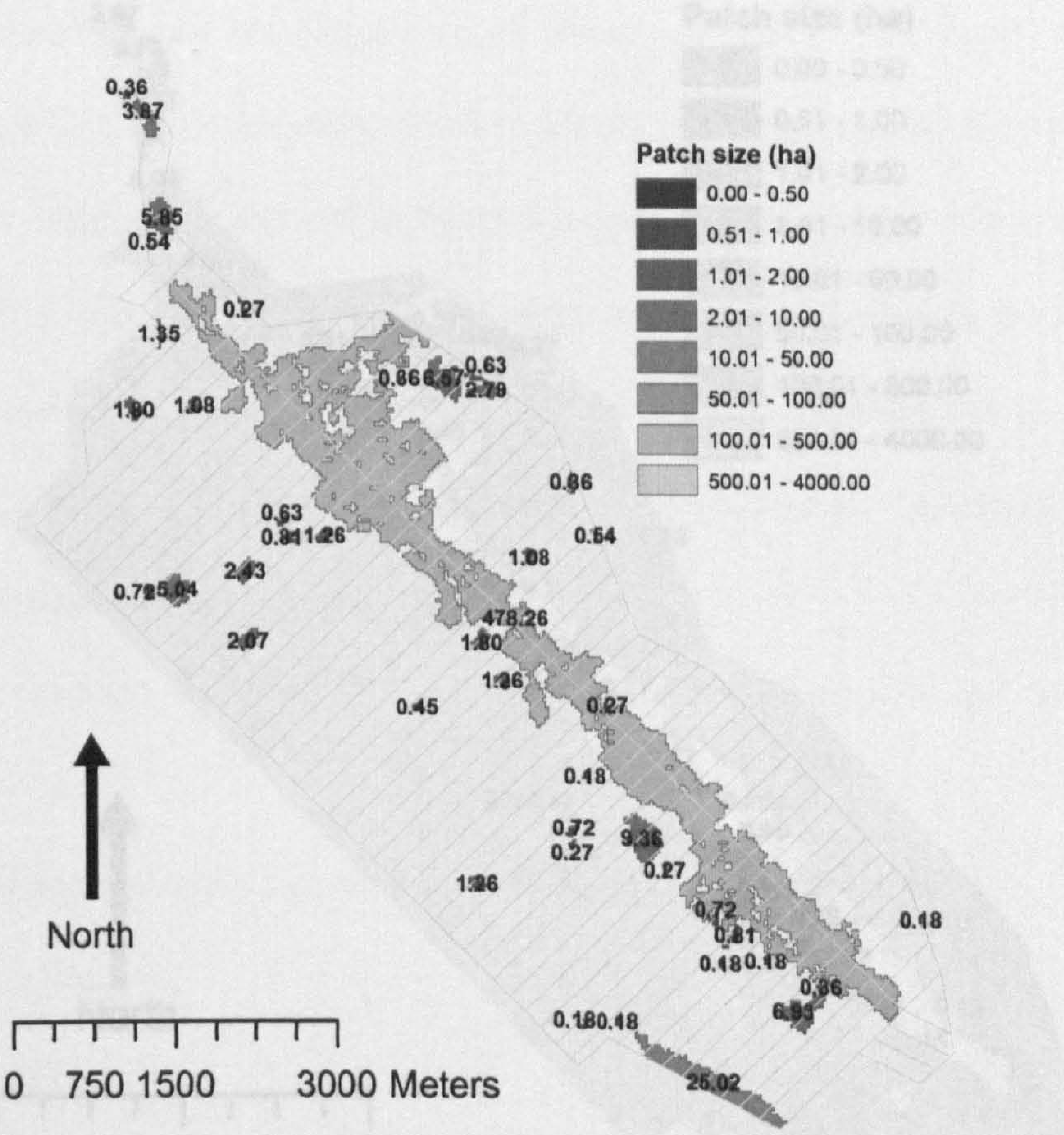


Figure 7.19: Distribution of non-forest patch sizes, Bogotá.

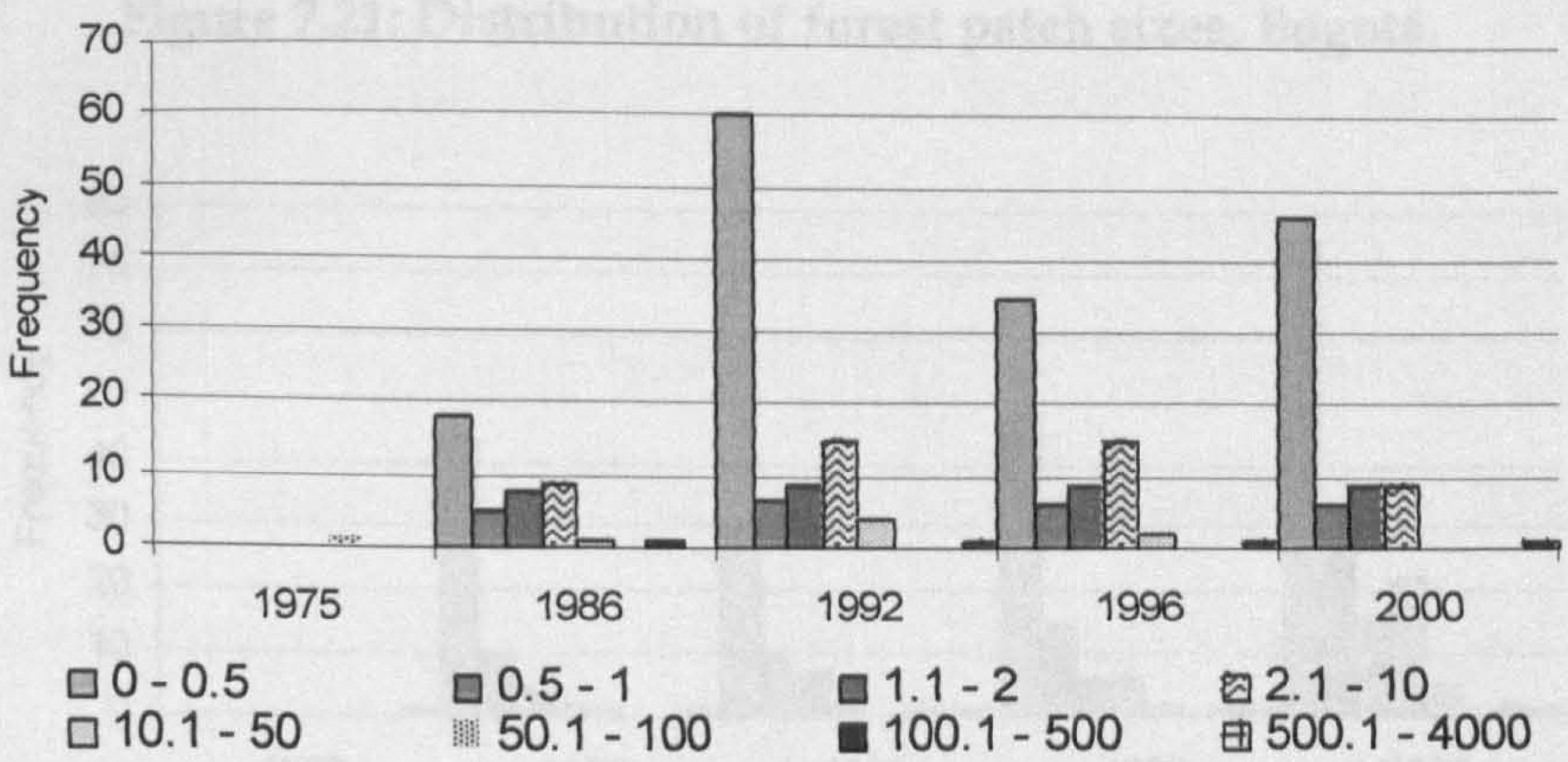


Figure 7.20: Forest fragments in Bogotá, 1986.

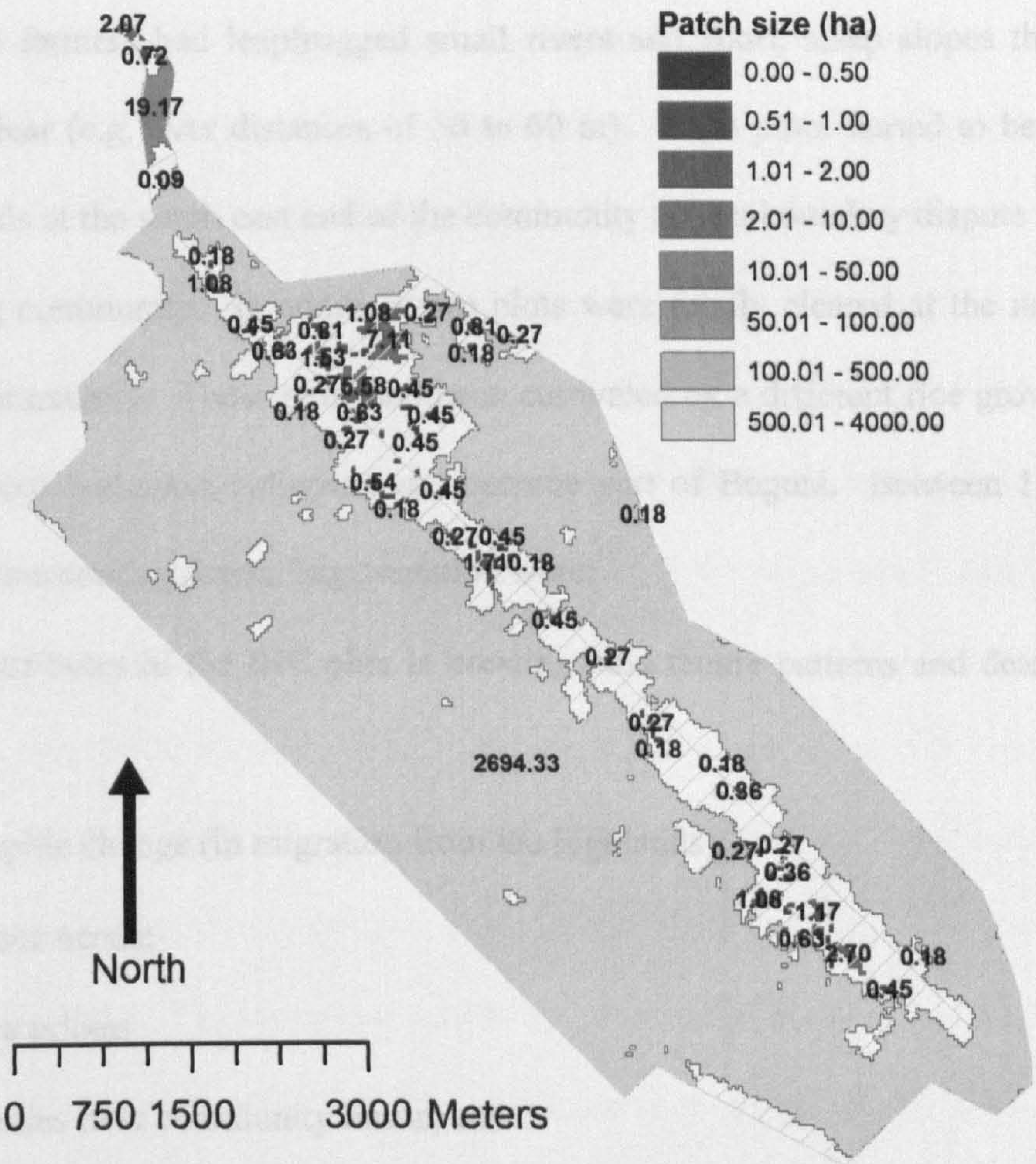
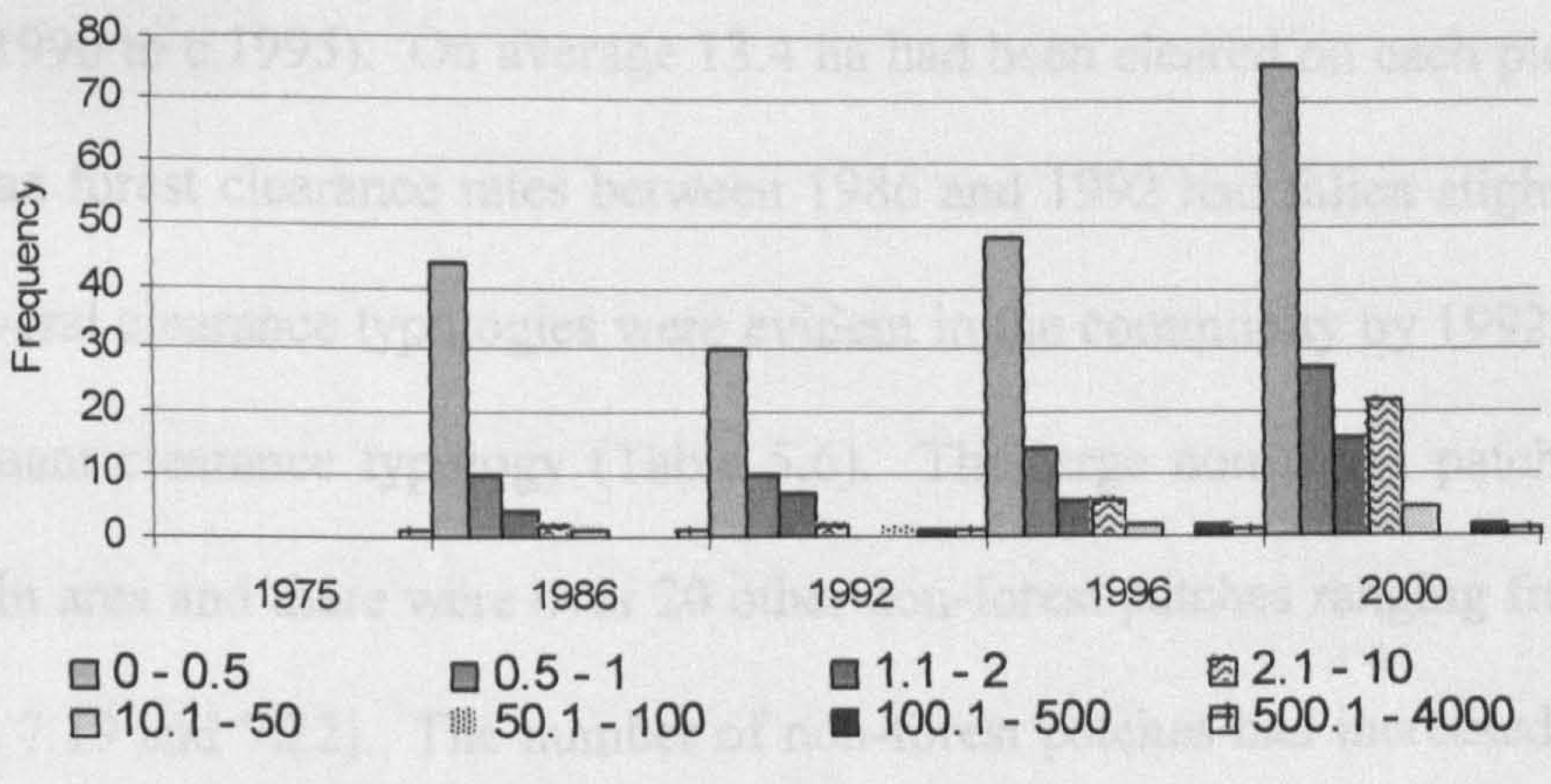


Figure 7.21: Distribution of forest patch sizes, Bogotá.



end of their plots because of the proximity of the access road. Some of the isolated patches of clearance in forest were identified by farmers as clandestine coca plots or places where farmers had leapfrogged small rivers and short, steep slopes that were difficult to clear (e.g. over distances of 30 to 60 m). Eight plots started to be cleared from both ends at the south east end of the community after a boundary dispute with the neighbouring community. In addition two plots were totally cleared at the northwest end of the community. These plots had been cultivated by a different rice growing co-operative which had since collapsed and become part of Bogotá. Between 1975 and 1986 the drivers causing forest fragmentation were:

- spatial attributes of the INC plan in creating land tenure patterns and determining access;
- demographic change (in migration from the highlands);
- subsistence needs;
- high coca prices;
- uncertainties over community limits; and
- topographic controls on clearance.

From 1986 to 1992 the farming activities were land-use stages B_3 *Coca (<74%), rice and pasture (>75%)* (c.1985 to c1990) and B_4 *Pasture (>75%), rice and some coca (<49%)* (c.1990 to c.1995). On average 13.4 ha had been cleared on each plot by 1992 and the mean forest clearance rates between 1986 and 1992 had fallen slightly to 1.19 ha yr^{-1}. Several clearance typologies were evident in the community by 1992, and there is no dominant clearance typology (Table 5.6). The large non-forest patch was now 1,008.6 ha in area and there were over 20 other non-forest patches ranging from 1 to 30 ha (Figures 7.19 and 7.22). The number of non-forest patches had increased to 96, but because there were many small patches the MPS was only 12.6 ha. The moderate PSSD

(104.4 ha) and high PSCV (827%) values indicate that there was high variability in patches sizes. The increased number of patches had decreased the MNN from 149.8 m to 76.8 m from 1986 to 1992, and indicate the ranges of distances was smaller (NNSD, 64.5 m) and the distances between patches were less variable than the previous time interval (NNCV is 84%). TEL has increased from 99,180 m to 143,790 m.

The forest had now been fragmented into six major patches ranging from 10.4 ha to 1,424.8 ha, (Figure 7.23) and these can be seen in the distribution (Figure 7.21). Despite this division the number of forest patches had decreased from 62 to 52 since 1986, because there was a reduction in the number of forest islands inside the non-forested area. The MPS (37.9 ha) had not changed much from 1986 (42.3 ha) but the PSSD (324.2 to 205.4 m) and PSCV (766 to 541%) had decreased significantly indicating less variability in forest patch sizes. MNN (63.0 m) had increased because the 'edges' of the large forest patches were further apart and there are fewer small patches close to them. The range and variability in distances between the patches were low NNSD (46.5 m) and NNCV (74%). TEL increased from 99,180 m in 1986 to 143,790 ha in 1992.

Farmers indicated that more emphasis had been placed on clearance for pasture between 1986 and 1992 because cattle stocks had increased, but that coca leaf continued to be cultivated. Some farmers had invested in cattle with the compensation from coca eradication. All the farmers continued to clear from the primary end of their plots, but many also cleared isolated patches of up to 3-5 ha deeper in their plots. At the secondary end of the plots in the southwest of Bogotá, a narrow strip of non-forest patches had been cleared to consolidate the community boundary and avoid encroachment by farmers from the neighbouring community.

PAGE NUMBERING AS IN THE ORIGINAL THESIS

Despite the creation of new forest fragments the number of forest patches had decreased slightly because the number of forest islands in the non-forest area had decreased. The number of non-forest patches had increased because the forest had become perforated with isolated non-forest patches. As a result of, the average distance between non-forest patches had decreased and a maze of narrow forest corridors had been created. The forest had become highly fragmented in the north east of the community where the plots were smaller and many had become cleared. The drivers of forest fragmentation between 1986 and 1992 were:

- spatial attributes of the INC plan in creating land tenure patterns and determining access;
- expansion of pasture;
- high coca prices; and
- access and securing of the community limits.

By 1996 for three of the four years from 1992 the community was under land-use stage B_4 *Pasture (>75%), rice and some coca (<49%)* (c.1990 to c.1995) and, for the final year in this period was under land-use stage B_5 *Pasture, rice and some coca (<24%)* (c.1995 to 2002). The average cleared area had reached 18.3 ha, and between 1992 and 1996 the rate of clearance (1.22 ha yr^{-1}) was similar to that between 1986 and 1992. There had been changes in the proportions of clearance typologies. In particular there was an increase in Type II clearance (24 to 40%) and a decrease in Type IV (37 to 21%) clearance (Table 5.6) indicating farmers had concentrated on the clearing of forest from the primary ends of their plots between 1992 and 1996. The isolated non-forest patches and secondary end clearances seen in 1992 had barely expanded and, in fact, many of the isolated patches had coalesced with clearance advancing from the primary ends of the plots (Figure 7.24).

Figure 7.24: Non-forest fragments in Bogotá, 1996.

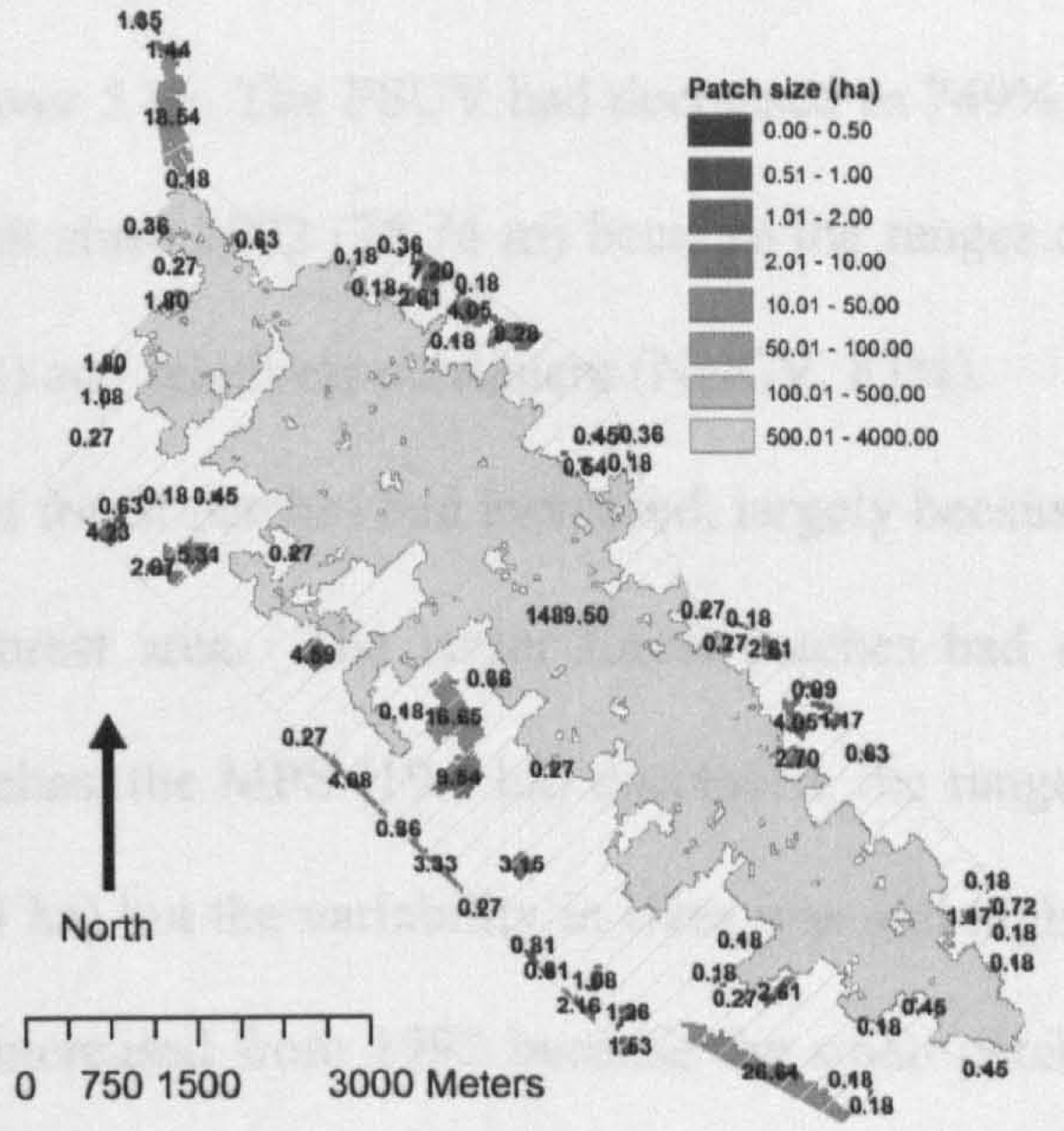
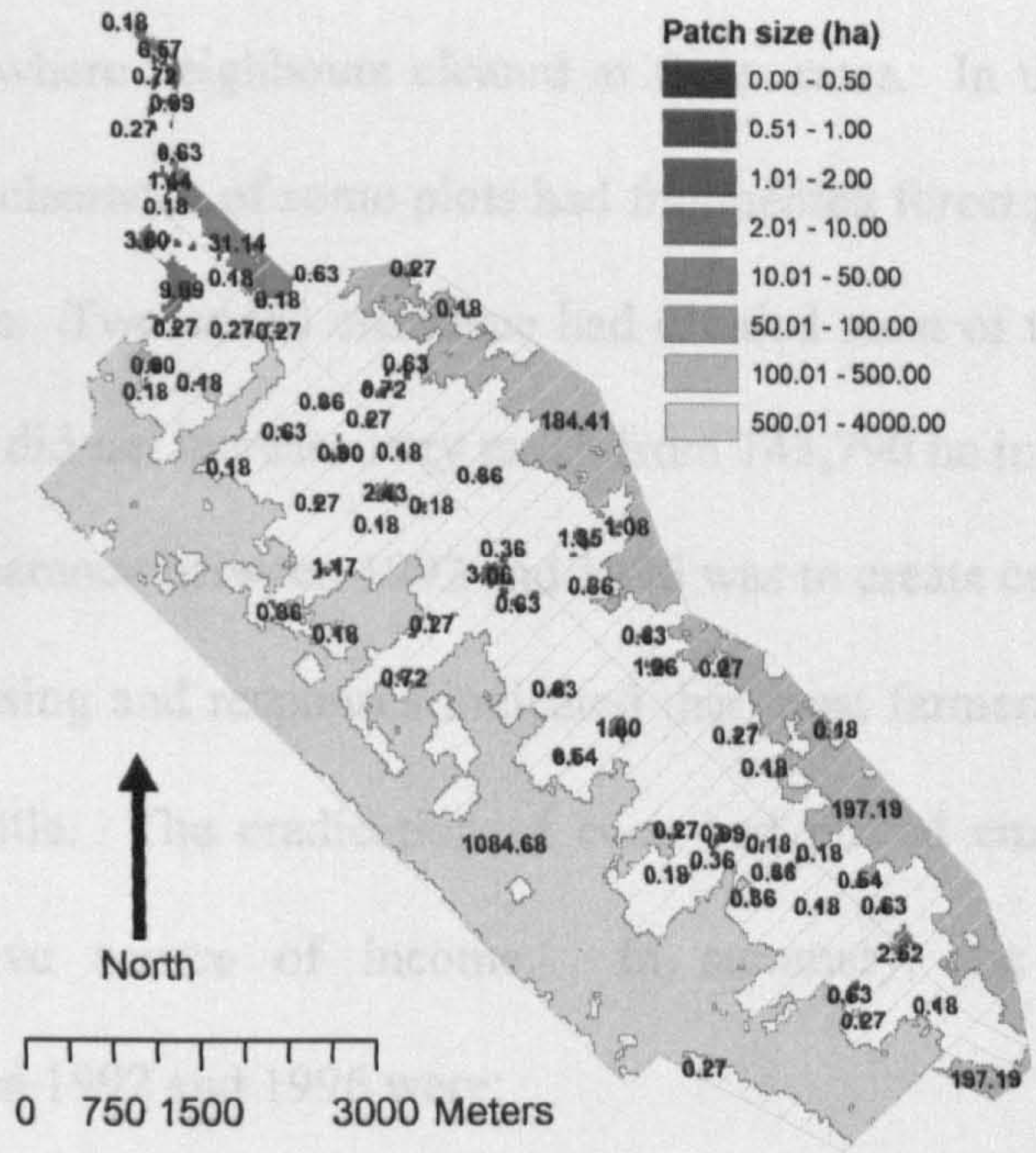


Figure 7.25: Forest fragments in Bogotá, 1996.



The coalescence and disappearance of isolated non-forest patches had reduced the number of non-forest patches. Both the MPS (24.2 ha) and the PSSD (181.6 ha) had increased because the largest patch was getting bigger, also because many of the isolated patches are over 5 ha. The PSCV had decreased to 749%. The MNN (82.6 m) had not changed much since 1992 (76.76 m) because the ranges of distances were still small (NNSD, 66.2 m) and relatively consistent (NNCV, 83%).

The number of forest patches had increased, largely because an increase in small patches in the non-forest area. The larger forest patches had shrunk, and, with the increase in small patches, the MPS (19.3 ha) decreased, the range of sizes had become smaller (PSSD, 125.3 ha) but the variability in sizes was still high (PSCV, 648%). The MNN (84.5 m) had increased from 1992 because the small patches were more spread out in the large non-forest area. Accordingly the NNSD (74.4 m) had a wider range and there is a slight increase in variability in MNN in between the patches (NNCV, 88%) than in 1992. The forest/non-forest boundary had a castellated shape caused by strips of forest between plots where neighbours cleared at faster rates. In the northeast of the community complete clearance of some plots had fragmented forest patches and created isolated forest patches. Two ended clearance had divided most of these forest patches (Figure 7.26). TEL did not increase very much from 143,790 ha in 1992 to 144,630 in 1996. Most forest clearance between 1992 and 1996 was to create cattle pastures. Herd sizes had been increasing and responses indicated that most farmers now had between 10 to 20 head of cattle. The eradication of coca had placed emphasis on cattle to provide an alternative source of income. In summary, the drivers of forest fragmentation between 1992 and 1996 were:

- spatial attributes of the INC plan in creating land tenure patterns and determining access;

- coca eradication; and
- expansion of cattle rearing.

