

Sustainable Forest Management for Small Farmers in Acre State in the Brazilian Amazon

by

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Declaration

I hereby declare that the work presented in this thesis has been performed by myself in the department of Plant and Soil Science, University of Aberdeen, and that it has not been presented in any previous application for a degree. All verbatim extracts have been distinguished by quotation marks and all sources of information specifically acknowledged by reference to the authors.

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Summary

This thesis has the aim of presenting a forest management system to be applied on small farms, especially in the settlement projects of the Brazilian Amazon, and to examine its sustainability by investigating the responses of the forest in terms of the changes in natural regeneration in felling gaps and the dynamics of the residual trees. Using the program CAFOGROM, an additional aim was to simulate the forest responses to different cycle lengths, harvesting intensities and silvicultural treatments to determine the theoretical optimum combination of these parameters. The proposed forest management system was designed to generate a new source of family income and to maintain the structure and biodiversity of the legal forest reserves. The system is new in three main characteristics: the use of short cycles in the management of tropical forest, the low harvesting intensity and environmental impact and the direct involvement of the local population in all forest management activities. It is based on a minimum felling cycle of ten years and an annual harvest of 5-10 m³ ha⁻¹ of timber. The gaps produced by logging in PC Peixoto can be classified as small or less often medium sized (canopy openness from 10% to 25%). Differences in gap size and canopy openness produced significant differences in the growth rates, species richness and species diversity of seedlings established in the gaps. Mortality rates of seedlings in the artificial gaps increased and recruitment rates decreased with increasing gap size. The density and recruitment of seedlings of commercial species was not different between gap sizes, but gap creation increased the growth rate of the seedlings of these species. Small and medium gaps (less than 25 % canopy openness) improved regeneration from the forest management point of view, with fewer pioneer plants, higher diversity and lower mortality, although they resulted in lower seedling growth rates. The mean periodic annual diameter increment of trees in the permanent sample plots (0.27 cm yr⁻¹) and mean annual mortality rates (2.1 % yr⁻¹) were similar to those found by other research in the tropics. Differences in species growth between crown exposure and species groups were statistically significant. The influence of management was positive in terms of diameter increment increase in both mechanised and non-mechanised forest management systems. The volume increment of commercial species for both kinds of forest management is compatible with the logging intensity and cycle length proposed, and the density and recruitment of commercial species were not affected by logging. Ten year cycles were the most appropriate compromise among the studied cycle length for sustainable forest management under the conditions examined in this study. A regular harvesting of 8 to 10 m³ ha⁻¹ cycle⁻¹ can be expected with the combination of a harvesting intensity of around 1.0 m² ha⁻¹ cycle⁻¹ and silvicultural treatments removing around 1.5 m² ha⁻¹ cycle⁻¹. However, the results of the simulations must be interpreted as indications of the behaviour of the forest in response to different interventions rather than as quantitative predictions. The project will continue as a part of the EMBRAPA research programme, and receiving additional support from the ASB (alternative to slash and burn) project. The continuation of the project will allow the continuation of research on forest dynamics and plant succession in the felling and artificial gaps.

CHAPTER 1

Sustainable Forest Management: an option for land use in Amazon

1.1 Introduction

The world's forest resources are being depleted or degraded for a variety of reasons. Commercial logging without a silviculture-based management plan, slash and burn agriculture, and cattle pasture establishment or other non-forest enterprises are among the main reasons for deforestation in the tropics (Whitmore, 1992). The major cause of uncontrolled use and misuse of tropical forests is the dependency of millions of rural people on forest resources, and the soil that they cover, for basic needs of food, energy and shelter (Hendrison, 1990).

It has been estimated that tropical rain forests have been converted at a rate of 15.4 million hectares a year over the period 1981 – 1990 (FAO, 1993) and 13.7 million hectares a year over the period 1990 – 1995 (FAO, 1997, 1999). The profits that come from alternative uses of the land, such as shifting cultivation, are greater than the use of these original ecosystems for forest management practices (Higuchi, 1994). In addition, even when managed, the increased access provided by forest harvesting (e.g. by skid trails) and demographic pressures after the first harvesting, means that forests are more likely to be converted than conserved.

At the end of 1990, 76 % of the tropical rain forest zone still remained intact, but the annual loss of biomass was estimated at slightly over 2,500 million tonnes, of which more than 50 % percent was contributed by Latin America, nearly 30 % by tropical Asia and about 20 % by tropical Africa (FAO, 1993). In both Brazil and tropical Asia, change from continuous forests occurs at a rate much higher than in tropical Africa, owing to the higher population density in Asia and planned resettlements/resource exploitation programmes (in Brazil and Asia) (FAO, 1993). In this way, tropical timber resources have been decreasing sharply in the recent past, especially in Southeast Asia (FAO, 1993), where traditional timber exporting countries are reducing or even banning (e.g. Thailand) timber harvesting activities (Johnson, 1997).

The decrease in the amount of timber production is in conflict with the growing demand from the furniture manufacturing and secondary processing industries, that has generated a substantial increase in timber imports in many

countries. In general, both exportation and importation of tropical timber have declined in recent years, and only in South America is production still increasing (Johnson, 1997).

It seems likely that in the near future the focus of tropical timber production will change to South America. An important issue in this context is that while for the most important commercial timber species, prices are dropping in Asia (e.g. for *Shorea* spp, from US\$800 per m³ in 1993 to US\$600 in 1995) and Africa (e.g. for *Entandrophragma utile*, from US\$750 per m³ in 1993 to US\$600 in 1994), the prices for the most important South American species (*Swietenia macrophylla*) remain constant, and will probably increase because of the ban on new concessions for *Swietenia macrophylla* and *Virola* spp in Brazil (Johnson, 1997). On the other hand there is a growing international pressure for the preservation of tropical forests. Proposals such as Target 2000 (ITTO, 1991) attempt to ensure that only wood from sustainably managed tropical forests is allowed to enter international markets. The idea that the forest must be preserved as a sanctuary has been replaced by a more realistic one where by it is argued that the only way to promote conservation of an ecosystem is by giving it a economic function (Barros and Uhl, 1995; FAO, 1998). All these factors would favour the development of forest management activities in South America.

However, the scientific understanding of tropical forest ecosystems is still far from complete. There is an urgent need to develop ecologically sound sustainable management techniques. Ecologically based management for sustainable harvesting requires, at a minimum, three types of measurements: (i) monitoring the effects of the logging practices on the composition and structure of the residual stand; (ii) estimates of the parameters of growth and survival that determine recruitment into harvestable sizes during stand development after logging; (iii) the density and composition of regeneration (Cannon *et al.* 1994).

Forest management is needed at two scales: management for large areas without heavy human population pressure and management for small areas in inhabited areas (Braz and Oliveira, 1994). In the first case, the traditional forest management systems, allied to governmental policies and legislation, are sufficient to achieve success. However, in the second case, specific techniques, policies, criteria and legislation must be created in most countries.

In this thesis I will present a forest management system for application on small farms, in the settlement projects of the Brazilian Amazon, and examine its sustainability by monitoring regeneration in felling gaps and the dynamics of the residual trees. Using the program CAFOGROM (Alder, 1995a, 1995b; Alder and

Silva, 1999), an additional aim is to simulate the response of the forest to different felling cycle lengths, harvesting intensities and silvicultural treatments in order to determine the theoretical optimum combination of these variables.

The objectives of this chapter are to provide an overview of the history and perspectives of forest management in the tropics, to review the most widely used silvicultural systems and to discuss their characteristics and constraints in the West Amazon tropical forest context.

1.2 Important silvicultural systems used in tropical forests

Many silvicultural systems have been developed and tested for tropical rain forest. These are briefly reviewed below in order to present possible options for small farmers in Amazon. Reviews of tropical silvicultural systems have been published (e.g. Jonkers, 1987; Silva, 1989, 1997, Higuchi, 1994; Philip and Dawkins, 1998). In summary, silvicultural systems were derived from the Selection System, in which part of the stand is harvested every 20-40 years or the Uniform System, in which the entire population of the marketable trees are removed in a single harvest. Many variations exist between these extremes. The most important in tropical forest silviculture are the various types of Shelterwood Systems, in which the leap from one rotation to another is neither as abrupt as in the Uniform System nor as prolonged as in the Selection System (Philip and Dawkins, 1998). The main characteristics of some of these systems are presented in Table 1.2.

There are also the semi-natural silvicultural methods, that create relatively even-aged stands similar to tree plantations after the total or partial removal of the original forest in one or more operations. These methods include the Taungya system (felling of demarcated areas of forest and planting of food crops and desirable species, originally applied in Myanmar) the Limba-Okume system (after clear-cutting the forest, *Terminalia superba* and *Aucoumea klaineana* are planted; introduced in West Africa), the Martineau system (systematic replacement of the natural heterogeneous forest by an even-aged plantation of valuable species, applied in extensive areas in Côte d' Ivoire) and the Recrû system (replacement of the forest in two steps, first by cutting shrubs and small trees up to 15-20 cm and second by poison-girdling of all or part of the remaining standing trees, used in Gabon). Other methods that involve planting, are "line planting" (planting of seedlings in opened lines in the forest) and the Placeaux method (planting of tree seedlings in 4 x 4 m plots spaced at 10 m intervals). All these techniques have been reviewed and described by Silva (1989, 1997).

Table 1.2: Main characteristics of the most well known silvicultural systems applied in tropical forests.

Silvicultural system	Main characteristics	References
The selective system	Polycyclic system; part of the stand is harvested ever 20 to 40 years after liana cutting to reduce damage during forest exploitation	Jonkers, 1982; 1987; Silva, 1989; Higuchi, 1994; Dawkins and Philip, 1998
The Indonesian selective system	Polycyclic system; minimum felling diameter 50 cm dbh; cycle length 35 years; harvesting intensity around 70 m ³ ha ⁻¹	Sudino and Daryadi, 1978; Whitmore, 1984
Selective logging system (Philippines)	Removal of all trees above 75 cm dbh; 70 % of the trees in the classes from 15-65 cm dbh and of the 70 cm dbh class are left as residuals; cycle length 20 to 40 years.	Virtucio and Torres, 1978; Reyes, 1978b; Silva, 1989
The Malayan Uniform System (MUS)	Monocyclic system involving the harvesting of all marketable trees; understorey cleaning two years after logging; thinning 10 years after logging repeated at intervals of 15 to 20 years; cycle length from 60 to 80 years	Wyatt-smith, 1963; Jonkers, 1987; Higuchi, 1994;
MUS modified for Sabah	Bicyclic system where some commercial trees are retained to provide an intermediate harvesting 40 years after the first harvesting; felling diameter limit fixed at 60 cm dbh	Ting, 1978; Munang, 1978; Schmidt, 1987, 1991; Thang, 1987; Mok, 1992
The Tropical Shelterwood System	Shelterwood systems involve successive regeneration fellings; old trees are removed by two or more successive fellings resulting in a crop that is more or less uneven	Lowe, 1978; Matthew, 1989; Higuchi, 1994
Andaman Canopy Lifting System	Harvesting of commercial trees above 63 cm; crown thinnings conducted at 6, 15, 30 and 50 years	Lowe, 1978; Thangman, 1982; Silva, 1989
The CELOS system	Polycyclic system designed to produce around 20 m ³ ha ⁻¹ in cycles of 20 years where the increment of the residual trees of commercial species is stimulated by several refining treatments during the felling cycle	De Graaf, 1986; De Graaf and Poels, 1990; De Graaf and Rompaey, 1990; Hendrison, 1990; Van Der Hout, 1999

A consensus now exists regarding the relative suitability of these systems for tropical forest management. Uniform systems have been gradually abandoned as it has become clear that they are unsuitable for sustained yield tropical forest management (Cheah, 1978; Higuchi, 1994; Dawkins and Philip, 1998). This unsuitability derives from the long length of the felling cycles and large areas of forest demanded (Thang, 1987). In addition, the heavy impact on forest structure means that uniform systems are only feasible when there is dense regeneration of desirable species and it is possible to implement silvicultural treatments (Lee, 1982, Jonkers, 1987). However, exceptions are still being applied such as the Strip Harvesting System in Palcazu Peru (Ocaña-Vidal, 1992).

Silvicultural systems such as the Tropical Shelterwood System and Selection System, which were developed, refined and used in Asia, are appropriate for most tropical forest regions on technical grounds. When appropriate management techniques are applied, growth and yield models suggest that there is no decline in forest productivity over a number of cycles (e.g. Vanclay, 1990). However, forest management has often failed as a result of factors such as land use pressure (e.g. Hon and Chin, 1978), illegal timber harvesting (Silva, 1989) and undervaluation of the forest resource. Two of the most important reasons for the failure of forest management are the lack of participation of local communities in the forest management activities and the long felling cycles. In addition, there are political, economic and social factors that must be considered alongside of the silvicultural factors (Whitmore, 1992).

The silvicultural systems presented above have some common characteristics such as long cutting cycles of 20 years or more, a requirement for implementation over large areas and a high demand for technology. Mechanisation requires heavy investment and prevents the local populations becoming involved. In addition, these systems involve silvicultural treatments before and after harvesting, and long-term investments which, allied with the unstable economies of many tropical countries, make forest management economically unattractive and difficult to implement, even on a large scale.

1.3 Community management systems

The felling and extraction of trees and other products in tropical forests is a traditional practice of the local people in the Amazon (Oliveira, 1989, 1992) and other tropical countries. For example in Indonesia, trees with diameters above 60 cm dbh are felled in strips of about 2 km in width along rivers, leaving a dense residual stand. However,

there has been a trend towards large scale logging operations in many tropical countries (Sudiono and Daryadi, 1978).

Although few of the techniques were designed specifically to be applied in collaboration with local communities, some attempts are being made in several places to make forest management possible at this level for sustainable production of timber and non-timber products (Perl *et al.* 1991; Batoum and Nkie, 1998). These activities usually develop in secondary forests (e.g. Castañeda *et al.* 1995) because the use of animal traction only allows the extraction of relatively small diameter logs.

Some attempts have also been made to work in primary forests. In this case the effective participation of the community is often limited and all activities are performed by third parties (e.g. lumber merchants). In some cases, the forest is bought by private enterprises that employ some of the community members (e.g. Tecnoforest del Norte in the Portico Project, Perl *et al.* 1991). In addition, competition from large enterprises usually prevents small farmers from working in primary forests because of the need to use heavy machinery for extraction of logs.

The involvement of the local population in forest management is an important factor in meeting the original objectives of forest management (Dickinson *et al.* 1996). Some systems designed for forest communities have been applied in Latin America with some success. These include the Boscosa project in Costa Rica (Perl *et al.* 1991; Howard, 1993), and the strip clear-cutting system developed in Costa Rica (Ocaña-Vidal, 1992), both of which had the effective involvement of the local population. The BOSCOA project is carried out in the Osa peninsula in Costa Rica. It is an integrated management project that includes agroforestry, agriculture and forest management (Kierman *et al.* 1992). The silvicultural prescriptions consist of two phases, termed conversion and maintenance. The conversion phase consists of in two or three conversion cuttings at 10 or 15 year intervals involving the removal of trees larger than 60 cm diameter. During the maintenance phase, a fixed percentage of the number of trees in diameter classes between 30 and 60 cm dbh is taken at each cutting (Howard, 1993). The cycle length is 15 to 25 years with an estimated production of around 20 m³ ha⁻¹ cycle⁻¹ (Perl *et al.* 1991). Strip clear-cutting was developed by the Tropical Science Centre in Costa Rica. The forest is harvested in long, narrow clear-cuttings designed to mimic natural disturbance caused by the fall of a single large tree. Natural regeneration is monitored over a period of 40 to 50 years (Ocaña-Vidal, 1992). The strips vary in width from 30 to 50 m and the harvesting includes all trees with diameter greater than 5 cm using animal power for log extraction (Ocaña-Vidal, 1992).

Small properties typically only produce small quantities, which is enough to meet the owner's needs and provide for the demands of local markets. Both the production and the quality of the products are usually low, but those factors can be improved in small-scale enterprises through the organisation of the work into co-operatives that allow technology to be acquired and products to be accumulated.

1.4 Land use and forest management in the Amazon

The great majority of deforestation in the Brazilian Amazon is followed by conversion of land to cattle pasture, either immediately or after 1-2 years of use under annual crops (ranchers are responsible for about 70 % of this practice and small immigrant farmers 30 %) (Fearnside, 1995). In the Brazilian Amazon, the rate of deforestation varies very much from place to place, and usually follows logging of the forest.

The Amazon experienced a high deforestation rate from the end of the 1970s to the end of the 1980s. A drastic reduction in the rate of deforestation was observed between 1988 and 1992, because of economic instability and the ending of financial credits for the clearance of forest for pastures in Amazon in 1990. From 1992 to 1995 the deforestation rate increased again following introduction of the "Plano Real" for the economy which stabilised the currency and favoured investments in the region. However, from 1995 to 1997 a decline in the deforestation rate was promoted by an economic crisis (INPE, 1998). In general, the deforestation rate has shown a tendency to decrease over time. The fluctuations in deforestation rates have been promoted more by the economic environment than by external pressures or the implementation of land use policies for Amazon (Table 1.1).

Table 1.1 Mean rate of gross deforestation ($\text{km}^2 \text{ year}^{-1}$) from 1978 to 1997 in the Brazilian Amazon*.

Amazon States	77-88 ¹	88-89	89-90	90-91	91-92	92-94 ²	94-95	95-96	96-97
Acre	620	540	550	380	400	482	1208	433	358
Amapá	60	130	250	410	36	-	9	-	18
Amazonas	1510	1180	520	980	799	370	2114	1023	589
Maranhão	2450	1420	1100	670	1135	372	1745	1061	409
Mato-Grosso	5140	5960	4020	2840	4674	6220	10391	6543	5271
Pará	6990	5750	4890	3780	3787	4284	7845	6135	4139
Rondônia	2340	1430	1670	1110	1110	2595	4730	2432	1986
Roraima	290	630	150	420	420	240	220	214	184
Tocantins	1650	730	580	440	440	333	797	320	273
Amazon	21130	17860	13810	11130	13786	14896	29059	18161	13227

* All data from INPE, 1998. 1. decade mean; 2. biennial mean

The east Amazon, especially along the Belém to Brasília and Cuiabá to Santarém roads, experienced heavy deforestation during the 1970s and 1980s, usually from logging followed by conversion to shifting cultivation and pasture formation (Uhl and Vieira, 1988; Homma *et al.* 1993). Rondônia State in west Amazon followed the same pattern of deforestation and land use change along the BR364 road as that described above. This State has the highest percentage of deforested land in the Amazon, that is, about 14 % of the total forest area (FAO, 1993).

When deforestation in Acre State began, it followed the same pattern as in Rondônia and east Pará (the Paragominas region). The BR364 road crosses Acre State for more than 700 km, linking Rio Branco to Cruzeiro do Sul and other State roads linking Rio Branco to cities such as Xapuri, Assis Brasil and Brasiléia on the border with Bolivia. Deforestation in Acre State is about 9 % of the total forest area (INPE, 1998) and is highly concentrated in the Acre river valley (FUNTAC, 1990).

Alternative land uses that preserve the forest, such as extractivism, are difficult to implement in Amazon because the rubber produced from native forest extraction is not competitive with imports from Southeast Asia in the absence of trade barriers (Fearnside 1995). It will take some time before markets develop for the other non-timber forest products that the Amazon forest has to offer (Barros and Uhl, 1995). Selective logging on a rotational basis is another activity that has a relatively low environmental impact on the forest (Uhl & Bushbacher, 1988). However, selective logging is also the first step in forest conversion, as it provides a subsidy for the creation and maintenance of croplands and pastures. The harvesting of marketable wood was used, and sometimes still is used, as an accessory activity to finance pasture formation. These activities are the main reason for the poor reputation of forestry in the Amazon, despite the fact that selective logging, in the absence of following any silvicultural intervention, preserves the structure of the forest rather than compromising the entire ecosystem by replacing forest with crops and pastures.

In the Brazilian Amazon, forest management is monitored and controlled by the Brazilian Institute for Environment and Natural Resources (IBAMA) through a document called "Forest Management Plan", which must be prepared in advance by the farmers or companies and approved by the Institute. However, because of the structural and manpower constraints on IBAMA and the large areas of forest in the Brazilian Amazon, the execution of forest management does not usually follow any silvicultural system. For example, in practice, the prescribed silvicultural treatments are very often not applied (EMBRAPA, 1996). The first official attempt to establish

forest management in Brazil was in 1965 with the publication of the new Brazilian Forest Code (Law 4771), which banned the use of the native forests unless a management plan was in place. However, Article 15, which was supposed to specify the silvicultural techniques required for sustainable forest management, was only approved in 1992 (Silva, 1992). During the intermediate period forest management was poorly regulated through governmental decrees which were technically brief and contributed little to the implementation of the appropriate use of the natural forests. Several forest management plans have been developed for the Amazon since then, especially in Pará State, east Amazon, and Mato-Grosso State in the southern Amazon (Leite, 1995). In practice, these plans have been rarely implemented and frequently they acted only as a formal authorisation for forest exploitation without the use of any silvicultural technique because exploitation was not controlled or adequately policed.

In Brazil the concept of sustainable yield management was introduced by FAO experts, who performed the first forest inventories in the 1950s. Forest management research started in the late 50s in the Curuá-Una forest on a project where Brazilian researchers from SUDAM worked with FAO researchers (SUDAM, 1978). This project was later extended to the FLONA (National Forest) Tapajós in Pará State (Silva, 1989). Pilot projects on forest management research are currently being carried out in Amazon. As well as the work been conducted by CPATU in FLONA Tapajós, the two other initiatives continuing in Pará State are managed by IMAZON and TFF (Tropical Forest Foundation). In Amazonas State about 80,000 ha of *terra-firme* forest is being managed by an international project (Precious Wood project, personal observation) near Manaus and an additional area of *várzea* forest in the Purús river near the Abufari Reserve is being managed by Carolina S.A., a plywood company. In Acre State the Antimari project (FUNTAC, 1989; Kierman *et al.* 1992), a multipurpose forest management project encompasses an area of 68,000 ha. In Pará State a number of private projects are now receiving direct technical support from EMBRAPA.

The FLONA-Tapajós and Curuá-Una projects resulted in the development of a silvicultural system for the Brazilian Amazon, proposed by Silva and Whitmore (1990). Another silvicultural system for the Brazilian Amazon was developed by INPA (Higuchi, 1991) and called SEL (Selection of Listed Species).

The Management System for a Brazilian "*terra-firme*" forest proposed by Silva and Whitmore (1990) originally had the following sequence of operations:

- ? 100 % pre-logging inventory of trees > 60 cm dbh and preparation of logging maps two years before logging
- ? Selection of trees for felling sufficiently distributed to avoid creating excessively large gaps; marking trees for felling and residual trees for retention; climber cutting if necessary to avoid logging damage; and establishment and measurement of permanent sample plots (PSPs) for growth and yield studies (two one ha plots for each 250-300 ha of productive forest) one year before logging
- ? Logging, observing directional felling wherever possible, at an intensity of 30-40 m³ ha⁻¹ and with a felling diameter limit of 60 cm dbh
- ? Measurement of the established PSP one year after logging to estimate logging damage and stocking of the residual stand
- ? Poison-girdling of non-commercial trees and severely damaged commercial species and reduction of the basal area to about one third of the original stand (including the reduction produced during logging and logging damage) two years after logging
- ? Measurement of the established PSPs three years, five and ten years after logging
- ? Refinement to assist growth of the residual commercial trees 10 years after logging
- ? Measurement of the PSPs and repetition of the silvicultural treatment every 10 years

However, despite the improvement of silvicultural systems, scientific knowledge and available data, forest management techniques are still far from being widely implemented (EMBRAPA, 1996, Poore, 1988) and the lack of policies and legislation to implement forest management effectively is still a widespread problem (Hummel, 1995).

1.5 The need for a small-scale forest management system in Amazon

The extension of forest management to small farmers is a way of preserving the forest structure and biodiversity by avoiding its conversion to the traditional land uses in the Brazilian Amazon (cattle ranching and shifting cultivation). However, a silvicultural system that is appropriate for local conditions (small forest areas, a shortage of investment and labour) is required. This system would have characteristics such as the use of animal traction and low harvesting intensities to

allow a reduction in the costs of traditionally expensive exploitation operations such as log extraction. However, at the same time it must not have too high a demand for labour because the farmers need to continue their other agricultural activities (fishing, hunting, crop planting, etc).

In this system, silvicultural treatments would be linked to some economic activity in the forest, such as using the non-commercial species for firewood or charcoal. In addition, short cycles, using low impact interventions in the forest that combine logging and silvicultural treatments, must be considered as an option. Reducing the time between harvests reduces the risk for long-term investments, and prevents the misuse of the forest or its conversion to agricultural land. The damage and costs associated with mechanised exploitation are constraints that can compromise the sustainability of the system both economically and ecologically. Light mechanisation can be considered, for example, for the transport of the planks from the forest edge to the secondary roads.

The Amazon has the advantages of a large stock of tropical timber and a relatively low human population density. The low human population allows a small farmer to own properties of around 100 ha. These properties have a sufficient forest area for the application of forest management techniques aimed at small-scale sustainable timber production. These activities would reduce short-term deforestation rates in the region and promote better use of the land. In addition, the wood produced by short-rotation plantations in Brazil is appropriate for pulp, firewood or charcoal but does not supply timber for sawnwood or wood-based panels. Therefore the output from plantations does not substitute for logging native forest (Fearnside, 1995).

Potential problems are the lack of appropriate control exerted by IBAMA (which allows illegal timber exploitation and the misuse of the system) and the limited expertise in forest management among farmers and colonists. Research institutions such as EMBRAPA have limited capacity to give technical support to farmers. The support comes from the EMATER, an institute that has a goal to provide technical support to colonists and farmers in traditional land uses (shifting cultivation and cattle ranching) but does not presently include forest management. Additional training must be provided to both parties (EMATER and farmers). This training could be provided not only by EMBRAPA and other research institutes (e.g. FUNTAC in Acre State), but also by NGOs with expertise in forest management, such as IMAZON in Pará State. Also, in contrast with the forests of Asia, the South American forests have a smaller number of marketable species. In general loggers move through the forest exploiting only species such as *Swietenia macrophylla* and *Cedrela* sp., without

attempting to consider harvesting as a step in regenerating the forest for the next cycle. However, as the currently most valuable species are becoming scarce, more species have been added to the list of commercial species (Whitmore, 1992).

Presenting, discussing and studying the forest management system I am proposing for small farmers in Acre state in this thesis will be an important step to the extension of the forest management activity in small farms and as consequence for the conservation of the structure and biodiversity of the Amazon forests.

CHAPTER 2

The Pedro Peixoto Colonisation Project

2.1 Introduction

The history of land occupation in Acre State is closely associated with rubber extraction. In the second half of the 19th century the first settlers of the region came by the Purús River, looking for rubber trees for latex extraction. This period marked the beginning of the rubber cycle, which was the most important economic cycle for the region until the European colonies in Asia started to produce latex in plantations in the 1920s. During this time latex was the most important export product of Brazil, and from 1880 to 1910 it accounted for an average of 25.7 % (measured by value) of Brazilian exports. The rubber cycle changed the socio-economic environment of the Amazon as it made some families rich very rapidly and attracted immigrants from the northeast of Brazil who were escaping the droughts between 1877 and 1880. This “golden era” of rubber had a renaissance during the Second World War, when the Japanese invaded and controlled the rubber tree plantations in what is now Malaysia. However, after the war ended, the rubber-based economy in Brazil collapsed (Cavalcanti, 1994).

At the beginning of the 1970s there was extensive transference of land to people from the south of Brazil. This occurred particularly in uninhabited areas and in former seringais (forest areas with a high abundance of rubber trees). Selling land was the only way found by the “Seringalistas” (the owners of the seringais) to repay their debts to BASA (the Amazonian Bank) following the failure of traditional extractivism. This failure was caused by a decline in the price of rubber on the international market. At the same time, the development policies of the federal government changed to a greater emphasis on cattle breeding. This change resulted in modification of the economy, from one which generated a high demand for labour to one with a low labour demand and hence low capacity to generate employment.

The seringais usually had only one owner, but several families lived on each property and worked as rubber tappers. When the land was sold, most of those people remained in the forest surviving through extractivism and shifting cultivation. Although most of the families had been working their land for all their lives, and in some cases for more than one generation, sometimes they had no documentation to prove their land tenure. The change in ownership resulted in the formation of an autonomous class of rubber tappers working without the control of the Seringalistas.

This created the conditions that stimulated disputes between farmers (the new owners of the land) who were seeking to convert the forest to pastures for cattle ranching and the rubber tappers who demanded that the natural forest was maintained for extractivism (Cavalcanti, 1994).

To control migration and pressure on land, the Federal Government created special areas at the end of the 1970s called "Directed Settlement Projects" (PAD) for the landless people (Cavalcanti, 1994). The settlement projects consist of lots of 50 to 100 ha, distributed along parallel trails perpendicular to a main road (Figure 2.1). These areas were distributed among ex-rubber tappers and migrants from the south of Brazil. The project focus on agricultural (shifting cultivation and extensive cattle ranching) and extractivism (Brazil nuts and rubber) and was developed with Government support (Cavalcanti, 1994).

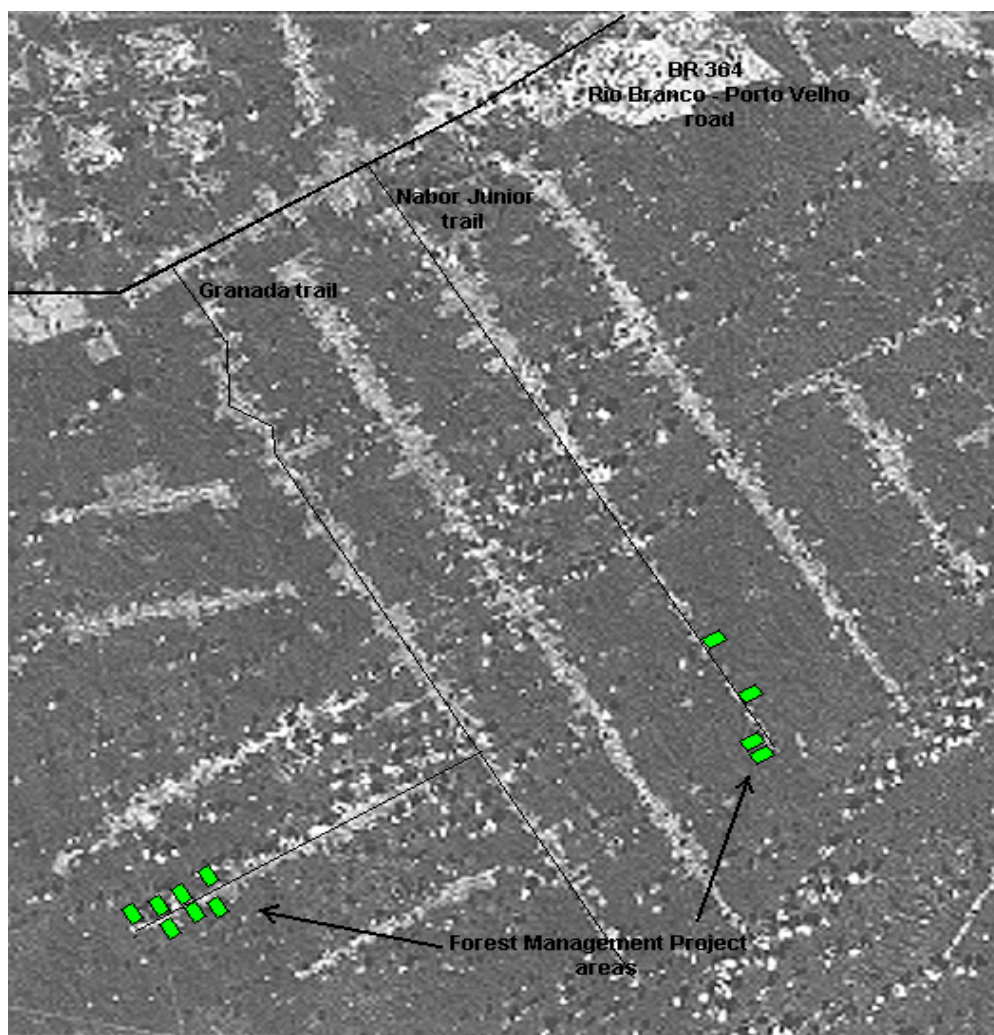


Figure 2.1 Landsat Satellite image of the Pedro Peixoto Colonisation Project. Pale tones are farms cleared from natural forest, which appears darker. Original scale 1 : 100,000.

The PAD Pedro Peixoto was created in 1977 on an area of 408,000 ha (later reduced to 378,395 ha). It included the municipal districts of Rio Branco, Senador Guiomar, and Plácido de Castro and was planned for the settlement of 3000 families. The initial plan for the implementation of the project foresaw three years for the settlement of families and establishment of the infrastructure, five years for the consolidation of the administration and 17 years for the total emancipation of the project from the federal government and its incorporation into the Acre State economy, including the re-payment of investments (Cavalcanti, 1994). Although this plan is not yet completed, settlement projects are being established throughout the Brazilian Amazon, and in Acre State alone there are 19,925 families living in colonisation projects (small farms with around 80 ha each) occupying an area of 1,562,000 ha (INCRA, 1999).

2.2 Geology, soil and topography

The underlying geology of the Pedro Peixoto Colonisation project consists of the Tertiary material of the Solimões formation and Holocene alluvial quaternary material (INCRA, 1978). Materials of the Solimões formation underlie the whole area, and the Holocene alluvial material is associated with the development of the rivers. The alluvial material can be divided into old deposits on high terraces and flood plain deposits (RADAMBRASIL, 1976). The area has a gentle topography, with a maximum altitudinal range of 300 m and is formed almost completely from a dissected surface with a regular topography (RADAMBRASIL, 1976). The predominant soils are dystrophic yellow latosols, with a high clay content (INCRA, 1978; Rodrigues *et al.* 1999).

2.3 Climate

The nearest meteorological station to the site is 70 km away at the CAPAF-ACRE meteorological station at 160 m altitude, 9° 58' 22" S and 67° 48' 40" W. The climate is classified as Aw (Köppen) with an annual precipitation of 1890 mm, and an average temperature of 25° C. The average daily maximum temperatures over the last 15 years was 31° C and the minimum 20° C, with an absolute maximum temperature (in 1995) of 36.8° C and a minimum of 11.8° C.

Rainfall is the most important climatic variable for distinguishing lowland tropical vegetation types as temperature is relatively homogeneous throughout the year. Wet and dry seasons can be recognised. The dry season occurs between the

months of June and September (this period is used to prepare the land by slashing and burning for crops, and for all operations related with forest management and forest exploitation) and the rainy season lasts from October to April. A water deficit the transpiration of the plants exceeds precipitation develops during June and July, and occasionally in August.

Total annual sunshine hours is, on average, 1783.8 hours (with a recorded maximum of 2138 hours in 1995) and the daily average is 4.8 hours. Humidity varies from around 70 % (during July to September) to more than 90 % (92 % on average) from February to April (all data from EMBRAPA, 1996a, b).

2.4 Vegetation

RADAMBRASIL (1976) described two types of forest in the Pedro Peixoto colonisation project area: dense tropical forests (forest with a uniform canopy and emergent trees) and open tropical forest (with a large occurrence of lianas, palm trees and bamboo). Both of these forest formations belong to the sub-region of the Amazonian low plateau. Tropical dense forest rarely occupies large continuous areas. The open forest dominates the dissected relief of the tertiary sediments. On the quaternary sediments dense forests usually appear associated with the open forest, which is usually more abundant. The dense forest is characterised by the presence of emergent species such as *Bertholletia excelsa*, *Hevea braziliensis* and *Cariocar villosum*, a standing timber volume of around 160 m³ ha⁻¹, and a sparse understorey. The dense forest is usually distributed in small patches, and is difficult to delimit on maps using scales such as those used by RADAMBRASIL (1:250,000).

In the tropical open forest the trees are well spaced and of medium to large stature. The forest has three distinct physiognomies: open forest dominated by palm trees (usually high wood volume), open forest dominated by bamboo (medium volume) and open forest dominated by lianas (low wood volume and usually tortuous trees). These formations occupy large areas or form small patches associated with other formations. In general, the open forest dominated by lianas occurs only in small patches. The understorey is dense, especially in the liana-dominated formation and the volume varies from around 60 m³ ha⁻¹ to 130 m³ ha⁻¹. The open bamboo forests are usually in the wetter places, in flooded areas and along streams. They are dominated by *Guadua* sp. in the understorey and especially in the gaps, which inhibits the regeneration of other species. This bamboo species can reach over 17 m in height. The open palm tree forest does not have a very dense understorey with

wood volume around 90 m³ ha⁻¹; the most common palm species are *Euterpe precatoria*, *Astrocaryum murmuru* and *Iriarteia paradoxa*.

LASA (1978) classified the forest of the Pedro Peixoto colonisation project according to the vegetative phenology of the species, humidity and floristic composition as tropical evergreen forest and tropical sub-evergreen forest. The tropical evergreen forest is tall and dense, evergreen during the dry season, richer in species in the canopy and in the understory. The sub-evergreen forest is tall, dense with many lianas and predominantly evergreen, but with some dry season deciduous species in the upper canopy. The most important commercial timber species in the region are: *Swietenia macrophylla*, *Bertholletia excelsa*, *Cedrela odorata* and *Carapa guianensis*.

2.5 Production and land use

Agricultural production is based on shifting cultivation of corn, rice, beans and cassava (subsistence annual crops) and cattle ranching. Some perennial crops, such as coffee and banana, are produced on a small-scale, but production of these kinds of crops is limited by access to markets. Therefore these crops are produced on home gardens and are consumed locally.

The way the farmers use the land has changed a great deal in recent years. In a survey in 1984, about 94 % of interviewed farmers had extractivism as a secondary economic activity, but in 1991 this number was only about 6 %. In the same way, almost all (99 %) had shifting cultivation as the most important activity in 1984 (none answered cattle ranching or extractivism), but only 59 % in 1991 (39 % had cattle ranching as most important activity (Cavalcanti, 1994).

The reason for this change was that rubber prices fell drastically between 1984 and 1991 and cattle ranching became more profitable than agriculture. The importance of cattle is that they have the capacity to act as a savings account for the farmers. Cattle represents an insurance, which they can be sold in an emergency. The same argument does not hold for other agricultural products, as the capacity for small farmers to store them is limited by the climate and pests. However, cattle diseases, problems of weed control in the pastures, and low soil fertility, have reduced the yields of cattle and most farmers are in debt to BASA (Amazonian Bank).

An attempt has been made to produce milk, but the pastures are too poor to supply the nutritional demand of the animals and the farmers do not have enough resources to invest in feed or the other necessary inputs. Agroforestry systems were

attempted in PAD Peixoto in a co-operative called the RECA project (Reflorestamento Econômico Consorciado e Adensado). This co-operative is a farmers' organisation financed by BILANCE (Netherlands Catholic Development and Co-operation Organisation) composed of 274 families and a reforested area of around 650 ha (Muniz, 1998). The main objective is to produce Brazil nuts (*Bertholletia excelsa*), Cupuaçu (*Theobroma grandiflora*) and Pupunha (*Bactris gasipaes*, a palm tree used to produce fruit and palmetto) in one system. The success of this project has been attributed to good organisation, initial investments and the possibility of primary industrialisation (fruits and palmetto) and storage (e.g. the frozen pulp of *Theobroma grandiflora*) of the products.

In general, agroforestry has been difficult to practice because of the high labour demand for establishment and maintenance of the crops. In addition, in some cases (e.g. *Theobroma grandiflora*) the product must be transported immediately after harvesting because it is not possible to process or freeze the products in the production area. Another limitation on the implementation of agroforestry systems is their low productivity when compared with mono-cultures. When crops start to become fashionable (e.g. *Theobroma*, *Bactris* and *Euterpe* spp) they also start to be produced in the south of Brazil in very high productivity systems usually very near to both agro-industries and markets. Thus the success of such projects depends on the capacity of local markets to absorb large-scale production, since competition with the markets in the south is unlikely to succeed.

Timber exploitation in settlement projects is performed as an accessory activity, usually before slashing and burning, and often in an illegal way. Logging is carried out under informal agreements between farm owners and the lumber merchants, where by the latter identifies marketable tree species and the farmer receives a payment that varies according to the size and species of the tree and the distance or accessibility of the farm. Although most of the timber production in Acre State comes from this kind of exploitation, the economic return for the colonists is invariably low. The fact is that selling the timber is a matter of opportunity (usually the lumber merchants make only one prior visit to close the deal with the farmers) and its illegality prevents formal contracts and price control.

2.6 Discussion

The colonisation of Acre State was led by two main waves of migration. The first was people from the northeast of Brazil seeking to extract rubber, at the end of the 19th century and during the Second World War and the second in the late 1960s when people from the south of Brazil sought the opportunity of free land for agriculture and cattle ranching. The conflict between these activities, and the failure of traditional extractivism, promoted land disputes and drastic changes in the social structure of the region. These changes were reflected in the land use, promoting the gradual decline of extractivism in the settlement projects and an increase in cattle ranching in the last 20 years.

Extractivism has its supporters (e.g. Fearnside, 1989) and is thought to be ecologically sound. However, is rarely successful because most of the potential products have no market and no fixed prices traditional products are widely dispersed in the forest so collecting them requires a lot of labour for a low yield and the quality of the product is also very low, limiting the possibility of further industrial use (e.g. rubber). Knowledge about how to manage of these potential products is also quite limited and the amount of production is unpredictable (e.g. the extraction of *Copaifera* spp oil does not usually kill the tree, but the number of years needed for the tree recover between harvests is unknown).

Cattle ranching in this region is not sustainable and the families living on colonisation projects are surviving by shifting cultivation. Sometimes pastures are only created as a means to increase the value of the land or in order to rent it to other farmers. These factors provide an incentive for forest clearance, as shown by the actual rates of deforestation of the settlement projects in Acre and Rondônia.

There is an obvious need for new land use technologies to be applied in these areas, since traditional shifting cultivation and cattle ranching are difficult to practice and have a questionable economic and ecological sustainability. The general view of the new colonists in Acre and the rest of the Amazon is that forest is an obstacle which needs to be removed for the implementation of the real land use. This point of view has been held since the 1960s and is based on the belief that the forest has no commercial value.

The Amazon still has characteristics that would facilitate the implementation of more suitable forms of land use and natural resource management. Although some demographic pressure already exists in the region, the properties are still big enough to provide for the subsistence of a family. This situation is quite different from

other tropical regions (Africa and Asia) where demographic pressure is much greater. In this respect Acre State has the advantage that it was the last State to be colonised, and the effect of the migration was diluted by settlements in the Mato-Grosso and Rondônia States.