Fragmentation patterns in 2000 were influenced by the fact that since 1995 Bogotá has been in land-use stage, B_5 *Pasture, rice and some coca (<24%)* (c.1995 to 2002). By 2000 the average area cleared was 20.2 ha per plot and the rate of clearance between 1996 and 2000 had decreased to 0.47 ha yr^{-1}. Type IV clearance typology increased from 21 to 55% between 1996 and 2000; and 6% of the plots had a Type VI clearance typology (Table 5.6). A majority of the community comprised a large 1,693 ha contiguous patch of non-forest, surrounded by a few non-forest patches of under 10 ha. There was a very slight increase in numbers of non-forest patches from 68 to 71 and because the large non-forest patch had expanded; this had increased the MPS slightly (25.6 ha) but there was still a wide range of PSSD (204.5 ha) and high variability in patch sizes (PSCV, 803%). The MNN (74.6 m) had not change much because the non-forest patches were confined to the remaining area of forest, and the range of distance (NNSD 64.5 m) and variability (NNCV 87%) also stayed low.

There was, however an increase in the number of forest patches, mainly inside the large non-forest patch. Only four forest patches were greater than 100 ha, the remaining patches were mostly forest patches under 10 ha in the non-forest area (Figure 7.27). The MPS had decreased to 9.2 ha, the range of patch sizes was low (PSSD, 70.78 ha), and the PSCV was high (771%) indicating the variation in patch sizes alluded too above. The MNN (57.9 m) had fallen because more patches were in closer proximity to one another. This had decreased accordingly the range of distances had decreased (NNSD, 38.1 m). The PSCV was 66%. TEL increased from 144,630 in 1996 to 217,950 in 2000.

Figure 7.26: Non-forest fragments in Bogotá, 2000.

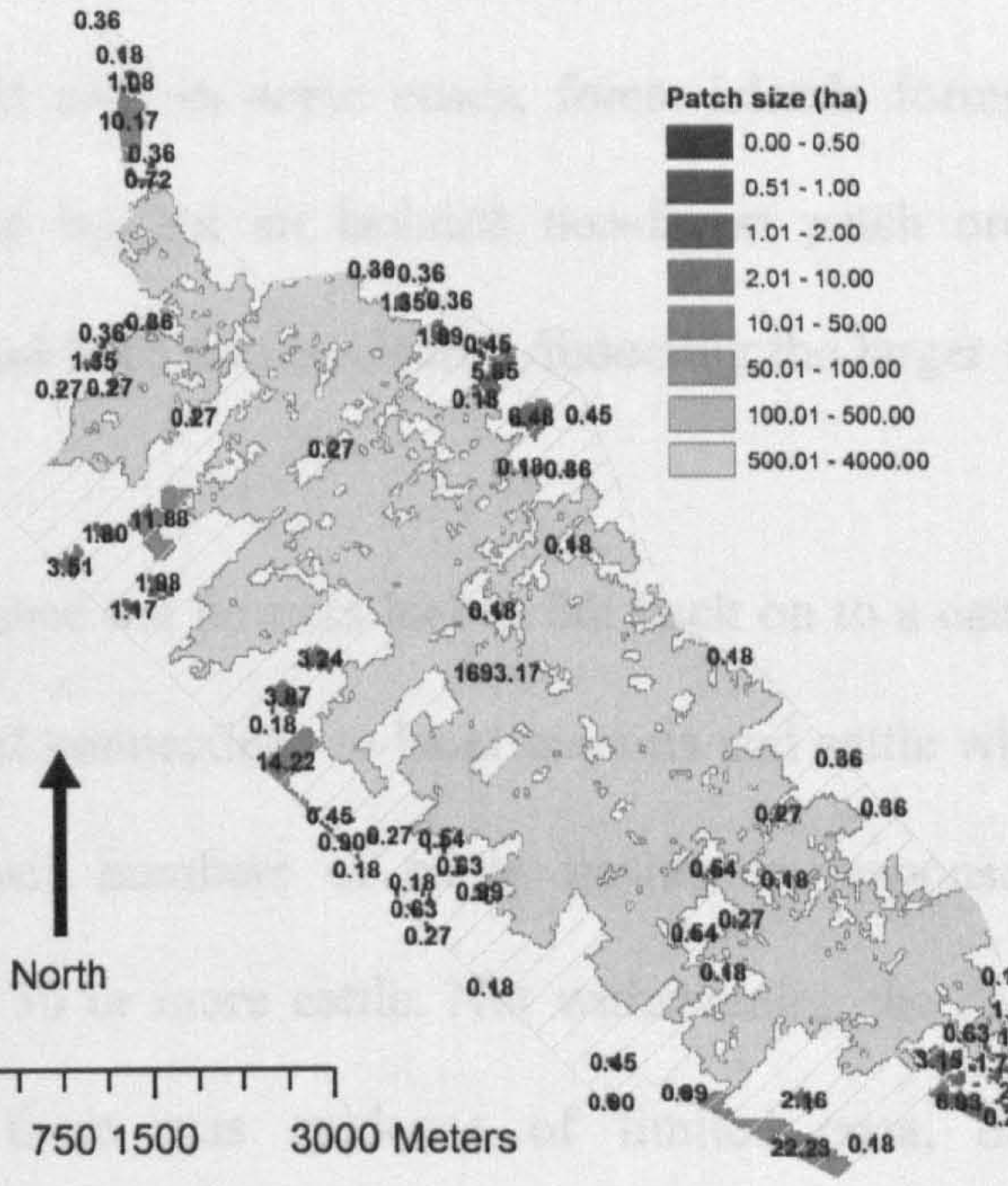
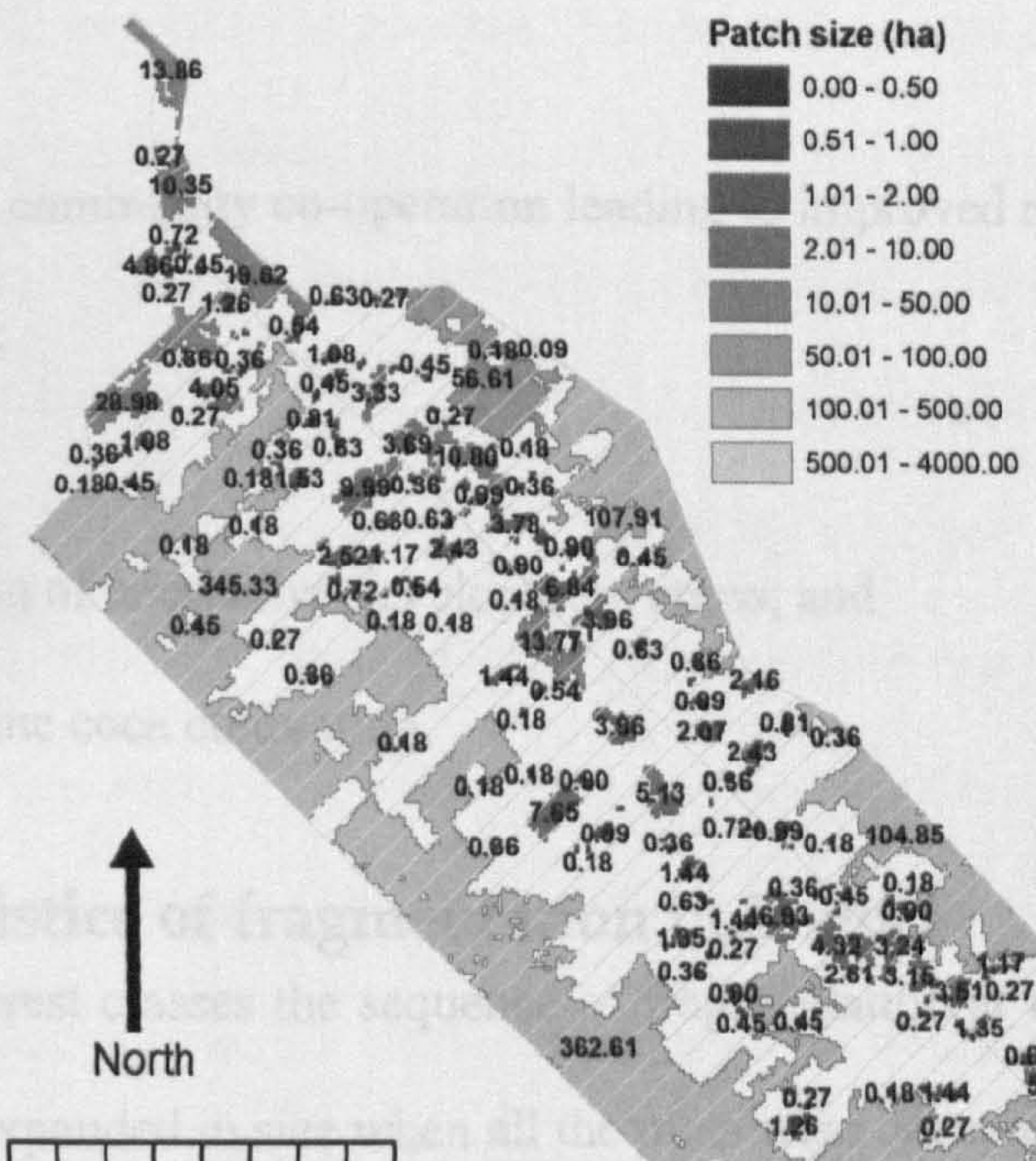


Figure 7.27: Forest fragments in Bogotá, 2000.



The forest clearance between 1996 and 2000 had mostly continued from the primary ends of the plots. As clearance had advanced along the plots, isolated non-forest patches had coalesced and, in some cases, forest islands formed if the farmers on adjacent plots cleared beyond an isolated non-forest patch on neighbouring plots. Several of the plots had been totally cleared dissecting the larger forest patches (Figure 7.27).

As a consequence the farmers had to fall back on to a cattle and rice economy, but one with improved connections to local markets and cattle wholesalers. Individual farmers increased their numbers of cattle further in response to this with some maintaining herds of 30 or more cattle. Not withstanding the dominance of the cattle and rice economy there was evidence of limited coca, citrus and alternative development projects in the community in 2002.

In summary the drivers of forest fragmentation between 1996 and 2000 were:

- spatial attributes of the INC plan in creating land tenure patterns and determining access;
- coca eradication community co-operation leading to improved market access;
- cattle expansion;
- rice cultivation;
- limited expansion of alternative development crops; and
- limited clandestine coca cultivation.

7.3.1 Characteristics of fragmentation in Bogotá

In the non-forest classes the sequence of fragmentation at Bogotá began with a single patch which expanded in size when all the plots were occupied. From 1986 small isolated non-forest patches of uneven sizes and spacing developed. By 1996 some of these had coalesced with the main non-forest patch and there was a small reduction in patches below 0.5 ha in area. In the forest category there was one large patch in 1976 which gradually fragmented into smaller patches as clearance occurred along the entire length of some plots. The number of patches between 1 and 10 ha gradually increased over the period analysed. After there was a decrease to 1993, the number of patches less than 0.5 ha in size increased when the non-forest area expanded and left small forest patches in the non-forest area.

7.3.2 Evolution of landscape metrics in Bogotá

Between 1975 and 2000 57% of the forest was lost in Bogotá so the fragmentation metrics should show a decrease for NoP, TEL and MPS and an increase for MNN according to Trani *et al.* (1996). In Figure 7.28 the NoP shows an increase although the trend of this increase differs slightly from that of Trani *et al.* (1996). The TEL (Figure 7.29) continued to increase (unlike in Trani *et al.*'s (1996) model); this was because of the large numbers of isolated forest patches and division of the large forest patch. The TEL continued to increase because there was high variability in rates of clearance between plots resulting in different cleared area and increased edge length between adjacent plots. The trends in MPS (Figure 7.30) and MNN (Figure 7.31) are similar to those proposed by Trani *et al.* (1996). The slight differences in the predicted curves for NoP, MPS and MNN and those for Bogotá are relatively easy to explain. For example, the decrease in NoP in 1992 occurred because there was a loss of small forest patches (<0.5 ha) in this year. This loss related to a period of cattle herd expansion in which large open areas of pasture were cleared. The mean forest patch size also exhibited a slight variation to the predicted logarithmic decay curve (Figure 7.30). Specifically, a huge fall in MPS between 1976 and 1986 occurred because the numbers of plots occupied by farmers increased as the rice growing co-operative changed to a much larger cattle rearing community. The MPS did not vary much until after 1996 because some plots had been cleared to their limits thereby dividing the forest into smaller fragments. The MNN follows the predictions of Trani *et al.* (1996) but there was little variation in values from 1986 to 2000 (39 m). This was because the small forest patches were confined to the non-forest area and were within short distances of the biggest forest patches.

Figure 7.28: Bogotá: Number of patches and percentage of forest lost, 1975 to 2000. Inset to the right is the comparison of Trani *et al.*'s (1996) curve. The unit for the x and y axis are the same for the main graph.

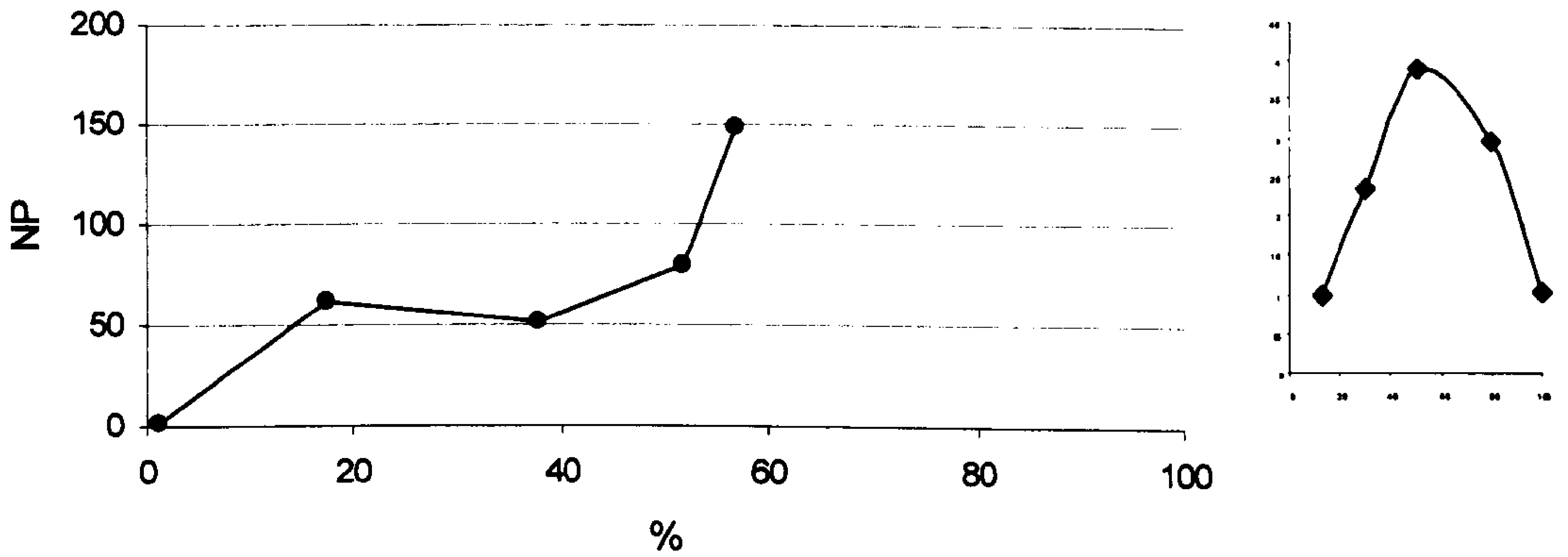


Figure 7.29: Bogotá: total edge length and percentage of forest lost, 1975 to 2000. For comparison of Trani *et al.*'s (1996) curve is inset to the right. The unit for the x and y axis are the same for the main graph.

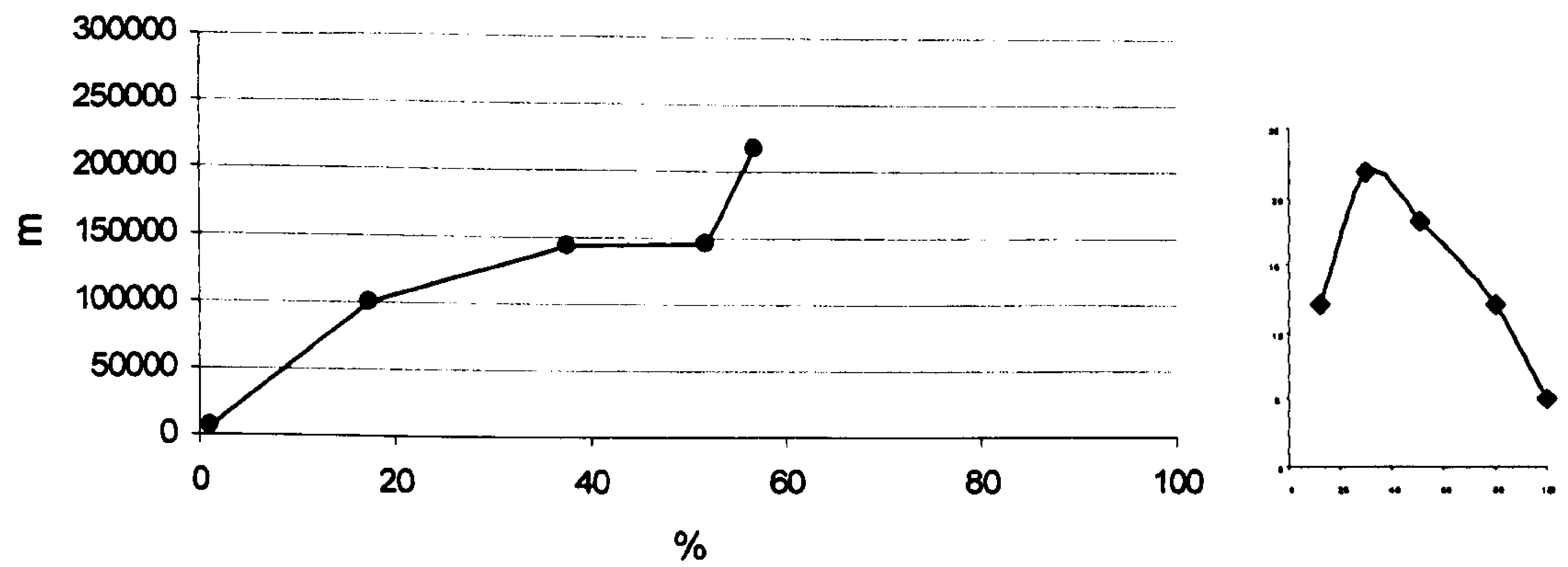


Figure 7.30: Bogotá: mean patch size and percentage of forest lost, 1975 to 2000. Inset to the right is the comparison of Trani *et al.*'s (1996) curve. The unit for the x and y axis are the same for the main graph.

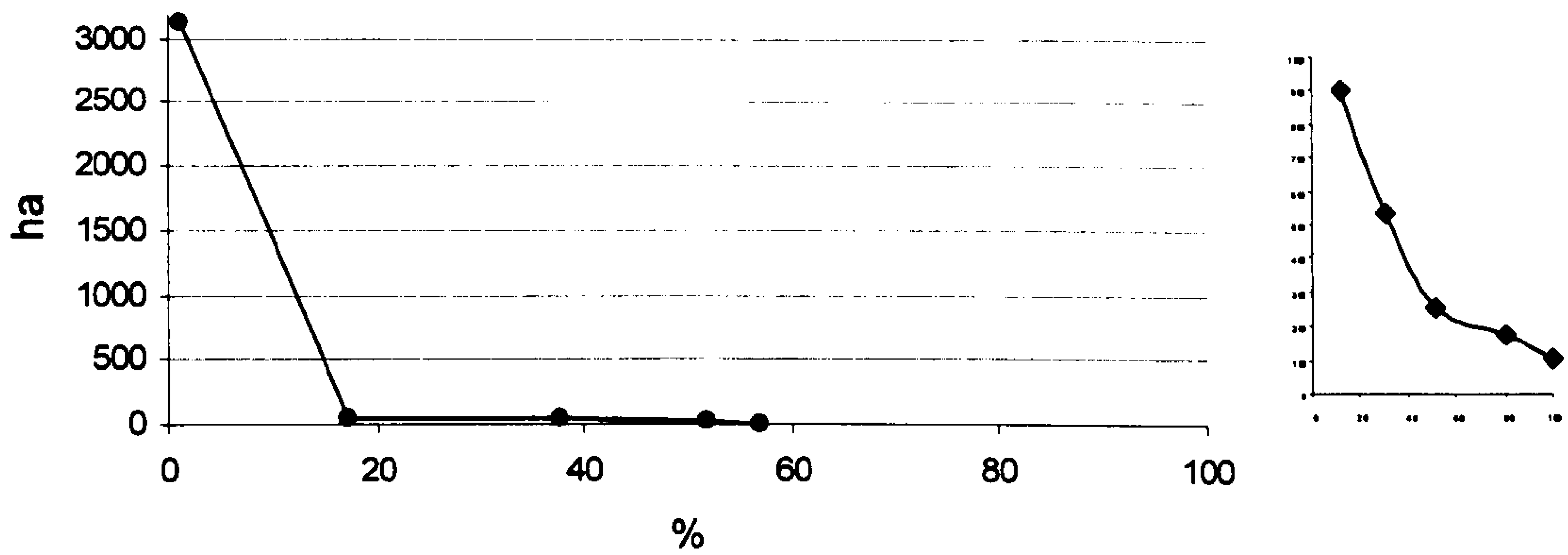
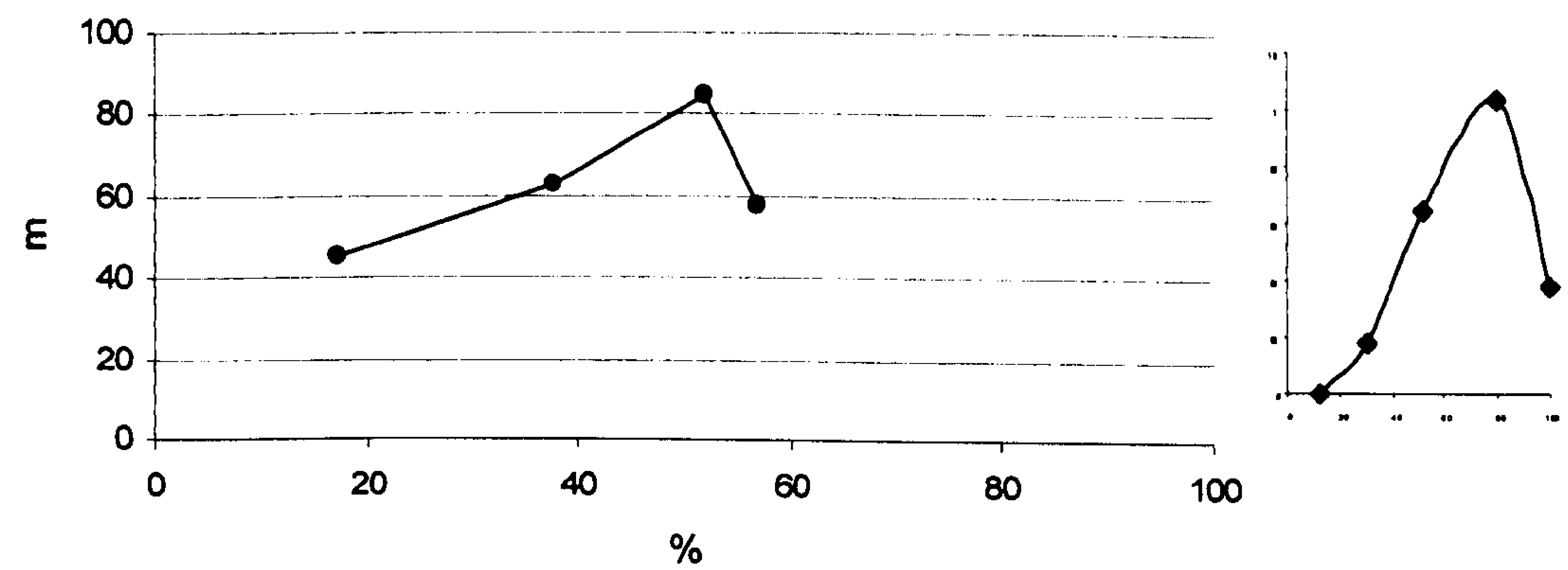


Figure 7.31: Bogotá: mean nearest neighbour and percentage of forest lost, 1975 to 2000. Inset to the right is the comparison of Trani *et al.*'s (1996) curve. The unit for the x and y axis are the same for the main graph.



7.4 Caracas

By 1976 there had been substantial clearance in Caracas, in comparison to Arequipa and Bogotá as the majority of the plots were occupied. Forest fragmentation up to 1976 was influenced by the land-use stages in, C_1 *Subsistence, rice and bananas* (c.1963 – c.1970) and C_2 *Rice and bananas* (c.1970 – c.1980). In 1976 most of the plots (57%) had Type II clearance with isolated patches (Table 5.10). Assuming that all the plots were occupied by 1963 – the founding date of the community – the average cleared area in the plots was 8.7 ha with clearance rates of 0.67 ha yr^{-1} between 1963 and 1976.

In 1976 a large non-forest patch of 892.4 ha had been cleared (Figure 7.32) which can be seen in the patch size distribution (Figure 7.33). There were also smaller patches of non-forest (29 in total) with an average size of 32.4 ha. But the range of sizes was high (PSSD, 163.1 ha), and there was a lack of consistency in size PSCV (504%). The MNN was 117.9 m; the patches were spaced over a wide range of distances NNSD (102.9 m) but were fairly evenly spaced thereby generating a low NNCV (87%).

Because some entire plots had been cleared, the forest had been dissected to four smaller patches ranging from 41.7 ha to 680.1 ha (Figure 7.34). There were also 18 small forest patches, each of which was under a hectare, within the non-forest area (Figure 7.32). The MPS was 61.2 ha, the wide range of sizes was indicated by the PSSD of 161.5 ha and the sizes were quite variable (PSCV, 263%). The MNN (119.7 m) indicated that patches were far apart. There was a moderate range of distances (NNSD, 66.7 m) which varied little (NNCV, 53%). The TEL was 66,780 m. A variety of government policies in the 1960s had encouraged the farmers to migrate to Chapare and Caracas was one such community in this new agricultural frontier. The pattern of fragmentation developed because the roads had been designed to access all the plots and farmers had simultaneously cleared them from this one end. Because the crops initially cultivated were unsuitable, farmers experimented with crops and consequently rates of deforestation were high. Investments in the transport infrastructure to the main market in Cochabamba in part made agricultural expansion viable in this community.

Figure 7.32: Non-forest fragments in Caracas, 1976.

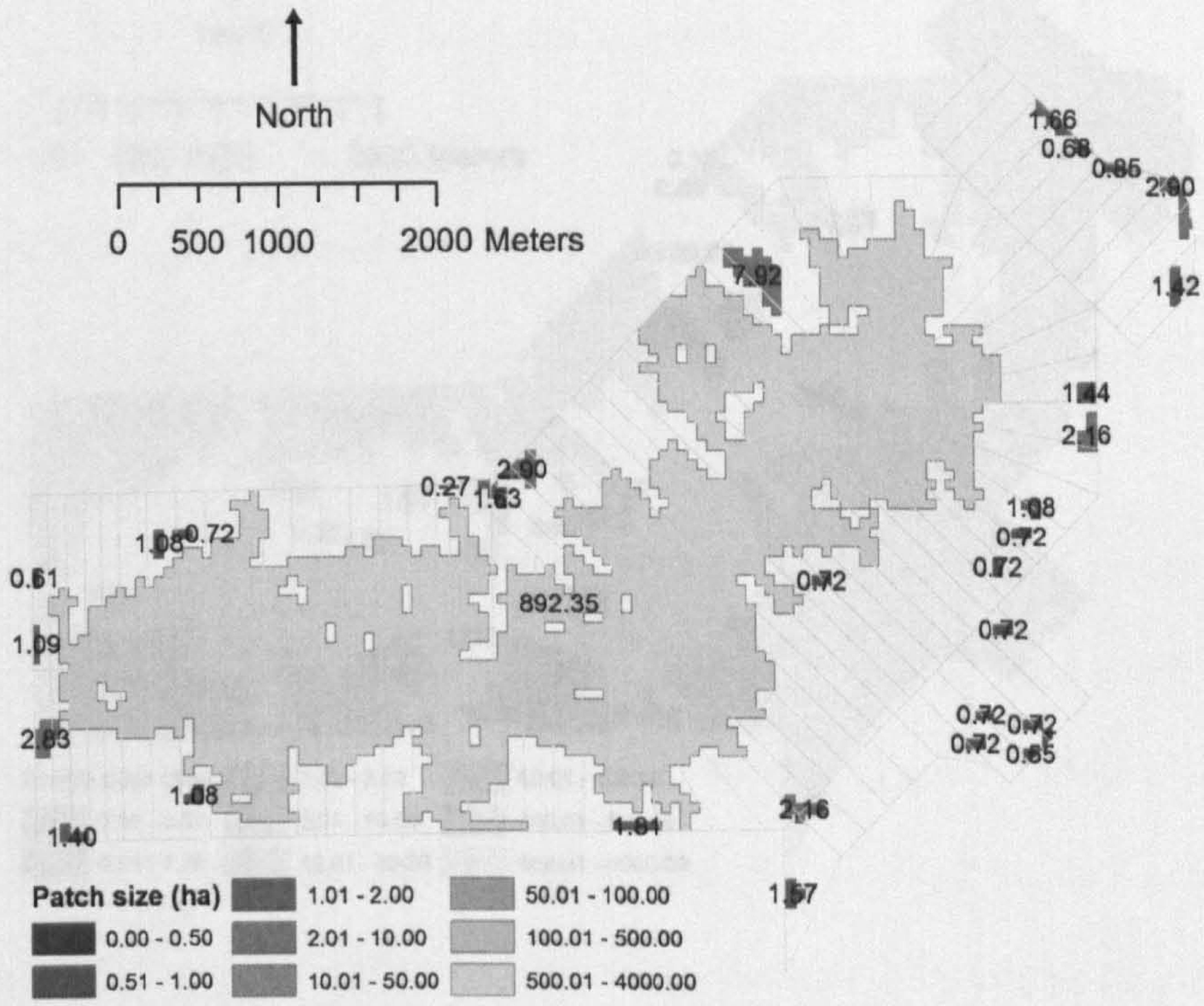


Figure 7.33: Distribution of non-forest fragments in Caracas, 1976 to 2000.

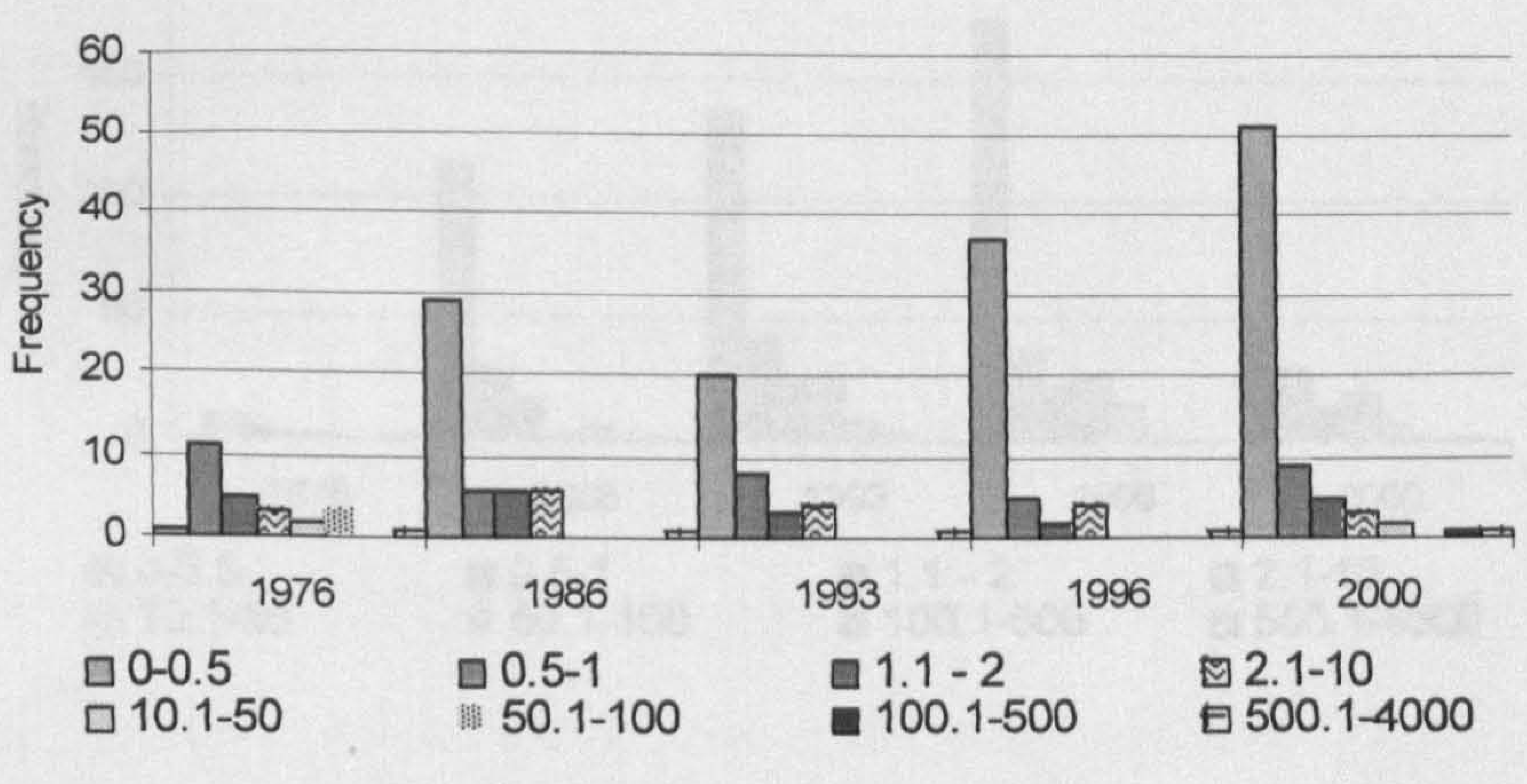


Figure 7.34: Forest fragments in Caracas, 1976.

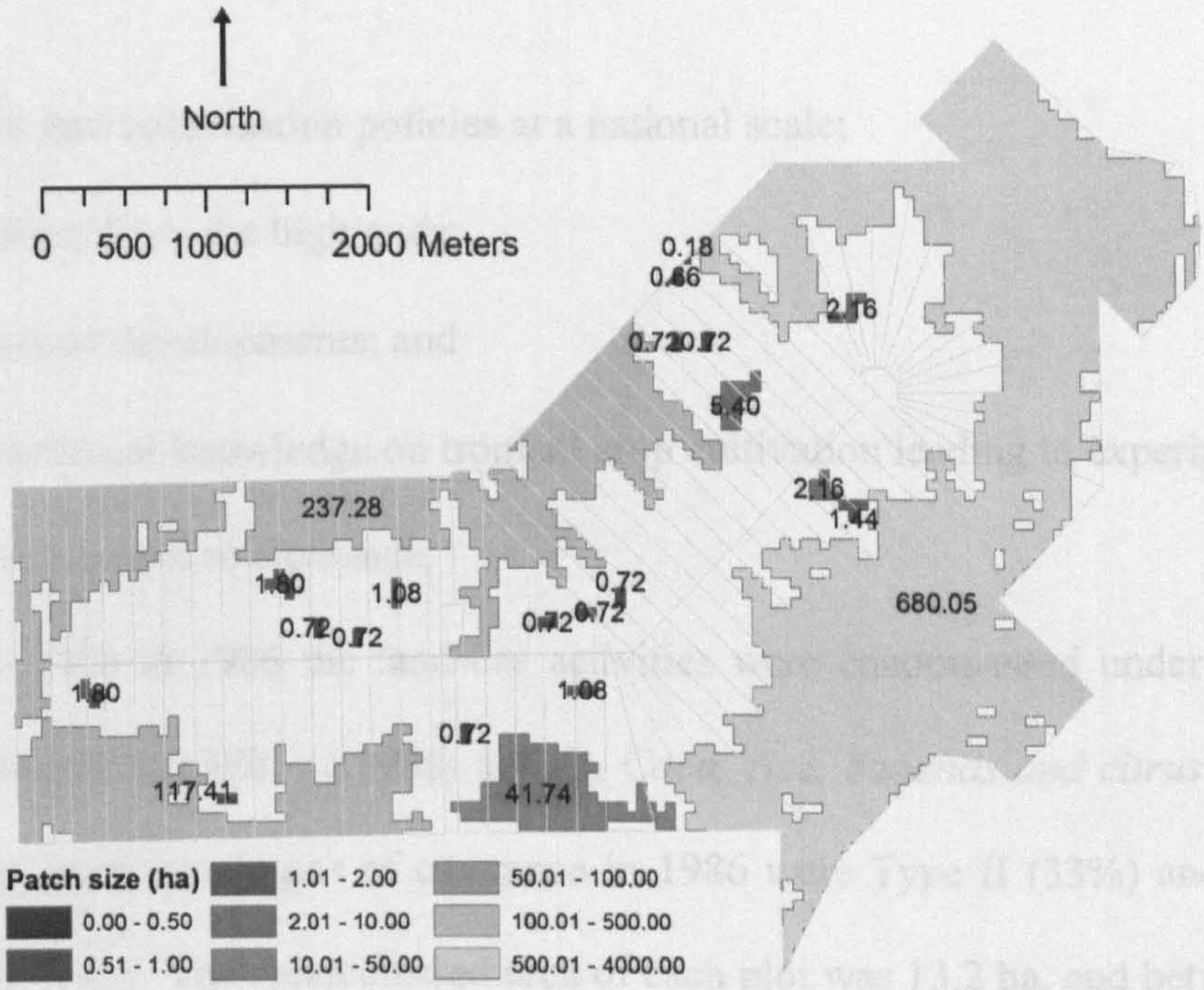
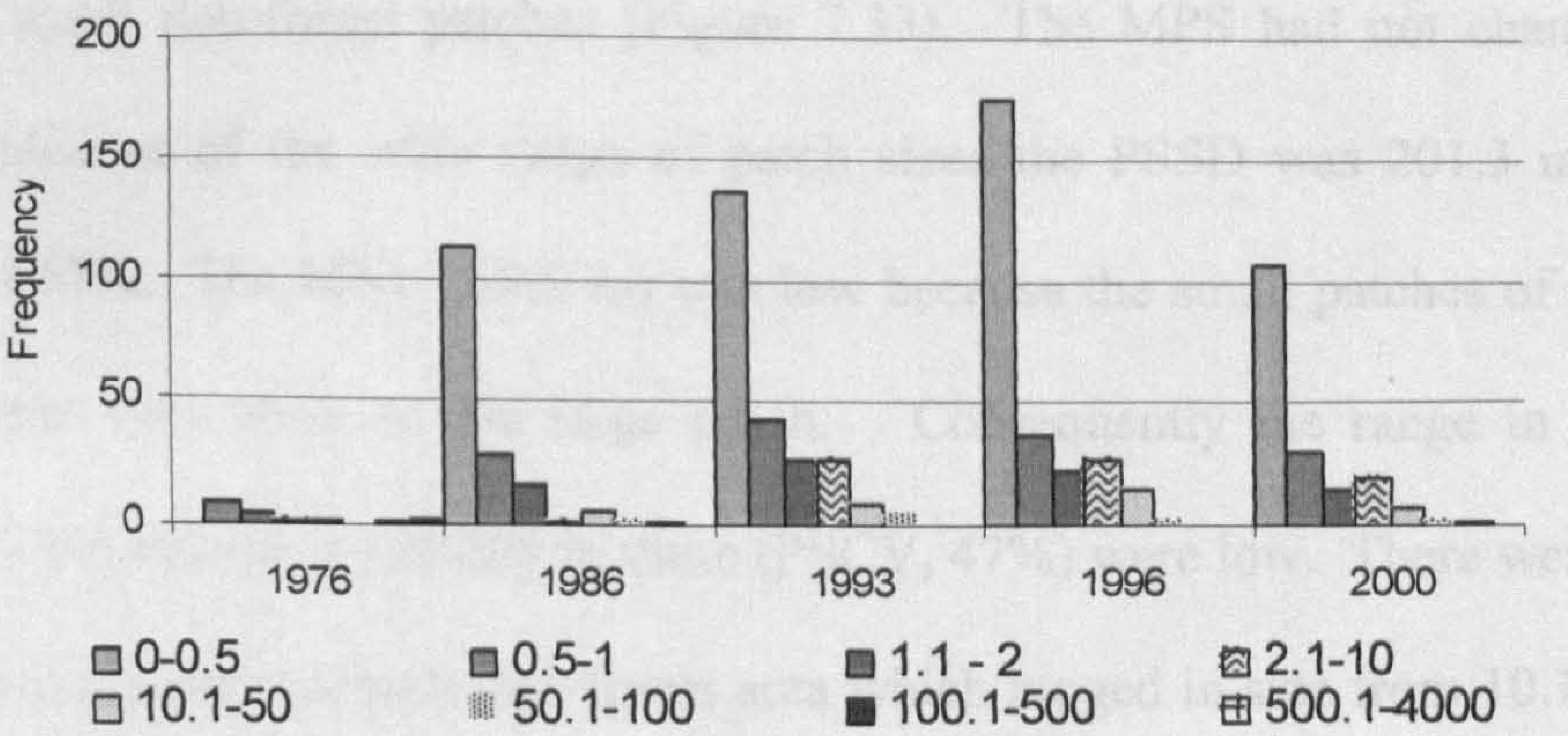


Figure 7.35: Distribution of forest fragments in Caracas, 1976.



Therefore the fragmentation patterns between 1963 and 1976 were driven by:

- spatial attributes of the INC plan in creating land tenure patterns and determining access;
- economic and colonisation policies at a national scale;
- in–migration from the highlands;
- infrastructure developments; and
- lack of technical knowledge on tropical crop cultivation leading to experimentation, failure and excessive clearance.

From 1976 to 1986 the land-use activities were encompassed under stages C_2 *Rice and bananas* (c.1970 – c.1980) and C_3 *Coca, rice, bananas and citrus* (c.1980 – c.1995). The main typologies of clearance in 1986 were Type II (33%) and Type VI (30%) (Table 5.10). The mean cleared area of each plot was 13.2 ha, and between 1976 and 1986 the rate of clearance, 0.45 ha yr^{-1}, was lower than the previous time period.

The large area of non-forest had now increased to 1,381.1 ha and there were isolated patches of non-forest of generally less than 3 ha in the forest patches (Figure 7.36). The distribution showed that there was one large patch in excess of 500 ha and a number of small non-forest patches (Figure 7.33). The MPS had not changed very much but because of the wide range of patch sizes the PSSD was 201.3 m and the PSCV was 667%. The MNN (59.9 m) was low because the small patches of clearance in forest were very close to the large patch. Consequently the range in distances (PSSD, 26.4 m) and the variability in these (PSCV, 47%) were low. There were several forest patches around the main non-forest area which ranged in size from 10.1 to 150.4 ha, and over 100 forest islands under 2 ha in the non-forest area (Figure 7.37). The increase in patches was a result of the division of the larger forest patches so the MPS

Figure 7.36: Non-forest fragments in Caracas, 1986.

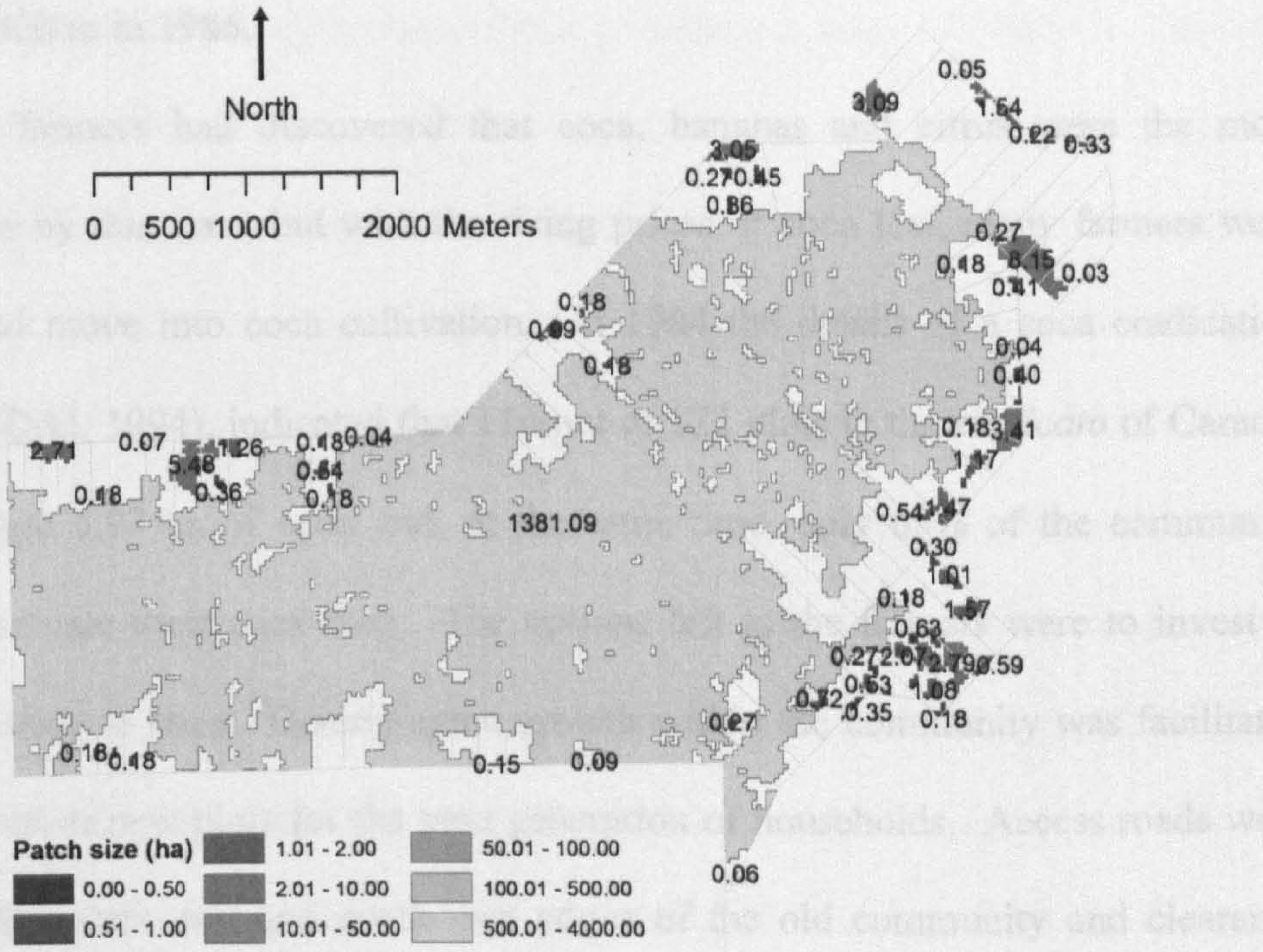
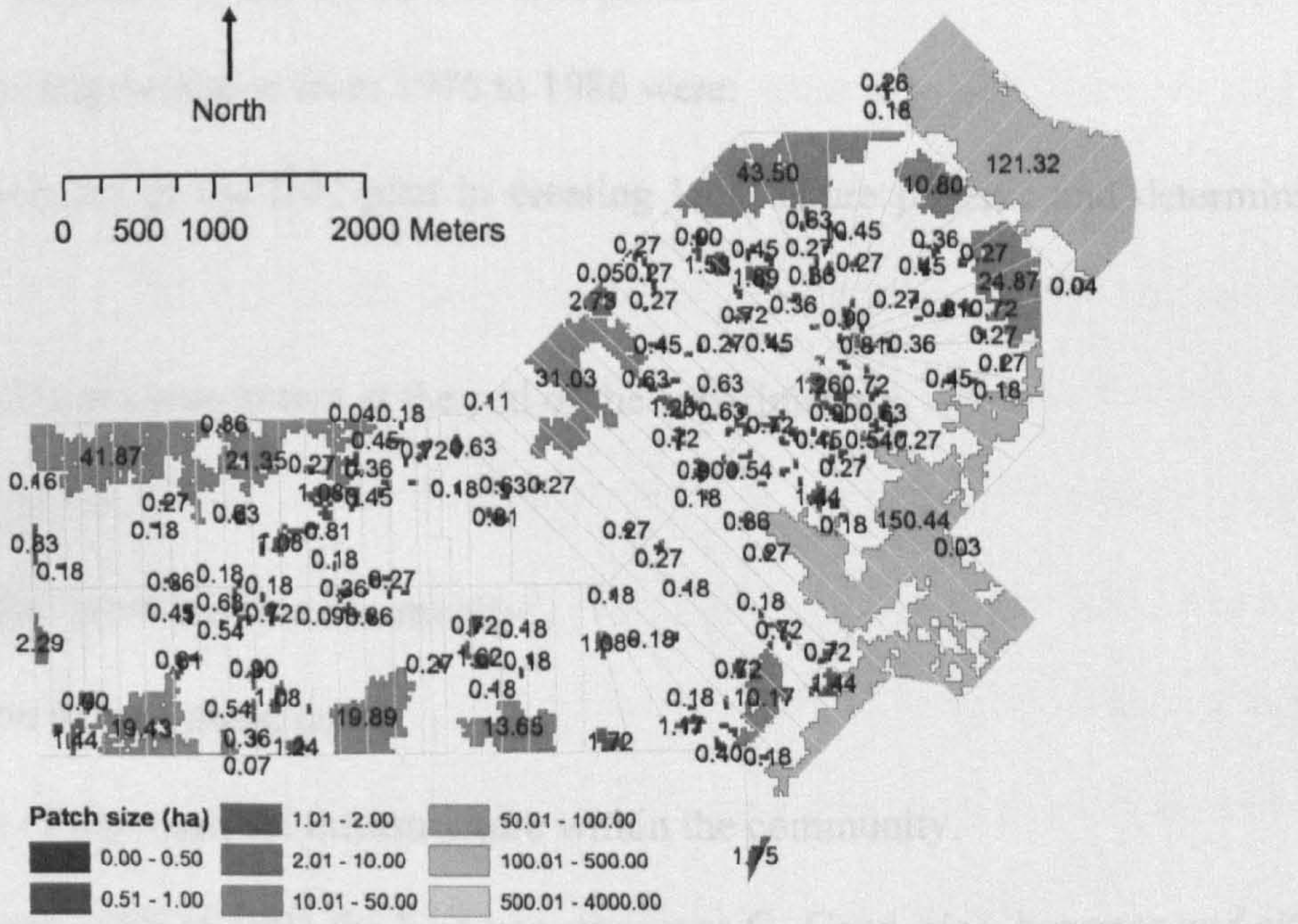


Figure 7.37: Forest fragments in Caracas, 1986.



(3.5 ha) had fallen, the range of sizes decreased (PSSD, 17.2 m) but the size range became more variable (PSCV, 517%). The MNN had also decreased (119.8 to 75.7 m;

NNSD, 58.6 m) and more consistent (NNCV, 77%). The TEL rose from 66,780 m in 1976 to 108,300 m in 1986.

Most farmers had discovered that coca, bananas and citrus were the most suitable crops by this time, but with the rising prices of coca leaf, many farmers were encouraged to move into coca cultivation. In 1984 the details of a coca eradication programme (DAI, 1994), indicated that 116 out of 122 plots in the *sindicato* of Caracas had on average 0.97 ha of coca and, at the same time, only 65% of the community agreed to eradicate their coca crop. The options left to the farmers were to invest in bananas or return to coca. Demographic growth within the community was facilitated by the addition of new plots for the next generation of households. Access roads were built along the north east and south east edges of the old community and clearance began from the primary ends of the new plots. Initially the clearance was for subsistence and coca. The new access roads also helped some farmers on the original plots to clear from the secondary ends of their plots.

The drivers of fragmentation from 1976 to 1986 were:

- spatial attributes of the INC plan in creating land tenure patterns and determining access;
- consolidation of crops grown at the end of the experimental;
- high coca prices;
- demographic growth in the community;
- the addition of new plots; and
- expansion of the transport infrastructure within the community.

Between 1986 to 1993 the land-use stage was C_3 *Coca, rice, bananas and citrus* (c.1980 – c.1995). By 1993 there had been an increase in Type V (26%) and a decrease in Type VI (to 24%) typologies (Table 5.10). This time point shows a period of net 'reforestation', overall there had been slight return of forest with average cleared areas of 12.0 ha and, as a consequence, the average rate of clearance was -0.17 ha yr^{-1}. The main non-forest patch had decreased to 1,273.0 ha and there were very few non-forest patches (Figure 7.38). This caused a slight decrease in the number of non-forest patches (43 to 36) with a MPS of 36.5 ha. There was a bimodal distribution of patch sizes (Figure 7.33) which demonstrates why there is a wide range of sizes (PSSD, 210.8 ha) and high variability in patch size (PSCV, 578%). The small patches were in close proximity to the large non-forest patch; the MNN remained low (63.6 m), range of distances increased (NNSD rose from 26.4 to 66.4 ha) and variability of distances doubled (NNCV rose to 104% from 47%). This indicates that the 'reforestation' was not uniform in the community, i.e. the variations in activities between different plots probably determine how much forest regrowth there was between non-forest patches.

The largest fragment of forest was 89.8 ha, but there were more than 150 forest islands of less than 1.5 ha (Figure 7.39). The number of forest patches had increased from 1986 to 1993 (169 to 254). This was caused by larger fragments being divided up and the development of small forest patches in the non-forest area. The MPS was small (2.9 ha) and in 1993 the patch sizes had a consistent size range (PSSD, 10.3 ha) but high variability within the range (PSCV, 352%). The MNN fell to the lowest levels in the sequence (40.9 m). The patches were evenly spaced as indicated by the small range in distances (NNSD, 19.3 m) and variability and (PSCV, 47%). The TEL rose from 108,300 m in 1986 to 236,400 m in 1993. Many farmers were cultivating coca at this time, but they had also begun to cultivate citrus in orchards in the previously cleared

Figure 7.38: Non-forest fragments in Caracas, 1993.