The practice of agriculture in the tropics is still controversial, but there are new technologies and land use systems available as alternatives to the traditional practices (e.g. agroforestry systems, rotation crops, etc). These systems and technologies were developed for application in areas where agricultural systems were already established on degraded land. Therefore, these techniques might improve the productivity and the sustainability of the traditional practices, but they cannot halt the continuing conversion of the natural forests.

CHAPTER 3

The Proposed Silvicultural System

3.1 Introduction

The conventional forest management system proposed for the Brazilian Amazon is not widely applied there because of the following constraints (Hummel, 1996).

- (1) There is a lack of appropriately trained foresters who have the necessary practical skills.
- (2) Forest management requires a legal document approved by the federal authority (IBAMA). To Acquire this document can be a complex and lengthy process.
- (3) Government policy for the Amazon originally focused on agricultural systems (especially cattle ranching) and effectively encouraged forest clearance.
- (4) The existing forest management system requires substantial investment, which is only worthwhile for large areas of forest. By contrast most properties posses only small areas of forest (e.g. in the settlement projects the area of the forest reserves varies from 30 to 50 ha).
- (5) The long length of the felling cycles (20 to 30 years) discourage owners from implementing forest management and they are then more likely to convert their forest area to non-forest use.
- (6) Forest conversion yields large volumes of timber, whilst managed forest produces less timber, with higher costs. Timber from both sources compete in the same market, with the result that timber prices are low.

As a result, formal forest management is only possible on large properties where investment potential is high, and even then is only occasionally viable when applied strictly (EMBRAPA, 1996).

This kind of forest management has been criticised by environmentalists because of the impacts it has on forest structure and biodiversity (e.g. the greater risk of species extinction and genetic erosion) resulting from a relative lack of knowledge about tropical ecosystems and the absence of appropriate management techniques for application to these forests. In the Brazilian Amazon, some studies have been carried out by governmental (e.g. EMBRAPA, INPA, Goeld Museum, IBAMA, and FUNTAC) and non-governmental (e.g. TFF and IMAZON) institutes, to fill these gaps in knowledge.

The viability of forestry in the Amazon is not determined solely by technical factors. However, a change in the dominant paradigm governing forest management

will be required if the small producers, such as colonists and rubber tappers, are to become involved. This change is needed to allow the implementation of techniques and levels of intervention appropriate to the scale of the proposed production and the availability of investment capital.

According to the Brazilian forest code, in the Brazilian Amazon 50 % of the area of a property must be preserved as a legal forest reserve, i.e. it cannot be converted to agricultural land or pastures. The only legal commercial uses of this land are extractivism and sustainable forest management. However, despite the governments efforts to control land use in the Amazon, some areas have already been converted to traditional shifting cultivation and pastures. In 1994, the mean area deforested on farms sampled in PC Peixoto and PC Theobroma (in Rondônia State) was 40 % of the total area which represented a mean deforestation rate of natural forest of 2.4 ha yr⁻¹ (Witcover *et al.* 1994). My research in Acre State, Brazil, focuses on small-scale timber production by farmers in these private forest reserves.

The forest management model I propose here was designed for small farmers and aims to generate a new source of family income by diversification of household economic activity, thereby alleviating poverty and increasing quality of life. An additional aim is the maintenance of the structure and biodiversity of the legal forest reserves, conferring more value on forest than alternative forest uses (Dickinson, 1996), while increasing their importance for conservation. Small-scale harvesting will change the emphasis of production on Brazilian Amazon properties (by incorporating a much broader range of legal forest reserves into the production system) and create new models of rural development for the region. This kind of strategy is also a popular means of protecting National Parks in developing countries. Sustainable management is an appealing alternative to deforestation (Howard, 1993).

The basic aim of the project is to provide an alternative to the standard model of forest management by creating a new one appropriate to small farmers and rubber tappers. The management system proposed here follows from the same theory as conventional management. Each property's legal reserve area (50 % of the total area) was considered as the production unit for the implementation of forest management. The number of harvesting compartments was determined on the basis of a minimum rotation cycle of ten years.

3.2 Description of the proposed system

There is a long history of forest exploitation in the Amazon based on traditional 'low technology' methods. Traditional forest exploitation methods have been applied since the beginning of forest exploitation in the Amazon. The main characteristic of these methods is the low level of technology applied which results in low production and a low financial return, but with low environmental impact (Oliveira, 1989, 1992). This kind of forest exploitation has been applied in the Amazon for over 100 years. However, it has not yet been formalised as a silvicultural system and has not been documented sufficiently to allow its application in a systematic way. The model I am proposing is a formalisation of these traditional methods.

In the flooded areas (*várzeas*) of the Amazon Basin "riverine" populations of small farmers have been harvesting timber for generations. In Amazonas State the production of timber by riverine populations of small farmers represents a significant proportion of total wood production (Santos, 1986; Bruce, 1989; Oliveira, 1992). Because of the low level of the harvesting (the harvesting intensity is low because only a few species are utilised and because of the high diameter felling limit) the practice as a whole is environmentally sound (Oliveira, 1992). This practice also is sometimes common in the *terra-firme* (high land) forest but varies in intensity according to access and market proximity. In both i.e. *várzeas* and *terra-firme* cases, the sustainability of the system is determined by the farmers' capacity to extract wood and the opportunity that they have to sell it, due the absence of rules and control.

The extraction of timber by small producers is a seasonal activity. This permits producers to continue other essential activities (hunting, fishing, non-timber product extractivism and subsistence agriculture) which makes an integrated management system feasible and promotes sustainable production without damaging the forest ecosystem (Oliveira 1989, 1992).

The existence of these traditional forest exploitation methods is proof of the ability of local people in the Amazon to implement forest management activities, and the fact that they have been implementing these methods for generations is a strong indication that forest management can be done in a sustainable way.

3.2.1 Ecological basis

The direct result of felling a canopy tree is a gap in the forest and an area of affected vegetation. In many aspects, forest management for timber production via selective logging, creates disturbances akin to natural tree falls and canopy openings that stimulate the growth of advanced regeneration (Uhl *et al.* 1990).

The conventional mechanised forest exploitation methods create a large number of gaps, all at the same time (Johns *et al.* 1996). Large gaps may take a longer period to recover than small gaps because succession starts at the pioneer phase. Pioneer plants establish and grow rapidly in response to canopy opening, but the desirable commercial species are set back in their growth because of competition with the pioneers, which imposes a longer cutting cycle and reduces yield. Smaller gaps may be closed rapidly by the crowns of trees surviving or recovering from the felling impact (Hendrison, 1990).

In addition, because mechanised logging operations are not usually planned, forest damage is greater, with the opening of unnecessary skid trails and excessive skidder manoeuvring (Uhl and Vieira, 1988; Oliveira and Braz, 1995; Johns *et al.* 1996). On the other hand, if the impacts of logging are distributed over time, a lower number of gaps will be created at the same time. Therefore it is likely that the contribution of pioneer species to the natural regeneration will be lower, and the contribution of the desirable species will be greater, in the non-mechanised system.

I suggest that the natural regeneration of desirable species is promoted by distributing the impacts over a longer time period as well as more uniform in space (see 3.2.2 below). Reduced competition from pioneer species might lead to a greater net yield of desirable species and lower amounts of damage to the forest ecosystem.

The proposal is based on the hypothesis that low-impact disturbance at short intervals, combined with silvicultural treatments, will create a gap mosaic of different ages and permit the maintenance of a forest with a similar structure and biodiversity to that of the original natural forest. The canopy opening associated with felling will allow young trees (less than 50 cm dbh) to grow faster, some of them reaching commercial size during the period. Standing trees of commercial size will be harvested in the next cycle or be preserved.

The management of the commercial species will be determined by their ecological and silvicultural aspects (such as growth rates, maximum size, abundance and seed production and dispersal). As a result the production system will have a tendency to focus on the dominant, fast growing commercial species. Harvesting at

ten year intervals will allow seed production and regeneration because most of the reproductively mature trees will be retained within the residual stand, in contrast to long-rotation production systems in which entire populations of adult trees can be removed at harvesting. Retaining seed trees between harvesting events helps to maintain the genetic diversity of populations over time, particularly for species with intermittent reproduction and buffers the population against the possibility of stochastic disturbance events eliminating smaller size classes (Primack, 1995).

The short rotation cycle avoids the larger impact caused by heavier interventions. Instead of harvesting all trees of commercial size at one time, they will be felled over three felling cycles. It is important to recognise that low impact harvesting will only work as a silvicultural system (and improve forest characteristics such as growth rate and species composition) if implemented in short cutting cycles. The extraction of small quantities of timber over long cycles would reduce yield to unacceptable levels and would not create suitable conditions for regeneration of some of the most desirable species such as *Cedrela odorata*.

3.2.2 Short cycles and harvesting intensities

There are many factors affecting decisions about cutting cycle length. The final choice is a balance of these factors as weighted by management objectives. The most important factors are species composition, financial needs and site.

In general, shorter cutting cycles allow better biological control than longer cycles because diseased or infested trees can be cut more often. It is also easier to salvage dead trees, if the smaller trees are marketable. On the other hand there is the need for a minimum harvesting volume intensity to make the activity economically viable. When working with small properties the cutting cycle may be shortened so that it equals the number of annual felling compartments in order to create an annual income that allows the owner to pay taxes and forest management costs (Leuschner, 1992).

Polycyclic silvicultural systems have been criticised for the damage they cause to the soil and the residual trees, because of the need to return to the forest at short intervals (Dawkins and Philip, 1998), but this damage can be minimised by re-utilising old logging roads and skid trails, and through better planned and controlled logging operations (Silva *et al.* 1989; Braz and Oliveira, 1995).

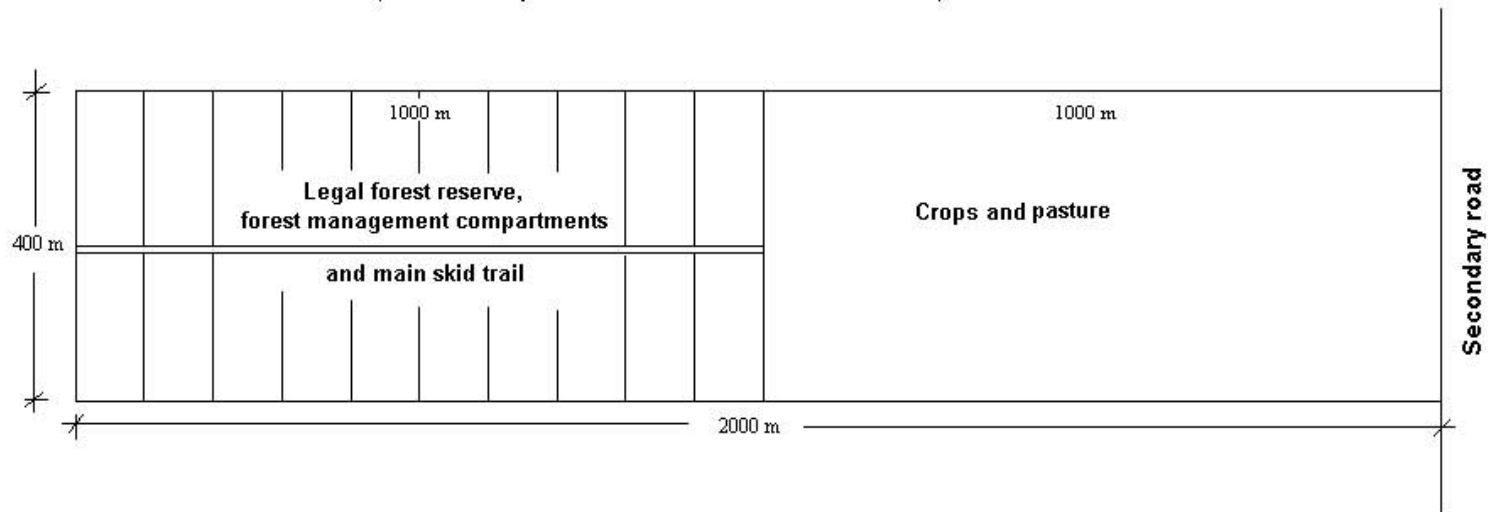
In the case of the Pedro Peixoto colonisation project, the decision on cutting cycle length, must consider its particular characteristics such as the small forest areas (no greater than 40 ha), the short period of time to execute all operations, the

limited labour availability and the use of animal traction for extraction. The small size of the felling area prevents the creation of many compartments (Figure 3.1) and eliminates the possibility of using long cycles (at least when annual incomes are desired). The other characteristics also predispose the system to the use of short cutting cycles. Animal traction drastically reduces harvesting damage relative to the opening of skid trails (Dykstra and Heinrich, 1992) and the limitation of time and labour reduces production.

The number of annual harvesting coupes was determined on the basis of a minimum felling cycle of ten years and harvesting intensity of 5-10 m³ of timber per hectare. A short cutting cycle has the advantage of increasing the frequency of silvicultural interventions in the forest, which diminishes the time needed for the forest to recover and decreases the risk of replacement of the forest by other agricultural activities. However, short cycles would limit production per hectare since it cannot be combined with heavy harvesting because the forest would not recover within the length of the cycle. Under short-cycle systems, harvesting operations must be well planned to minimise damage to the residual trees. Thus the use of mechanised logging in short-cycles systems is probably limited for both economic and technical reasons. However, light mechanisation (e.g. the use of small tractors for the removal of the planks to the main skid trail Figure 3.1) can be considered for the future.

I have based the harvesting recommendations on a conservative yield estimate of 1 m³ ha⁻¹ yr⁻¹ (Silva *et al.* 1996), although I envisage that predicted yields may increase in the future following the growth studies on permanent plots. In terms of usable timber volume the net increment of a managed forest can be increased silviculturally up to 5 m³ ha⁻¹ yr⁻¹ (Miller, 1981; Silva *et al.* 1996). For the moment, the low yield predictions are based, in part, on the low level of silvicultural intervention that will be used. An additional harvesting rule will be applied, whereby a maximum of one third of the total commercial volume (stems of commercial species > 50 cm dbh) is taken. A similar harvesting rate was used in Osa Peninsula, Costa Rica, where all trees with dbh above 60 cm were felled in three cycles of ten years (Howard, 1993). This rule guarantees that there will be at least three rotations of the management system. However this is a conservative estimate of lifetime of the management system given the tendency for currently lesser-known and lower-value species to become incorporated into the market in the future.

Figure 3.1: Layout of a typical farm on the Pedro Peixoto colonisation project, Acre State, Brazil, showing the distribution of agricultural land (crops and pastures) and the legal forest reserve (with the compartments and main skid trail indicated).



The volume of commercial timber in the study site is currently around 20-30 m³ ha⁻¹. Although the conventional forest management system in the Amazon employs a harvesting rate around 30 to 60 m³ ha⁻¹ on a cutting cycle of 30 years, it does not usually exceed 30 m³ ha⁻¹ (Johns *et al.* 1996). Thus, the outcome in terms of yield, will be equivalent to the standard rotation of 25-30 years established by IBAMA (Brazilian Institute for the Environment and Natural Resources) for mechanised management. The annual felling rate should not fall below 5 m³ ha⁻¹ cycle⁻¹, otherwise harvesting is likely to be uneconomic returning less than the minimum salary practised in Brazil around US\$ 100.00.

3.2.3 Techniques and basic concepts

The formalised systematic application of the forest management practices used by small farmers in the Brazilian Amazon requires the implementation of techniques for the evaluation of the production capacity of the forest, planning of exploitation activities, and monitoring (Braz and Oliveira, 1996b). Formalisation of these procedures helps to reduce *ad hoc* changes in the method when external conditions change, such as falls in the price of extractivist products, economic recession or third-party greed. In the absence of formal procedures, short-term changes in economic circumstances undermine the long-term perspective required for sustainable forest production by small producers and may lead to fluctuations in harvesting rates and damaging impacts on the forest.

The management system I am proposing has the same theoretical basis as conventional management in the Brazilian Amazon. It is based on a forest inventory which serves both harvesting and silvicultural treatments (Hendrison, 1990).

Forest inventory

The main objective of the forest inventory is to characterise the structure and species composition of the forest and identify the potential for wood production. During 2000 EMBRAPA has planned to perform an inventory of the whole forest area of Pedro Peixoto colonisation project (150,000 ha). This inventory will be used for future forest management planning in this site.

Prospective forest inventory

A prospective forest inventory is performed in the compartments one year before harvesting. All trees with dbh > 50 cm are measured, marked and plotted on a map. The purpose of this inventory is to allow planing of exploitation activities, defining the trees to be treated, logged or preserved and other features when necessary (e.g. streams and topographic variation). The resulting map also allows the location of the skid trails and areas to total preservation to be planned.

Tree felling and converting logs to planks

Trees are directionally felled to facilitate their transport and minimise damage to the forest. The logs are converted by chainsaw or one-man sawmills into planks, boards or other products according to the characteristics of the timber and market demand. After felling the tree, the conversion of logs to planks is performed in the forest. This phase is the most expensive and labour-intensive component of the entire system and executed according the following sequence of events (Figure 3.2):

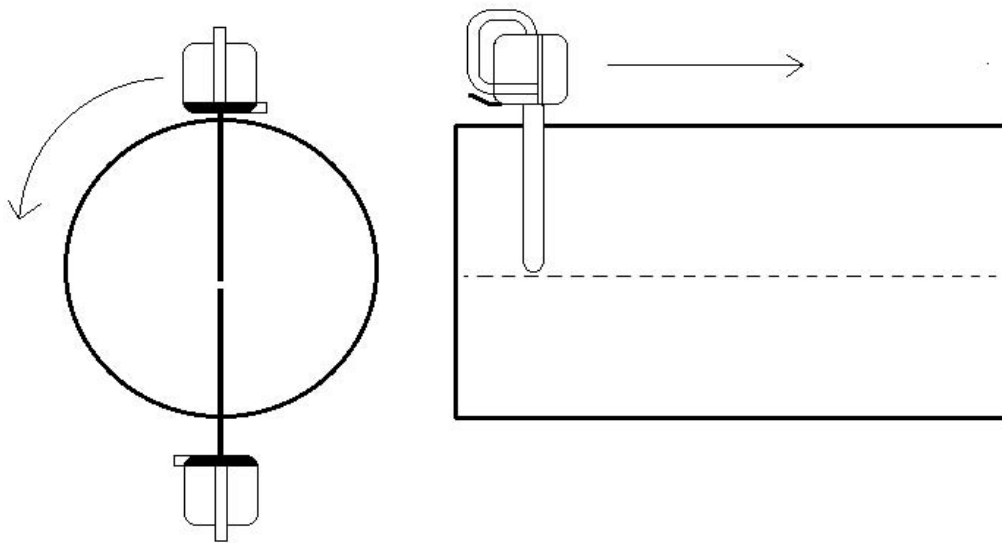
(1) Division of the trunk into logs usually 2.15 m in length by transverse cuts using chainsaw

(2) Movement of the log away from the trunk. The log is rolled aside to allow access to its extremities for the chainsaw operator.

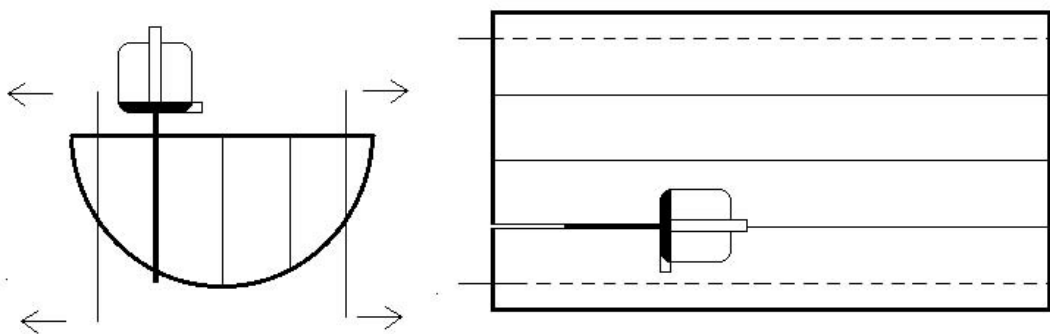
(3) Division of the log. The log is divided into two sections, creating two half-logs of approximately the same size. When the diameter of the log is greater than the length of the chainsaw blade this operation must be performed using two cuts, which involves another rolling of the log.

(4) Cutting of the planks. On each half-log lines are marked to be followed during cutting of the planks. These lines are marked using a string impregnated with ink (used engine oil) from one end of the log to the other. The cutting is carried out perpendicular to the diameter plane.

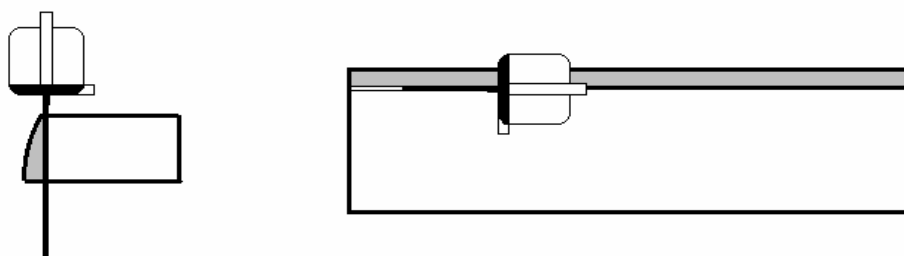
(5) Bark removing – The bark of the tree is removed from the plank



Division of the log: one or two (according to dbh) longitudinal cuts dividing the log into two half-logs



Cutting of the borders and planks. Two cuts are made in the borders to remove the bark and irregularities in the log and parallel cuts are made to separate the planks



A final cut is made to remove remaining bark and to correct irregularities in the edge plank's borders



Plank ready to be skidded

Figure 3.2 Sequence of activities during the conversion of logs into planks in the Pedro Peixoto colonisation project.