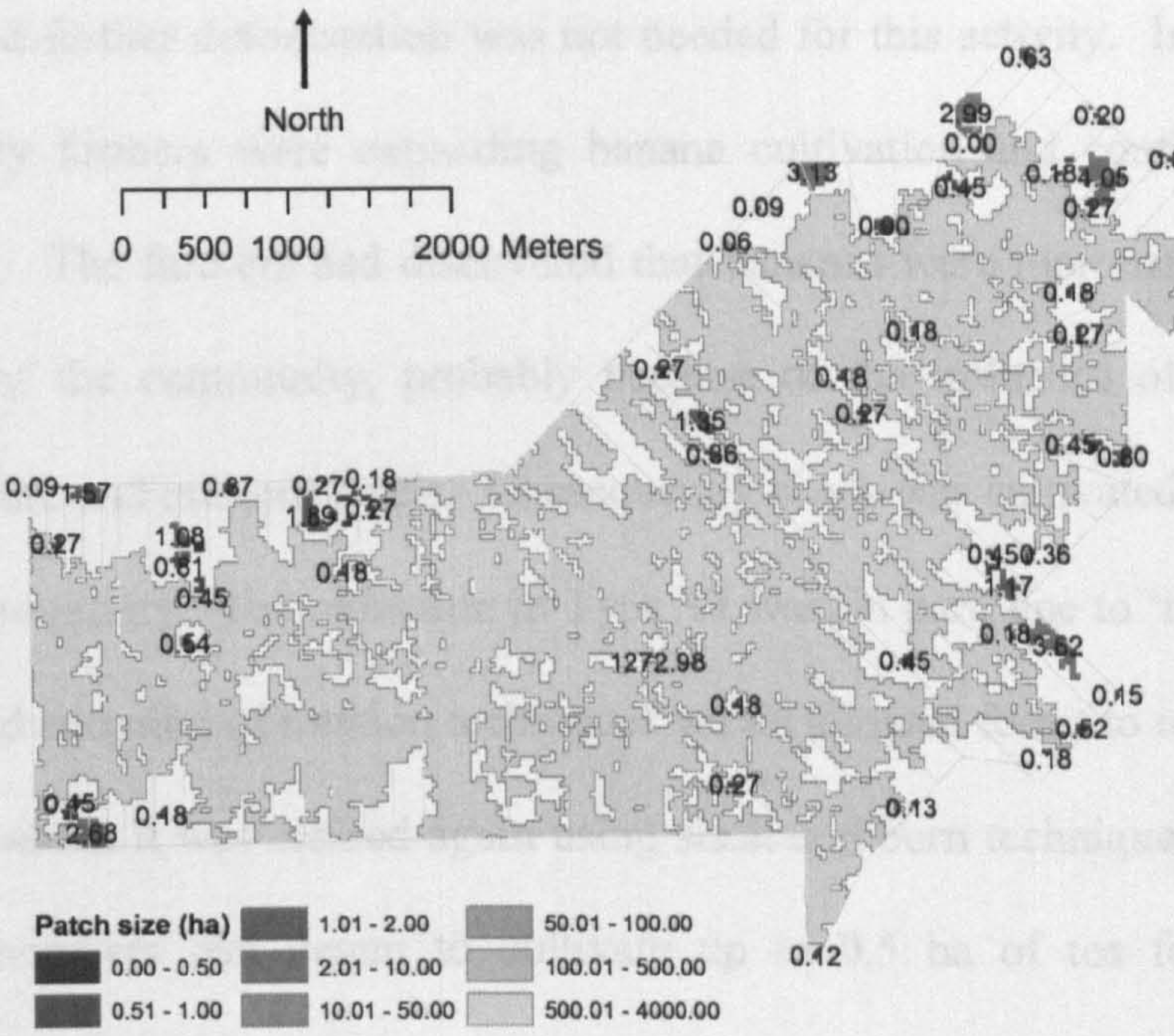
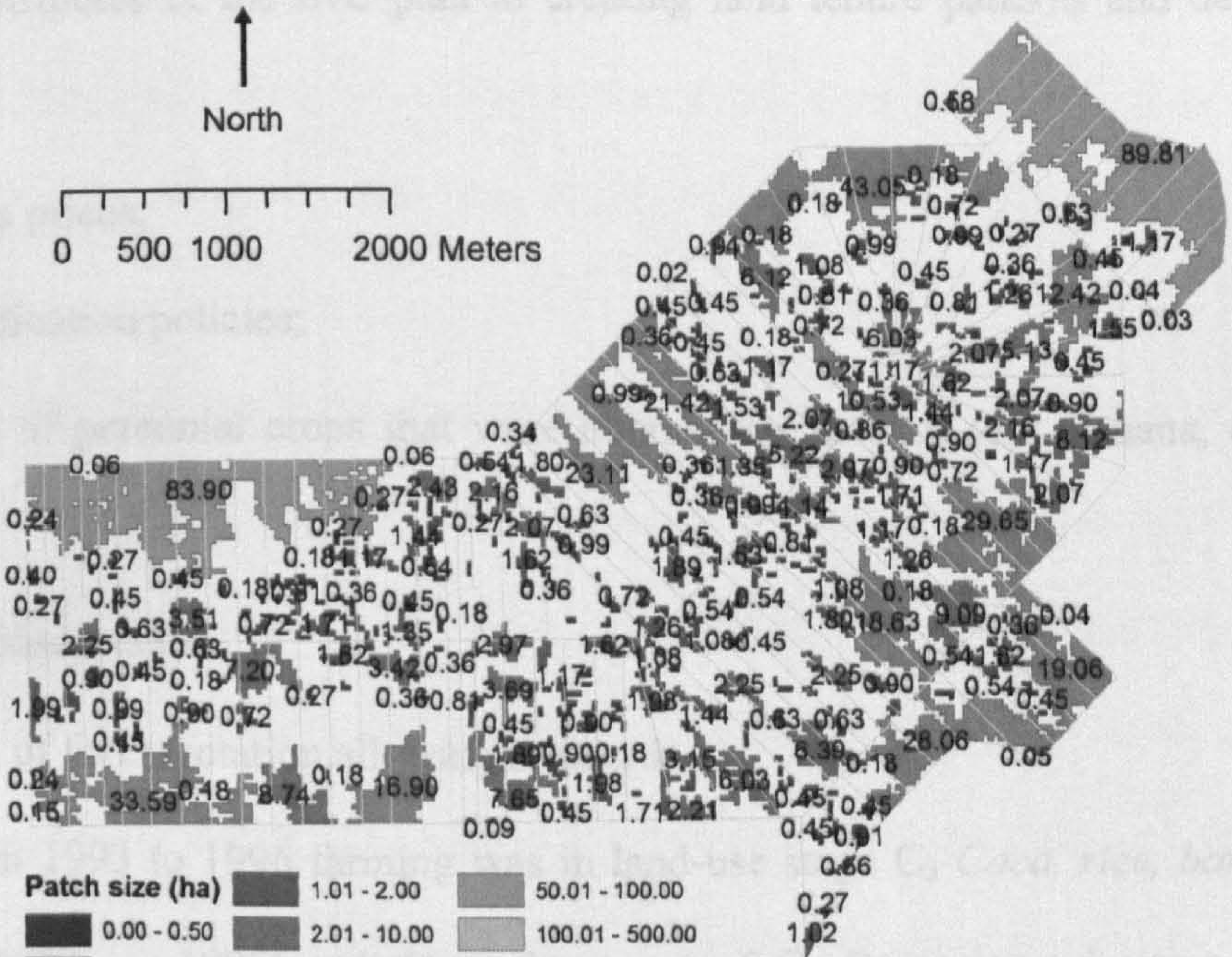


Figure 7.39: Forest fragments in Caracas, 1993.



areas towards the primary ends of their plots. Because this area had previously had been cultivated further deforestation was not needed for this activity. In other parts of the community farmers were expanding banana cultivation and continuing to clear forest for this. The farmers had discovered that bananas were more successful on the eastern side of the community; probably because of the influence of rivers on soil texture, moisture and nutrient levels. Consequently citrus was cultivated on the western side of the community. The reduction in Type VI was, in part, due to 'reforestation' of some plots and adoption of rotation techniques which allowed forest to regenerate for 3-8 years after which it was cleared again using slash and burn techniques. Some of the community members had begun to cultivate up to 0.5 ha of tea for the new tea processing plant situated in the community. Tea is a perennial and provided a year round harvest, this would also have relieved a small amount of pressure to clear new forest. In summary, the drivers of forest fragmentation from 1986 to 1993 were:

- spatial attributes of the INC plan in creating land tenure patterns and determining access;
- high coca prices;
- coca eradication policies;
- adoption of perennial crops that were alternatives to coca (e.g. banana, citrus and tea);
- soil attributes; and
- adoption of forest rotation allowing regrowth.

From 1993 to 1996 farming was in land-use stage C_3 *Coca, rice, bananas and citrus* (c.1980 – c.1995) and the early stages of C_4 *Bananas and citrus* (c.1995 – 2002). By 1996 37% of the plots have been completely cleared (Type VI) and 30% had been cleared from both ends with isolated patches (Type V) (Figure 5.10). In the short period between 1993 and 1996, the average cleared area increased slightly to 13.1 ha, and the rate of clearance between 1993 and 1996 was 0.34 ha yr^{-1}.

The non-forest patch increased in size to 1,396.1 ha and there were a few isolated non-forest patches above 10 ha (Figures 7.33 and 7.40). The numbers of non-forest patches were slightly lower in 1993 (36) and increased to 49 in 1996. Because there were many small patches the MPS was small (2.4 ha), had a wide range (PSSD, 201.4 ha) and was highly variable (PSCV, 681%). The MNN value (54.1 m) the range in distances were low (PSSD, 33.1 ha) and the variability (PSCV, 61.3%) was low because further forest loss had decreased the distances between the non-forest patches.

There were few large forest fragments left, only 10 patches above 10 ha (Figure 7.35) and most of the forest patches that were within the non-forest area were below a hectare in size (Figure 7.40). The MPS was low at 2.1 ha. The patches were consistent in their size range (PSSD, 6.3 ha) but the variability in forest patch size was quite high (PSCV, 299%). Because of the large number of forest patches the MNN (54.0 m) was low and the range of inter-patch distances was fairly even (NNSD, 31.7 m) and their variability (NNCV, 58%) was low. The TEL fell from 236,400 m in 1993 to 189,210 m in 1996.

Between 1993 and 1996, eradication policies forced farmers to rely less on coca. Following the reduction in coca cultivation, the new plots to the northeast and southeast were cleared rapidly for bananas. The construction of cleaning and packing sheds for export bananas encouraged more farmers to begin banana cultivation on the older plots where the secondary end of the plot was in the vicinity of these facilities. Established crops, e.g. citrus fruits and tea, had matured and were being harvested. As in the previous time point most of the plots had been cleared and rotation crops and forest re-growth was being practiced.

Figure 7.40: Non-forest fragments in Caracas, 1996.

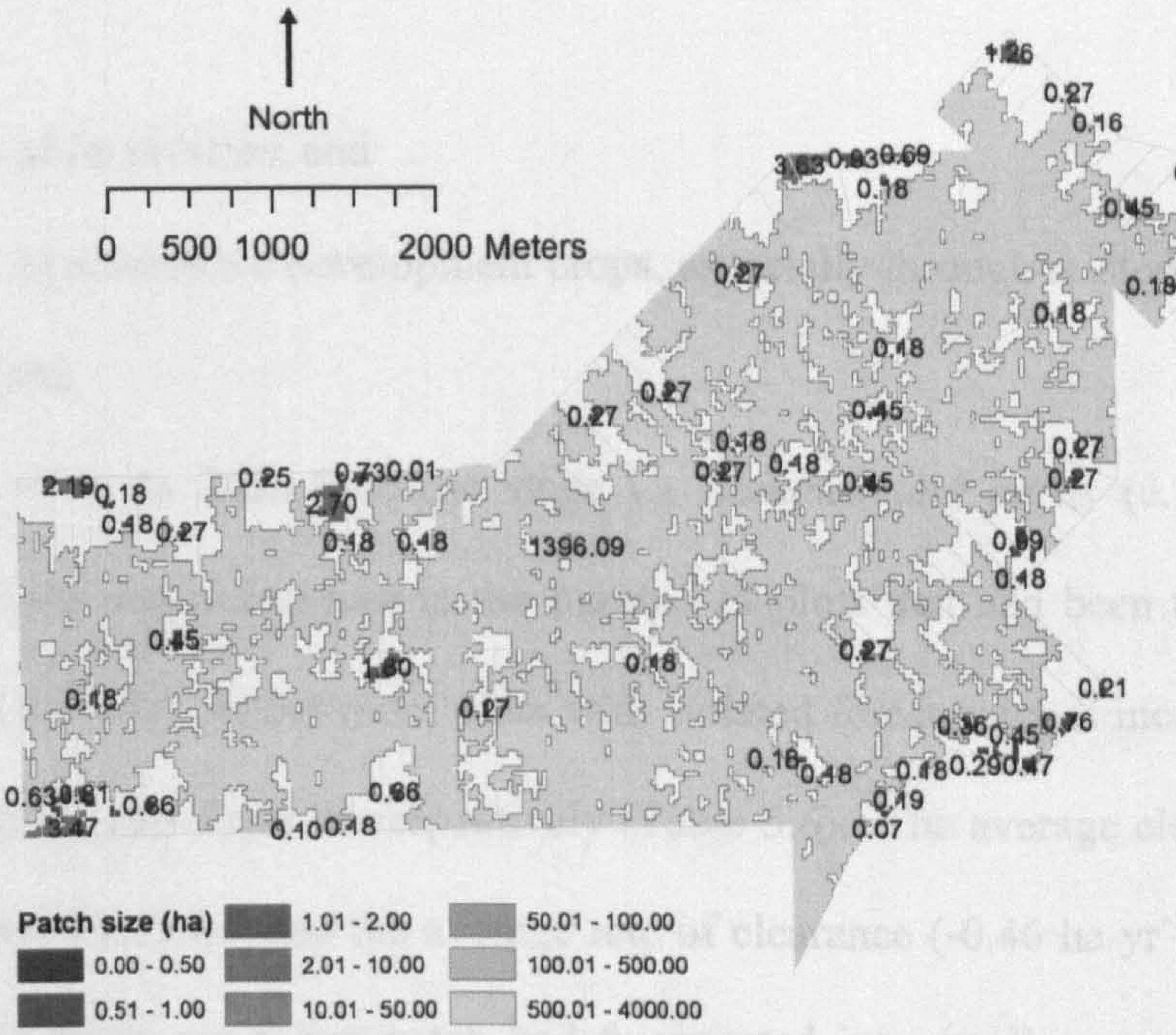
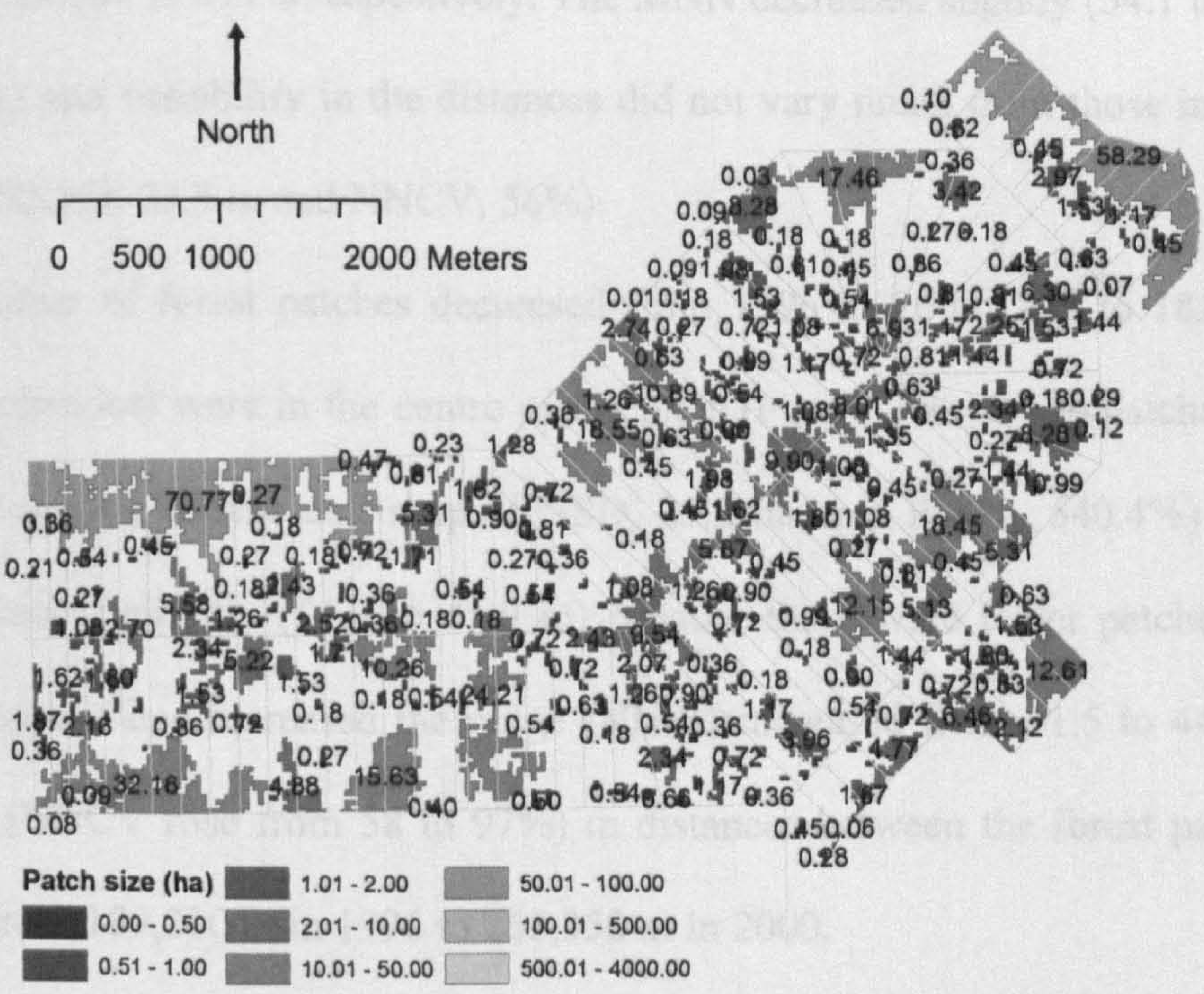


Figure 7.41: Forest fragments in Caracas, 1996.



The main drivers of forest fragmentation between 1993 and 1996 were:

- spatial attributes of the INC plan in creating land tenure patterns and determining access;
- coca eradication policies; and
- promotion of alternative development crops, especially through related infrastructure developments.

From 1996 to 2000 land-use stage C_4 *Bananas and citrus* (c.1995 – 2002) prevailed. There was a decrease in the number of plots that had been totally cleared (Type VI fell to 16%), whilst those plots with isolated forest patches increased to 30% and 35%, Type V and Type IV respectively (Table 5.6). The average cleared area had fallen to around 11.35 ha, and the average rate of clearance (-0.46 ha yr^{-1}) had become negative. The large non-forest patch had fragmented into smaller non-forest patches (Figure 7.42). This increased the number of non-forest patches from 49 to 92, and the range (PSSD) and variability (PSCV) in patch sizes decreased slightly from 201.4 ha to 113.8 ha and from 681 to 657% respectively. The MNN decreased slightly (54.1 to 41.8 m) but the range and variability in the distances did not vary much from those in 1996 and were low (NNSD, 23.5 m and NNCV, 56%).

The number of forest patches decreased from 1996 to 2000 (247 to 182) and most of the patches lost were in the centre of the plots (Figure 7.43). The patches had become less consistent in size and shape (PSSD, 25.2 ha; and PSCV, 540.4%). The MNN had decreased slightly (54.0 to 45.9 m) because there were fewer patches and bigger gaps, and this had increased the range (NNSD increased from 31.5 to 44.3 m) and variability (NNCV rose from 58 to 97%) in distances between the forest patches. The TEL rose from 189,210 m in 1996 to 265,350 m in 2000.

Figure 7.42: Non-forest fragments in Caracas, 2000.

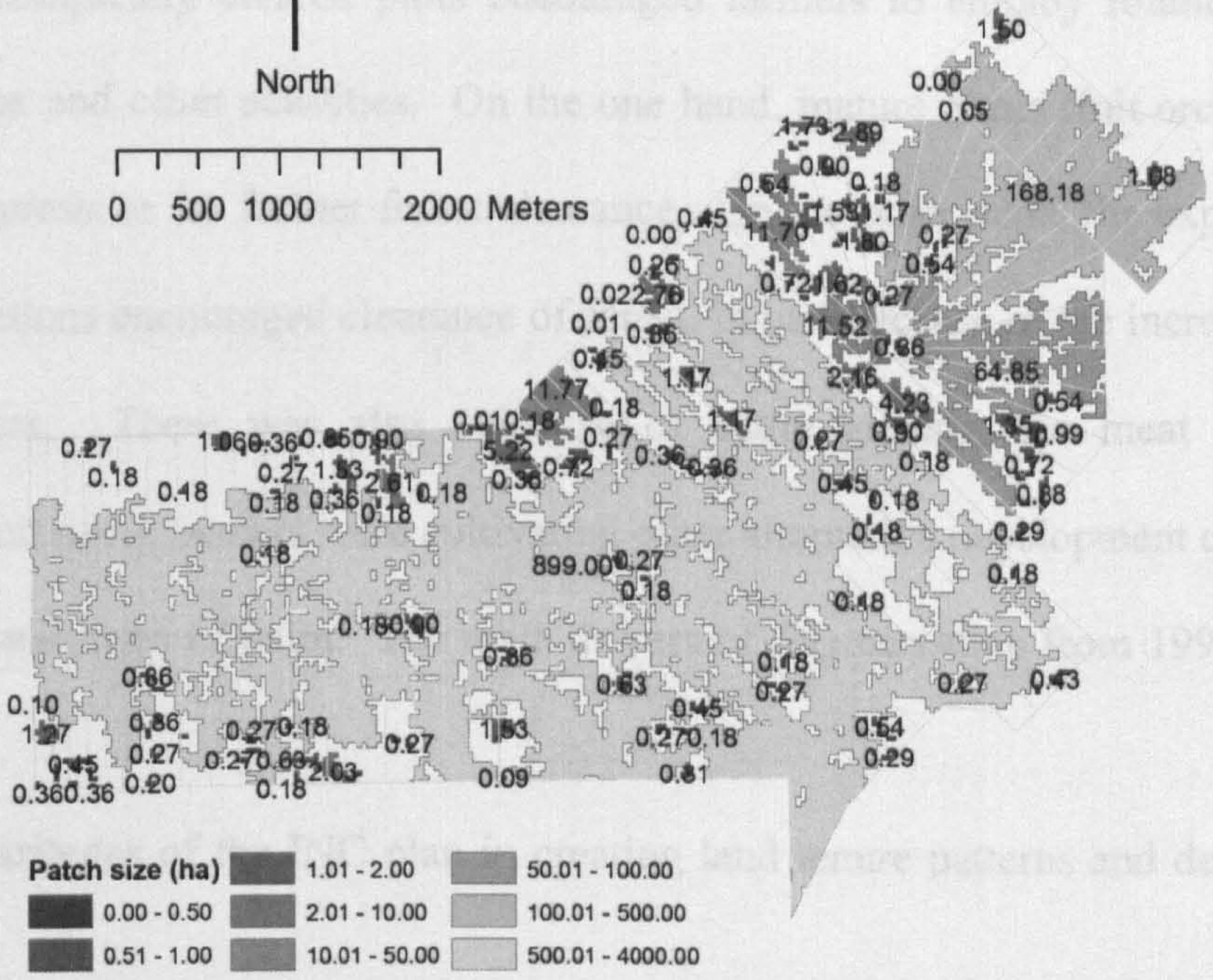
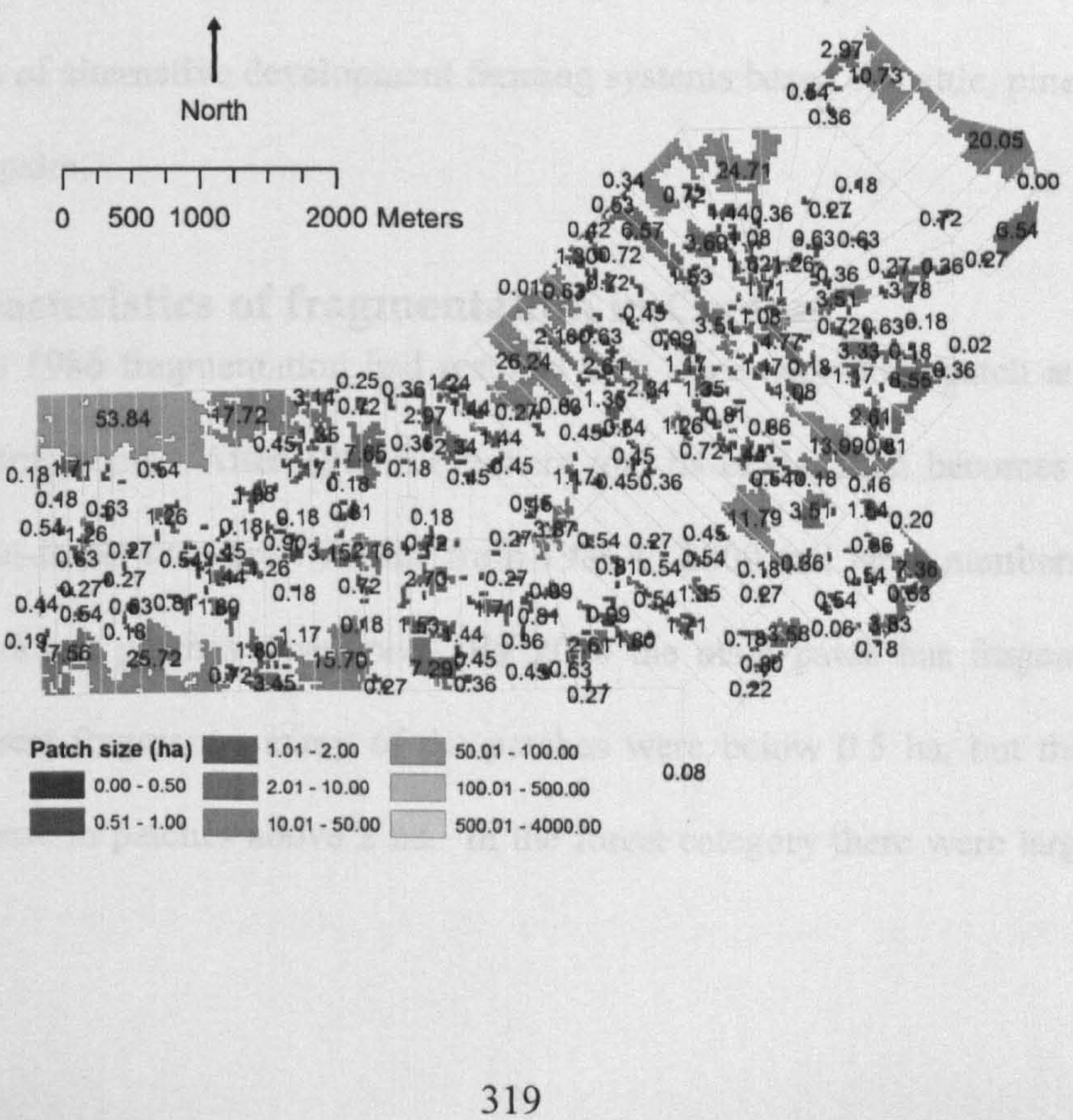


Figure 7.43: Forest fragments in Caracas, 2000.



A number of processes that had caused fragmentation in this period had increased because the land-use strategies had become more complex. The increasing numbers of completely cleared plots encouraged farmers to employ rotation and to diversify crops and other activities. On the one hand, mature citrus fruit orchards had removed the pressure for further forest clearance. On the other hand, the expansion of banana plantations encouraged clearance of forest, in part because of the increase in the export markets. There was also evidence of cattle grazing, for meat and milk production, and some farmers were cultivating other alternative development crops such as pineapple and heart of palm. The main drivers of fragmentation from 1996 to 2000 were:

- spatial attributes of the INC plan in creating land tenure patterns and determining access;
- widespread adoption of crop-forest rotation;
- maturity of citrus orchards;
- export of banana cultivation, in part encouraged by export potential; and
- adoption of alternative development farming systems based on cattle, pineapple and heart of palm.

7.4.1 Characteristics of fragmentation in Caracas

Up to 1986 fragmentation had resulted in a large non-forest patch and several large forest fragments. After 1986 the pattern and its explanation becomes complex. The large non-forest area grew in size from 1986 to 2000 and large numbers of small isolated non-forest patches developed. By 2000 the main patch has fragmented into large non-forest fragments; many of the patches were below 0.5 ha, but there was a general increase in patches above 2 ha. In the forest category there were large patches of forest up to 1986 which then fragmented to sizes between two and 50 ha from 1993 onwards.

7.4.2 Evolution of landscape metrics in Caracas

In 1986, 33% of the forest remained in Caracas, it increased to 42% in 1993, then decreased again to 32% in 1996 and by 2000 was 45%. This means that the percentage of forest was always to the right of the curves in Trani *et al.*'s (1996) model unlike Arequipa and Bogatá, which were to the left i.e. as 33% of the forest remained, the values NoP, TEL and MPS should be decreasing while MNN should be increasing. However, even after accounting for the kinks in the curves due to the fluctuations in the forest cover both the NoP (Figure 7.44) and TEL (Figure 7.45) increased. From 1976 to 1986 the MPS (Figure 7.46) decreased as expected but the MNN (Figure 7.47) did not increase as predicted in the Trani *et al.* (1996) model. In both cases the forest area subsequently began to fluctuate and the relationship between the metric and forest area deviated from the expected trend.

The differences between the trends at Caracas and those predicted by Trani *et al.* (1996) most likely occurred because the spatial patterns of forest patches are highly variable in location and size and (Figures 7.36 to 7.43) therefore the forest does not fragment in a predictable fashion. The forest patches are a result of many different activities within and between individual plots (which comes with the maturity of the community) where farmers make a variety of decisions. For example, a farmer may clear forest for a new crop whilst another farmer in the next plot may be consolidating his current crop, or rotation may allowing forest re-growth at the edges of forest patches. The choice of activity determines if a forest fragment is cleared, divided or allowed to regrow. The result is that the fragmentation becomes spatially complex. In such circumstances, the 'parabolic curve' will continue slowly and randomly until a particular driving force which influences the majority of the farmers becomes dominant. This may encourage them to clear all their plots or the (current) spatial limits that the farmers are confined to are removed and the area of cultivation can extend once again.

Figure 7.44: Caracas: number of patches and percentage of forest loss. Inset to the right is the comparison of Trani *et al.*'s (1996) curve. The unit for the x and y axis are the same for the main graph.

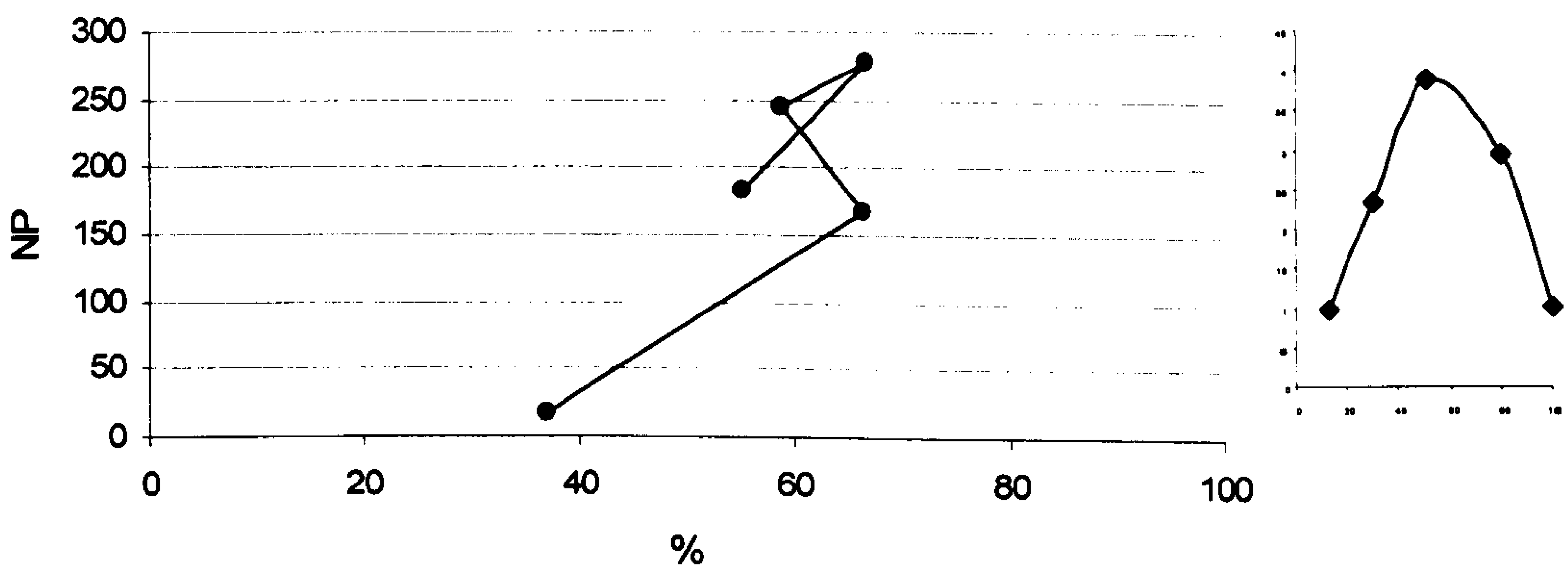


Figure 7.45: Caracas: total edge length and percentage of forest loss. Inset to the right is the comparison of Trani *et al.*'s (1996) curve. The unit for the x and y axis are the same for the main graph.

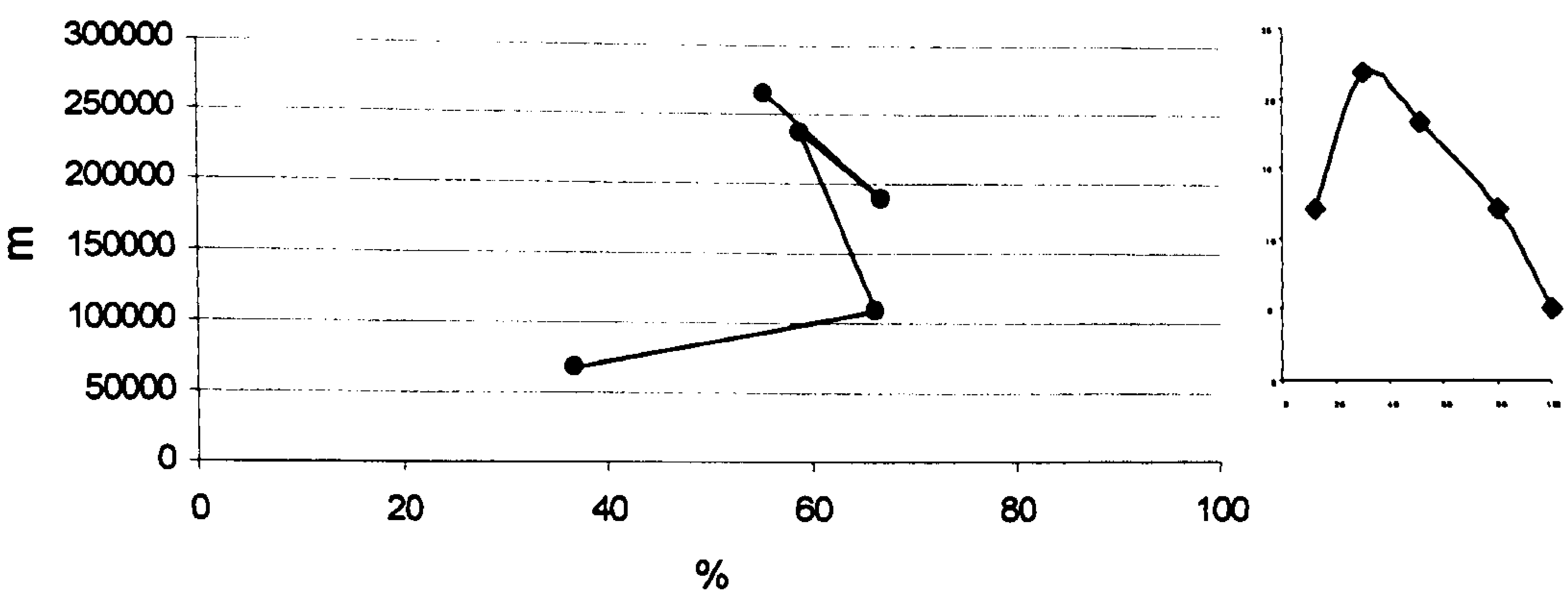


Figure 7.46: Caracas: mean patch size and percentage of forest loss. Inset to the right is the comparison of Trani *et al.*'s (1996) curve. The unit for the x and y axis are the same for the main graph.

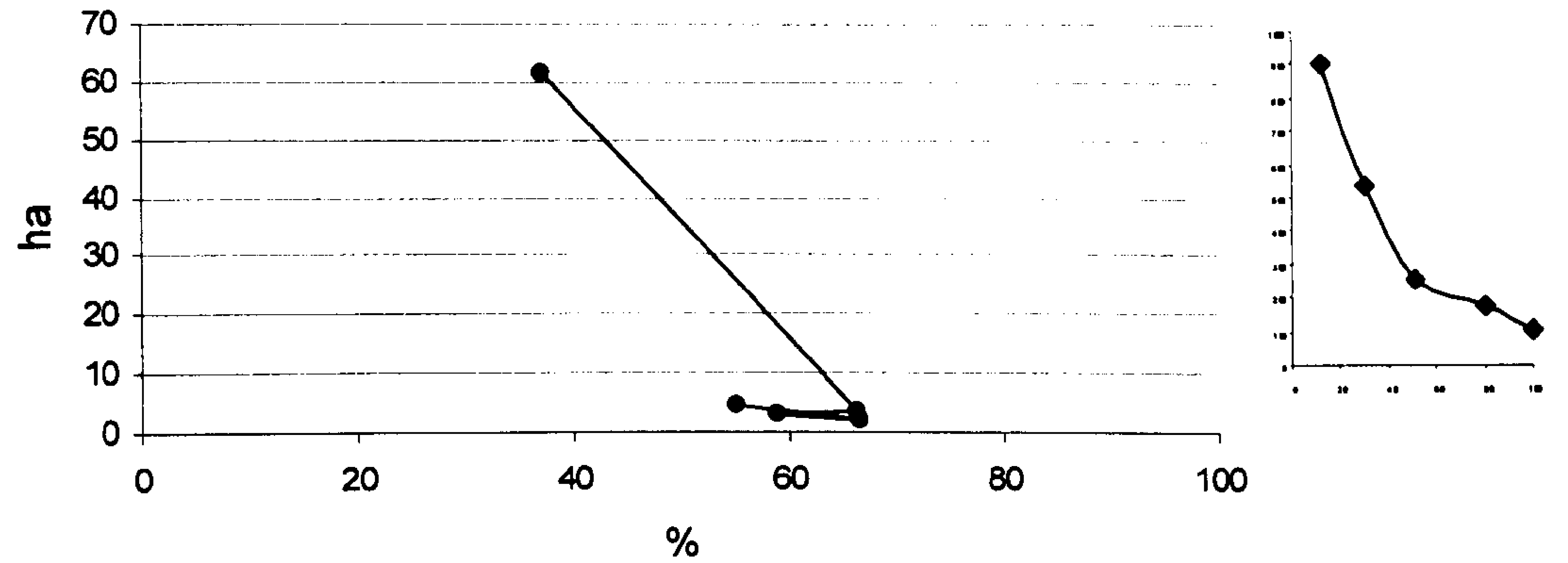
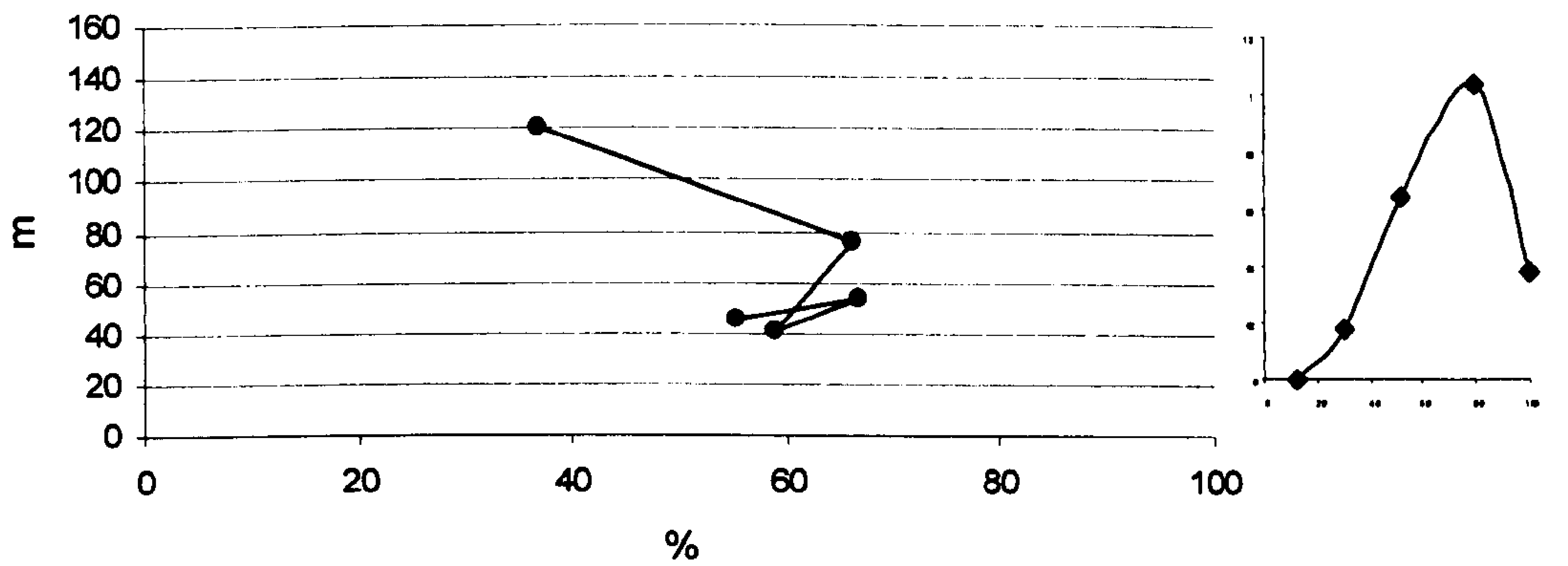


Figure 7.47: Caracas: mean nearest neighbour and percentage of forest loss. Inset to the right is the comparison of Trani *et al.*'s (1996) curve. The unit for the x and y axis are the same for the main graph.



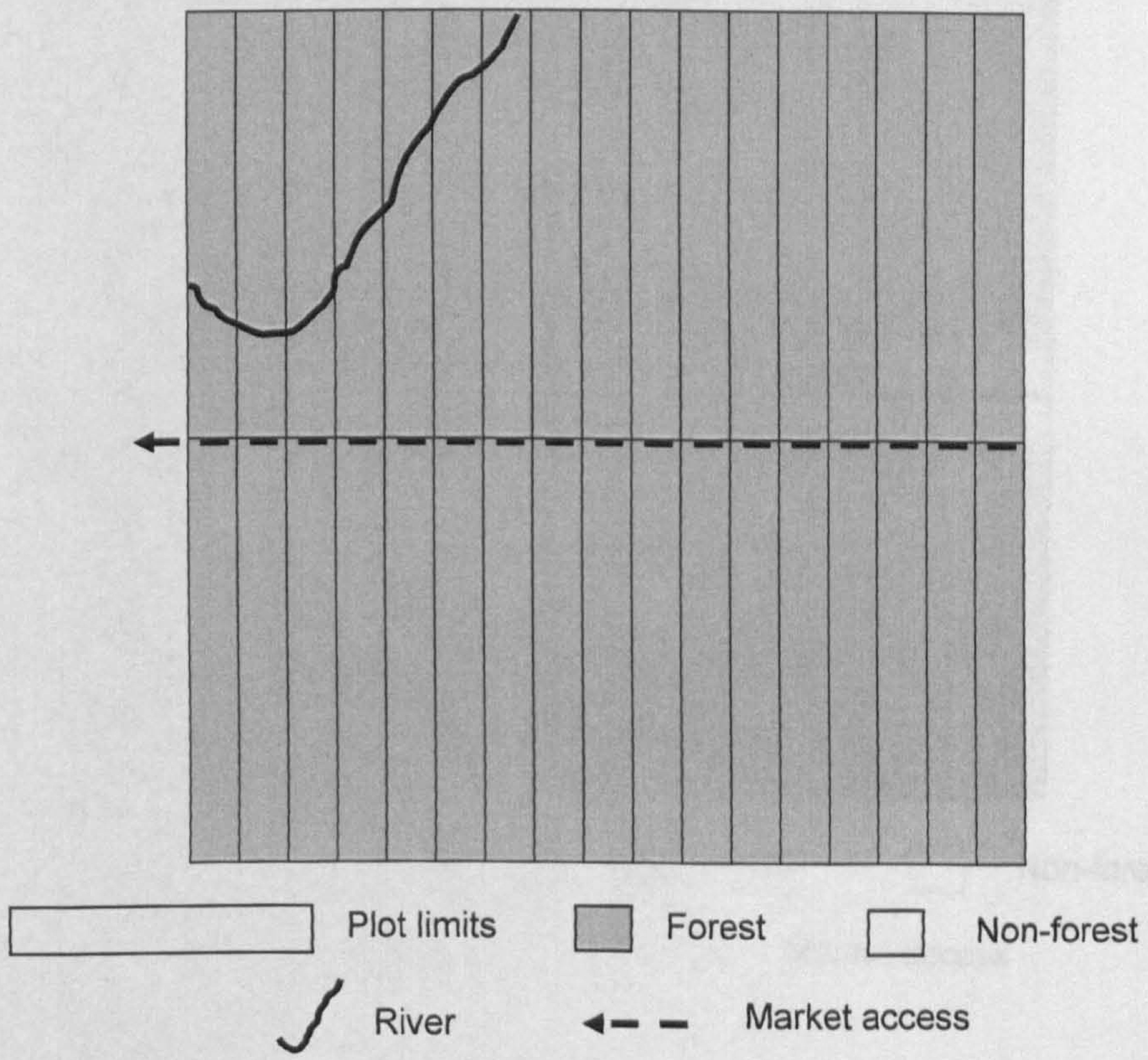
7.5 Conceptual model for forest fragmentation for the communities in Chapare

From the prior sections in this chapter it is clear that forest fragmentation in the communities over time, and between the communities, has varied in response to the influences of different driving forces. Moreover, comparing the trends from Trani *et al.* (1996) it is evident that in some circumstances key landscape metrics do follow the predictions of Lambin (1997), though in other circumstances they do not. In the previous chapter (6.6) the rates of forest clearance were seen to vary through time and deforestation trajectories developed to leave a 'colonist footprint' that differs (a) between the communities, and (b) from the findings of Brondizio *et al.* (2002). In this section I develop a conceptual model to explain why these deviations occurred and show a progressive sequence of fragmentation.

7.5.1 Planning stage

The model is represented by a community with a grid of 34 plots of equal dimensions. Each plot borders a central track which allows access to the market. The surface is assumed to be flat and uniform with the exception of seven plots that have a river passing through (Figure 7.48). In the *planning stage* all the plots have Type I clearance (i.e. no clearance) as no colonists have arrived yet.

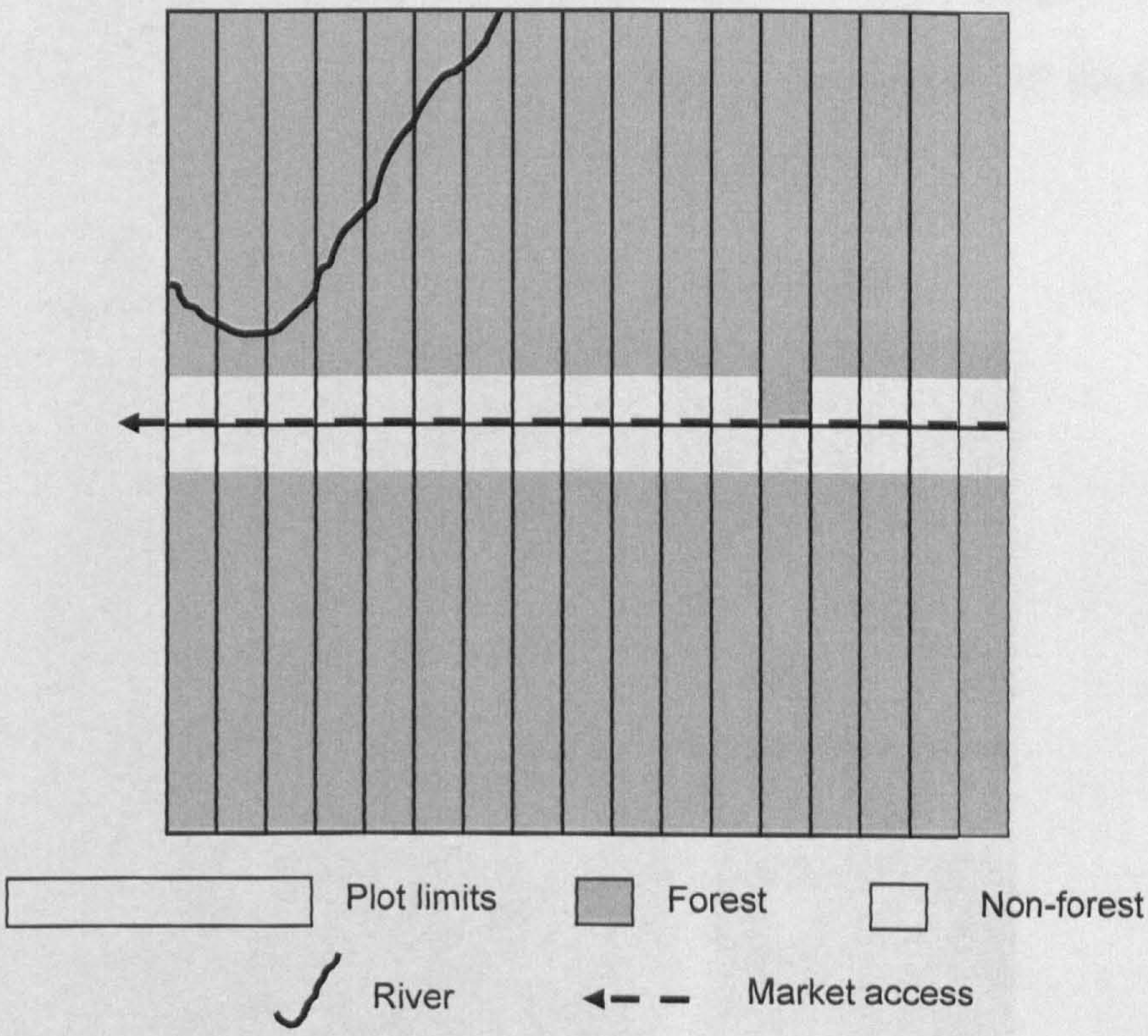
Figure 7.48: Planning of the community.



7.5.2 Early colonisation stage

Initial clearance occurs along the line of access from the primary ends of the plots (Figure 7.49). The forest in the community is divided into two patches and one central non-forest patch bordering the access road is created. The Type II clearance is more-or-less simultaneous along the road and at similar (high) clearance rates because most of the colonists arrived in the same year and needed to clear rapidly for subsistence and to consolidate their household needs. The Phase I deforestation trajectory of Brondizio *et al.* (2002) is applicable to this *early colonisation stage*, and fragmentation metrics begin to progress along the parabolic curve predicted by Lambin (1997) and according to Trani *et al.*'s (1996) curves.

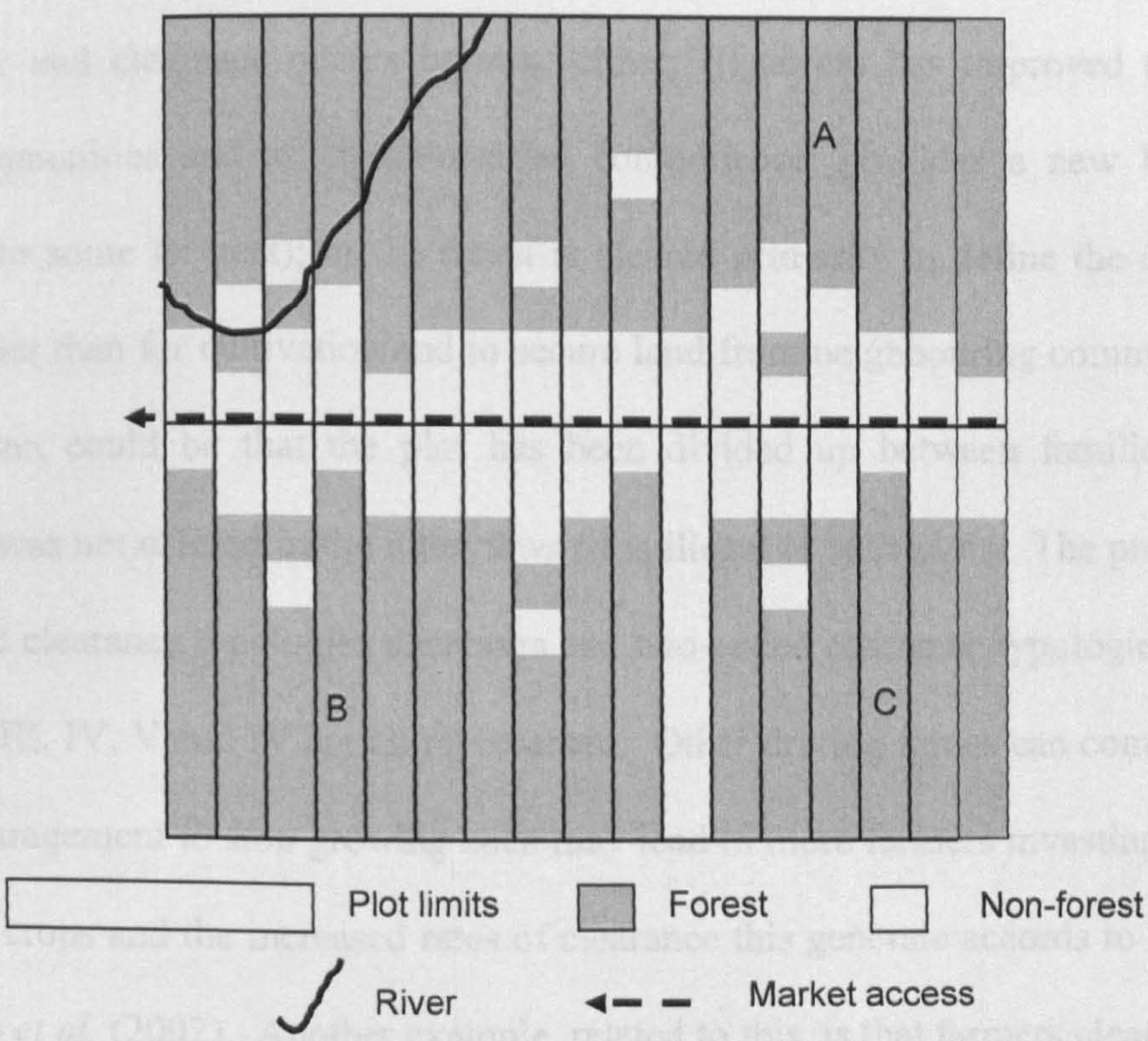
Figure 7.49: Early colonisation stage.



7.5.3 Illicit cultivation stage

As time progresses farmers continue with subsistence and begin to invest in perennial crops. A few farmers have cleared more forest than others but very few have cleared the lengths of their plots because they choose to cultivate land-hungry fruit crops (e.g. bananas) or extend their plot for pasture. Some farmers may encounter topographical difficulties when clearing forest (e.g. a river) and have to leapfrog the obstacle thereby creating isolated patches of non-forest. The clearance typologies are mainly one ended (Type II clearance) with some plots with isolated patches (Type IV clearance) and occasionally some Type VI clearance (Figure 7.50). The forest is now in at least three large patches (A-C on Figure 7.50) and there are a few forest patches in the non-forest area. The non-forest area consists of a large patch and a number of smaller isolated patches that are irregularly spaced. In Caracas the cultivation of coca leaf is not the crop of choice at this time and Phase II (Brondizio *et al.*, 2002) appropriately describes the change in clearance rates. But in Arequipa and Bogatá the choice of land management activities includes a big element of illicit coca leaf cultivation and LULCC in these two communities do not

Figure 7.50: Illicit cultivation stage.



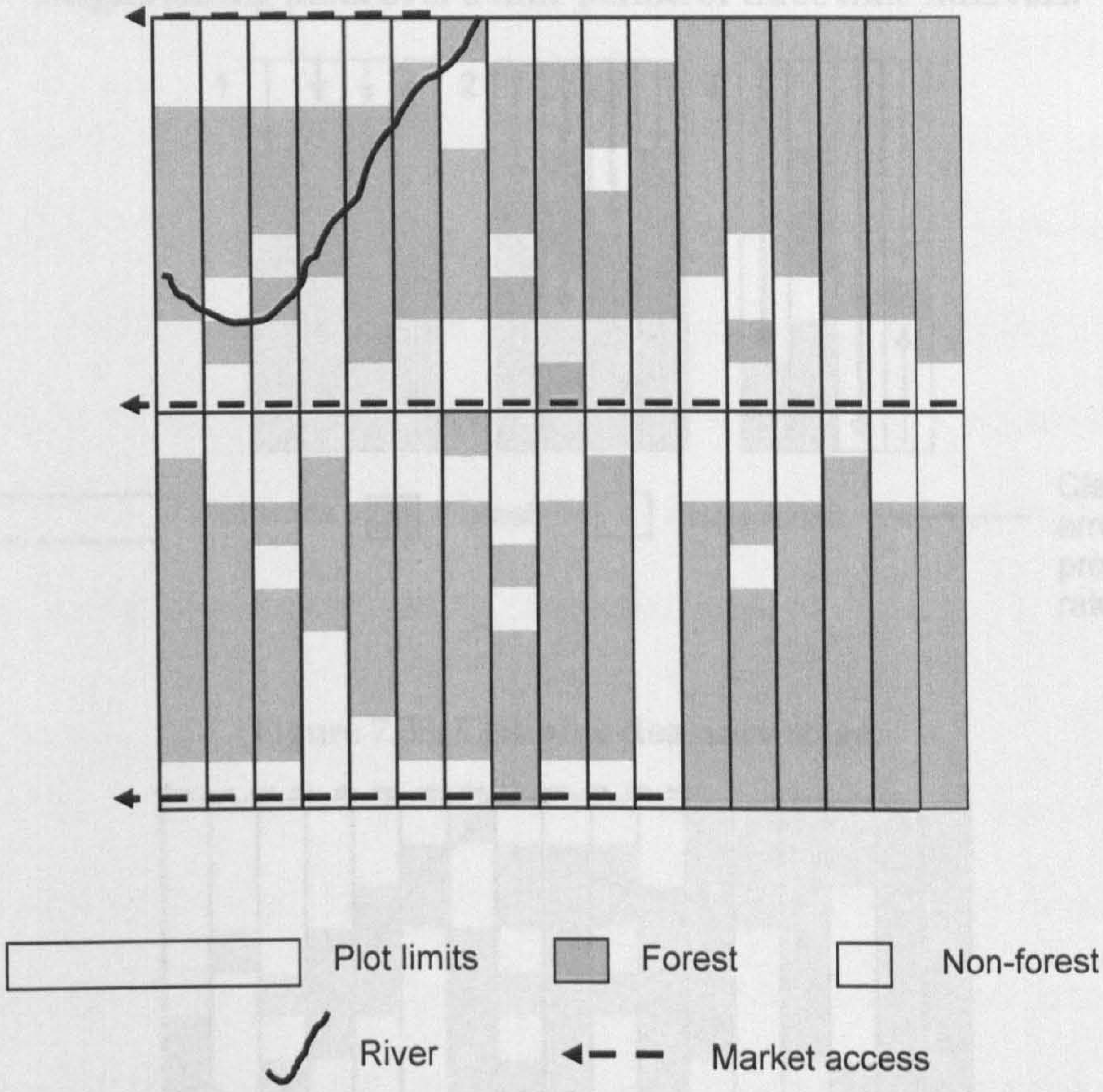
follow the predictions of Brondizio *et al.* (2002). By definition the deforestation trajectory is phase II but the rates of clearance are lower than predicted.

Those farmers who choose to invest in coca leaf cultivation only need to clear small amounts of land and later attempts to eradicate coca bush plantations encourages some farmers to cultivate isolated patches deeper in their plots which causes deviations from the predicted behaviour of landscape metrics. Fragmentation metrics which are not spatially descriptive proceed as expected because the forest is still being progressively divided. However TEL increases because of the cumulative contribution of the small patches and MNN in the forest patches does not vary much because the patches are in close proximity to each other.