Plank skidding

In the floodplain areas (*várzea* forest), the extraction and movement of logs is facilitated by river-transport, i.e. without the use of heavy machinery on land. Timber harvesting trails are opened to locate the commercial trees and are positioned according to the opportunities presented for log extraction by river during the rainy season, when transport is most easy. Stems of marketable tree species with commercial diameters (> 50 cm dbh) which are found along the timber harvesting trails and in the neighbouring areas are marked in the dry season (Oliveira 1989, 1992).

In inland (*terra firme*) forests, such as at Pedro Peixoto, these methods are varied somewhat. There is a need to saw the logs into planks or boards to allow animal traction to be used for skidding them from the forest to the secondary roads. Haulage by animals has the advantage of generating less soil compaction and modification, and less damage to residual trees, than mechanical skidding equipment (Dykstra and Heinrich 1992; Ocaña-Vidal, 1992; FAO, 1995). Also the fact that planks will be extracted from the forest rather than logs contributes to a reduction in the soil compaction that usually occurs when logs are skidded using heavy machinery (e.g. Nussbaum *et al.* 1995).

For this system, a main skid trail crossing the middle of the compartment is created, perpendicular to the direction of the nearest secondary road (see Figure 3.1). This trail is permanent and opened according to the need for implementation of management from the first to the tenth compartment in a rate of 100 m (the width of the compartment) per year (Figure 3.1). The main skidding trail (1 to 1.5 m in width) is wide enough to allow the passage of small wagons pulled by animals. The skidding of the planks is performed in two stages, the first from the felled tree to the main skid trail with the use of a “zorra” (an implement used regionally to skid planks) and the second stage, from the main skid trail to the secondary road, where the primary transport of the planks is by wagon.

In the first year of the project an alternative system was used involving a combination of mechanised and animal skidding, in which animals (oxen) were used to perform the first stage, and a small tractor pulling a wagon with a capacity of about 3 m³ of timber for the second stage. The loading and unloading of the zorra and the wagon were carried out manually.

Silvicultural treatments

At the moment, the only silvicultural treatment incorporated into the management system is climber cutting. One year before felling, climbers are cut in the compartments to be harvested, at the same time as the prospective inventory is being carried out. Climber cutting has long been considered a useful silvicultural tool and, by cutting climbers sufficiently ahead of time, damage caused by felling in climber infested areas may be significantly reduced (Fox, 1968; Liew, 1973). Climbers often bind one tree to another and when one tree is felled it brings down others. Climber cutting is carried out one year before felling in the hope that considerable reduction in felling damage can be achieved. Therefore climber-cutting can be considered as an effective silvicultural operation for not only achieving the desired objective of reducing damage during felling, but also reducing damage to felled timber (Chai and Udarbe, 1977).

Because of the low harvesting impact (no greater than two trees per hectare), treatments such as protective tree marking (Chai and Udarbe, 1977) are not necessary and the residual trees will be protected using the prospective inventory information (i.e. map of trees) and the practice of directional felling. The control of the extraction operation is simplified by the use of animal traction. The animals are easy to manoeuvre to avoid natural obstacles, such as big trees. The skid trails are planned previously on the basis of the prospective forest inventory.

Girdling of trees is not proposed because some of the trees poison-girdled in the present might become marketable in the future. However, poison girdling could be applied in the future to remove damaged trees and to promote canopy opening in order to maintain or increase forest productivity.

Artificial regeneration

One of the challenges of forest management is the promotion of the regeneration of species with high economic value, in order to maintain their populations, and preserve their genetic variability. The regeneration of some desirable species is difficult to achieve without intervention (Evans, 1986). This difficulty is characteristic of several species that are under strong exploitation pressure in tropical forests (e.g. *Swietenia* in S. America, *Khaya* and some *Entandrophragma* spp in West Africa). The natural regeneration of some desirable species under exploitation pressure in the Amazon is often very poor or non-existent (Evans, 1986).

Disturbance to the forest during forest exploitation creates modifications to these ecosystems, that favour the regeneration of pioneer species and species with secondary characteristics (secondary recent and secondary late, Budowski, 1955). Most of the species under exploitation pressure in Amazon possess these characteristics. However, during vegetation succession, in the first years of gap colonisation, more fast growing species such as *Trema micrantha*, and *Cecropia* spp, tend to become dominant (Lamprecht, 1993). A series of other factors (phenology, seed viability, predation, dispersion and availability of seeds) also influence the regeneration success of these desirable species. These species may, on occasion, regenerate successfully without intervention, but this appears to be unusual (Evans, 1986).

Where appropriate selective cleaning and weeding will be implemented after logging in Pedro Peixoto colonisation project to maximise the development of natural regeneration. Artificial regeneration should also be carried out by transplanting seedlings of desirable or valuable species with natural regeneration problems (Oliveira, 1994). Long-term changes in forest floristic composition, tree growth and natural regeneration will be monitored by EMBRAPA – CPAF/ACRE scientists using permanent sample plots in the managed forest.

The implementation of artificial regeneration is strongly limited by economic factors and the heavy demand for labour (Thang, 1980). Therefore, its adoption can only be enforced by the force of law (presupposing an effective policing) in very favourable economic conditions (e.g. financing, subsidies, fiscal incentives or elevated return rates) or only at small or medium management scales (Ramos and del Amo, 1992). The most common technique is enrichment planting which consists of the clearing of bands of different widths through the forest and then planting lines or groups of trees within these bands (Ramos and del Amo, 1992). In practice, the application of enrichment planting techniques has not been effective in Amazon since growth and survival has been low in these bands (e.g. Verissimo *et al.* 1995).

The artificial regeneration technique proposed for Pedro Peixoto colonisation project site is to establish species such as *Swietenia macrophylla*, *Torresia acreana*, *Ceiba pentandra*, *Bertholletia excelsa*, and *Cedrela odorata* in gaps and skidding trails immediately after forest exploitation, using the planting techniques proposed by Oliveira (1994). The proposal is to intervene in the process of natural regeneration after exploitation, with the purpose of improving regeneration by planting, in gaps and skid trails, seedlings of the desirable species under high exploitation pressure. The planting will be carried out in gaps created by tree felling and skid trails using a spacing of around 5 m x 5 m. Before planting, manual cleaning of the areas must be

executed. The farmers will plant seedlings of about 30 cm in height at the end of the dry season between the months of October and December. No cleanings or any other type of silvicultural treatment needs to be carried out after planting.

Monitoring forest dynamics

The monitoring of the forest responses to the forest management is carried out through the study of the forest dynamics (growth, ingrowth, recruitment, damage and mortality) in permanent sample plots (PSP). The PSPs are 1 ha each, sub-divided into 100 sub-plots each of 100 m². All trees over 20 cm dbh, are tagged, identified and measured. In 20 randomly selected sub-plots in each PSP, all trees > 5 cm dbh, are also tagged, identified and measured. The measurements are started one year before harvesting and will be performed at three years intervals.

3.2.4 The sequence of operations defining the forest management system

- (1) A forest inventory, one to two years before the first harvesting is conducted. This inventory determines the potential of the forest for forest management and harvesting.
- (2) Compartments and permanent sample plots are established.
- (3) A 100 % prospective inventory of trees > 50 cm dbh and tree mapping are conducted. The exploitation plan is prepared on which, trees for felling are marked and permanent sample plots for growth and yield studies are established and measured one year before logging.
- (4) Species are selected and the felling rate determined on the basis of species diameter distribution, growth rate and seed dispersal.
- (5) Logging is then conducted, observing directional felling wherever possible. Logging is carried out at an intensity of 5-10 m³ ha⁻¹ and on the basis of a felling limit of 50 cm dbh.
- (6) Desirable species are then planted in the felling gaps and on skid trails immediately after logging.
- (7) One year after logging the permanent sample plots are measured to estimate logging damage and stocking of the residual stand.
- (8) Three and five years after logging the permanent sample plots are again measured
- (9) Growth of the residual commercial trees and artificial regeneration of desirable species are assisted by refinement if necessary.

(10) Ten years after logging the permanent sample plots are measured.

(11) The cutting cycle, cutting rate and silvicultural treatments are redefined according to data provided by the permanent sample plots before the beginning of the next cycle (after ten years).

3.3 Methods

3.3.1 Forest inventory

A forest inventory was performed in the managed areas of the Pedro Peixoto colonisation project. The total area was 440 ha divided into 11 legal forest reserves of around 40 ha each. The inventory was performed using a systematic sampling design (Higuchi, 1985), with plots of 10 x 100m distributed along ten lines. There were 20 plots for each area, totalling 214 samples and a total sampled area of 21.4 ha, 4.87 % of the total area. Later these lines were used as access routes for the implementation of all activities of the management plan.

All plants greater than 10 cm dbh were measured and identified. The natural regeneration (plants taller than 1.5 m and less than 10 cm dbh) were sampled in 10 x 10 m sub-plots located in the first 10 m of each plots. The species were identified by FUNTAC (Acre State Technological Foundation) mateiros (people usually from the forest, with great experience in field identification of species and herbarium work) using vernacular names.

3.3.2 Prospective forest inventory

All trees with dbh > 50 cm were measured, identified and plotted on a map. Usually only commercial species are measured in such inventories, but considering the small size of the plots, and the possibility that silvicultural treatments might be used in the future, to have all trees mapped was considered helpful in deciding which trees would be silviculturally treated. In addition the list of commercial species is changing rapidly and recording all trees on prospective inventories helps to locate the commercial stems at future harvests.

3.3.3 Forest exploitation

Tree-felling and conversion of logs to planks

The study was performed in two managed areas of Pedro Peixoto colonisation project, one off the Nabor Junior secondary road and other off the Granada secondary road. The data were collected at four logging events, using trees from 45 to 97 cm dbh of three species (*Guarea pterorachis*, *Hymenolobium excelsum* and *Dipteryx odorata*). A total of 28 logs each of 2.2 m in length were processed, by a team of three men. The study was considered three different phases (felling the tree, cutting the log and the conversion of the logs to planks). The time required for each phase was measured and the efficiency of the conversion measured as the rate of the final volume in planks by the initial volume of the logs.

Planks skidding

This study was carried out in two managed areas in Pedro Peixoto colonisation project both off the Granada secondary road. The data were collected in five skidding events and 40 skidding cycles, where planks of four species were being skidded (*Couratari macrosperma*, *Dipteryx odorata*, *Protium apiculatum* and *Peltogyne* sp.). The skidding distances varied from 200 to 1400 m and the planks were loaded onto a zorra (a implement used in the region to skid planks). In this study I considered a skidding cycle as: the travel unloaded from the edge of the secondary road to the felling gap in the forest, loading of the planks, the time to travel back to the secondary road and the unloading of the planks. The time need to rest the animals was considered as “wasted” time. The skidding was performed with two teams of two men working with an ox on each team. The oxen used for skidding the planks were two individuals of the Melore breed of age five and eight years and a weight around 500 kg.

Forest management general costs and economic analysis

The costs were estimated on the basis of the minimum salary offered in Brazil in 1997 of US\$ 100.00 per month, a working day of six hours, a five day working week and a team of three people for all activities except the skidding of the planks, where the team consisted of only two men. The depreciation of the chainsaw was calculated

as 25 % yr⁻¹, and the useful life of the oxen 10 years. The harvesting and conversion of the logs to planks was performed with a Sthill 051 chainsaw.

3.4 Results

3.4.1 Forest inventory

Structure and floristic composition

The vegetation is predominantly evergreen tropical forest with some deciduous species (e.g. *Tabebuia serratifolia*, *Ceiba pentandra* and *Cedrela odorata*). The forest varied from open (low stature forest with a dense understorey and high occurrence of lianas and palm trees) to dense (taller forest with greater standing timber volume and no dense understorey), according to the drainage (streams formation and design) and topographic status of the site.

In the samples of the systematic forest inventory, 307 species were identified, drawn from 185 genera and 54 families (Appendix 1). The most common family was the Caesalpinaceae, with 18 genera and 23 species sampled. The distribution of the species across the area was very irregular, with some species common (e.g. *Protium apiculatum*) whilst other rare species were sampled only once in all 214 samples (e.g. *Macrobium acaceifolium*). The species area curve demonstrates that the sampling intensity was sufficient to capture most species, but that some very rare species were probably not sampled (Figure 3.3).

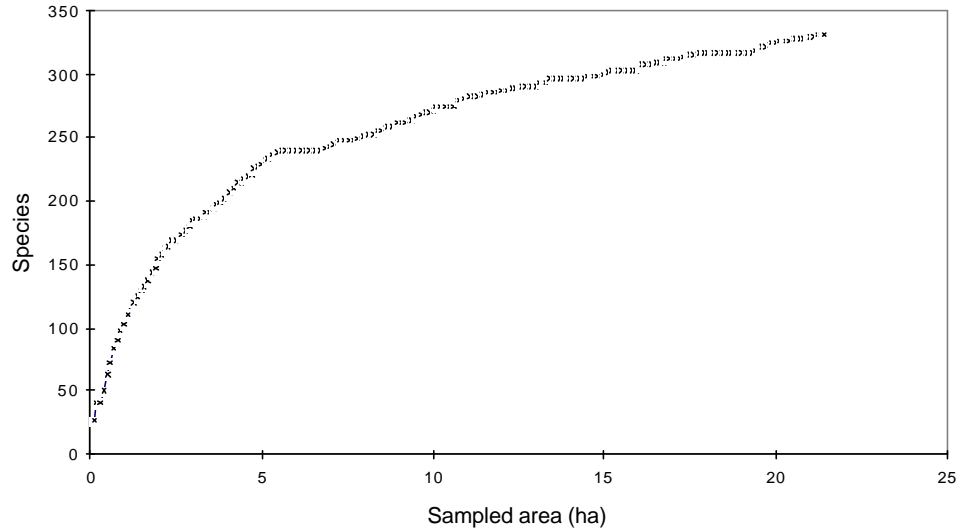


Figure 3.3: Species-area curve for trees > 10 cm dbh growing on 1000 squared meters plots of forest on the Pedro Peixoto colonisation project and sampled during a systematic survey of 214 plots for a forest inventory.

The forest had an average of 375 trees ha⁻¹ (trees > 10 cm dbh), an average basal area of 22 m² ha⁻¹ and total volume of 180 m³ ha⁻¹. The volume of trees below 50 cm dbh (i.e. commercial size) was 107.4 m³ ha⁻¹ and the volume of trees above 50 cm dbh was 73.1 m³ ha⁻¹ (Table 3.1).

Table 3.1: Results of the forest inventory at Pedro Peixoto colonisation project showing mean values of tree density (stems > 10 cm dbh) basal area, volume (in stems 10-50 cm dbh, > 50 cm dbh and total), the standard deviation and 95 % confidence interval for estimates of total volume, and the area of each plot, total sampled area and the area covered by the inventory.

Forest inventory area	440.0 ha
Area of each plot	1000.0 m ²
Total volume (dbh > 10 cm) average	180.4 m ³ ha ⁻¹
Sampled area	21.4 ha
Volume dbh > 50 cm	73.1 m ³ ha ⁻¹
Volume 10 cm > dbh > 50 cm	107.4 m ³ ha ⁻¹
Basal area	22.0 m ² ha ⁻¹
Volume Confidence Interval (p > 0,05)	
Minimum	171.0 m ³ ha ⁻¹
Maximum	189.7 m ³ ha ⁻¹
Standard deviation	71.6
Standard error (%)	4.8
Number of trees (dbh > 10 cm) ha ⁻¹	375.4

The forest contained a high volume of commercial species, ($46.5 \text{ m}^3 \text{ ha}^{-1}$ above 10 cm dbh) (Table 3.2). This volume is composed of hardwood species used in construction, such as *Dipteryx odorata* and *Hymenaea courbaril*, and species with an intermediate commercial value, such as *Aspidosperma vargasii*, *Protium apiculatum*, and *Peltogyne* sp. Highly desirable species such as *Cedrela odorata* and *Torresia acreana* were present but with low commercial volume (Table 3.2).

Table 3.2: Mean density (stems > 10 cm dbh ha⁻¹), basal area (stems > 10 cm dbh ha⁻¹), frequency (%), and volume (stock, stems 10-50 cm dbh; commercial, stems > 50 cm dbh; and total) of commercial species recorded in the forest inventory at Pedro Peixoto colonisation project.

Scientific designation	Density	Frequency	Basal area	Volume (m ³ ha ⁻¹)		
	(plants ha ⁻¹)	(%)	(m ² ha ⁻¹)	Stock	Commercial	Total
<i>Aniba canelila</i>	0.09	0.93	0.01	0.06	0.00	0.06
<i>Apuleia molares</i>	2.33	19.15	0.50	0.70	3.87	4.57
<i>Aspidosperma vargasii</i>	3.79	29.91	0.17	0.74	0.60	1.34
<i>Astronium lecointei</i>	2.85	20.09	0.23	1.14	0.73	1.87
<i>Bulchebavia</i> sp.	0.70	6.08	0.11	0.31	0.70	1.01
<i>Carapa guianensis</i>	1.92	9.35	0.08	0.55	0.11	0.66
<i>Cariniana</i> sp.	0.28	2.80	0.09	0.09	0.70	0.79
<i>Caryocar glabrum</i>	0.09	0.93	0.01	0.07	0.00	0.07
<i>Cedrela odorata</i>	0.98	8.41	0.08	0.61	0.00	0.61
<i>Copaifera multijuga</i>	0.93	8.41	0.10	0.30	0.57	0.87
<i>Cordia alliodora</i>	1.21	11.21	0.03	0.22	0.00	0.22
<i>Cordia goeldiana</i>	1.26	9.81	0.03	0.20	0.00	0.20
<i>Cordia</i> sp.	0.05	0.47	0.01	0.01	0.00	0.01
<i>Couratari macrosperma</i>	3.08	26.17	0.46	1.10	2.96	4.06
<i>Diplostropis purpurea</i>	0.09	0.93	0.01	0.04	0.00	0.04
<i>Dipteryx odorata</i>	1.50	12.62	0.33	0.64	2.38	3.02
<i>Enterolobium schomburgkii</i>	0.47	4.67	0.05	0.31	0.08	0.39
<i>Golpia glabra</i>	0.24	1.40	0.01	0.06	0.00	0.06
<i>Guarea kunthiana</i>	1.82	14.49	0.04	0.28	0.00	0.28
<i>Guarea pterorachis</i>	3.41	25.70	0.11	0.52	0.34	0.86
<i>Guarea purusana</i>	0.14	0.93	0.04	0.04	0.30	0.34
<i>Heisteria ovata</i>	3.51	25.70	0.14	1.00	0.09	1.09
<i>Hymenaea oblongifolia</i>	0.75	6.54	0.10	0.33	0.54	0.87
<i>Hymenaea courbaril</i>	0.19	1.87	0.05	0.01	0.43	0.44
<i>Hymenolobium excelsum</i>	1.35	11.69	0.07	0.49	0.09	0.58
<i>Hymenolobium</i> sp. 1	0.09	0.93	0.02	0.01	0.13	0.14
<i>Hymenolobium</i> sp. 2	0.66	5.14	0.09	0.32	0.49	0.81
<i>Manilkara surinamensis</i>	0.84	7.01	0.10	0.38	0.51	0.89
<i>Mezilaurus itauba</i>	0.14	1.40	0.04	0.00	0.36	0.36
<i>Myroxylum balsamum</i>	0.93	7.48	0.05	0.38	0.00	0.38
<i>Parkia pendula</i>	0.23	2.33	0.01	0.05	0.00	0.05
<i>Peltogyne</i> sp.	3.79	24.30	0.45	1.75	2.14	3.89
<i>Protium apiculatum</i>	13.97	51.87	0.92	6.40	0.92	7.32
<i>Qualea grandiflora</i>	2.43	18.69	0.20	0.94	0.65	1.59
<i>Qualea testamannii</i>	0.70	6.08	0.08	0.38	0.35	0.73
<i>Tabebuia impetiginosa</i>	1.82	14.49	0.12	0.97	0.00	0.97
<i>Tabebuia serratifolia</i>	4.63	30.84	0.29	1.89	0.36	2.25
<i>Terminalia</i> sp.	1.02	8.88	0.15	0.17	1.22	1.39
<i>Torresia acreana</i>	0.37	3.74	0.06	0.06	0.52	0.58
<i>Vataeria</i> sp.	0.14	1.40	0.01	0.03	0.09	0.12
<i>Vatairea sericea</i>	1.12	8.88	0.08	0.33	0.37	0.70
Total	65.51		5.53	23.88	22.60	46.48

Natural regeneration

The natural regeneration was very abundant in the managed forest of Pedro Peixoto colonisation project and, as expected, concentrated in the class of seedlings from 1.5 m to 3.0 m in height. Some species were very common in the regeneration such as *Rinorea publiflora*, but others were rare, e.g. *Chrysophyllum* sp. Some species were recorded only in the regeneration and not in the adult population (e.g. *Piper hispidinervium*) because they have a low maximum size or are shrubs (Table 3.3).

Table 3.3: Mean abundance (stems ha⁻¹) of three size classes of the natural regeneration for the 12 most common species. Size classes are indicated as follows; class 1, seedlings 1.5-3.0 m in height; class 2, saplings 3 m in height – 5 cm dbh; class 3, poles 5-10 cm dbh .