7.5.4 Improved access stage

In Figure 7.51 it is evident that the spatial patterns of clearance and forest fragmentation have changed because clearance has occurred at the limits of the community (at the secondary ends of the plots) as well as from the central access road. Secondary end clearance occurs because either: (i) access has improved (usually to other communities and as an unintended consequence, provides a new link to the markets for some farmers); or (ii) forest is cleared primarily to define the community limits rather than for cultivation and to secure land from neighbouring communities. A third reason could be that the plot has been divided up between families but this evidence was not offered in the interviews (it is illegal to split plots). The proportion of one-ended clearance typologies decreases and two-ended clearance typologies increase, Types II, III, IV, V and IV are all represented. Other driving forces can come into play e.g. encouragement to stop growing coca may lead to more farmers investing into legal perennial crops and the increased rates of clearance this generate accords to Phase II of Brondizio *et al.* (2002). Another example, related to this, is that farmers clear at

Figure 7.51: Improved access stage.



different rates because of different crop choices. The main non-forest patch is still present and there are isolated non-forest patches. Intermediate non-forest patches develop because of adjacent plots cleared from the secondary ends have coalesced. Fragmentation of the forest continues and the number of isolated forest patches may increase because of variations in clearance rates between plots (Figure 7.52). The increased numbers of forest patches and their location in the non-forest patch cause deviations from the parabolic curve for the NoP, MNN and TEL metrics. Apart from these deviations fragmentation tends to follow Lambin's (1997) parabolic.

7.5.5 Complex clearance stage

As clearance progresses complexity develops in the model. The main non-forest patch becomes larger, and advancing clearance along plots has led to coalescence of non-forest areas and the creation of some patches of non-forest (Figure 7.53).

Figure 7.52: The formation of isolated forest patches (A and B) by clearance in neighbouring plots over a time period of three time intervals.

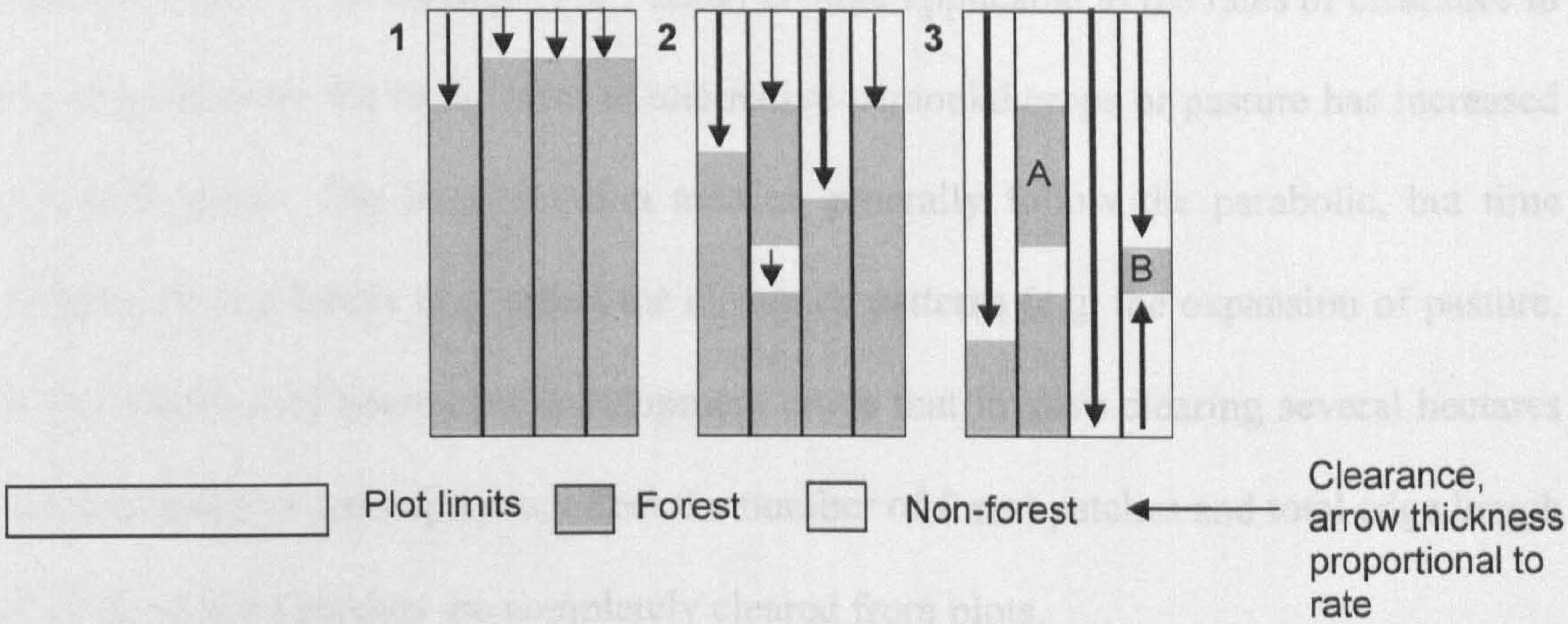
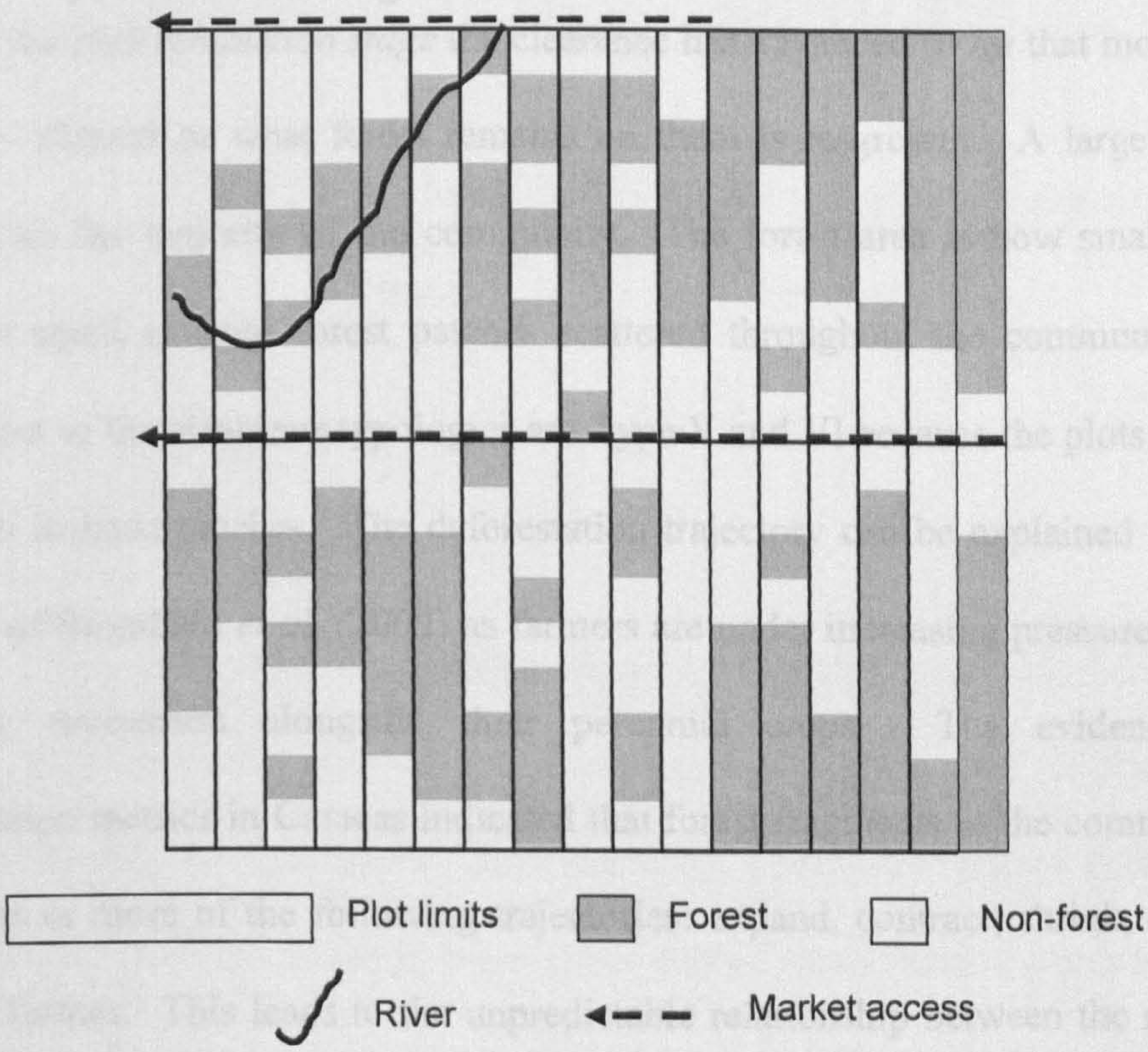


Figure 7.53: Complex clearance stage.

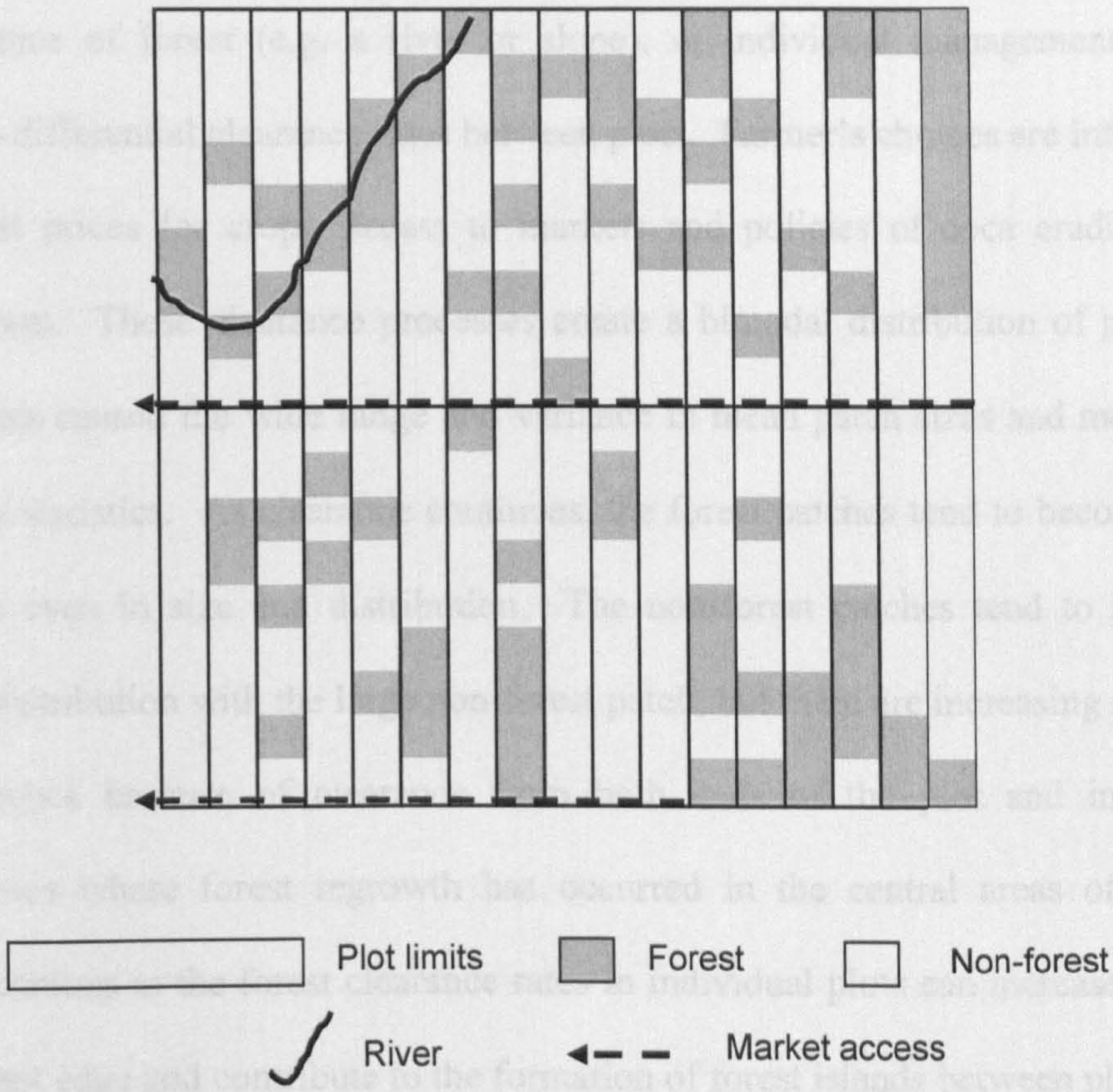


The forest is now highly fragmented, the large patches of forest have been reduced in size and the number of forest patches has increased. Primary and secondary end access, clandestine cultivation and topographic variations in the community have combined to lead to clearance Types II to IV being present. The increased clearance has been driven by the development of an agricultural economy based on alternative crops to coca and community wide agreements to stop coca cultivation. The deforestation trajectory Phase II (Brondizio *et al.*, 2002) is more applicable to the rates of clearance in this stage because the investment in alternative perennial crops or pasture has increased clearance rates. The fragmentation metrics generally follow the parabolic, but time variable driving forces may affect the clearance patterns (e.g. the expansion of pasture, or the adoption of alternative development crops that involve clearing several hectares of land), and as a consequence, affect the number of forest patches and total edge length because isolated patches are completely cleared from plots.

7.5.6 Plot exhaustion stage

In the *plot exhaustion stage* the clearance has advanced so far that most plots are effectively cleared or what forest remains on them is re-growth. A large non-forest patch covers the majority of the community. The forest area is now small and only comprises small isolated forest patches scattered throughout the community (Figure 7.54). Most of the clearance typologies are Type V and VI because the plots are cleared or contain isolated patches. The deforestation trajectory can be explained in terms of Phase III of Brondizio *et al.* (2002) as farmers are under increasing pressure to manage secondary succession alongside their perennial crops. The evidence of the fragmentation metrics in Caracas indicated that forest fragments in the community may follow one or more of the following trajectories: expand, contract, shrink, coalesce or fragment further. This leads to the unpredictable relationship between the metrics and forest area. Phase III (Brondizio *et al.*, 2002) still explained this period as rotation of forest and non-forest area was accountable, but the fragmentation parabolic (Lambin, 1997) will not be completed unless the forest patches continue to be divided up and decrease in area.

Figure 7.54: Plot exhaustion stage.



7.6 Summary

- **Fragmentation patterns**

Analysis of the three communities shows that the drivers of LULCC can be used to explain fragmentation patterns if spatial attributes of the plans and physical attributes in the community are considered simultaneously. Arequipa and Bogotá illustrated fragmentation for communities in the early stages of clearance and Caracas illustrated the events of fragmentation in the later stages of clearance. In the early stages of farming the forest is divided by a large non-forest patch cleared from the central access road into two large forest patches. Access at the other ends of plots or securing of community limits can also contribute to the spatial patterns of fragmentation, forming larger non-forest patches disconnected from the main non-forest patch. Small forest patches are left in the non-forest area and non-forest patches appear in the forest area.

The small forest patches are related to either physical attributes of the area preventing the clearance of forest (e.g. a river or slope), or individual management decisions leading to differential clearance rates between plots. Farmer's choices are influenced by the market prices for crops, access to markets and policies of coca eradication and development. These clearance processes create a bimodal distribution of patch sizes, and this has caused the wide range and variance in mean patch sizes and mean nearest neighbour statistics. As clearance continues, the forest patches tend to become smaller and more even in size and distribution. The non-forest patches tend to retain their bimodal distribution with the large non-forest patch, but there are increasing numbers of small patches because of clearance from both ends of the plot and in the older communities where forest regrowth has occurred in the central areas of the plots. These variations in the forest clearance rates in individual plots can increase the length of the forest edge and contribute to the formation of forest islands between plots.

- **Patterns of landscape trajectories**

The comparison of trends in four key fragmentation metrics, number of patches, (NoP), mean patch size (MPS), total edge length (TEL) and mean nearest neighbour (MNN) in the three communities with existing models presented in Trani *et al.* (1996) shows that some of the metrics do not follow the parabolic behaviour suggested by Lambin, (1997) and with those that do, the peak value of the metric does not correspond with the same percentage of forest cover. In comparison to the data from Trani *et al*, (1996) Arequipa and Bogotá could only be compared for 47 and 57% forest loss and Caracas for up to 68% forest loss however the three communities showed that there are small variations from the simulations of Trani *et al.* (1996). In Arequipa and Bogotá these variations could be related to economic and policy drivers impacting on land management and the clearance patterns between individual plots (e.g. the creation of clandestine non-forest patches or the removal of forest patches to create pasture). In Caracas the relationship between the metric and percent forest cover was no longer proportional when forest area began to fluctuate. The breakdown of the relationship occurred as a large number of plots had been cleared and the land-use management decisions were impacting in a number of different ways on the non-forest patches, i.e. some were expanding, some were contracting and some remained the same size. To compound this, the same forest patch which may cross several plot limits may be allowed to expand by one farmer yet cleared in a different place by another farmer. The final stages of the fragmentation models of Lambin (1997) and Trani *et al.* (1996) were not completed in Chapare as yet. In the Brondizio *et al.*, (2002) model, the shifts in economic and policy drivers and the complex forest management, when forest area began to fluctuate did not necessarily follow the Phases in the 'colonist footprint' model in Chapare.

- **Development of fragmentation in Chapare**

The evidence from the three communities in Chapare was used to construct a conceptual model with six stages for forest fragmentation in Chapare. The stages were, planning, early colonisation, illicit cultivation, improved access, complex clearance and plot exhaustion. The model shows how different drivers impact on the spatial patterns in an area planned for colonisation. These impacts cause the rates of clearance and determine the landscape configuration (metrics) and the differences and similarities of the models of the Chapare communities with the research of Lambin (1997) and Brondizio *et al.* (2002) have been discussed.

Chapter 8

Conclusions

Chapter 8

Conclusions

8.1 Introduction

My research findings have shown how changing economic and policy drivers, mainly those related in some way to coca / cocaine, have influenced land-use and land-cover change in Chapare, Bolivia. These drivers, other socio-economic changes, land tenure plans, and spatial variations in baseline environmental parameters have influenced government land-use planners and decision-making by peasant farmers leading to distinct patterns of land-use and land-cover change, and particular forms of landscape fragmentation. In the three communities investigated, the conversion of forest to agriculture has occurred at rates which have varied over time and between communities. High rates of clearance occurred before the boom in coca leaf cultivation in the 1980s when colonists first cleared their land holdings for subsistence. The shift into coca leaf cultivation reduced demands on forest and the resulting low rates of clearance lasted until the anti-coca and alternative development policies made an impact on land-use in the mid-1990s. After the mid-1990s clearance rates increased once again and the forest was fragmented further. This was because, at this stage, most farmers cleared more land to compensate for the deficits in household incomes from the loss of coca bushes and replacement with alternative crops. In addition there was the clearance of small patches in the remaining forests for clandestine coca cultivation. These changes in land-use and land-cover at the local level were influenced by economic and policy drivers that operate at the national and international levels, as is the case in other colonisation areas in Amazonia. In Chapare, however, international scale economic and policy drivers have impacted directly on local land-use decision-making because of the nature of the coca economy. This differs from the other colonisation areas studied in South America.

The remainder of this chapter summarises the key findings from Chapters 5-7 (Section 8.2); the research undertaken to answer objectives outlined in Chapter 1 is evaluated in Section 8.3; the contributions to land-use and land-cover change science more generally are commented on in Section 8.4, and, finally some potential directions for future research are explored in Section 8.5.

8.2 Key research findings

8.2.1 Land-use and land-cover change trends

- **Forest clearance trajectories at the community level:** Overall the amount of forest lost was greatest in Caracas (77%), least in Arequipa (47%) and in between in Bogotá (57%). The rates of clearance varied between the image time points and between the communities, even when farmers arrived in the communities at the same time.
- **Structural metrics:** The general trends from 1975 to 2000 showed that as there was an increase in the numbers of forest patches there was a decrease in both the size (10 ha on average) and consistency in the size of forest patches. The mean nearest neighbour remained similar and consistent (50 to 100 m). For the non-forest patches sizes generally increased and were inconsistent in size. The mean nearest neighbour was generally between (150 and 70m) with a low variability. In Caracas the patterns in non-forest statistics generally fluctuated as the percentage of forest decreased.
- **Plot clearance typologies:** There were different land-use management patterns within and between plots. Some farmers cleared from one end only, others farmers adopted a double ended clearance strategy and many farmers cleared with isolated

patches. Five typologies were used to describe the combinations of plot clearance. These land-use management plans also varied over time.

- **Land-cover change at the plot level:** Although amounts of clearance showed that there were atypical and typical plots, the range of land-use practices varied, and this diversity tended to increase the longer a plot had been occupied.
- **Synopses:** Each community was generally orientated around a specific set of land-uses, i.e. fruit (Caracas), cattle (Bogotá) or coca (Arequipa) but the interviews showed how these economies evolved from a subsistence economy. Between 1985 and 1995, however, there was a period where coca cultivation dominated the activities of all three communities.

8.2.2 Temporal drivers of land-use and land-cover change in Chapare

- **Economic drivers:** There are national markets for fruit and meat, however the farmers must use middlemen to transport the perishable, bulky goods out of the region. Prices of fruits were seasonal and susceptible to boom-bust scenarios. However, there were increasing opportunities for exports for specific fruit varieties in the 1990s. Cattle prices had remained stable throughout the period.
- **Policy drivers:** In the 1960s national policies were responsible for the expansion of agriculture in the Chapare region. In the 1970s investment was prioritised towards hydrocarbon exploration and support for agriculture declined. In the late 1970s and early 1980s government corruption encouraged an illicit coca / cocaine economy favouring the cultivation of coca bushes. In the 1980s and 1990s policies focussed on: (i) the destruction and removal of coca bushes; and (ii) encouraging substitute crops.

- **The coca / cocaine economy:** From the 1970s the market for coca leaf expanded, because of the international market for cocaine. Coca leaf prices were high but variable and despite their lowest prices throughout the 1990s coca leaf gave far better economic returns than fruit cultivation, meat and dairy products. Significantly, in terms of land-use and land-cover change farmers did not need to, and a household labour force could not, cultivate much more than a hectare of coca. Furthermore in order to match the returns of a hectare of coca with an alternative crop a much larger area of forest was required.
- **LULCC responses to the drivers:** A comparison of synopses of the three communities showed that when national level economic policies dominated (1963 to 1979), rates of clearance were high and the land-use stage could be described as 'pre-coca dominant' with fruit and cattle. When the national level policies weakened the international level economic drivers strengthened (1980 to 1995), the rates of clearance decreased and the land-use stage was described as 'coca-dominant', with coca cultivation. From 1995 the national level policies were driven by international pressure (1996 to 2003), the clearance rates increased again (if land was available to clear) and the land-use was described as 'post-coca dominant', with the original activities of the 'pre-coca dominant' period plus alternative development crops.
- **The difference in clearance trajectories to the 'colonist footprint' model:** The clearance rates – Phase I – of the Brondizio *et al.* (2002) model was generally applicable to the three communities. However, Phase II was not as clear in all three communities because at this time coca cultivation was either the main crop or it dominated over legal activities (fruit growing and cattle rearing). Phase III of the model was complicated by the policy shifts against coca leaf cultivation and market fluctuations of fruit prices in comparison to the time of colonisation.

- **Scales of drivers:** Drivers occur at international, national and local levels. International drivers were related to the coca / cocaine economy, interacted right through to local level activities and affected national level policies. At the national level macroeconomic policies were responsible for the colonisation and development of agriculture in the region, although these policies were weak. At the local level the choice of land-use activities were a response to the economic and policy shifts and caused the differential rates and patterns of forest clearance.

8.2.3 Spatial drivers of land-use and land cover change

- **Fragmentation patterns:** In Arequipa and Bogotá initially clearance began with the creation of a large non-forest patch which divided the forest into two main patches. Individual management decisions driven by market prices, access and policies on coca eradication and development resulted in the creation of forest and non-forest patches, through differential clearance rates, clandestine coca cultivation and biophysical parameters. The clearance caused a bimodal distribution for forest and non-forest patches with wide ranges and variability in patch sizes. As clearance progressed the distribution of forest patches became less bimodal, and the patch size decreased and variability increased, conversely the non-forest patches retained their distribution, range and variability in size. In Caracas, where forest clearance had progressed further than that of the other two communities, clearance continued and plots were virtually cleared. The forest area fluctuated along with the forest patch size and variability. The large non forest patch also began to divide into smaller patches.
- **Patterns of landscape trajectories:** The parabolic curve in the model of Lambin (1997) does not represent the trajectories of four key fragmentation metrics, number of patches, (NoP), mean patch size (MPS), total edge length (TEL) and mean nearest

neighbour (MNN), when compared to landscape metrics modelled by Trani *et al.* (1996). In Arequipa and Bogotá the development of fragmentation patterns generally followed the patterns of Trani *et al.* (1996) but there were features on the metric curves which were related to specific drivers of LULCC. In Caracas the metrics did not follow the patterns of Trani *et al.* (1996) because the forest began to fluctuate in area and the fluctuations of small forest patches were subject to individual clearance decisions.

- **Development of fragmentation in Chapare:** With the research findings a model with six stages of forest fragmentation: planning, early colonisation, illicit cultivation, improved access, complex clearance and plot exhaustion was developed that illustrates how different drivers impact on the spatial patterns and determine the landscape configuration (metrics) in the Chapare communities.

8.3 Research objectives

It is appropriate at this point in my thesis to consider to what extent I met my research objectives and, in doing so, I describe the work I carried out under each objective.

1) Analyses of the political, social and economic histories of Chapare from 1960

This objective was needed in my research to show how Bolivian government policies became focused on Chapare (and other parts of lowland Bolivia) after 1960, and is reported in Sections 1.3.2, 6.3 and 6.4.

Initially colonisation of the lowlands by highland out-migrants was promoted by modernisation policies in areas like agricultural improvement, transport and infrastructure development. Policies became specifically oriented towards the elimination of coca in the 1980s, mainly at the demand of the US Government. By the 1990s, the anti-narcotics focus had become balanced by alternative development policies. Discussions with the farmers about the histories of plot clearance synchronised land-use changes with shifts in policies (Sections 5.2.5, 5.3.5 and 5.4.5). The economic history presented in section 6.2 showed that coca leaf prices, even when low were more economically competitive than other crops or cattle rearing. The histories of plot clearance and their linkages to markets and the policy arena were, however, sometimes difficult to address because of the: (i) difficulties in discussing the coca economy with farmers (Section 5.2.4, 5.3.4 and 5.4.4); and (ii) inconsistencies in government economic data for the region (Section 6.2.2).

The time frame of this analysis (1960-2003) was too narrow to place Chapare in a broader context. However, an historical review of the region (Section 1.3.2) showed how Chapare had been designated as an agricultural region in a national economic model which aimed at diversifying the Bolivian economy and lessening the dependence on mining.

2) Detailed surveys of farms, farmer's activities and decision-making processes in relation to LULCC.

Reaching this objective provided details on spatial and temporal changes in land-use, and the impacts of farming and other land management practices on land-cover (Sections 5.2.4, 5.3.4 and 5.4.4).

Most farmers were easily able to recall their land management activities over the time for which imagery had been acquired and, in most cases, remembered when these had changed. It was more difficult for them to reconstruct previous layouts of their plots, but comparisons of land-use information between farmers provided benchmarks with which I could reconstruct the land-use activities (Sections 5.2.4, 5.3.4 and 5.4.5). These reconstructions showed that there have been three periods of land-use since the 1970s which I have defined in relation to coca: pre-coca dominant period, coca-dominant period and post-coca dominant period in the three communities, (Sections 6.4.1, 6.4.2 and 6.4.3). The diversity in land management strategies was revealed from the interviews with farmers, and I was able to learn about market problems, crop failures, labour constraints, problems within the communities and the roles of institutions within Chapare from farmer interviews. Ideally I would have randomly sampled farm plots but the presence of a white researcher (*gringo*) in an area of coca cultivation meant that only some people were willing to talk to me. I had to rely on networks of contacts like the local church, dominant members of the *sindicato*, and the more open members of the community who were willing to share their experiences. However, the range of RRA techniques I employed allowed me to cross reference the interview data.

3) Mapping and monitoring LULCC from 1975 to 2000.

The mapping of LULCC from Landsat imagery allowed me to quantify temporal rates of forest clearance (Sections 5.2.2, 5.3.2 and 5.4.2), map spatial patterns of LULCC (Sections 5.2.1, 5.3.1 and 5.4.1) and examine the evolution of landscape fragmentation (Sections 7.2.1, 7.3.1 and 7.4.1). The images were classified into forest and non-forest then the INC plans were over-laid on the classification to calculate cleared area and rates of clearance per plot. Over-laying the INC plans on the images for each community allowed me to develop a classification of six typologies of land clearance. The maps also provided me with 'visual prompts' during interviews with farmers and broadened the discussions beyond the farmer's plots.

A major drawback was the difficulty in obtaining cloud-free imagery which would have allowed clearance rates to be calculated over shorter time intervals than was the case. The spatial and spectral resolution of the imagery was too coarse to differentiate some of the smaller patches of non-forest.