Scientific name	Class 01	Class 02	Class 03	Total
<i>Brosimum alicastrum</i>	56.4	9.9	6.1	72.4
<i>Eugenia</i> sp.	50.8	12.2	10.8	73.8
<i>Hirtella</i> sp.	90.2	20.7	5.6	116.6
<i>Inga tomentosa</i>	157.9	25.4	26.8	210.1
<i>Ocotea neesiana</i>	48.9	5.6	5.2	59.7
<i>Piper hispidinervium</i>	253.8	2.4	0.0	256.2
<i>Protium apiculatum</i>	50.8	7.5	4.7	63.0
<i>Pseudolmedia laevis</i>	58.3	5.6	20.7	84.6
<i>Psychotria</i> sp.	642.9	44.2	25.4	712.5
<i>Rinorea publiflora</i>	325.2	55.5	3.3	384.0
<i>Siparuna decipiens</i>	88.4	19.3	11.3	118.9
<i>Tachigalia paniculata</i>	80.8	9.4	7.5	97.8
Total for all species	3305.0	463.9	468.1	4237.1
Total for most common species	1905.3	219.6	98.7	2249.6

Almost all commercial species were found in the regeneration. Some of the species not present in the inventory samples (e.g. *Torresia acreana*) were later sampled in the natural regeneration of the felling gaps study (Table 3.4).

Table 3.4: Mean abundance (stems ha⁻¹) of commercial species in the natural regeneration at Pedro Peixoto colonisation project. Size classes are indicated as follows; class 1, seedlings 1.5-3.0 m in height; class2, saplings 3 m in height – 5 cm dbh; class 3, poles 5-10 cm dbh .

Scientific designation	Class 1	Class 2	Class 3	Total
<i>Apuleia molaris</i>	5.6		1.4	7.1
<i>Aspidosperma vargasii</i>	9.4	3.3	5.6	18.3
<i>Astronium lecointei</i>	3.8	1.4	1.4	6.6
<i>Bulchenavia</i> sp.	1.9			1.9
<i>Carapa guianensis</i>		0.5	0.9	1.4
<i>Cedrela odorata</i>		0.5		0.5
<i>Copaifera multijuga</i>	3.8		0.5	4.2
<i>Cordia alliodora</i>		0.9	1.9	2.8
<i>Cordia goeldiana</i>	5.6	2.8	1.4	9.9
<i>Cordia</i> sp.			0.5	0.5
<i>Couratari macrosperma</i>	43.2	1.9	3.3	48.4
<i>Dipteryx odorata</i>	5.6	0.9	0.5	7.1
<i>Golpia glabra</i>	1.9			1.9
<i>Guarea kunthiana</i>	22.6	5.6	3.8	32.0
<i>Guarea pterorachis</i>	18.8	2.3	6.1	27.3
<i>Guarea purusana</i>	3.76			3.8
<i>Heisteria ovata</i>	5.6	1.9	2.8	11.3
<i>Hyminaea courbaril</i>	1.9			1.9
<i>Hymenolobium excelsum</i>	7.5		0.5	8.0
<i>Hymenolobium</i> spp			0.5	0.5
<i>Hyminaea oblongifolia</i>	9.4		1.4	10.8
<i>Manilkara surinamensis</i>	1.9			1.9
<i>Mezilaurus itauba</i>			0.5	0.5
<i>Parkia pendula</i>			0.5	0.5
<i>Parkia</i> sp.		0.5		0.5
<i>Peltogyne</i> sp.	3.7	0.5	3.8	8.0
<i>Protium apiculatum</i>	50.8	7.5	4.7	63.0
<i>Qualea grandiflora</i>	3.8	0.5	1.4	5.6
<i>Qualea tesmannii</i>	1.9	0.5		2.4
<i>Tabebuia impetiginosa</i>	1.9			1.9
<i>Tabebuia serratifolia</i>	1.9		0.9	2.8
<i>Terminalia</i> sp.	1.9	0.9		2.9
<i>Vatairea sericea</i>	1.9			1.9
Total all species	3305.0	463.9	468.1	4237.1
Total commercial species	223.72	33.4	46.06	303.1

3.4.2 Forest exploitation preliminary results

Tree-felling and conversion of logs to planks

The efficiency of conversion (in volume terms) of logs to planks was between 61 % and 41 % for the biggest and smallest trees respectively, with an average of around 50 %. The total time to convert one cubic metre was 5.1 man-hours. For a 6-hour working day a team of three people were able to produce 3.6 m³ of sawn timber, which represents a very low productivity even when compared with a small sawmill (around 10m³ day⁻¹). On the other hand, as the annual potential production of these farms is only about 40 m³ (10 m³ ha⁻¹ x 4 ha year⁻¹), the maximum annual labour requirement is therefore only about 18 man-days to convert this unsawn timber into about 20 m³ of planks (Table 3.5).

Table 3.5: Means and standard deviation of the man-hours required to complete each of the phases involved in felling trees and converting the timber into planks in the Pedro Peixoto colonisation project

Phase	Time for the complete tree (man-hours)	Sd	Time for 1 m ³ (man-hours)
Cutting the tree	0.5	0.20	0.1
Cutting the logs	1.0	0.07	0.2
Converting logs to planks	23.0	0.80	3.5
Chainsaw maintenance	6.0	0.88	0.9
Wasted time	1.8	0.32	0.4
Total time	32.3	1.97	5.1

Skidding the planks

The number of skidded pieces varied between one to four per ox, per trip according to their shape and weight. The load therefore varied from around 0.19 m³ (*Dipteryx odorata*) to 0.39 m³ (*Couratari macrosperma*) with an average of 0.28 m³. The loading and unloading of the “zorras”, was also strongly affected by the shape and specific weight of the wood. The pace of the oxen was approximately 4 km hr⁻¹, and was kept constant even when the skidding distance increased from 200 to 1200 m. However, when the distance increased to 1400 m the time required to load and unload the zorras was not long enough to rest the animals for continuous operation. The total volume skidded in one day by a team of two men and one ox varied according to skidding distance, from 1.14 m³ (skidding distance 1400 m) to 3.36 m³ (skidding distance 250 m) (Table 3.6).

Table 3.6: Breakdown of the performance and volumes skidded by two teams of two men with one ox per team over three skidding distances (200, 1200, and 1400 m) in the managed forest of the Pedro Peixoto colonisation project.

Skidding distance (m)	200	Sd.	1200	Sd.	1400	Sd.
Effective work day average (men hour ⁻¹)	13.7		11.00		12.3	
Total wasted time per day (men hour ⁻¹)*	0.5		1.0		2.0	
Average time for complete cycle (men hour ⁻¹)	1.1	0.19	1.7	0.13	1.1	0.45
Number of cycles per day	12		6		6	
Average volume skidded per cycle (m ³)	0.28	0.07	0.28	0.04	0.19	0.07
Average volume skidded per hour (m ³)	0.43		0.26		0.13	
Total volume skidded by day (m ³)	3.36		1.68		1.14	

*The time to rest the animal was accounted as wasted time

Costs and economic analysis of the proposed forest management system

The production costs were between US \$ 33.5 and US\$ 35.5 per cubic metre of sawn planks at the road-side before transport to the market (Figure 3.4). Even considering the costs of transportation, at around US \$ 15 m³, the total costs would be around US \$ 50 m³.

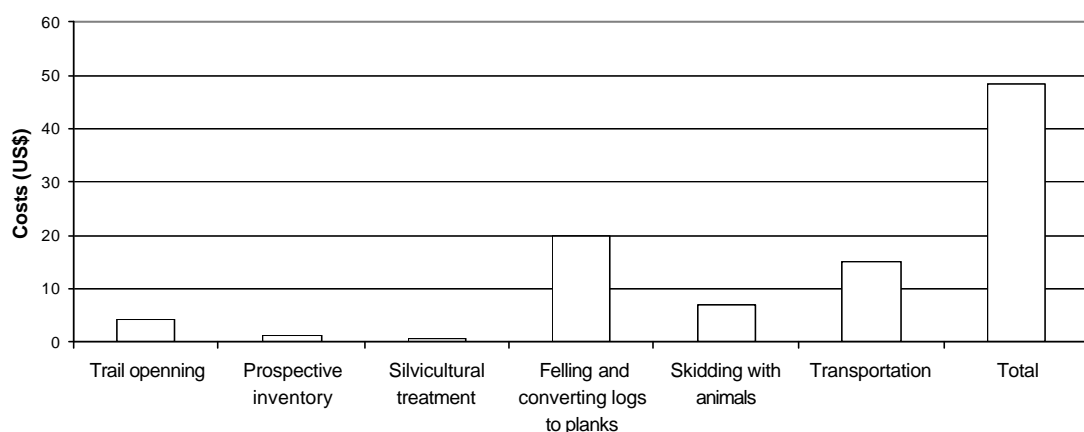


Figure 3.4: Mean and total costs of each phase of the forest management system per cubic metre of harvested timber (US\$).

3.5 Discussion

Limitations and strengths of the proposed system

Monitoring has shown that production is very low in lightly exploited forests without silvicultural treatments (e.g. De Graaf 1986). In addition, the increased growth of the trees remaining after harvesting tends to disappear after only three to four years after the harvesting (Silva, 1989). Therefore, harvesting timber in a simple polycyclic system, and leaving the forest to regenerate without further silvicultural assistance, is not a satisfactory approach for the maintenance of the forest productivity (De Graaf 1986).

For the management system proposed here, the short cutting cycle should provide for continuing benefits of enhanced growth of the residual trees. Nevertheless, additional silvicultural treatments should be considered, such as the elimination of badly formed trees, refinements (of undesirable species), crown liberation (for commercial species) and gap liberation (*sensu* Kuusipalo *et al.* 1997). The goal of refinement should not be to eradicate undesirable species, but to reduce their proportion in the stand, and to ensure that dominant individuals do not become unduly competitive (De Graaf, 1986).

The proposed system will facilitate the application of silvicultural treatments, which are planned as part of the conventional system but (due their high labour demand and costs) are usually not executed. Small farmers regularly enter or cross the forest management area on their properties during the working day for hunting, fishing and rubber tree tapping. Therefore, it would be a simple matter for the silvicultural treatments proposed here (liana cutting, protection of rare or desirable seedlings, weeding and cleaning) to be carried out as part of the daily schedule of work.

The proposed yields are deliberately conservative in order to ensure preservation of biodiversity and the functioning of the whole ecosystem. The implementation of liana cutting, directional felling and planning the skid trails reduces the damage caused by logging and extraction and contributes to the maintenance of forest productivity (Pinard and Putz, 1996; Blate, 1997). In the future, with more data on forest dynamics, new silvicultural techniques should be applied to improve yields.

The use of the “zorra” over long distances reduces the productivity of this phase. Alternatively, a small wagon pulled by one ox has been tried for the primary transport of the planks from the main skid trail to the edge of the secondary roads. Under this scenario the skidding by zorra is limited to the distance from the felled tree

to the main skid trail, or a maximum journey of 200 m, which will not compromise the productivity of the overall operation.

Acquisition of more data from permanent sample plots will allow the system to be fine-tuned by calculating future harvesting rates and the length of future felling cycles. This phase may be executed by a partnership between research and teaching institutes and the local people. The system also allows on-going modifications of the basic model according to feedback provided monitoring and data acquisition.

A potential problem with forest management is the effects it can have on the fauna, by changing the abundance of individual species, their food availability, the distribution of microclimate or other environmental conditions and changes in competitive relationships (Johns, 1997). These changes also affect potentially pollination, seed production and seed dispersal (e.g. Mahogany in Budongo forest in Uganda, Plumptre, 1995), are usually correlated with logging intensity (e.g. seed predators in Gorupi Forest Reserve, Johns, 1997) and usually tend to decrease or even disappear over time (e.g. number of species of understorey birds in Kerala National Park in Uganda, Drauzoa, 1998). In the case of PC Peixoto the impact of the management on the fauna will probably be minimised by the low harvesting intensity, the relatively high number of commercial species (diluting the effect of reducing the density of a single species e.g. the exploitation of Mahogany in Pará State East Amazon, Verissimo *et al.* 1995), and the use of animal traction instead of mechanised log extraction (reducing the damage produced by the opening of the skid trails). In addition, hunting throughout the year is a common practice among most of the farmers, and this activity might produce a much higher impact on the fauna and seed dispersal (e.g. Guariguata and Pinard, 1998) than the forest management, which is restricted in space (the compartment) and time (the cycle length of ten years).

Changing in commercial species

The marketable species are those classified as either “noble” species (*Torresia acreana*, *Swietenia macrophylla* and *Cedrela odorata*, species with high prices in any market), those species with a high wood density (usually shade-tolerant species with slow growth rates), and some species with low wood density (in the region, white wood “madeira branca”, is usually derived from pioneer species with growth rates varying from medium to fast). There is a potential market for plywood species (e.g. *Ceiba* spp), which was not considered due to the low prices in the local market for

the wood sold in logs. Some pioneer species such as *Schizolobium amazonicum* and *Jacaranda copaia* have a use in matches production, but due to their low total volume in the forest, this market is not accessible to the small farmers. There are two potentially economic species which were not considered because they are protected by law (*Bertholletia excelsa* and *Hevea brasiliensis*). Finally the group of commercial species is changing quickly and very soon selling timber will become more a matter of accessibility of markets than species identity. An example of this is one factory in Rio Branco which produces houses with “wood bricks”. According to the owner, after treatment, timber of any species could be used for this purpose.

In the medium-term, the list of commercial species will be likely to increase, with expansion of the market to include potential species such as *Pouteria* sp. and *Micropholis venulosa*. Other species might improve their value on the international market such as *Couratari macrosperma* and *Manilkara surinamensis*.

The results of the forest inventory were used to design the silvicultural techniques to improve natural regeneration and the growth of desirable species. These data and the volume of trees with dbh \geq 50 cm suggest that the yield will increase in future rotations. The presence of *Bertholletia excelsa* in the regeneration and its widespread distribution in the forest are an indication that these areas possess the right ecological conditions for its establishment. This species should be considered for management for timber in the future.

The introduction of new species (and products) onto the market decreases pressure on the few currently exploited species and the risks of biodiversity loss and genetic erosion. The constant restrictions on the availability of the timber of certain highly valued species, combined with international pressure for preservation of some of these species, has created a strong incentive for the introduction of new species to the market, especially those with similar timber properties to the species already in use.

The price of timber is likely to increase in the future because of the rise in the demand for tropical timber worldwide and the restriction in supply, especially of the more valuable timbers (e.g. Mahogany). Therefore the current standing stock of timber represents an investment rather like a savings account. This may be true even for stems of species which are not highly valued at present, because new species become marketable over time.

Involvement of local people

The involvement of the local population in forest management in the Pedro Peixoto colonisation project is in contrast to the situation in industrial concessions in Southeast Asia, and is an important factor in meeting the original objectives of the plan. For example, to improve yields in the future it will be necessary to invest in training the farmers. Additional studies time and work rationalisation studies are required and can be achieved through monitoring of all the forest management activities involved in the forest management system.

All forest management activities must be performed by the farmers themselves, and where possible, collectively. This avoids the costs of contracting the work to a third party. For the consolidation of this proposal some changes to forest legislation will be necessary and policies must be implemented to enforce and promote these changes.

A specific legislative framework covering inspection and implementation of management plans on small properties was approved in 1998. This legislation established the use of short cycles and animal traction by the Brazilian Institute for Environment and Natural Resources (IBAMA) agencies.

The existence of large uninhabited forest areas and large properties in the Amazon (sometimes with more than a million hectares) has been an incentive for the exclusive use of these areas for forest management. The exploitation of forests within colonisation projects or inhabited areas is usually restricted to logging prior to converting them to shifting cultivation and to illegal timber exploitation in the legal forest areas.

Future prospects

It seems that human populations in the Amazon have a natural tendency to increase. As a result, parts of the Amazon are already famous for the problems and violence caused by land tenure conflicts. In this context, reduction in the amount of land on farms that does not generate revenue resulting from the inclusion of the forest in the economic system will make it easier to respond to future problems e.g. when the forest industry starts to extend pressure on farmers to allow access to and exploiting of the forest areas on their properties.

The failure of most silvicultural systems (e.g. the Shelterwood in Nigeria and Malaysian Uniform System in Malaysia) was caused by demographic pressure and competition with other land uses. In the colonisation projects in the Brazilian Amazon there are no very strong demographic pressures yet and, at least in law, the only

possible competition for forest management is extractivism, which is not currently economically viable (Homma, 1997).

Small-scale forest management for small farmers provides an opportunity to fill a gap in land use in the Amazon, by allowing small farmers to use the forest reserves on their properties in an economic and sustainable way. Forest management will help to maintain and preserves these reserves, which are currently under strong pressure to be converted to pastures and shifting cultivation.

Economic and social benefits

The current market price for this kind of wood in Rio Branco varies between US \$ 100 and US \$ 150 m³, according to species and the quality of the planks. Therefore, even with the low-level of technology and experience available to the farmers for this activity, it was possible to achieve ratio of benefits to costs of around 2:1 (Figure 3.4). In similar conditions (small-scale forest management for timber production, animal traction, and conversion of logs to planks by chainsaw) Castañeda *et al.* (1995), found a return of U\$ 47 per workday and production costs around U\$ 43 to U\$ 65 per cubic metre for managed forest in Pedro Peixoto colonisation project.

However, it must be recognised that the system has a low profitability when compared with the yields obtained by mechanised forest management. A low profitability is to be expectable for a system designed to be applied in communities with a shortage of investment capital. In this case the social benefits obtained by returning low profits to the colonists rather than higher profits to forestry companies, can be used to justify the application of the system. On the other hand, the other available land use options for small farmers and colonists (shift-cultivation, extractivism and small-scale cattle ranching) also usually return low profits. The small property, as a unit of production, does not prevent collective or co-operative agreements between neighbouring proprietors. Indeed the aggregation of producers into larger units may facilitate the acquisition of new technologies (e.g. one-man sawmills, oxen and small tractors), result in increased prices in local markets and reduced costs of overheads such as transport. Collective working might generate a substantial increase in the yields from forest management, and my expectation is that within a short time the profits generated by the forest management as proposed here will increase significantly.

CHAPTER 4

Implications of the Management System for forest regeneration

4.1 Introduction

The environment of a plant may vary at many temporal and spatial scales, including daily and seasonally and in forests both vertically and horizontally. The scales at which variability occur are determined by many factors, including climate, geographical location, geomorphological features, the number and kind of species present and the nature of site disturbances. Natural or non-natural disturbances in plant communities initiate succession, which is defined as a process of continuous colonisation and extinction on a site by species populations (Bazzaz, 1979). There are at least two schools of thought about succession: the holistic and the individualistic views. The holistic view sees succession as a deterministic progression to an end point known as the climax community, and the individualistic view stresses the importance of the individual characteristics of an organism and how these relate to the observed pattern which may (or may not) be a successional sequence (Adlard *et al.* 1989). However, succession in tropical forests is dynamic and probabilistic, in contrast to the temperate-biased view of succession as a predictable linear process (Bazzaz and Pickett, 1980).

The canopy of a forest changes continually as trees grow up and die (Whitmore, 1978). This forest growth cycle, initiated by a disturbance (usually a treefall) may be arbitrarily subdivided into gap, building and mature phases. Thus, any forest is a spatial mosaic of these structural phases which change over time as a result of a dynamic process (Watt, 1947; Richards, 1952; Torquebiau, 1986; Whitmore, 1978 1989) influenced by a range of different biotic and abiotic conditions (Martinez-Ramos *et al.* 1989). Tree falls determine microenvironmental variations, the magnitude of which are affected by gap size (Arriaga, 1988). Gaps are recognised as important factors in forest regeneration because they drive the forest cycle and influence plant growth and establishment according to their size, age, the microhabitat that are created within them and identity and size of plants that establish within them (Uhl *et al.* 1988; Whitmore and Brown, 1996). The gap phase is the most important stage of the growth cycle for the determination of future regeneration (Brokaw, 1985a, 1989; Whitmore, 1989). Creation of a gap in the canopy acts on patterns already established in the understorey of the closed phase (Brokaw, 1989) and is the starting point for succession.

A number of environmental changes occur soon after gap formation in a forest. Light availability increases and root competition declines (Richards, 1952) because of the death of trees toward the centre of the gap (Hartshorn, 1978; Brokaw, 1985a), and as consequence litter decomposition can be accelerated (Bormann and Likens, 1979). In gaps the availability of resources such water and soil nutrients may temporarily increase (Swaine *et al.* 1997; Denslow *et al.* 1998). Competition for nutrients tends to increase from the time of opening to around the fifth year.

The greater exposure of the forest floor to irradiance promotes changes in humidity and temperature conditions in the gaps relative to closed forest. The changes in temperature and plant exposure affect evaporation and transpiration. Changes in irradiance result in modifications of resource availability (water and nutrients), and micro-climate conditions (humidity and temperature), both of which will affect plants in gaps (Brokaw, 1985b). Light affects seedlings in two ways: variation in radiant energy, irradiance, (which affects photosynthesis and hence growth), and variation in light quality in particular, the ratio of red to far-red light which is known to affect the allocation of biomass to different plant parts as well as seed germination (Swaine *et al.* 1997).

Variation in the amount of irradiance usually generate differences in seedling growth rates, species composition and survival in gaps. Irradiance is positively correlated with gap size (Barton *et al.* 1989; Brown, 1993), but different gap sizes can produce similar irradiance (canopy openness) (Whitmore *et al.* 1993). In addition, as gap size increases, light can penetrate even greater distances into the understorey adjacent to the gaps (Canham *et al.* 1987 and 1990).

Differences in species response to irradiance (e.g. Agyeman *et al.* 1999) are important because the forest light environment is continually changing because of natural tree falls, logging and other disturbances. Light is variable in the forest varying from full sunlight in cleared sites to less than 1 % of full sunlight in the deepest forest shade (Swaine *et al.* 1997).

In forests, the environmental factors showing variation relevant to seed germination and dormancy are light and temperature, or associated increases in the diurnal ranges of these factors (e.g. Vazquez-Yanes and Orozco-Segovia, 1982) and water. Temperature tends to be constant in forest shade but it may be substantially elevated following canopy opening. Water at the soil surface is usually abundant, but may be unavailable for imbibition during dry seasons and in surface soil in gaps after canopy opening (Swaine *et al.* 1997).

Seed germination is strongly affected by exposure to sunlight. The affect can enhance or depress germination (Bazzaz and Pickett, 1980). Dormancy mechanisms

exist that allow viable seeds to persist on the forest floor until the canopy is opened by a tree fall (Hartshorn, 1978; Hall and Swaine, 1980). However, most tree species that are dependent on gaps for establishment do not appear to have seed dormancy (Hartshorn, 1978).

Species that germinate and establish only in canopy gaps are termed secondary or pioneer species (Swaine and Whitmore, 1988). Dependence on canopy opening for germination and seedling establishment has been used to define the difference between pioneer and non-pioneer species. However, seedling survival in gap conditions more likely to be the factor that differentiates species (Swaine and Whitmore, 1988; Kennedy and Swaine, 1992; Kyereh *et al.* 1999).

Some pioneer species can germinate in darkness, but they usually fail to establish under this condition. The most probable cause is that the small seedlings of pioneers which emerge in the forest shade receive insufficient light to maintain a positive carbon balance (Swaine *et al.* 1997).

Gap size has a strong influence on seedling growth. Light is the principal limiting factor for plant growth in all forests, and species have evolved in different ways to maximise light capture (Brown, 1993; Veenendaal *et al.* 1996; Tuomela *et al.* 1996). Pioneer species have high mortality in forest shade but respond strongly to increases in irradiance, while non-pioneers have lower mortality in the shade but respond less strongly to increases in irradiance (Hartshorn, 1978; Brokaw, 1985a; Kobe *et al.* 1995; Swaine *et al.* 1997). These differences affect the proportions of different species in forests with different frequencies or intensities of disturbance (Brokaw, 1989). Therefore, a combination of pioneer and non-pioneer species can be seen in canopy gaps whereas the pioneers are absent from closed canopy forest (Chandrashekara and Ramakrishnan, 1994).

Logging produces gaps of different sizes, according to the size of the felled tree, topography, surrounding forest structure, and logging method (e.g. mechanised or animal traction logs-skidding) and logging intensity. Felling gaps (gaps originated by the felling of a tree) have very variable characteristics and the study of the influence of the gap size on natural regeneration has been carried out by using artificial gaps (artificial gaps with particular characteristics such as size, topographic position, orientation, etc.). This technique has been used by several authors to study natural regeneration of tropical forests (Brown and Whitmore, 1992; Kennedy and Swaine, 1992; Toumella *et al.* 1996, Whitmore and Brown, 1996).

Changes in the environment after gap creation (light, temperature, water and nutrient availability) triggers the growth of non-pioneer species, which have the capacity to germinate under a closed canopy, and which remain suppressed until a

gap is created (Bazzaz and Pickett, 1980; Brokaw, 1985a). The size of a gap may influence which species do or do not colonise a gap (Hartshorn, 1978). Thus, colonisation by pioneer species occurs although the rate of colonisation will vary in relation to the size and origin of the gap. This process usually results in an increase in the density of seedlings (Brokaw, 1985a).

Tree fall gaps are thought to contribute to the diversity of plants in tropical forests by providing opportunities for niche differentiation in modes of regeneration (Grubb, 1977, Welden *et al.* 1991). Several hypotheses have been proposed to explain how local diversity is produced or maintained in tropical forests. Connell (1978) suggests two general categories by grouping these hypotheses into equilibrium and non-equilibrium hypotheses. Non-equilibrium hypotheses are those where the species composition of communities is seldom in a state of equilibrium, and high diversity is maintained only when the species composition is continuously changing. The equilibrium hypotheses advocate that the species composition of communities is usually in a state of equilibrium and after a disturbance it recovers to that state (Connell, 1978).

The nature of the dynamics of tropical forests as reported by numerous authors (e.g. Foster and Brokaw, 1982; Hartshorn, 1990; Lieberman *et al.* 1990; Whitmore, 1992) shows a high occurrence of natural disturbances at different scales which suggests that probably, the non-equilibrium hypothesis might be more realistic. However, Tilman (1994) demonstrated that spatial subdivision of habitats can explain the stable coexistence of an unlimited number of competing species, because species with high dispersal rates can persist in sites not occupied by superior competitors. Hubbell *et al.* (1999) have found support for this hypothesis in their long-term study of tropical forest Barro Colorado Island in Panama.

Therefore, no single theory of succession is likely to be complete because of the large number of potentially relevant processes and scales (Sheil, 1998), and most of the ecological hypotheses are not mutually exclusive. The challenge is to determine the contribution of each mechanism to the maintenance of species diversity (Hubbell, 1998). In addition, there is still controversy over whether the internal heterogeneity of treefall gaps (e.g., trunk and crown zones) (Orians, 1982, Brandani *et al.* 1988 and Nuñez-Farfán and Dirzo, 1988) is responsible for generating different responses in the natural regeneration. Although there is no strong evidence for species partitioning of gaps (Denslow, 1980), partitioning might be expected because the germination and survival of tropical tree species are affected by light conditions, and the proportion of pioneer and non-pioneer species will vary in relation to position in the gap and soil conditions. According to Orians (1982), the fall of a

canopy tree creates a disturbance that is internally heterogeneous, with different zones (termed root, bole and crown zones), providing variation in light and nutrient availability that could favour the establishment of different species.

This study aims to identify relevant changes in the growth, recruitment, mortality, and species richness and diversity, of tree seedlings produced by logging the forest using the techniques described in Chapter 3. These aims will be achieved by the comparison of areas disturbed by exploitation operations with undisturbed adjacent areas (Hawthorne, 1993). Due to the high heterogeneity of the felling gaps (in terms of their size, orientation and topography), additional studies were carried out in artificial gaps in the forest of CPAF-ACRE.

4.2 Objective

- To study the growth, recruitment, mortality, density, richness and diversity of seedlings in artificial gaps, felling gaps and in the natural forest in order to understand the effect of the proposed management system on natural regeneration in the felling gaps.

4.3 Research questions

- Can felling gaps provide adequate conditions for establishment of the seedlings of the commercial species to allow sustainable timber production?
- How do the seedling populations respond to gap creation in terms of species richness and diversity, density, growth rate, mortality and recruitment according to (a) their ecological characteristics (pioneer vs. non-pioneer species), (b) gap size (c) canopy openness and (d) gap position?

4.4 Methods

4.4.1 Gap creation and plot establishment

Natural regeneration was studied using plots located in the undisturbed forest and in gaps. The study was carried out in artificial gaps (in CPAF-ACRE, Experimental Station) and in felling gaps (in the PC Peixoto managed areas), and the undisturbed forest was used to compare with data from the gaps. The artificial gaps were created in 1997 during the dry season months of July and August by removing all trees and seedlings above 1 m height. The felling gaps were created in the same period in the

managed areas of PC Peixoto, during forest exploitation (tree felling, conversion of logs to planks and skidding the planks, Chapter 3).

4.4.2 Artificial gaps experiment

The gap concept varies between authors and the use of different sampling methodologies complicates the comparison of results from different studies (Popma, 1988; Almeida, 1989). For gap size determination in this study, Brokaw's gap definition was used (projection of open conditions to the forest floor, Brokaw, 1982). Although this definition has been criticised (e.g. by Popma *et al.* 1988, who recommend the inclusion of the disturbed area at the edges as a part of the gap), it was used because it allows a simple control and definition of gap size during gap creation and data collection. It is also impossible to identify the area that will be disturbed in the field, before the gap is created (as required by the definition of Popma *et al.* 1988). In this study, the gaps were created by cutting down all plants above 1m height at one time. However, immediately after gap creation no seedlings of more than 1 m height survived. The measurements in the plots started one year after gap creation.

Artificial gaps were classified according to their size, with the following gap size classes.

Gap size classes:

1. 100 m² (small)
2. 400 m² (medium)
3. 800 m² (big)
4. 1200 m² (very big)

The experiment was installed in four lines of eight gaps on each, with sixteen replicates of the small gaps (100 m²), eight replicates of the medium gaps (400 m²), and four replicates of the other sizes. The study involved the measurement of seedling growth, recruitment, mortality, density and species richness and diversity on plots located in each of these 32 gaps. All seedlings of woody species above 1 m height were tagged, identified and measured for diameter at 0.30 m height. Immediately after gap creation no seedlings of more than 1 m height survived. The measurements in the plots started one year after gap creation. The data were collected annually on plots of 5 m x 5 m located on transects that crossed the gaps an

East – West direction, so that there were two to eight plots per gap depending on gap size. Two more plots were added to one end of the transect inside the forest understorey beyond the edge of the gap. These plots sampled the regeneration in the margins of the gaps from 0 m to 5 m inside the forest (forest edge 1) and from 5 m to 10 m inside the forest (forest edge 2). Four additional transects consisting of eight contiguous 5 x 5 m quadrats were established in forest understorey parallel to the central portion of each of the four gap lines and offset from the gap borders by 50 m (Figure 4.1).

The plots were classified according their position in the gap as:

1. Forest edge 2 (plot in the forest understorey without contact with the gap edge)
2. Forest edge 1 (plot in the forest understorey in contact with the gap edge)
3. Gap edge (plots in the edge of the gaps)
4. Gap centre (plots in the centre of the gap)

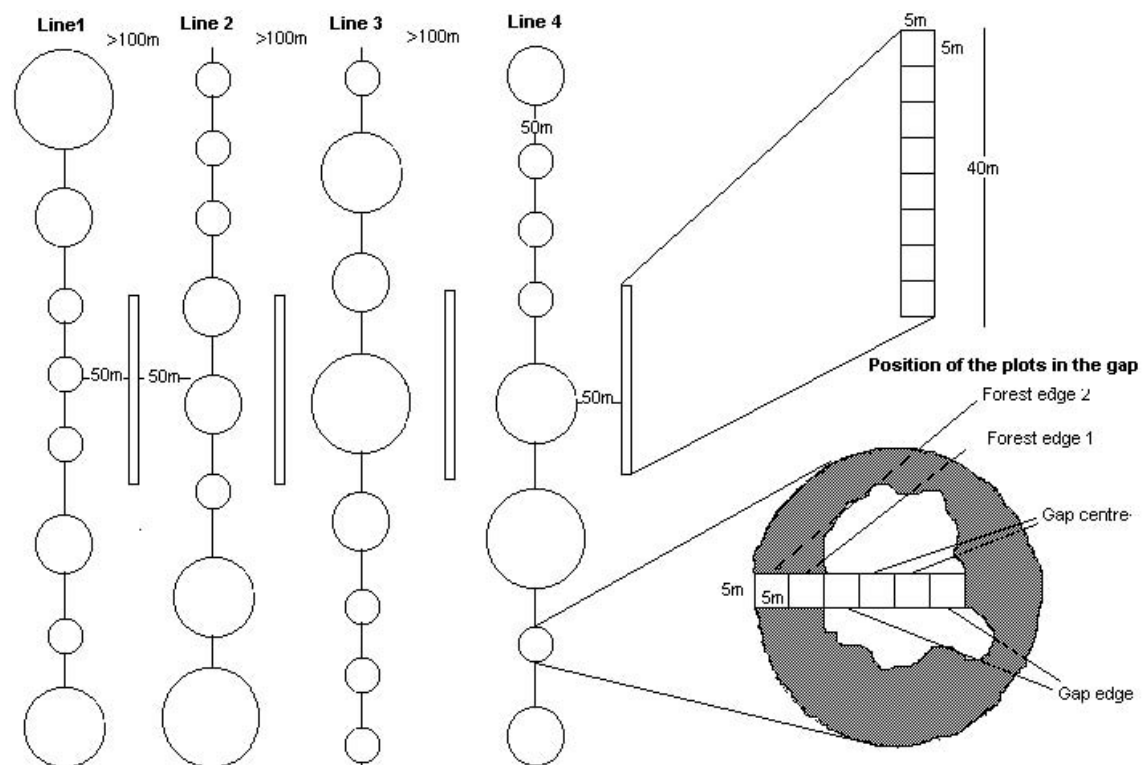


Figure 4.1 Distribution of the gaps, gap plots and forest understorey plots in the artificial gap experiment

4.4.3 Felling gaps experiment

As in the artificial gap experiment, this study involved the measurement of seedling growth, recruitment, mortality, density and species richness and diversity. All seedlings of woody species above 1 m height were tagged, identified and measured for diameter at 0.30 m height. Plots in gaps were classified according to their position in either the crown or the trunk zone (Orians, 1982; Popma *et al.* 1988).

The plots were marked out before the tree was felled in the area of the future gap. This was possible because directional felling allowed me to predict the location of the gap. Plots in gaps were classified according to their position in either the crown or the trunk zone (Orians, 1982; Popma *et al.* 1988). To cover the future gap area, eight 5 m x 5 m plots were used, four in the trunk zone and four in the crown zone. The experiment consisted of seven replicate gaps and five additional transects consisting of eight contiguous 5 x 5 m quadrats distributed at random in the undisturbed forest around the felled trees. Ten gaps were chosen at random in the managed areas of PC Peixoto, a hemispherical photograph was taken in the centre of each and its area measured in the field following Brokaw's (1982) definition.

4.4.4 Hemispherical photography

Hemispherical photographs of the gaps were obtained to measure the percentage of canopy openness (Whitmore *et al.* 1993) and allow comparison of results with other studies (e.g. Brown, 1993).

The data were obtained using digital hemisphere photographs processed using Winphot version 4.0 (Ter Steege, 1994), for the measurement of canopy openness. Before canopy openness measurement the pictures were processed using the "Threshold" command in Adobe Photoshop version 4.01. The Threshold command was used to convert the greyscale to high-contrast black-and-white images. Using this command, a particular level of the greyscale is specified as a threshold. All pixels lighter than the threshold are converted to white, and all pixels darker than the threshold are converted to black. A threshold of 250 (on a scale up to 255) was selected by trial and error (Figure 4.2), and applied to the hemispherical photographs. The aim of this procedure was to avoid operator bias in the interpretation of photographs (e.g. in distinguishing between grey trunks and open canopy or between clouds and tree crowns).

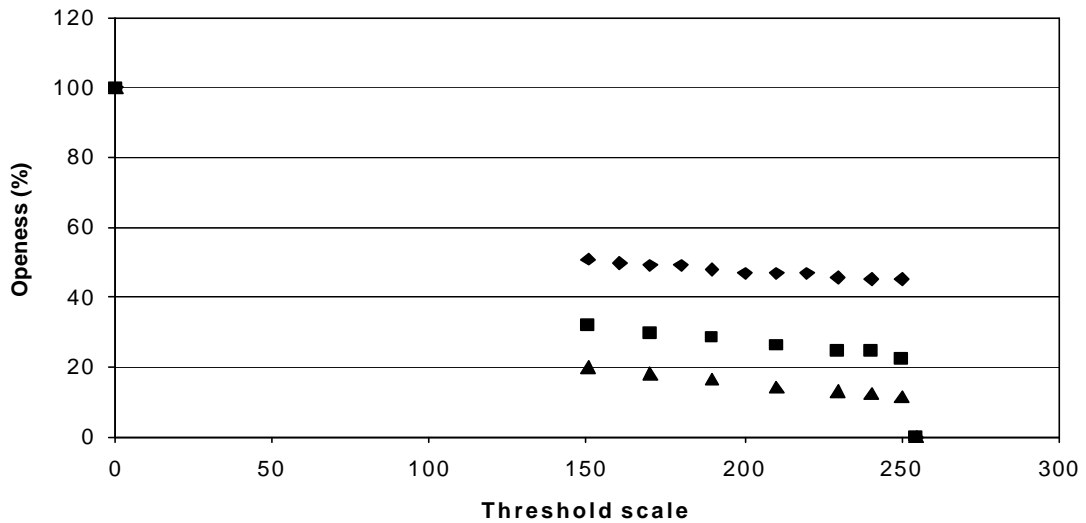


Figure 4.2: Canopy openness measurement variation in hemispherical photographs through the threshold scale for big gaps (pyramids), medium gaps (squares) and small gaps (triangles).

4.4.5 Data manipulation and analysis

Mortality rates

Mean annual mortality rates were calculated as suggested using Sheil *et al.* (1995), by the formula:

$$M = 1 - (N_1/N_0)^{1/t}$$

Where N_0 and N_1 are population counts at the beginning and end of the measurement interval, t

Recruitment rates

Recruitment was considered as all seedlings in the quadrats which reach the minimum measurement height of 1 m. Recruitment rate was standardised by dividing the total number of recruits in one census by the number of adults in the previous census, then dividing by the census interval (Condit *et al.* 1995).

Growth rates

Growth rates were calculated by the formula

$$(dbh_2 - dbh_1) / t$$

Where dbh_1 and dbh_2 are diameters of the beginning and end of interval t .

Species richness was defined as the total number of species in the plots (Kent and Coker, 1992) and diversity calculated by the Fisher's λ . Fisher's λ was chosen because it is stable with changing sample size and can be extrapolated to predict the number of species in larger plots (Condit *et al.* 1996 and 1998). The statistical differences of relative density were tested by the χ^2 test (Manokaran and Kochummen, 1994).

Artificial gaps experiment

Some small gaps were entirely covered by only one or two sub-plots and these were classified as gap centre plots because of the it was not possible to identify gap edges in small gaps. Statistical analysis of growth, mortality and recruitment rates were carried out in four steps.

(1) Data from all four gap sizes were analysed by analysis of variance using a model that reflected the nesting of "position" treatments within gaps, using just the three positions that could be identified in all gaps (forest edge 1, forest edge 2 and gap). The factors line and size were considered as main plot factors and were tested for significance against the main plot error term, while position and the position by size interaction terms were tested for significance against the remaining error variance.

(2) For the three largest size classes of gap it was possible to identify two position within gaps (gap edge and gap centre). Growth, recruitment and mortality data were analysed by analysis of variance using a model that reflected the nesting of "position" treatments within gaps. The factors line and size were considered as main plot factors and were tested for significance against the main plot error term, while position and the position by size interaction terms were tested for significance against the remaining error variance.

(3) Data from all four gap sizes were analysed by analysis of variance using a model that reflected the nesting of “position” treatments within gaps, using just the two positions located out of the gap, forest edge 1 (plot in the forest in contact with the gap border) and forest edge 2 (plot in the forest without contact with the gap border). The factors line and size were considered as main plot factors and were tested for significance against the main plot error term, while position and the position by size interaction terms were tested for significance against the remaining error variance.

(4) The analysis of variance of gap sizes for growth, recruitment and mortality was carried out using a model considering the factors line and size and the statistical differences among gap sizes tested by Tukey test ($p < 0.05$)

The effect of canopy openness on growth, recruitment and mortality of the seedling populations in the artificial gaps and undisturbed forest understorey was analysed by regression.

Felling gaps experiment

The effect of gap position (trunk zone and gap zone) was compared with the control plots by analysis of variance using one way anova. The differences in growth, mortality and recruitment between crown and trunk zones were analysed using paired T-tests.

Whether was evidence that the residuals were not normally distributed, the data were transformed using square root transformation. The anova tables are presented in the Appendix 5.

4.4.6 Species groups

According to Swaine and Whitmore (1988), there are two qualitatively distinct groups of tree species, termed pioneer and climax or non-pioneer species respectively. Subgroups are acceptable, so long as it is realised that they are arbitrary segments of a continuum. Pioneer species are those that demand exposure to sunlight in order to germinate or survive. The major concern of this study is to identify changes in the composition and structure of the seedling community after canopy opening. Thus, the relative density of the pioneer species was used as an environmental parameter to demonstrate the differences among the natural forest, gap edges and the different gap sizes.

Species groups:

Pioneer species (Appendix 4)

Non-pioneer species

Commercial species: species which have been sold in the Rio Branco city market by the farmers (Appendix 2).

4.5 Results

4.5.1 Artificial gaps

4.5.1.1 Species composition, richness and diversity

The ten most common species in the artificial gaps and natural forest represented respectively 42 % and 31 % of the total seedling population. The difference was not so great because the artificial gaps were considered altogether, but even so, a single species (*Solanum* sp.) represented about 17 % of the total population. As expected, almost all of the species in the artificial gaps were pioneers and in the natural forest shade-tolerant species (Table 4.1).

Metrodorea flavia regenerates well in both gaps and forest understorey, but some species were confined to either gaps or natural forest environments. Sprouts of some of the less common species in the regeneration (e.g. *Micropholis venulosa* and *Brosimum rubescens*) were found in the gaps.

The number of species present in the seedling community varied in relation to gap size (Table 4.2). Forest edge plots, the undisturbed forest understorey and small and medium gaps, possessed a similar mean number of species, genera and families, but fewer species were found in the seedling communities in the big and very big gaps one and two years after opening (Table 4.2). In the first year species diversity was higher in the undisturbed forest understorey than in the big and very big gaps. After two years, small gaps, medium gaps and plots at the boundary of the gaps (forest edge 1) showed a higher Fisher's diversity index than the forest understorey. In general, the species diversity of the disturbed areas (gaps and forest edge 1) increase over time while in the non-disturbed areas (forest understorey and forest edge 2) species diversity remained about the same (Table 4.2). Two years after gap opening, the plots inside the gaps showed a greater number of species and diversity index than in the previous year. The plots in the forest edge 1 (close to the gaps) also showed a higher species richness and diversity in the second year.