4) Measurement of forest fragmentation

I used four key landscape metrics, number of patches, (NoP), mean patch size (MPS), total edge length (TEL) and mean nearest neighbour (MNN), to show the progression of forest and non-forest fragmentation at the community level through the image sequences. Arequipa and Bogotá were used for the early stages of fragmentation and Caracas for the later stages of fragmentation. The fragmentation process was as follows: as the large non-forest patch developed, the forest area was gradually divided into smaller fragments and because of the different clearance rates in the plots isolated non-forest patches coalesced and small forest patches formed. When most of the forest had been cleared the sizes of these forest patches remained small but fluctuated in size. During the fragmentation process the metrics behaved as follows:

NoP: the number of forest and non-forest patches generally increased and then varied around a similar value;

MPS: mean forest patch size decreased and then varied around a similar value, but mean non-forest patch size generally increased then, fluctuated before showing indications of a further increase;

TEL: total edge length generally increased and then began to fluctuate.

MNN: mean nearest neighbour for both forest and non-forest did not show consistent patterns between the communities but did show a tendency to fall initially and then gradually fluctuate around similar values.

The way I employed fragmentation metrics was appropriate to the community level, but explanations of why the spatial and temporal patterns shown by these metrics had developed required knowledge of the plot-scale management strategies by farmers (which were explained by the typologies) (Section 5.2.3).

Interpreting these metrics was not straight forward, without examining the patch size distribution and spatial distribution, the high ranges and variance of patch sizes could not be explained. Also the 1975 and 1976 images were a different resolution (from a Landsat MSS image) and strictly speaking these metrics should not be directly compared with the others (from a Landsat TM image), however the first image dates provided temporal and spatial continuity to the development of forest fragmentation.

5) Linking farm surveys, LULCC and measurements of forest fragmentation to understand how socio-economic drivers of LULCC lead to specific patterns of forest fragmentation in farming communities with different types of agriculture.

I aggregated the information from the farm surveys (Section 5.5) over five-year intervals, partly to overcome the specific timing inherent in the oral history methods I had employed. Reaching this objective allowed me to identify a three-fold division of land use in the three communities - the pre-coca dominant (1960 to 1979), coca-dominant (1980 to 1995) and post-coca periods (Section 6.5). I evaluated the rates of forest clearance and styles of fragmentation in this framework so that they could be more easily related to the main economic and policy drivers prevailing in each time period. During my field visit in 2003, the value of this information was enhanced by showing the farmers images of their communities, which allowed them to explain what was happening in their plots and discuss events in a wider context of the whole community. The spatial patterns of deforestation were also discussed and some farmers were able to identify clandestine plots of coca that had been cultivated in the past. In the pre-coca dominant period the results showed that weak national level policies and economic drivers were causing high rates of clearance in the older community Caracas. The colonisation plans resulted in the creation of large non-forest patches. The national economic policies continued into the coca-dominant period and encouraged further settlement in Arequipa and Bogotá, where initially there were high rates of clearance for subsistence. This was then followed by variable clearance rates depending on the activity in a particular community as the coca / cocaine economy strengthened. Isolated patches of non-forest which could not be attributed to biophysical parameters were due to clandestine coca cultivation. In the final post-coca dominant period, the economic drivers were overcome by the anti-coca policies employed in the area, this forced farmers to concentrate on the original activities with low economic returns and to alternative development with, initially, poorly researched markets. The clearance rates increased in communities where there was forest left to clear, new land management strategies resulted in the fluctuation of the forest fragmentation metrics.

6) Evaluating models of (i) forest clearance, and (ii) the development of landscape fragmentation for LULCC in Chapare.

I used data on rates of forest clearance in the three communities to evaluate the applicability of the 'colonist footprint' model of Brondizio *et al.* (2002) to Chapare. The three communities clearly corresponded to the first stage of this model in the early years of colonisation. But the deforestation rates in Chapare in the second and third stages of the model did not correspond to those in Altamira, the region in Brazil where the model was developed, because of the impacts of coca cultivation and coca eradication. Specifically, investment into the perennial crop of coca was not land-hungry and clearance rates remained low, and the enforcement of alternative development meant that the LULCC response was no longer economically driven (Section 6.6).

I also evaluated Lambin's (1997) model - which links landscape fragmentation to forest loss - for the three communities in Chapare. The curved nature of the relationship between forest cover and landscape fragmentation hypothesised by Lambin (1997) is not represented by a specific metric, so I used metrics employed by (Trani *et al*, 1996) to parameterise Lambin's model. My analysis was limited by the ranges of forest cover over the period investigated: i.e. 100 to 66% in Arequipa, 100 to 43% in Bogotá and 63 to 34% in Caracas. I used four landscape ecology metrics: number of patches (NoP); mean patch size (MPS); mean nearest neighbour (MNN); and total edge length (TEL). The metrics behaved in the following ways:

NoP: the number of patches followed the model up to 57% forest remaining but then began to fluctuate as forest loss varied;

TEL: the total edge length increased but continued to increase until after 57% forest remaining when the values began to fluctuate as forest loss varied;

MPS: the mean patch size decreased as predicted but after 57% forest remained the values began to fluctuate as forest loss varied; and

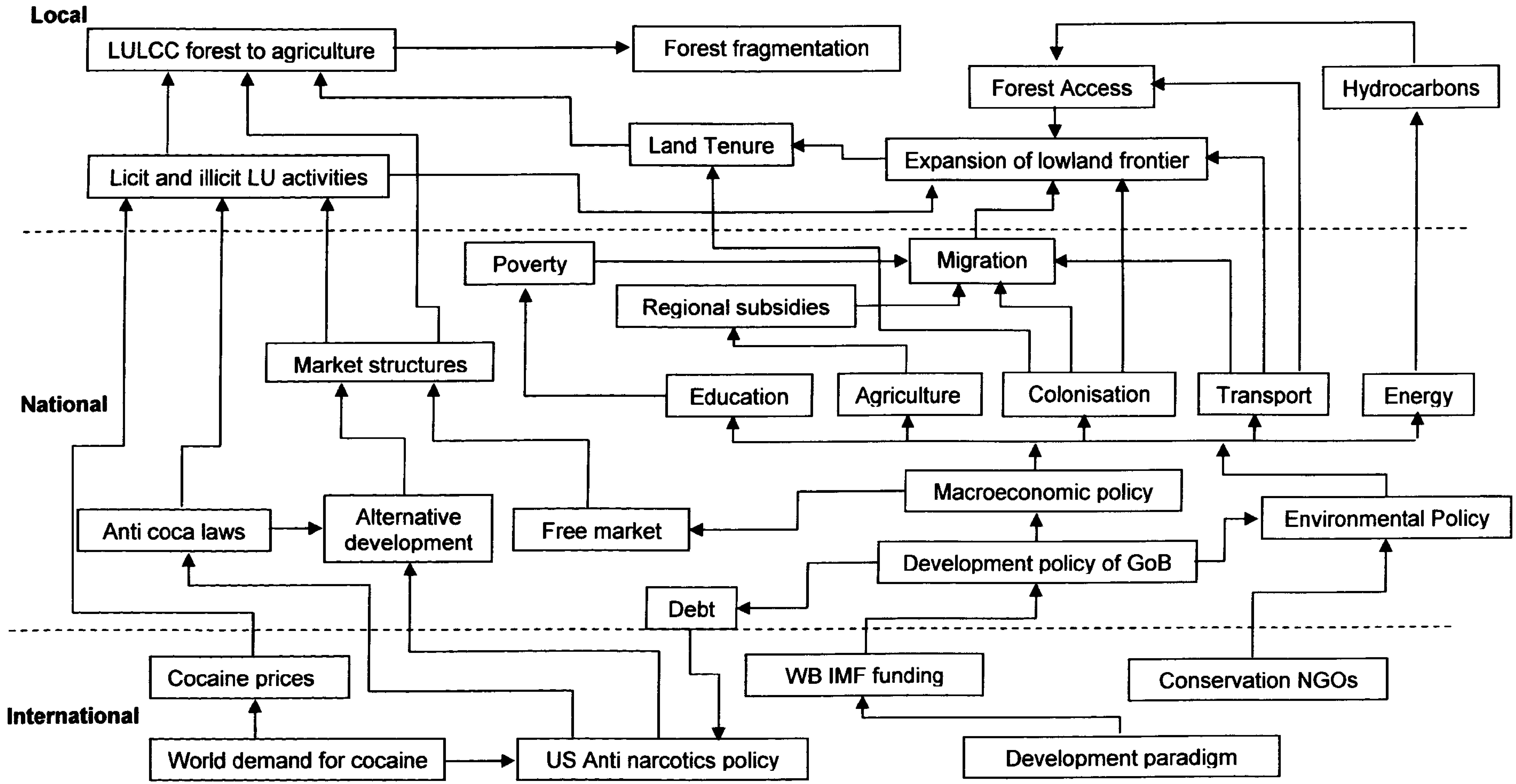
MNN: mean nearest neighbour behaviour varied between the communities but after 57% forest loss the values began to fluctuate as forest loss varied.

Notably as the metrics began to vary after 57% forest clearance there was no clear relationship between the forest metric and the area of forest lost. These metrics showed that in a colonisation zone the fragmentation progression of Lambin (1997) is not completed, i.e. the sequence of land-use drivers does not follow the same predicted progression, and that when forest is almost exhausted, the spatial impact of different land-use management activities in plots, (e.g. crop rotation), does not result in an absence of forest cover as the metrics of Trani et al. (1996) suggest.

7) Refining the conceptual model of LULCC for Parque Nacional Carrasco to explain LULCC in Chapare.

In Figure 8.1 a modified version of the conceptual model introduced in Figure 1.1 as it pertains to the lowlands of Chapare. The international and national-scale drivers remained largely unchanged. However changes have been made at the local level. The coca / eradication cycle in the initial model was elaborated upon to include market structures and the economic and policy driving forces were separated. The revised model shows that fluctuations in the demand for, and prices of, coca globally are an international driver that acts directly on Chapare. Other coca-related international drivers influence LULCC in Chapare with only minimal modification at the national level. International drivers affecting LULCC in Chapare in the arenas of conservation, development and economic restructuring are mediated at the national scale to a far greater degree than the coca-related drivers. The model is dynamic and the importance of drivers has changed over time. For example, the national level drivers had the greatest influences for two decades from 1960, and international drivers have dominated during the 1980s and 1990s.

Figure 8.1: Driving forces of LULCC in the Chapare region



8.4 Research findings in the broader context of LULCC science

Orthodox views suggest single factor causes dominate in land-use and land-cover change scenarios such as the economic gains of growing populations. My research on Chapare has provided an interesting analysis into the range of geographical scales over which economic signals can influence land-use and the temporal dynamics of these influences and embraced anti-orthodox views (Section 2.4.1). In addition, and perhaps more importantly, the research shows how policy initiatives with very strong political backing and financial support can overcome market forces.

In the 1960s and early 1970s a combination of relatively weak national-level policy initiatives such as colonisation and infrastructure development were most important in Chapare and grew in strength. However, the success of the national policies, which was measured through how strongly they influenced land-use change, depended on finding markets for crops such as tropical fruits. On the basis of the research I carried out in conjunction with others (reported in Millington *et al.* 2003), discussions I had with farmers about the early years of colonisation (especially in Caracas) and the rates of deforestation for the same period, it appears that the strength of the national policy drivers of land-use change was highly dependent on prices for crops in the urban markets in Bolivia, and the difficulties in getting these crops to market. During this period, both the policy arena and the economics of agriculture of Chapare were almost entirely dominated by national-level drivers.

In the late 1970s, throughout the next decade and into the early 1990s, the extremely strong economic driver of coca / cocaine gradually gained primacy over all other drivers of land-use change in Chapare. There were two major reasons for this: first, the exceptionally high selling returns that coca leaf cultivation had over other tropical crops, and second, the weak (national) policy environment, at least up until the mid 1980s. This driver was international and was barely mediated at the national-level, if at all. Essentially the illegal trade of the coca / cocaine economy was the epitome of the free market.

In reality the global free market economics were controlled, otherwise land-use change in Chapare would still have been driven by the coca / cocaine market as demand for cocaine remains high globally. This situation pertains in the coca-growing regions of Colombia to this day, but not in Chapare where other land-use change drivers have dominated since the mid-1990s. These drivers are firmly routed in the policy arena, which gained momentum in the Reagan administration's 'War on Drugs' in the 1980s. Consequently policies acting on Chapare are inherently international and have undergone only moderate amounts of modification by the Bolivian Government. In terms of land-use change drivers, as in the everyday life of the farmers in Chapare, anti-coca policies did not overcome the choice of a farmer to enter the coca / cocaine cycle. However, as alternative development programmes were introduced to support the coca eradication policies, policy drivers overcame market drivers. By the mid-1990s it is clear from my research that many farmers had turned much, if not all, of their attention to legal alternative crops; even though these provided poorer returns on their investments compared to coca. Clearly this was not a rational economic choice, but one forced and encouraged on farmers by strongly-supported, well-financed policies led by the development agencies, namely USAID. The changes in land-use that this initiated reflected the shift from a dominant economic driver(s) to a dominant policy driver(s).

Most commentators would argue that a switch from a local economy dominated by coca / cocaine to one dominated by legal alternative crops is good. The economic losses may be offset by social gains locally, and certainly the social gains globally come at the expense of an illegal international economy. But the impacts on land-use and land-cover change show distinct environmental consequences which international policy on narcotics has taken precedent over. This research illustrated that under the influence of the coca / cocaine driver lower rates of deforestation existed in Chapare than under either the weak national policy / economic drivers of the pre-coca dominant era, or than under the strong international / national policy arena of the post-coca dominant era. Here then is the paradox hinted at by Henkel (1995: 558) "...approximately 80% of farms are less than 10ha....to create viable systems of agriculture to replace coca, farmers would have to increase the farm size to at least 20 ha..." which, for the first time, I have shown with detailed spatial analysis linked to the narratives of farmers. Furthermore, if the success of the growers associations is to be repeated and farmers are integrated into a globalised economy with economically sustainable activities, this means moving over to monocultures (rather than the current trends in plot diversification) which may not be environmentally sustainable (Hellin, 2001). The social gains that accumulate from giving up coca / cocaine by farmers and communities in Chapare not only have to be offset against lower farm incomes but also the more rapid consumption of limited land resources and further landscape degradation.

8.4.1 Implications for the wider research community

Although this research was site specific there are outcomes which are relevant to the LULCC community, biodiversity conservation and development policy in humid tropical forest regions.

In this research drivers of LULCC were identified at different scales, as the model in Figure 8.1 scales up, the driving forces become relevant to LULCC at greater scales, e.g. Chapare could be considered as one nested example in a regional framework, and the regional framework can be nested in a global framework. This approach would support the NASA land-cover and land-use change programme which aims to create regional LULCC and predictions of water and carbon cycles in their different social contexts (Gutman *et al.* 2004). Identifying different levels of drivers can also help identify the levels of impacts of policy and which levels policymaking should be tailored for (Tschkert, 2005).

Cross comparisons of LULCC studies will help the LULCC community to agree on a global synthesis of LULCC. This research showed the value of comparing drivers in two study areas, an area of LULCC research not explored in great depth. The comparison has shown that in areas considered to have similar LULCC outcomes different LULCC trajectories occurred because of different drivers. Identifying and understanding these differences again has implications for policy making at different spatial scales.

In this research I have shown that there are areas of uncertainty in the data and the interpretation of the data. While this uncertainty exists the LULCC community has a limit to the resolution of their interpretations. This is a relatively unexplored area in LULCC studies and as the LULCC produces ever more individual studies perhaps we should be reporting our results to an agreed level of uncertainty to aid cross comparisons.

At the local level, there were findings useful for LULCC modellers. It was clear that there was huge complexity in the detail of land-cover and land-cover change because of the dynamism between households. Modellers need to consider how to scale the land-management response and the drivers, for example a statistical aggregation of household responses is a move in this direction.

In this study I addressed drivers of illicit activities and as a result there were issues of confidentiality between myself, the farmers and the scientific community. Confidence building and relationships with people have been forged with long and patient efforts. Insensitive exposure of the results could, at least, break relations at key sites and, at worst, damage the livelihoods of those who have been open and willing to participate – hardly a reward of their trust. A question for the LULCC community to address: how is this confidentiality is maintained in communication to the wider scientific community?

Clearance in Chapare has implications for biodiversity conservation and development particularly at the foothills of the Andean mountain chain. Birds, reptiles, amphibians and mammals all have high levels of endemism particularly in the montane forest region to the south. Chapare is located in the proximity of the Vilcabamba – Amboró forest ecosystem[1], part of the Andes Biodiversity hotspot (section 2.3.1) (Myers 1993). Scaling up to the 300+ communities of Chapare forest fragmentation at the regional level has compromised the biodiversity and connectivity in the transition between the montane forests to the south and the humid tropical forests to the north. Understanding how this has developed is especially vital because development will happen along the Andean foothills. By understanding the drivers of LULCC and forest fragmentation there are lessons that can be taken forward for conservation and development in tropical forest regions. Clearly the back-to-back planning of the property grids in the 1960s did not allow for ecological connectivity, time is now short to identify and preserve corridors of connectivity particularly as the anti-coca policies accelerated clearance rates. In the future where development clashes with conservation property layouts should allow for ecological connectivity, and land that has a lower

[1] One of several locations identified by the Critical Ecosystem Partnership to maintain connectivity between sites of high biodiversity.
http://www.cepf.net/xp/cepf/where_we_work/tropical_andes/full_strategy.xml,

ecological value can be set aside for agriculture, that way development can progress yet maintain ecological connectivity. A challenge to this planning is identifying those areas of low diversity and to prevent drivers that encourage people to encroach into the zones of connectivity, to hunt, log and cultivate coca.

At the local level there are still limited possibilities to preserve stepping stones in the small forest fragments, but these fragments are highly disturbed and often consist of lower quality re-growth because of the dynamics of land-use management between plots, however understanding the dynamics of these small patches is also of consequence to those interested in modelling global carbon stocks, since carbon sequestration is rapid in forest re-growth. In an area where agriculture has been confined to the property grids there are questions to be answered - what influence does management of small isolated patches have on the carbon balance?

8.5 Data uncertainty and scenario building

Using several datasets at different spatial and temporal scales and of differing quality inevitably leads to some uncertainty in their collective interpretation. These areas of uncertainty need to be identified as information from retrospective analysis is used in the construction of quantitative LULCC models for LULCC scenario building. These areas of uncertainty need to be identified to provide a range of realistic outcomes in modelling. For example areas of uncertainty to be addressed in this research included: plot areas; the representation of land-cover; irregular intervals of land-cover change monitoring and aggregated data of land-management decisions. The uncertainty of the plot boundaries was brought about through digitising, image distortion and conflicting ground surveys. These errors can be evaluated (Figure 4.6) and these evaluations can then be incorporated into model calculations. In this research these particular uncertainties were not an issue in the identification of different clearance dynamics or the identification clearance typologies because these were qualitative.

Land-cover was represented by a hard classification, and because of an uncertain class a conservative estimate of forest clearance was chosen. Some of the detail in the complexity of land-use management at the forest / non-forest edge was therefore lost in the definition of the classification. A worst case scenario could have been created using the ambiguous class to create a non-conservative estimate thus creating an envelope of uncertainty to give a best and a worst case scenario. Refinement of this area of uncertainty could also be made by using imagery to calculate plant productivity, wetness and brightness indexes into classification decision rules, however seasonality and growth cycles could equally add more uncertainty.

It was not possible to gather anniversary imagery using Landsat TM and ETM, thus the calculations of clearance rates and land-cover change was averaged between irregular time intervals and without repeat imagery it was difficult to account for large scale biophysical parameters e.g. climatic variability. This creates a window of uncertainty between shifts in policy and a land cover change response. Plugging these gaps with different satellite sensors would present a higher temporal resolution of land-cover change but additional technicalities of analysing data measured at different spatial resolutions would add further uncertainty. In these cases the imprint of land-management on LULCC would become more complex, and again we are challenged with the difficulties of trying to synchronise annual LULCC with farmer recall.

Farmers will and will always have difficulty in being precise about dates and the exact arrangement of land use in their plots. The results of the land-use synopsis were therefore aggregated into five year intervals, but as with the satellite imagery there is a measure of uncertainty of exactly when there was a land-management response to a change in driver. These uncertainties make scenario building all the more difficult, and models need to be robust enough to allow and account for these problems.

In the three communities there are several different LULCC scenarios, which could cause different rates of forest loss, amongst many are: legalisation of cocaine; economic changes through the collapse of fruit and cattle markets; or an influx of agro-industries. In the event of the legalisation of cocaine, one would predict that many farmers would revert back to the high economic rent from coca leaf cultivation, decreasing deforestation rates, but not all farmers will abort their land-management strategies as some farmers may now be committed in the long term to substitute crops. Furthermore there are changes in social and cultural factors effecting land-management, as some farmers may now have adopted a moral stance and refuse to re-enter in the coca/cocaine cycle. There are a number of different outcomes given one policy change and because of this it is healthier to construct opposing reactions making scenario building all the more challenging.

8.6 Potential directions for future research

A number of potential directions for future research have been opened up by my research. First, the community synopses can be used as agricultural templates for land-use and land-cover change studies in other communities in Chapare (and possibly elsewhere), and can be used as a benchmark to determine what perturbations related to rates of clearance and fragmentation occur in these communities. The templates could be considered as the basis for a model, in the sense that Brondizio *et al.* (2002) developed the 'colonist footprint' model. However the templates could be used to investigate other controls and influences on LULCC that my research has not accounted for such as spatial and temporal properties in soils (Ferrufino *et al.*, 2003), the roles of institutions (e.g. grower's associations (Hellin, 2001) and *sindicatos*) and commercial enterprises (e,g, recently established agro-industries) acting on individuals and land-use in communities.

Secondly, the trends in forest loss and landscape fragmentation can be used for predictive modelling of future LULCC in Chapare. For example, models may show that the continued emphasis on alternative development in Arequipa and Bogotá will lead to the plot exhaustion phenomena found currently in Caracas within the next decade unless there is a shift back to coca cultivation or another economic or policy driver becomes predominant. As the LULCC trajectory at Caracas shows, such trajectories may not lead to a totally deforested landscape, because there are subtle shifts in forest area as forest was returning as well as being removed.

The research has shown that Chapare is a variant from the models of Lambin (1997), Trani et al., (1996) and Brondizio *et al.* (2002). There is scope for further testing in other communities of Chapare as well as colonisation zones in different locations of South America to understand the variation in socio-economic drivers, the spatial arrangement of land tenure, and land-use impact on landscape fragmentation patterns.

Finally, my research has shown that there is considerable variation in agricultural management between farmers in the confines of the single community. These differences represent subtle responses to the driving forces mediated through land management practices and crop choices. The forests of Chapare have declined significantly in the last four decades and it is intriguing to speculate whether understanding future LULCC in Chapare may require theories and concepts developed in well-established agricultural areas in the tropics, rather than deforestation frontiers. In addition, biodiversity conservation policies will be less relevant in this area and further environmental degradation must now be related to sustaining agricultural production. For example, do whole communities need to conserve the environment to preserve their livelihoods in the same way that communities co-operated over coca reduction in the mid 1990s?

My research has also demonstrated that a deforestation frontier strongly influenced by an illicit coca / cocaine economy has followed LULCC trajectories somewhat dissimilar to a 'typical' South American colonisation zone - Altamira. There are probably lessons that can be carried forward to other regions that are or may come under the influence of coca cultivation. For example, northeast Ecuador faces a threat from coca cultivation because of the proximity of these activities over the border in Colombia (Walsh *et al.*, 2003). Currently most farmers here are sustaining their livelihoods by growing coffee or rearing cattle. The collapse of either or both of these markets could encourage coca leaf cultivation. In the Upper Huallaga Valley of Peru, counter-narcotics policies have been imposed on coca growers (Young, 2004). The policies of alternative forms of local economy could be planned so the deforestation rate does not increase dramatically as it has done in Chapare. The trajectories of deforestation I have identified in Chapare, and the model of landscape fragmentation I have developed should provide templates for such studies.

Research in the areas dominated by narcotics provides relatively risky, but intellectually interesting and richly rewarding arenas for land-use change science. They deserve more attention.

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Appendix 1.1

Glossary

Spanish italicised words

Arroyo – stream or brook.

Arroz – rice

Asentamientos – settlers

Chaco – refers to measured plot of land for farming in the forest.

Chumi – forest re-growth or fallow.

Curichal – waterlogged or boggy forest

Dirigentie – head of organisation.

Monte – forest.

Sindicato – the community agricultural union.

Palmito – heart of palm

Transportistas – Haulers that take produce from the producers to the markets.

Yuca – manioc

Crop weights and measures

Cabeza – bunch of bananas, referring to the all bananas on the inflorescence (flower stalk)

Cato – 130sq feet (~12m sq)

Carga – Large bag (100lbs) equivalent to 100 *libre*

Chipa – bunch of bananas – see *Cabeza*

Cogollo – Centre cord of a young palm tree

Fanega – 0.66ha

Libre – Sack for coca

Quintale (qq) – 100lbs (Imperial), ~ 45kg (metric).

Paquete – small bag of coca

Racimo – Translation 'bunch', 8 hands of bananas, and equivalent to a layer in a banana box, also referred to as (i) *capa* (ii) a *coja*

Tallo – Centre cord of a young palm tree.

Tarea – 10 *tareas* are equivalent to 1 hectare

Appendix 3.1

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Appendix 4.1

Questionnaire: English Version (translation from Spanish)

Household Details

Community: Date: N° of questionnaire:

Name: Age: Time of possession:

Property claim (date): Extension of property:

Age of males (in family): Age of females (in family):

Section 1

Structure of property, sequence and quantity of crops / areas of pasture (relative or measured depending on cooperation of the informant

1.- Primary agricultural products and / or cattle (volume of production and numbers of cattle)

Months	Agricultural products	Volume of harvest	**Type of cattle**	**Numbers**	**Use**	Consumption	Market

Further details: ....

2.- Prices of products at the local market

Agricultural products	Type of cattle	Units	Local price	Market price

Further details: ....

3.- Numbers of parcels inside the chaco, types of agricultural production, area for cattle. In the enlargement for each parcel and the parcels you enlarged each year are they the breadth of the chaco? (Draw / informant sketch).

Road

Description: ....

4.- Is there a rotation of parcels (each time parcels are enlarged)?

Is there a rotation of crops (each time parcels are enlarged)?

Are the parcels rested for a time?

Section 2

Clearance of forest for agricultural production inside the property.

5 a.- The process of clearance of land for production, how and when? (Draw / informant sketch).

Description: ....

5b.- Clearance of land for agricultural production

Year	Extension	Major activity	Number of cattle
1960			
1970			
1980			
1985			
1990			
1995			
2000			

6.- Extent of clearance of land for agriculture and/or grazing in the first year, clearance of sowing?

7.- Factors that iniciated the farmers in the claim of land for agricultural production (markets/ roads / organisations / quality of land / grazing / others)

8.- Market destination of the agricultural products and cattle.

Products or cattle	Markets or local	Santa Cruz	Cocha-bamba	Other Country	Market before?	What year?

Comments:...

Section 3

Changes in agricultural production.

9a.- Change of original crop with alternative crops or cattle.

Change	year	Original crops	Year	Alternatives (type of crop or cattle)	Benificial change? y /n ?
1					
...					
8					

Details:...

9b.- Why change? What was the Project?

Change	Government support	ONG support	*Sindicato* support	Other organisations
1				
...				
8				

Details: ....

Section 4

Use of the natural resources in the forest, and this (or next) years extent of clearance.

11.- What factors determine the major use or advance into the forest? (market / quality of land / more labour / family numbers / others)

Why?:

12.- How much land is the farmer going to clear the next year and what Hill he cultivates?

13.- What is the use of the forest now, and the future?

14.- What extent of forest is there in the property

15.- Estimate the amount of time the forest will exist in the property?

16.- What will follow alter the property has been completely claimed for agricultura? (Buy another property / search for another community / return to the community of origin / reduce crop production) Why?

17.- What do you wish for from policies, the government, municipality and community

Questionnaire: Spanish Version (original version)

Comunidad: Fecha: No Boleta:

Comunario: Edad:T Tiempo de posesión:

Ubicación de Chaco: Extensión de chaco:

Hombres edad: Mujeres edad:

Sección 1

Estructuraría de la chacos, secuencia y cantidad de cosechas / Areas de pastoreo (relativo o medida, dependiente de la cooperación del informante

1.- Principales productos agrícolas y / o ganadería (volumen de producción y cantidad)

MESES	PRODUCTOS AGRÍCOLAS	VOLUMEN DE COSECHA	TIPO DE GANADO	CANTIDAD	USO	CONSU MO	MERCA DO

Detalles: ....

2.- Precios de los productos mercado local

PRODUCTOS AGRÍCOLAS	TIPO DE GANADO	UNIDAD DE MEDIDA	PRECIO LOCAL	PRECIO MERCADO

Detalles:..

3.- Numero de parcelas dentro el chaco, tipos de producción agrícola area de vacunas. ¿En cada parcela y las parcelas ampliadas son la anchura del chaco cada año? (Dibuje / el boceto).

Acceso.

Descripción: ....

4.- ¿Rotación de parcelas cada que tiempo?

¿Rotación de cultivos cada que tiempo?

¿Descanso de las parcelas que tiempo?