Table 4.1 Total number of plants recorded and relative density of the most common species in the artificial gaps and forest understorey two years after gap creation.

Artificial gaps		
Species	Number of plants	Relative density(%)
<i>Solanum</i> sp.	402	17.2
<i>Cecropia</i> sp.	131	5.6
<i>Urera</i> sp.	104	4.4
<i>Aegiphila</i> sp.	92	3.9
<i>Sapium marmiere</i>	61	2.6
<i>Justicia</i> sp.	55	2.4
<i>Metrodorea flavia</i>	43	1.8
<i>Cassia lucens</i>	39	1.7
<i>Schizolobium amazonicum</i>	38	1.6
<i>Piper hispidinervium</i>	36	1.5
Total most common species	1001	42.7
Total	2342	100.0
Natural forest		
Species	Number of plants	%
<i>Psychotria</i> sp.	57	7.1
<i>Annona ambotay</i>	34	4.2
<i>Brosimum uleanum</i>	29	3.6
<i>Tetragastris altissima</i>	23	2.9
<i>Piper hispidinervium</i>	20	2.5
<i>Neea</i> sp.	20	2.5
<i>Quararibea guianensis</i>	19	2.4
<i>Metrodorea flavia</i>	18	2.2
<i>Pithecellobium</i> sp	18	2.2
<i>Galipea trifoliata</i>	16	2.0
Total most common species	256	31.9
Total	802	100.0

The percentage of pioneer species in the seedling community increased from the edges to the centres of gaps. However, there were no significant differences between plots in forest edge or forest understorey positions. The differences between forest edge plots and those in gaps were significant, and the differences between the gap edge and the gap centre plots were also significant (χ^2 , test $p < 0.05$) (Table 4.2).

Table 4.2 Total number of plants on all plots, with the and relative density of pioneer species, species richness, and Fisher's α diversity index in the artificial gaps (classified by gap size and plot position in the gap), forest edges and undisturbed forest understorey, one (1998) and two (1999) years after canopy opening.

1998	Number of stems	Pioneers (%)*	Species richness	Fisher's α
Understorey	802	4.1a	112	35.4
Gap position				
Forest edge 2	870	3.3a	115	35.5
Forest edge 1	782	4.2a	109	34.4
Gap edge	1236	38.9b	134	38.2
Gap centre	1243	48.6c	132	37.3
Gap size				
Small gap	553	30.2b	108	40.1
Medium gap	680	46.4c	105	34.7
Big gap	582	38.0d	89	29.3
Very big gap	669	45.1c	80	23.7
1999	Number of stems	Pioneers (%)*	Species richness	Fisher's α
Understorey	803	3.0a	114	36.3
Gap position				
Forest edge 2	852	3.2a	113	34.9
Forest edge 1	802	5.8b	121	39.6
Gap edge	1191	36.9c	140	41.2
Gap centre	1277	45.4d	138	39.3
Gap size				
Small gap	672	28.5a	127	46.3
Medium gap	667	42.8b	114	39.5
Big gap	534	36.8c	93	32.5
Very big gap	595	52.4d	87	28.1

* percentages followed by the same letter are not significantly different (χ^2 test, $p < 0.05$)

The size and canopy openness of the gaps influenced the proportion of pioneer species in the seedling community. The proportion of pioneer species in the gaps varied from around 30 % to over 50 %, according to gap size and canopy openness. There were also significant differences in the relative density of pioneer species in relation to plot position. Only very big gaps showed an increase in relative density of pioneer species from the first to the second year. For all other gap sizes it remained constant (Table 4.2, Figures 4.3 and 4.4).

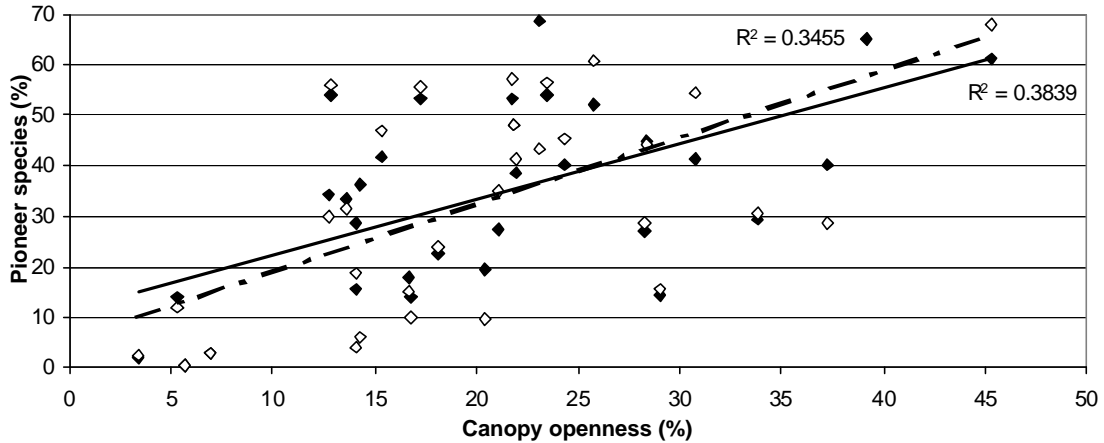


Figure 4.3: Mean percentage of pioneer species in the seedling community in relation to canopy openness one (closed symbols) and two (open symbols) years after gap creation. The regression lines indicated are as follows: $y = 12.4 + 0.25x$ ($R^2 = 0.32$, $DF = 35$, $p < 0.001$) one (interrupted line) and $y = 11.6 + 0.271x$ ($R^2 = 0.29$, $p = 0.001$) two (full line) years after gap creation.

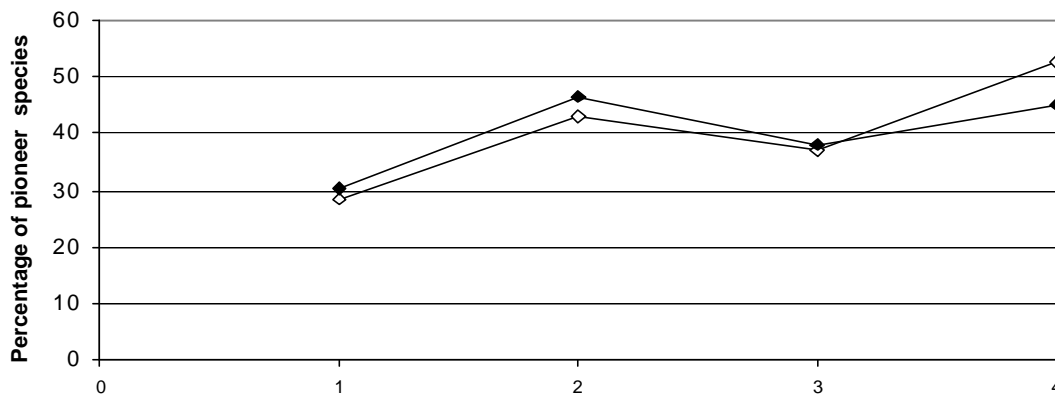


Figure 4.4: Mean percentage of pioneer species according gap size (1. small, 2. medium, 3. big, 4 very big) one (closed symbols) and two (open symbols) years after opening.

The proportion of pioneer species in the seedling community increased linearly with increasing canopy openness (Figure 4.3). Therefore, small gaps had a lower proportion of pioneer species in the seedling community than the other gap sizes. The proportion of pioneer species on plots increased from the smallest gaps to the largest ones, and differed significantly in relation to the other gap sizes (Table 4.2, Figure 4.4).

If the gap size classification is compared to canopy openness as measure of gap size, it is clear that some larger gaps are misclassified because they possess

lower canopy openness than smaller gaps. These misclassifications are caused by the structure of the surrounding forest (Figure 4.5).

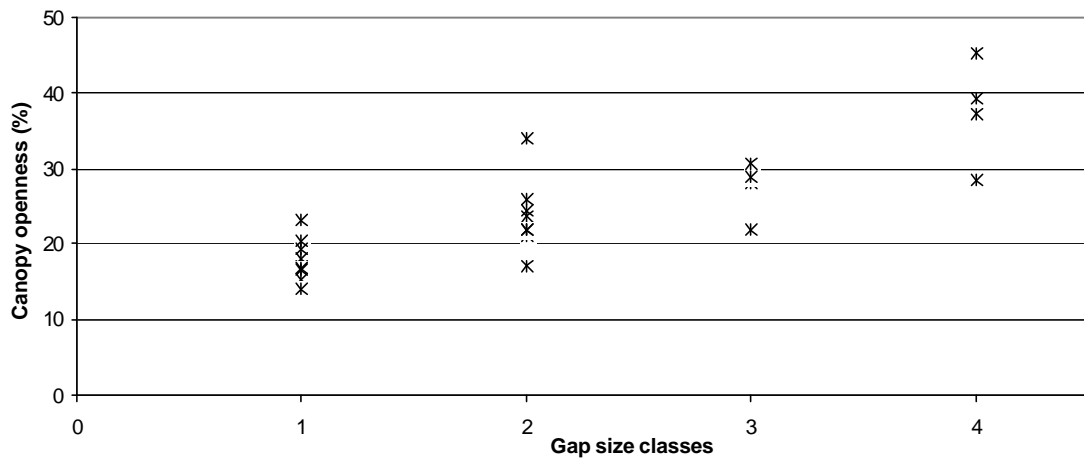


Figure 4.5: Canopy openness according to gap size classes (1-small, 2-medium, 3-big and 4-very big).

4.5.1.2 Seedling growth

To analyse growth in the artificial gaps I assumed that the plants had grown from nothing at the time of the gap creation. This assumption is reasonable because gap creation destroyed all seedlings. It was not possible to “select” seedlings to save during the gap creation procedures. Both gap size and canopy openness had an influence on seedling growth. Seedling growth was slower in the smallest gaps, but there were no significant differences between small, medium and big gaps and only the very big gaps showed a significantly greater growth (Table 4.3). Canopy openness also strongly affected the growth of seedlings in the gaps. Canopy openness was strongly correlated ($R^2 = 0.61$, $p < 0.001$) with mean diameter increment during the first two years after gap creation (Figure 4.6).

Table 4.3: Mean and standard error diameter increment (cm yr⁻¹) in the gaps in the first two years after gap creation. F and P values are derived from analysis of variance to test effects of gap size alone.

Gap size	Plots	Mean growth rate (cm yr ⁻¹)*	Standard error	F- value	p-value
Small	16	1.04a	0.06		
Medium	8	1.29ab	0.08		
Big	4	1.24ab	0.12		
Very big	4	1.53b	0.12	5.62	< 0.004

* means followed by the same letter are not significantly different (Tukey test, p < 0.05).

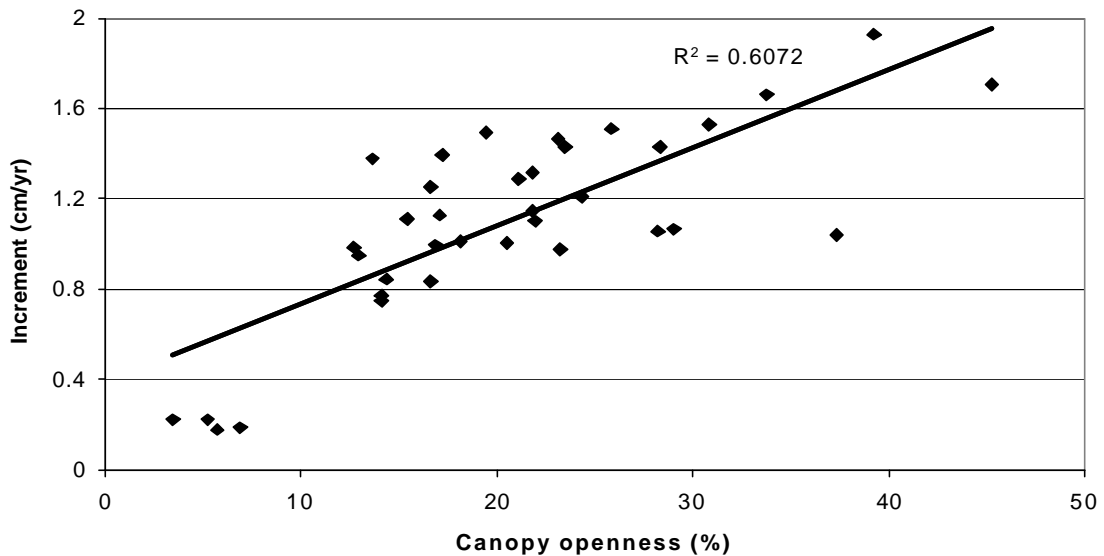


Figure 4.6: Mean diameter increment in relation to canopy openness for seedlings growing in the 32 artificial gaps and in the forest understorey in the first two years after gap creation. The regression line indicated has the form $y = 0.387 + 0.0347 x$ ($R^2 = 0.61$, $DF = 35$, $p = 0.001$).

Seedling growth rates were similar in the forest understorey and forest edge 2 and 1 plots. There were no differences in the growth rates of seedlings in gap edge or gap centre positions, but seedlings in gaps grew significantly than seedlings in forest edge 1 and 2 positions (Table 4.4).

Table 4.4 Mean annual and standard error diameter increment (cm yr^{-1}) of seedlings two years after gap creation and results of ANOVA to compare effects of gap size and gap position. F and P values are derived from analysis of variance to test (i) effects of forest edge position nested within gap size using data from all four gap sizes, (ii) effects of within gap position (edge vs. centre) nested within gap size using data from the three largest gap size classes and (iii) effects of plot position considering forest edge 1, forest edge 2 and the four gap sizes altogether nested within gap size

	Gap position	N	Mean growth rate (cm yr^{-1})	Standard error	F-value	p-value
(i)	Forest edge 2	32	0.27	0.04	1.63	0.21
	Forest edge 1	32	0.35	0.04		
(ii)	Gap edge	21	1.26	0.04	1.97	0.18
	Gap centre	21	1.35	0.04		
(iii)	Forest edge 1	32	0.27	0.04	161.00	< 0.001
	Forest edge 2	32	0.35	0.04		
	Gap	32	1.27	0.04		
	Forest understorey	4	0.20	0.01		

4.5.1.3 Seedling density

Seedling density in the gaps one year after gap creation was similar to that of the natural forest except in the small gaps, where density was lower. In the second year after gap creation the differences among gap sizes decreased either because of a higher recruitment in the small gaps or a higher mortality in the larger gaps. In the second year the three larger gap sizes experienced a reduction in seedling density, while density in small gaps increased (Table 4.5). Two years after gap creation the correlation between seedling density and canopy openness was insignificant ($R^2 = 0.0$, DF 35, $p > 0.91$) (Figure 4.7).

The density in the gaps two years after gap creation was lower than in the forest understorey. Gap position did not affect seedling density, as the mean values for gap edge and gap centre plots were similar. seedling density in the forest edges 1 and 2 plots, were also similar (Table 4.5).

Table 4.5 Mean and standard error seedling density (number of plants ha⁻¹) in the artificial gaps (by gap size), and in the undisturbed forest understorey in the first (1998) and second (1999) year after gap creation.

	N	Year			
		1998	Standard error	1999	Standard error
Understorey	4	9675	619	10150	449
Gap size					
Small	16	5829	491	7375	632
Medium	8	9431	898	9389	835
Big	4	9913	724	9185	1004
Very big	4	9725	1250	8862	1443
Gap position					
Forest edge 2	32	10875	624	10887	624
Forest edge 1	32	9762	693	10350	688
Gap edge	21	8421	509	8643	576
Gap centre	32	8397	604	8719	699

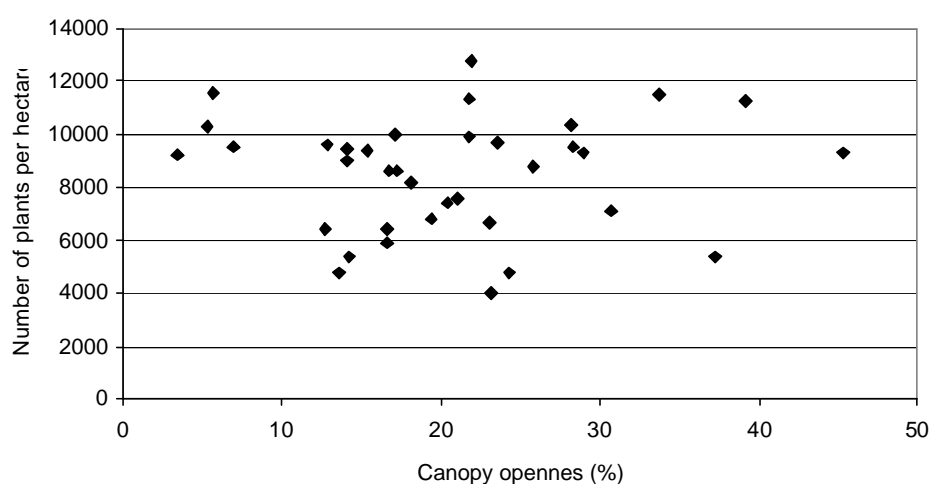


Figure 4.7 Mean seedling density in relation to canopy openness in the 32 artificial gaps and in the four transects in the forest understorey, two years after gap creation.

4.5.1.4 Recruitment

Since there were no plants above 1 m height in the gaps after their creation in 1997, the values of seedling density recorded in 1998 were taken as recruitment for this period. There were no significant differences in recruitment between were found among gap sizes. Recruitment was lower in the forest understorey than in the gaps and similar to values in forest edge 2 plots. When plots adjacent to gaps of all four sizes were compared those closed to the gap edge (forest edge 1) had a higher

recruitment than those further from the gap edge (forest edge 2). For the three largest gap size classes, recruitment was greater on centre than edge plots (Table 4.6). In the same period, the correlation between canopy openness and recruitment was insignificant ($R^2 = 0.03$, $DF = 35$, $p > 0.29$) (Figure 4.8).

Table 4.6: Mean and standard error number of recruits in the artificial gaps according gap size and plot position in the second year after gap creation and in the undisturbed forest understorey. F and P values are derived from analysis of variance to test (a) effects of gap size alone, (b(i)) effects of forest edge position nested within gap size using data from all four gap sizes, (b(ii)) effects of within gap position (edge vs. centre) nested within gap size using data from the three largest gap size classes and (b(iii)) effects of plot position considering forest edge 1, forest edge 2 and the four gap sizes altogether nested within gap size.

	N	Recruitment (plants ha ⁻¹)	Standard error	F-value	p-value
(a) Gap size					
Small	16	2250	260		
Medium	8	1261	367		
Big	4	1133	520		
Very big	4	979	520	1.03	> 0.05
(b) Gap position					
(i) Forest edge 2	32	350	215		
Forest edge 1	32	987	215	9.13	0.004
(ii) Gap edge	21	1129	235		
Gap centre	21	1833	235	4.48	0.049
(iii) Forest edge 1	32	350	171		
Forest edge 2	32	987	171		
Gap	32	1406	171	9.79	< 0.001
Forest understorey	4	606	145		

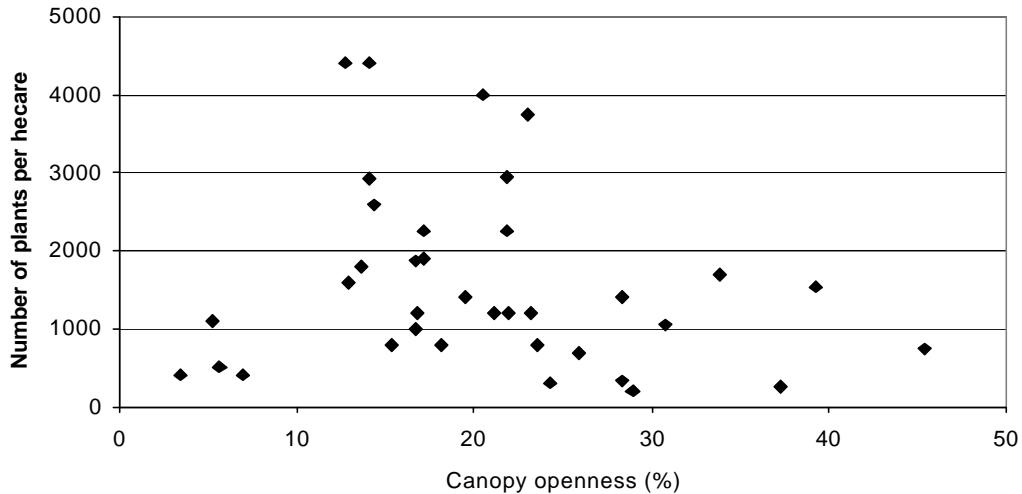


Figure 4.8 Mean number of recruits in relation to canopy openness in the 32 artificial gaps and in the four transects in the forest understorey, in the first two years after gap creation.

4.5.1.5 Mortality

Mean annual mortality rate of seedlings was 3.9 % in the forest understorey. Mortality rates did not differ between gap size classes or in relation to plot position within or around gaps. However, mortality in the gaps was significantly higher than in the forest edge plots (Table 4.7). Canopy openness showed a relatively high correlation with mortality ($R^2 = 0.24$, $DF = 35$, $p < 0.002$) with a clear tendency to increase with increasing canopy openness (Figure 4.9).