Sección 2

Habilitación de tierras dentro el chaco para producción agrícola en el tiempo.

5 a.- ¿Proceso de habilitación de tierras en el chaco después de su adjudicación y como? ¿Cuando? (Dibuje / el boceto).

Descripción:..

5b.- Habilitación de tierras para producción agrícola.

Año	Extensión	Mayor Actividad	No. de vacas
1960			
1970			
1980			
1985			
1990			
1995			
2000			

6.- ¿Extensión de habilitación de tierras para agricultura ó ganado? ¿En el primer chaqueo y que siembra?

7.- Factores que inciden en la habilitación de tierras para producción agrícola. (mercado/ carretera / organizaciones, calidad de tierra, ganado y otros)

8.- Destino de los productos agrícolas o ganado al mercado.

PRODUCTOS O GANADOS	MERCADO LOCAL?	SCZ	CBBA	OTRO PAÍS	MERCADO ANTES	QUE AÑO?

Comentario:..

Sección 3

Cambios en la producción agropecuaria.

9a.- Cambio de cultivo original con productos alternativos o ganado.

CAM BIO	AÑO	CULTIVOS ORIGINALES	AÑO	ALTERNATIVOS (TIPO DE CULTIVO Ó GANADO)	BENEFICIOS O SI / NO?
1					
...					
8					

Detalles:..

9b.- ¿Porque cambio? Tipo de proyecto.

CAMBIO	AYUDA GUBERNAMENTAL	APOYO DEL ONGS	APOYO DE SINDICATO	OTRAS ORGANIZACIONES
1				
...				
8				

Detalles:..

Sección 4

Uso de RRNN del monte y la extensión que será habilitada este año.

11.- ¿Que factores determinan para mayor uso ó avance hacia el monte? (mercado / calidad de tierra / mas peones / mayor No. familia y otros) Porque?

12.- ¿Cuánto va a chaquear el próximo año y que cultivos?

13.- ¿Que uso tiene el monte ahora, en el futuro

14.- ¿Que extensión de monte queda en el chaco.

15.- ¿Cuánto tiempo estima la existencia de su monte? Como?

16.- ¿Que sucede si el chaco (monte) es totalmente habilitado para la agricultura? (Compra otro chaco / busca otro comunidad / retornar a comunidad de origen / reduce los cultivos) Porque?

17.- ¿Que esperas de las políticas del gobierno, municipio o comunidad?

Appendix 4.2

Spatial and spectral properties of Landsat missions, adapted from Campbell (1996)

Platform	Sensor	Band number	Resolution (m)	Spectral range (μm)	Region in electromagnetic spectrum
Landsat-7	ETM+	1	30	0.45 to 0.515	Blue-green
		2	30	0.525 to 0.605	Green
		3	30	0.63 to 0.690	Red
		4	30	0.75 to 0.90	Near infrared
		5	30	1.55 to 1.75	Mid infrared
		6	60	10.40 to 12.5	Far infrared
		7	30	2.09 to 2.35	Mid infrared
		PAN	15	0.52 to 0.90	Panchromatic
Landsat 4-5	TM	1	30	0.45 - 0.53	Blue-green
		2	30	0.52 - 0.60	Green
		3	30	0.63 - 0.69	Red
		4	30	0.76 - 0.90	Near infrared
		5	30	1.55 - 1.75	Mid infrared
		6	120	10.40 - 12.50	Far infrared
		7	30	2.08 - 2.35	Mid infrared
Landsat 4-5 (1-3)	MSS	1 (4)	80	0.5 - 0.6	Green
		2 (5)	80	0.6 - 0.7	Red
		3 (6)	80	0.7 - 0.8	Near infrared
		4 (7)	80	0.8 - 1.1	Near infrared
		(8)	237	10.41 - 12.6	Far infrared

Appendix 4.3

Documentation Centres

USAID, Development Alternatives Incorporated., Edificio Los Tiempos, Cochabamba, Bolivia.

CERES, Avenida Oduendo, Cochabamba, Bolivia

CEDIB, Centre de documentación, e Información – Bolivia, Calle Calama, No E-0255, Cochabamba, Bolivia

Casa de la Cultura, Avenida de las Heroínas, Cochabamba, Bolivia

Museo de Arqueológico, UMSS, Calle 25 de Mayo, Cochabamba, Bolivia

La Biblioteca de la Iglesia, Avenida de Libertador Bolívar, Cochabamba, Bolivia

INE, Instituto Nacional de Estadísticas, Avenida Hamiraya, Cochabamba, Bolivia

Caminos Vecinales, km 4 Cochabamba-Santa Cruz, Cochabamba, Bolivia

Universidad de Católica, Calle Oruro, Cochabamba, Bolivia

INRA, Instituto reforma de Agraria, Calle 16 de Julio, Cochabamba, Bolivia.

APPENDIX 4.4

(a)**Arequipa** **2000**

Class	Possible Land-cover class	Justification	Probable land-cover class	Qualitative estimate of confidence
1	Forest canopy	Rivers have been masked out where identifiable, some remaining pixels are mixels of forest canopy above water	Forest	Certain
2	Forest Canopy	Exists in the forested area, with a few pixels in contiguous cleared area	Forest	Certain
3	Forest Canopy	Exists in the forested area, with a few pixels in contiguous cleared area	Forest	Certain
4	Forest Canopy and potential forest non-forest boundary edge effects	Mainly isolated pixels in forest area although some are inside the cleared area and at forest edge	Forest	Certain
5	Forest, disturbance, secondary regrowth	50% forest, 50% non-forest. Generally a contiguous class, existing along access road, occurs at the forest edge as mixels of forest and non-forest and as groups of non-forest within the forest canopy	Forest	Uncertain
6	Open ground / recent clearance	Corresponds to roads and clearance patches at forest / non-forest interface	Non-forest	Certain
7	A specific unknown crop type, but potential edge effects with forest	Linked to clearance patches but with a few pixels in forest areas	Non-forest	Certain
8	A type of clearance	Distinct patches of clearance for agriculture	Non-forest	Certain
9	A type of clearance, probably bananas	Distinct patches of clearance for agriculture	Non-forest	Certain
10	A specific clearance type including roads, and urban areas	Distinct patches of clearance for agriculture	Non-forest	Certain

(b)

Arequipa	1996			
Class	**Possible Land-cover class**	**Justification**	**Probable land-cover class**	**Qualitative estimate of confidence**
1	Some clearance and open ground	Similar spectral properties to river beds, hence open ground, included water which was then masked from the image	Non-forest	Certain
2	Forest canopy	Contiguous groups of pixels in forested areas	Forest	Certain
3	Forest canopy	Contiguous groups of pixels in forested areas	Forest	Certain
4	Forest canopy	Contiguous groups of pixels in forested areas	Forest	Certain
5	A type of clearance but includes possible edge effects between forest and non-forest	Mainly found associated with non-forest, very few isolated non-forest pixels	Non-forest	Certain
6	Forest including edge effects	Contiguous groups of pixels found in forested areas and sometimes found at the forest edge	Forest	Certain
7	A type of clearance	Distinct patches in non-forest areas	Non-forest	Certain
8	Exists in clearance and within forest class	53% forest and 48% groups of pixels in both forest and non-forest areas	Non-forest	Uncertain
9	A type of clearance	Small groups of contiguous pixels related to non-forest	Non-forest	Certain
10	A type of clearance	Distinct patches of non-forest	Non-forest	Certain

(c)

Arequipa	**1993**			
Class	**Possible Land-cover class**	**Justification**	**Probable land-cover class**	**Qualitative estimate of confidence**
1	Canopy shadow and some canopy over narrow water bodies	Widespread in image area pixels in ribbon patterns, relate to watercourses	Forest	Certain
2	Forest canopy	Contiguous groups of pixels in forest area, few isolated pixels in non-forest area	Forest	Certain
3	Forest canopy	Contiguous groups of pixels in forest area, few isolated pixels in non-forest area	Forest	Certain
4	Forest canopy	Contiguous groups of pixels in forest area, few isolated pixels in non-forest area	Forest	Certain
5	Forest canopy and edge effects	Contiguous groups of pixels in forest area, few isolated pixels in non-forest area, but found on forest / non-forest border	Forest	Certain
6	Forest canopy and edge effects	Contiguous groups of pixels in forest area, few isolated pixels in non-forest area, but found on forest / non-forest border	Forest	Certain
7	Clearance type, road and canopy	68% forest, 31% non-forest, cannot split as contiguous groups of forest occur in the non-forest area, ribbons of pixels correspond to the road and isolated pixels occur in the forest	Non-forest	Uncertain
8	A type of clearance	Distinct patches of non-forest	Non-forest	Certain
9	A type of clearance	Distinct patches of non-forest	Non-forest	Certain
10	A type of clearance	Distinct patches of non-forest	Non-forest	Certain

(d)

Arequipa 1986

Class	Possible Land-cover class	Justification	Probable land-cover class	Qualitative estimate of confidence
1	Forest canopy	Water masked out, insufficient evidence to identify individual pixels water, of water which may be shadowing in the canopy	Forest	Certain
2	Forest canopy	Contiguous groups of pixels in forest area	Forest	Certain
3	Forest canopy	Contiguous groups of pixels in forest area	Forest	Certain
4	Forest canopy	Contiguous groups of pixels in forest area	Forest	Certain
5	Forest canopy	Contiguous groups of pixels in forest area	Forest	Certain
6	Forest canopy	Contiguous groups of pixels in forest area	Forest	Certain
7	Strong edge effects	59% forest and 41% non-forest, forest / non-forest edge is too uncertain to give this a forest or nonforest classification	Forest	Uncertain
8	A type of clearance	Mainly large patches but some isolated pixels in forest areas	Non-forest	Certain
9	A type of clearance	Distinct patches of pixels in non-forest areas	Non-forest	Certain
10	A type of clearance	Distinct patches of pixels in non-forest areas	Non-forest	Certain

(e)

Bogotá 2000

Class	Possible Land-cover class	Justification	Probable land-cover class	Qualitative estimate of confidence
1	Canopy shadowing agriculture at forest edges and semi cleared forest	Consistently north west to south east rows of pixelsbetween the forest / non forest. There are also groups of pixels corresponding to plot boundaries which are in the forest	Non-forest	Certain
2	Forest Canopy	Contiguous groups of pixels in forest area	Forest	Certain
3	Disturbed forest canopy	Forest edge effects consists of forest / non-forest mixels, may indicate abandonment of forest	Forest	Certain
4	Forest and non-forest	42% forest, 58% non-forest. Includes forest regrowth or forest pixels in non-forest areas, edge effects between forest and non-forest. Contains contigous groups of pixels considered as illuminated canopy, which was masked from the image. Related to non-forest but in areas could be forest canopy	Non-forest	Uncertain
5	Clearance type	Distinct patches of pixels in non-forest areas, but also has some illuminated canopy which was masked from the image	Non-forest	Certain
6	Clearance type	Distinct patches of pixels in non-forest areas	Non-forest	Certain
7	Clearance type	Distinct patches of pixels in non-forest areas	Non-forest	Certain
8	Clearance type	Distinct patches of pixels in non-forest areas	Non-forest	Certain
9	Clearance type	Distinct patches of pixels in non-forest areas	Non-forest	Certain
10	Clearance type	Distinct patches of pixels in non-forest areas	Non-forest	Certain

(f)

Bogotá 1996

Class	Possible Land-cover class	Justification	Probable land-cover class	Qualitative estimate of confidence
1	Forest canopy	Contiguous groups of pixels in forest area. Cloass included shadow and water which was masked from the image.	Forest	Certain
2	Forest canopy	Contiguous groups of pixels in forest	Forest	Certain
3	Forest canopy	Contiguous groups of pixels in forest	Forest	Certain
4	Forest canopy, some disturbance	55% forest, 45% non-forest. Marginal category, represents edge effects between forest and non-forest represents fragments of non-forest and illumination of forest canopy	Forest	Uncertain
5	A type of clearance	Patches clearly related to plot boundaries. Includes illumination which was masked from the image	Non-forest	Certain
6	A type of clearance	Groups of pixels occur in non-forest area, some isolated non-forest pixels in the forest canopy class	Non-forest	Certain
7	A type of clearance	Groups of pixels occur in non-forest area, some isolated non-forest pixels in the forest canopy class	Non-forest	Certain
8	A type of clearance	Distinct patches of forest occur in cleared area	Non-forest	Certain
9	A type of clearance	Distinct patches of forest occur in cleared area	Non-forest	Certain
10	A type of clearance type and road surface	Distinct patches of forest occur in cleared area	Non-forest	Certain

(g)

Bogotá	1992			
Class	**Possible Land-cover class**	**Justification**	**Probable land-cover class**	**Qualitative estimate of confidence**
1	Forest canopy	Contiguous groups of pixels in forested area. Included water which was masked out and shaded areas re-coded to non-forest	Forest	Uncertain
2	Forest Canopy	Contiguous groups of pixels in forest	Forest	Certain
3	Forest Canopy	Contiguous groups of pixels in forest	Forest	Certain
4	Forest Canopy	Contiguous groups of pixels in forest	Forest	Certain
5	Forest Canopy and non-forest patches and mixels at forest edge	66.1% forest, 33.89% non-forest. Mixels of non-forest and forest	Forest	Unertain
6	A type of clearance type plus illumination	Distinct patches of non-forest but groups of pixels in forest canopy	Non-forest	Certain
7	A type of clearance type plus illumination	Distinct patches of non-forest but groups of pixels in forest canopy	Non-forest	Certain
8	A type of clearance type plus illumination	Distinct patches of non-forest but groups of pixels in forest canopy	Non-forest	Certain
9	A type of clearance type plus illumination	Distinct patches of non-forest but groups of pixels in forest canopy	Non-forest	Certain
10	A type of clearance	Distinct patches of non-forest but groups of pixels in forest canopy	Non-forest	Certain

(h)

Bogotá	1986			
Class	**Possible Land-cover class**	**Justification**	**Probable land-cover class**	**Qualitative estimate of confidence**
1	Forest canopy	Contiguous groups of pixels including water which was masked from the class and shadow over non-forest areas recoded to non-forest	Forest	Certain
2	Forest Canopy	Contiguous groups of pixels in forest	Forest	Certain
3	Forest Canopy	Contiguous groups of pixels in forest	Forest	Certain
4	Forest Canopy	Contiguous groups of pixels in forest	Forest	Certain
5	Forest Canopy	Contiguous groups of pixels in forest	Forest	Certain
6	Forest Canopy	Contiguous groups of pixels in forest	Forest	Certain
7	Forest canopy and non-forest	57% forest, 43% non-forest. Only possible to separate according to position and context	Forest	Uncertain
8	A type of clearance	Distinct groups of pixels in non-forest area	Non-forest	Certain
9	A type of clearance	Distinct groups of pixels in non-forest area	Non-forest	Certain
10	A type of clearance	Distinct groups of pixels in non-forest area	Non-forest	Certain

(i)

Bogotá	**1975**			
Class	**Possible Land-cover class**	**Justification**	**Probable land-cover class**	**Qualitative estimate of confidence**
1	Water	Related to water courses	Water	Certain
2	Forest canopy and canopy over water	Forest with mixels of water and forest	Forest	Certain
3	A type of clearance and gravel river beds	Related to water courses and non-forest areas	Non-forest	Certain
4	Forest canopy	Contiguous groups of pixels in forest area	Forest	Certain
5	Forest canopy	Contiguous groups of pixels in forest area	Forest	Certain
6	Forest canopy	Contiguous groups of pixels in forest area	Forest	Certain
7	Forest canopy	Contiguous groups of pixels in forest area	Forest	Certain
8	A type of clearance and gravel river beds	Cleared area, and dry river beds	Non-forest	Certain
9	Disturbed forest	Groups of pixels in forest areas and canopy covering water courses	Forest	Certain
10	A type of clearance	Distinct patches of non-forest	Non-forest	Certain

(j)

Caracas	2000			
Class	Possible Land-cover class	Justification	Probable land-cover class	Qualitative estimate of confidence
1	Shadow in forest canopy	Shadow associated with forest canopy and water which was masked from the class	Forest	Certain
2	Forest canopy	Most class in forested area, some inside non-forest area identified by the shadows cast over non-forest area	Forest	Certain
3	Forest canopy	Most class in forested area, some inside non-forest area identified by the shadows cast over non-forest area	Forest	Certain
4	Forest of non-forest class	Forest 50%, non-forest 50%. Can be forest in non-forest or non-forest in forest	Non-forest	Uncertain
5	Forest canopy	Appears at forest edges advanced secondary forest growth in former non-forest	Non-forest	Certain
6	A type of clearance	Distinct patches of clearance in non-forest area	Non-forest	Certain
7	A type of clearance	Distinct patches of clearance in non-forest area	Non-forest	Certain
8	A type of clearance	Distinct patches of clearance in non-forest area	Non-forest	Certain
9	A type of clearance	Distinct patches of clearance in non-forest area	Non-forest	Certain
10	A type of clearance	Distinct patches of clearance in non-forest area	Non-forest	Certain

(k)

Caracas	1996			
Class	**Possible Land-cover class**	**Justification**	**Probable land-cover class**	**Qualitative estimate of confidence**
1	Water bodies	Water masked from image	Forest	Certain
2	Forest Canopy	Contiguous groups of pixels in forest area	Forest	Certain
3	A type of clearance of forest	40% forest 60% non-forest related, major problem exists in places between forest and non-forest and in isolated patches patches. Band 4 higher values than forest reflectance	Forest	Uncertain
4	A type of clearance and road surfaces	Roads, and areas of non-forest clearance	Non-forest	Certain
5	A type of clearance	24% forest 76% non-forest. Confusion at forest / non-forest boundaries, and with individual non-forest pixels in forest	Non-forest	Certain
6	A type of clearance	Distinct groups of pixels in non-forest areas	Non-forest	Certain
7	A type of clearance	Distinct groups of pixels in non-forest areas	Non-forest	Certain
8	A type of clearance	Distinct groups of pixels in non-forest areas	Non-forest	Certain
9	A type of clearance	Distinct groups of pixels in non-forest areas	Non-forest	Certain
10	A type of clearance	Distinct groups of pixels in non-forest areas	Non-forest	Certain

(l)

Caracas	1993			
Class	**Possible Land-cover class**	**Justification**	**Probable land-cover class**	**Qualitative estimate of confidence**
1	Water bodies	Water masked from image	Forest	Certain
2	Forest canopy	Contiguous groups of pixels in forest areas	Forest	Certain
3	Forest canopy	41% forest, 58% non-forest, often found at forest / non-forest boundaries	Forest	Uncertain
4	Forest canopy / clearance	62%cleared 37% forest, as class 3 - inconclusive	Forest	Certain
5	A type of clearance	Distinct patches of clearance	Non-forest	Certain
6	A type of clearance	Distinct patches of clearance	Non-forest	Certain
7	A type of clearance	Distinct patches of clearance	Non-forest	Certain
8	A type of clearance	Distinct patches of clearance	Non-forest	Certain
9	A type of clearance	Distinct patches of clearance	Non-forest	Certain
10	A type of clearance	Distinct patches of clearance and road surfaces	Non-forest	Certain

(m)

Caracas	1986			
Class	**Possible Land-cover class**	**Justification**	**Probable land-cover class**	**Qualitative estimate of confidence**
1	Water bodies	Related to water courses, masked from image	Forest	Certain
2	Forest canopy	Contiguous groups of pixels related to forest	Forest	Certain
3	Forest canopy and edge effects	75% forest, 25% non-forest, tends to be related to edges of non-forest. Forest in non-forest and non-forest in forest areas	Forest	Uncertain
4	A type of clearance	Distinct patches of pixels in non-forest areas	Non-forest	Certain
5	A type of clearance	Distinct patches of pixels in non-forest areas	Non-forest	Certain
6	A type of clearance	Distinct patches of pixels in non-forest areas	Non-forest	Certain
7	A type of clearance	Distinct patches of pixels in non-forest areas	Non-forest	Certain
8	A type of clearance	Distinct patches of pixels in non-forest areas	Non-forest	Certain
9	A type of clearance	Distinct patches of pixels in non-forest areas	Non-forest	Certain
10	A type of clearance	Distinct patches of pixels in non-forest areas	Non-forest	Certain

(n)

Caracas	1976			
Class	**Possible Land-cover class**	**Justification**	**Probable land-cover class**	**Qualitative estimate of confidence**
1	Water bodies	Related to water courses, masked from image	Forest	Certain
2	Forest canopy	Contiguous groups of pixels in forested areas	Forest	Certain
3	Forest canopy	Contiguous groups of pixels in forested areas	Forest	Certain
4	Potential edge effects between forest and non-forest	Contiguous groups of pixels in forested areas	Forest	Certain
5	Potential edge effects between forest and non-forest	Tends to be found in forest classes and edges	Forest	Uncertain
6	A type of clearance type plus community areas and road surfaces	Distinct groups of pixels in non-forest areas	Non-forest	Certain
7	A type of clearance	Distinct groups of pixels in non-forest areas, some non-forest in forest areas	Non-forest	Certain
8	A type of clearance	Distinct groups of pixels in non-forest areas, some non-forest in forest areas	Non-forest	Certain
9	A type of clearance	Distinct groups of pixels in non-forest areas	Non-forest	Certain
10	A type of clearance	Distinct groups of pixels in non-forest areas	Non-forest	Certain

Appendix 4.5

Definitions of Landscape metrics from MaCaragil and Marks (1994)

(www.umass.edu/landeco/research/fragstats/fragstats.html)

Mean Patch size	$$MPS = \frac{A}{N}\left(\frac{1}{10,000}\right)$$
Description	MPS equals the total landscape area (m^2), divided by the total number of patches, divided by 10,000 (to convert to hectares).
Units	Hectares
Range	The range is limited by the grain and extent of the image.
Comments	
Mean Patch Size Standard Deviation	$$PSSD = \sqrt{\frac{\sum_{i=1}^{m}\sum_{j=1}^{n}\left[a_{ij}-\left(\frac{A}{N}\right)\right]^2}{N}}\left(\frac{1}{10,000}\right)$$
Description	PSSD equals the square root of the sum of the squared deviations of each patch area (m2) from the mean patch size, divided by the total number of patches, divided by 10,000 (to convert to hectares); that is the root mean squared error (deviation from the mean) in patch size. Note this is the population standard deviation not the sample standard deviation.
Units	Hectares
Range	PSSD ≥ 0
Comments	PSSD =0 when all patches in the landscape are the same size or when there is only one patch. (i.e. no variability in patch size)
Mean Patch Size Co-Variance	$$PSCV = \frac{PSSD}{MPS}(100)$$
Description	PSCV equals the standard deviation in patch size (PSSD) divided by the mean patch size (MPS), multiplied by 100 (to convert to percent); that is, the variability in patch size relative to the mean patch size. Note this is the population co-efficient of variation, not the sample co-efficient of variation.
Units	Percent
Range	PSCV ≥ 0 without limit
Comments	PSCV = 0 when all patches in the landscape are the same size or when there is only one patch (i.e. no variability in size)

Mean Nearest Neighbour	$$MNN = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n'} h_{ij}}{N'}$$
Description	MNN equals the sum of the distance (m) to the nearest patch of the same type, based on edge to edge distance, for each patch in the landscape with a neighbour, divided by the number of patches with a neighbour.
Units	Meters
Range	MNN > 0 without limit.
Comments	MNN is reported as 'none' if none of the patches have a nearest neighbour (i.e. every patch type consists of only one patch)
Mean Nearest Neighbour Standard Deviation	$$NNSD = \sqrt{\frac{\sum_{i=1}^{m}\sum_{j=1}^{n'}\left[h_{ij} - \left(\frac{\sum_{i=1}^{m}\sum_{j=1}^{n'} h_{ij}}{N'}\right)\right]^2}{N'}}$$
Description	NNSD equals the square root of the sum of the squared deviations of each patches' nearest neighbour equal distance of the corresponding patch type (MNN), divided by the number of patches; that is the root mean squared error (deviation from the mean) in the patch nearest neighbour distance. Note this is the population standard deviation, not the sample standard deviation.
Units	Meters
Range	NNSD ≥ 0, without limit
Comments	NNSD = 0 when all patches have the same nearest neighbour distance (i.e., no variability in nearest neighbour distance)
Mean Nearest Neighbour Co-Variance	$$NNCV = \frac{NNSD}{MNN}(100)$$
Description	NNCV equals the standard deviation in nearest neighbour distances (NNSD) divided by the mean nearest neighbour distances (MNN), multiplied by 100 (to convert to percent); that is the variability in the nearest neighbour distance relative to the mean nearest neighbour distance. Note, this is the population co-efficient of variation, not the sample co-efficient of variation.
Units	Percent
Range	NNCV ≥ 0, without limit
Comments	NNCV = 0 when all patches have the same nearest neighbour distance (i.e., no variability in nearest neighbour distance; NNSD = 0)

Total (Class) Area	$$CA = \sum_{j=1}^{n} a_{ij} \left(\frac{1}{10,000} \right)$$ a_{ij} = area (m^2) of patch ij.
Description	CA equals the sum of the areas (m^2) of all patches of the corresponding patch type, divided by 10,000 (to convert to hectares); that is, total class area.
Units	Hectares
Range	CA > 0, without limit. CA approaches 0 as the patch type becomes increasing rare in the landscape. CA = TA when the entire landscape consists of a single patch type; that is, when the entire image is comprised of a single patch.
Comments	*Class area* is a measure of landscape composition; specifically, how much of the landscape is comprised of a particular patch type. In addition to its direct interpretive value, class area is used in the computations for many of the class and landscape metrics.

Number of Patches	$$NP = N$$ N = total number of patches in the landscape.
Description	NP equals the number of patches in the landscape. Note, NP does not include any internal background patches (i.e., within the landscape boundary) or any patches at all in the landscape border, if present.
Units	None
Range	NP ≥ 1, without limit. NP = 1 when the landscape contains only 1 patch.
Comments	*Number of patches* often has limited interpretive value by itself because it conveys no information about area, distribution, or density of patches. Of course, if total landscape area is held constant, then number of patches conveys the same information as patch density or mean patch size and may be a useful index to interpret. Number of patches is probably most valuable, however, as the basis for computing other, more interpretable, metrics. Note that the choice of the 4-neighbor or 8-neighbor rule for delineating patches will have an impact on this metric.

Patch Density	$$PD = \frac{N}{A}(10,000)(100)$$ N = total number of patches in the landscape. A = total landscape area (m^2).
Description	PD equals the number of patches in the landscape, divided by total landscape area (m^2), multiplied by 10,000 and 100 (to convert to 100 hectares). Note, PD does not include background patches or patches in the landscape border, if present. However, total landscape area (A) includes any internal background present.
Units	Number per 100 hectares
Range	PD > 0, constrained by cell size. PD is ultimately constrained by the grain size of the raster image, because the maximum PD is attained when every cell is a separate patch.
Comments	*Patch density* is a limited, but fundamental, aspect of landscape pattern. Patch density has the same basic utility as number of patches as an index, except that it expresses number of patches on a per unit area basis that facilitates comparisons among landscapes of varying size. Of course, if total landscape area is held constant, then patch density and number of patches convey the same information. Like number of patches, patch density often has limited interpretive value by itself because it conveys no information about the sizes and spatial distribution of patches. Note that the choice of the 4-neighbor or 8-neighbor rule for delineating patches will have an impact on this metric.
Total Edge	$$TE = E$$ E = total length (m) of edge in landscape.
Description	TE equals the sum of the lengths (m) of all edge segments in the landscape. If a landscape border is present, TE includes landscape boundary segments representing 'true' edge only (i.e., abutting patches of different classes). If a landscape border is absent, TE includes a user-specified proportion of the landscape boundary. Regardless of whether a landscape border is present or not, TE includes a user-specified proportion of internal background edge.
Units	Meters
Range	TE ≥ 0, without limit. TE = 0 when there is no edge in the landscape; that is, when the entire landscape and landscape border, if present, consists of a single patch and the user specifies that none of the landscape boundary and background edge be treated as edge.
Comments	*Total edge* is an absolute measure of total edge length of a particular patch type. In applications that involve comparing landscapes of varying size, this index may not be as useful as edge density (see below). However, when comparing landscapes of identical size, total edge and edge density are completely redundant.

Edge Density	$$ED = \frac{E}{A}(10,000)$$ E = total length (m) of edge in landscape. A = total landscape area (m^2).
Description	ED equals the sum of the lengths (m) of all edge segments in the landscape, divided by the total landscape area (m^2), multiplied by 10,000 (to convert to hectares). If a landscape border is present, ED includes landscape boundary segments representing 'true' edge only (i.e., abutting patches of different classes). If a landscape border is absent, ED includes a user-specified proportion of the landscape boundary. Regardless of whether a landscape border is present or not, ED includes a user-specified proportion of internal background edge. Note, total landscape area (A) includes any internal background present.
Units	Meters per hectare
Range	ED ≥ 0, without limit. ED = 0 when there is no edge in the landscape; that is, when the entire landscape and landscape border, if present, consists of a single patch and the user specifies that none of the landscape boundary and background edge be treated as edge.
Comments	*Edge density* has the same utility and limitations as Total Edge (see Total Edge description), except that edge density reports edge length on a per unit area basis that facilitates comparison among landscapes of varying size.