4.5.1.6 Regeneration of commercial species

The total number of seedlings of commercial species on the plots was too low to conduct a statistical analysis. However, two years after gap creation, the relative density of seedlings of commercial species in the seedling community showed a tendency to decrease from the smaller to the larger gaps. Recruitment of commercial species varied in an irregular way, with peaks in the small and very big gaps and similar values in the medium and big gaps. The growth of this group of species varied in a similar way as to that of all plants analysed together. The higher mean growth rate of these species in the natural forest (0.38 cm yr^{-1}) compared with the growth of all species together (0.24 cm yr^{-1}) might be because some of them are pioneers (Table 4.8).

Table 4.7: Mean and standard error annual mortality of seedlings in the artificial gaps two years after gap creation and in the undisturbed forest understorey. F and P values are derived from analysis of variance to test (a) effects of gap size alone, (b(i)) effects of forest edge position nested within gap size using data from all four gap sizes, (b(ii)) effects of within gap position (edge vs. centre) nested within gap size using data from the three largest gap size classes and (b(iii)) effects of plot position considering forest edge 1, forest edge 2 and the four gap sizes altogether nested within gap size.

		N	Mortality (% yr ⁻¹)	Standard error	F-value	p-value
(a)	Gap size					
	Small	16	11.82	0.02		
	Medium	8	13.80	0.03		
	Big	4	18.99	0.04		
	Very big	4	18.04	0.04	1.33	0.287
(b)	Gap position					
	(i) Forest edge 2	32	2.65	2.19	0.36	0.554
Forest edge 1	32	4.50	2.19			
(ii)	Gap edge	21	17.75	2.44	0.19	0.667
	Gap centre	21	16.03	2.44		
(iii)	Forest edge 1	32	4.49	2.06	4.22	< 0.05
	Forest edge 2	32	2.65	2.06		
	Gap	32	13.06	2.06		
	Forest understorey	4	3.91	2.87		

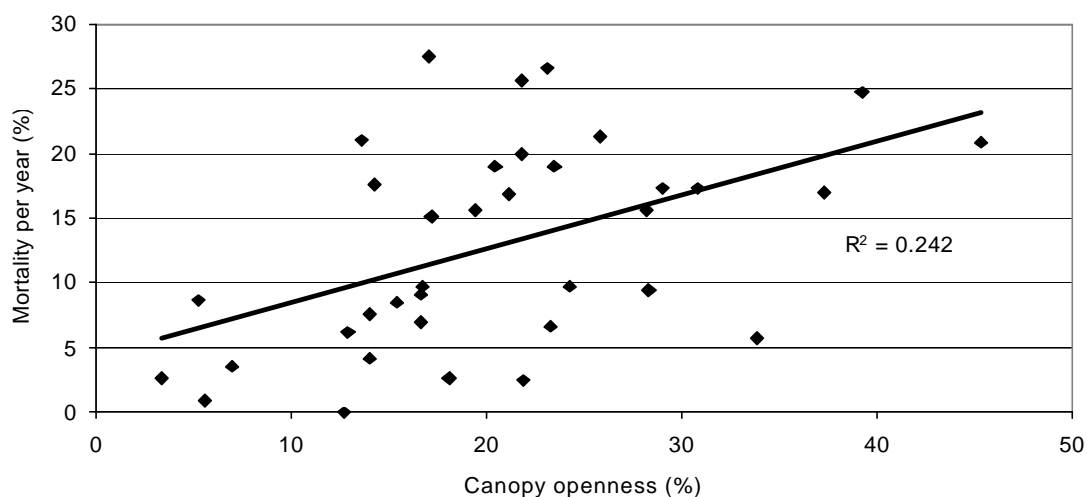


Figure 4.9 Seedling mortality rate according to canopy openness in the 32 artificial gaps and in the forest understorey, in the first two years after gap creation. The regression line shown has the form $y = 4.33 + 0.416x$ ($R^2 = 0.24$, $DF = 35$, $p < 0.02$)

Growth rates showed a very low correlation with canopy openness ($R^2 = 0.0046$, $DF = 35$), probably because of the low number of plants (Figure 4.10). As expected mortality was highest in the very big gaps. In general mortality patterns for commercial species are not different from the other species (Table 4.8).

Table 4.8: Mean and standard error seedling density (seedlings ha^{-1}), recruitment (seedlings ha^{-1}), growth ($cm\ yr^{-1}$) and mortality ($\%\ yr^{-1}$), of commercial species in the artificial gaps and in the undisturbed forest understorey

Density	N	Number of plants (ha^{-1})	Standard error.
Small	16	892	221
Medium	8	728	141
Big	4	562	72
Very big	4	646	294
Understorey	4	1137	275
Recruitment		Number of plants (ha^{-1})	Standard error.
Small	16	471	215
Medium	8	71	38
Big	4	98	35
Very big	4	200	82
Understorey	4	150	54
Growth		Mean diameter increment($cm\ yr^{-1}$)	Standard error
Small	16	0.87	0.08
Medium	8	1.00	0.09
Big	4	1.08	0.13
Very big	4	0.99	0.17
Understorey	4	0.38	0.09
Mortality		Annual mortality rate (%)	Standard error
Small	16	2.08	2.01
Medium	8	7.71	3.84
Big	4	3.55	3.55
Very big	4	13.00	9.43
Understorey	4	3.08	1.08

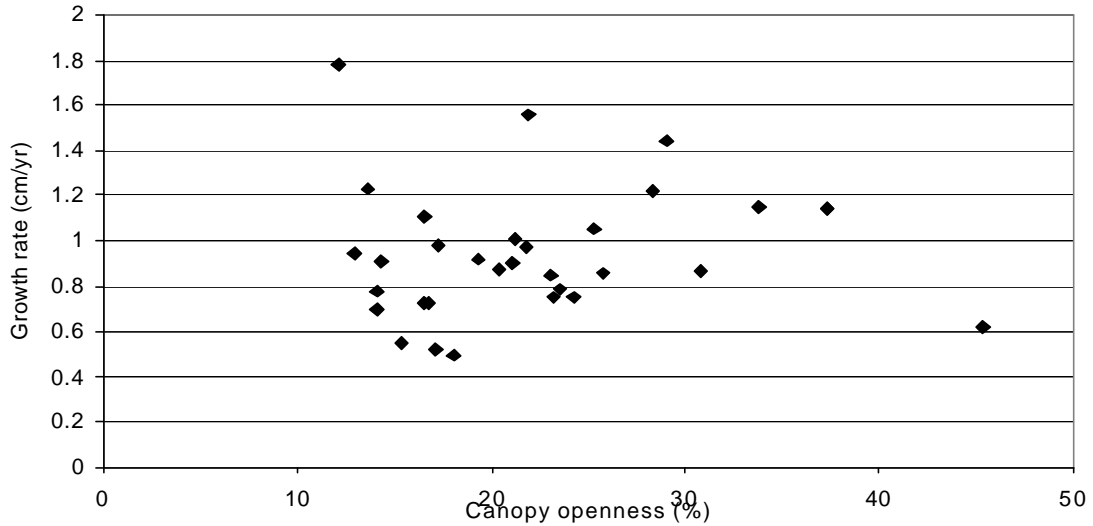


Figure 4.10: Mean seedling growth rate (cm yr⁻¹) of commercial species, in the 32 artificial gaps and in the four transects in the forest understorey, in the first two years after gap creation, in relation to canopy openness.

4.5.2 Natural regeneration in the felling gaps and natural forest in PC Peixoto managed areas

The felling gaps varied in size from 190 to 550 m² with an average of 340 m². Canopy openness was also variable ranging from a minimum of 11 % to a maximum of 23 % and averaging 17 % (Table 4.9).

Table 1: Gap area (m²) and canopy openness (%) for ten gaps in the managed forest of PC Peixoto.

Gap	Area (m ²)	Canopy openness (%)
1	345.5	20.6
2	335.5	22.2
3	641.0	22.6
4	546.3	20.6
5	173.5	16.3
6	240.5	15.7
7	190.5	10.8
8	315.5	12.2
9	329.0	10.7
10	280.2	22.4
Average	339.7	17.4

4.5.2.1 Species richness and diversity

The species richness and diversity of the seedling community in the forest understorey at PC Peixoto were a little lower than in the forest understorey in the CPAF-ACRE forest (Tables 4.2 and 4.10). However, in the felling gap zones, sampled before logging, the calculated diversity was very similar to or even higher than in the CPAF-ACRE forest understorey. The percentage of pioneer species in the seedling community at PC Peixoto before harvesting was 1.5- 2.1 % (Table 4.10). One year after harvesting it has risen to 30 % in the crown zone and 45 % in the trunk zone, both similar to the percentages found in the small gaps in the artificial gaps experiment (Table 4.10). In the second year after logging there was a tendency for both disturbed areas to have a similar proportion of pioneers (35-36 %). As expected, diversity of the seedling community varied a great deal in response to logging. However, two years after logging diversity was already similar to that in the undisturbed forest understorey (Table 4.10).

Table 4.10 Mean species richness, Fisher's α diversity index and relative density of pioneers in the felling gaps (trunk and crown zones) and in the undisturbed forest understorey before gap creation (1997) one (1998) and two (1999) years after gap creation.

1997	Number of species	Number of stems	Pioneers (%)*	Fisher's α
Understorey	104	746	1.9a	32.86
Trunk	98	478	1.5a	37.33
Crown	101	534	2.1a	36.86
1998	Number of species	Number of stems	Pioneers (%)*	Fisher's α
Understorey	105	826	1.6a	31.89
Trunk	30	92	44.6b	15.47
Crown	58	369	29.5c	19.33
1999	Number of species	Number of stems	Pioneers (%)*	Fisher's α
Understorey	108	848	2.4a	32.83
Trunk	55	186	35.4b	26.36
Crown	76	377	35.9b	28.68

* percentages followed by the same letter are not significantly different (χ^2 test, $p < 0.01$)

4.5.2.2 Seedling density

Seedling density in the natural forest at PC Peixoto in 1997 (7546 plants ha⁻¹) was similar to that in the plots of the future felling gaps before harvesting in both crown (7786 plants ha⁻¹) and trunk zones (6829 plants ha⁻¹). After harvesting, seedlings density in the gap zones fell drastically especially in the trunk zone where the logs were transformed into planks. This conversion process required movement of the logs and resulted in the mortality of most seedlings in the trunk zone (Tables 4.11).

Table 4.11 Mean and standard error seedling density (number of plants ha⁻¹) and standard error, in the five plots in the natural forest and in the seven plots in the crown zone and seven in the trunk zone in the felling gaps, before gap creation (1997), one year after gap creation (1998) and two years after gap creation (1999).

	N	1997	Standard error
Natural forest	5	7546	255
Felling gap (trunk)	7	6829	320
Felling gap (crown)	7	7786	536
		1998	Standard error
Natural forest	5	7182	215
Felling gap (trunk)	7	1300	313
Felling gap (crown)	7	5143	608
		1999	Standard error
Natural forest	5	7371	158
Felling gap (trunk)	7	2286	562
Felling gap (crown)	7	5229	546

4.5.2.3 Seedling growth

Seedling growth was measured from the first to the second year after logging. Seedling growth rates were greater in the crown zone (0.40 cm yr⁻¹) than in the forest understorey (0.21 cm yr⁻¹) (one way anova, $p < 0.05$), but did not differ significantly between the trunk zone (0.29 cm yr⁻¹) and forest understorey. Seedlings growth rates also was significantly higher in the crown zone than in the trunk zone (paired t-test, $p < 0.05$) (Table 4.12).

Table 4.12 Mean and standard error annual diameter increment (cm yr⁻¹) in trunk and crown zones of the gaps and in forest understorey two years after gap creation.

	N	Mean diameter Increment*	Standard error	F-value	p-value
Understorey	5	0.21	0.01		
Trunk zone	7	0.29	0.05	1.18	0.300
Understorey	5	0.21	0.01		
Crown zone	7	0.40	0.03	17.17	0.002
	N	Mean diameter Increment**	Standard error	t-value	p-value
Trunk zone	7	0.29	0.05		
Crown zone	7	0.40	0.03	1.84	0.116

* means tested by one way anova

** means tested by paired t-test

4.5.2.4 Recruitment

The mean recruitment rate in the forest understorey was 462 recruits ha⁻¹ yr⁻¹. In the crown zones of the felling gaps the mean recruitment was 1392 recruits ha⁻¹ yr⁻¹ and in the trunk zones 1350 plants ha⁻¹ yr⁻¹. The differences in recruitment between the crown zones and the forest understorey were significantly different (anova one way p < 0.05) but the difference between the trunk zones and forest understorey were not significant (Table 4.13). The seedling community in the trunk zones after logging was entirely composed of recruits (Table 4.13)

Table 4.13: Mean and standard error number of recruits of seedlings > 1 m height onto plots in managed forest over two years, in undisturbed forest understorey and the trunk and crown zones of the felling gaps in PC Peixoto managed area (number of plants ha⁻¹) two years after logging.

	N	Recruits yr ⁻¹ (plants ha ⁻¹)*	Standard error	F-value	p-value
Understorey	5	462	118		
Trunk zone	7	1392	238	9.45	0.012
Understorey	5	462	118		
Crown zone	7	1350	211	10.67	0.008
	N	Recruits yr ⁻¹ (plants ha ⁻¹)**		t-value	p-value
Trunk zone	7	1392	238		
Crown zone	7	1350	211	0.11	0.919

* means tested by anova one way

** means tested by paired t-test

4.5.2.5 Seedling mortality

Seedling mortality in the forest understorey was 4.62 % yr⁻¹ over two years. In the crown zones of gaps created by felling trees, seedling mortality after logging was 59.61 % and in the trunk zones 100 % (Table 4.14). From the first to the second year after logging there were no differences in seedling mortality rates between forest understorey and gaps. The seedling mortality rate for the period from 1997 to 1999 in the forest understorey was 4.62 % and was significantly lower than both gap zones (Table 4.14).

Table 4.14: Mean and standard error seedlings mortality (% of plants yr⁻¹) in the felling gaps (trunk and crown zones) and in the undisturbed forest understorey one year after logging (1997-1998) from the first to the second year after logging (1998-1999) and in the two first years after logging (1997-1999).

	N	Annual mortality rate (%) 1997-1998*	Standard error	F-value	p-value
Understorey	5	5.41	2.28		
Crown zone	7	59.61	13.04	19.27	0.001
Trunk zone	7	100.00	0.00		
		Annual mortality rate (%) 1998-1999*	Standard error	F-value	p-value
Understorey	5	2.86	7.53		
Crown zone	7	11.59	4.36	0.01	0.942
Understorey	5	2.86	7.53		
Trunk zone	7	3.34	9.31	3.65	0.085
		Annual mortality rate (%) 1998-1999**	Standard error	t- value	p-value
Trunk zone	7	3.34	9.31		
Crown zone	7	11.59	4.36	1.81	0.121
		Annual mortality rate (%)* 1997-1999*	Standard error	F-value	p-value
Understorey	5	4.62	1.48		
Crown zone	7	44.31	1.72	26.54	< 0.001
Trunk zone	7	100.00	0.00		

* means tested by anova one way

** means tested by paired t-test

4.5.2.6 Commercial species regeneration

The density and recruitment of seedlings of commercial species into the seedling community did not differ between undisturbed forest understorey and the gap zones two years after logging. Mean growth rates were higher in the crown and trunk zones but, the total number of seedlings of commercial species on the plots was too low to conduct a statistical analysis (Table 4.15).

Table 4.15: Mean and standard error density (ha^{-1}), recruitment (seedlings ha^{-1}) and growth (cm yr^{-1}) and mortality ($\% \text{ yr}^{-1}$) of commercial species in the felling gaps and undisturbed forest understorey two years after gap creation.

Density	N	Number of plants ha^{-1}	Standard error
Understorey	5	209	47
Trunk zone	7	114	49
Crown zone	7	135	30
Recruitment		Number of plants ha^{-1}	Standard error
Understorey	5	44	9
Trunk zone	7	136	36
Crown zone	7	114	30
Growth rate		Mean annual diameter increment (cm yr^{-1})	Standard error
Understorey	5	0.35	0.11
Trunk zone	5	0.35	0.14
Crown zone	7	0.85	0.22
Mortality		Annual mortality rate (%)	Standard error
Understorey	5	2.36	2.36
Trunk zone	7	100.00	0.00
Crown zone	7	61.10	8.91

4.6 Discussion

4.6.1 Artificial gaps

Some well-known pioneer species were present only in the gaps (e.g. *Trema micrantha*., *Schefflera morototoni*, *Jaracatea spinosa*. and *Ceiba* sp.) as well as species that are common in flooded areas (e.g. *Calycophyllum* sp., *Erythrina* sp. and *Hura crepitans*). The *Ceiba* species in the East and Central Amazon are common only in the *várzea* (flooded) forests, and apparently only in Acre and Rondônia States are they found in *terra-firme* forests (personal observation). Some non-pioneer species such as *Micropholis venulosa* and *Brosimum rubescens*, were found only in the gap areas. The sprouts produced by the felled trees and residual seedlings explain the presence of these “classical” non-pioneer species only in the gaps. This factor also explains the high species richness of the gaps.

The small differences in species diversity between small, medium and big gaps, and the natural forest and forest edges plots just one year after gap creation, supports Hawthorne (1993) who found little evidence to suggest that low intensity logging reduced either species diversity as a whole or the diversity of non-timber forest products in Ghana. The low woody plant seedlings diversity in the big and very big gaps, in the first year after gap creation, was a consequence of the high impact of gap creation on the original seedling community. The diversity index increased over time in all gaps, so that the small and medium gaps showed higher values than the forest understorey plots by in the second year. However, there was a clear indication that diversity will recover slower in gaps larger than 1000 m², or in gaps with high canopy openness (e.g. greater than 30 %). Fortunately, such gaps are rare even when mechanised forest exploitation is practised (e.g. Uhl and Vieira, 1988). In addition, the trends suggest that the number and diversity of species in the very big gaps will increase as succession proceeds (e.g. Rajesh, 1996) and reach higher values than the natural forest.

The significant increases in the relative density of pioneer species with increasing gap size and canopy openness over the first two years is supported by the work of Barton (1984) who showed that the density of seedlings of pioneer species in a forest in Costa Rica is higher in larger gaps. Barton (1984), also showed that the seedling density of non-pioneer species did not differ among gap sizes, and that there was no evidence for the hypothesis that pioneer species regenerate more effectively in the gap centre and non-pioneer species in the gap edges. In contrast, in my experiment the relative density of pioneer species was significantly greater in the gap

centres than the gap edges. The removal of all seedlings during gap creation probably favoured the entrance of more pioneer species, which did not have to compete with an already established seedling community.

The low seedling density in the gaps compared with the forest understorey two years after gap creation can be interpreted as resulting from a high mortality rate of new recruits in the second year, particularly in the larger gaps (Table 4.7). Only in small gaps did recruitment continue at high levels in the second year. 1998 was an “el Niño” year which resulted in a long dry season in Acre. As a result, the micro-climate in the gaps (temperature, humidity and water availability) would have been less favourable for seedling survival (Schumpp *et al.* 1989; Welden *et al.* 1990). Finally the big gaps were colonised by an unidentified species of grass (vernacular name Taquari), which was not present in the small gaps and might have competed strongly with the seedlings of woody plants thereby reducing their recruitment (personal observation).

Seedling growth rates were also affected by gap size and canopy openness. After two years, mean diameter growth rates showed a high correlation with canopy openness (Figure 4.6). In very large gaps, light levels are higher and composed of higher proportions of photosynthetically active wavelengths than small gaps or in adjacent forest understorey (Denslow *et al.* 1990).

Plot position within gaps did not influence growth rate of the seedlings. Although, canopy gaps provide heterogeneous environments for the growth of seedlings, it is known that PAR receipts typically decline away from the gap centre (Brown, 1996) and it was expected that growth rates would be greater in gap centres than gap edge, particularly for pioneers.

The regeneration of commercial species was highly variable between gap size classes in terms of the density and recruitment of seedlings, but showed no overall trend. It is possible that, the recruitment of some commercial species with pioneer traits, such as *Cedrela odorata*, might have benefited from the gap creation but the response was hidden by pooling all commercial species into one group.

4.6.2 Felling gaps

The size of the gap created by felling a tree depended on the size of the tree and the structure of the surrounding forest. Small gaps consisted only of the crown zone, while larger ones created the classical “chablis” (Oldeman, 1978) shaped gap (formed by the area of the former crown of the felled tree and the crown zone after felling). Thus, the felling of a tree sometimes produced disturbed areas in places other than the site

where the crown fell. These areas may or may not receive increased canopy openness. Therefore, they may or may not be considered as part of the gap (e.g. Brokaw, 1982, Popma *et al.* 1988). For felled trees, these areas are usually around the trunk, because felling does not result in uprooting. As a result this zone was sometimes disturbed, but did not receive a different amount of irradiance from the natural forest.

In this experiment, the trunk zone was used to convert the logs to planks that were later removed from the gap area, causing some soil compaction and leaving a large amount of wood residue covering the soil. In general, the gaps produced by the logging in PC Peixoto could be classified as small (openness around 20 %) or, less often, medium gap (canopy openness greater than 20 % but less than 25 %). The felling gaps of PC Peixoto were also measured in the field, but this practice demanded high labour and probably was not precise and was abandoned.

The composition, richness and diversity of species in the seedling community in the areas before logging were similar, with values of Fisher's λ between 32 and 37; they were also similar to the undisturbed forest understorey in CPAF-ACRE (Tables 4.2 and 4.10). The colonisation of the crown zone of the felling gaps was slower than in the artificial gaps. These differences might be caused by the branches of the crown's acting as a barrier to the germination of seeds and establishment of seedlings, thereby limiting recruitment in this zone. A similar effect was reported by Putz (1983) who showed that seedlings of pioneer species were concentrated in the root zone (*sensu*, Orians, 1982) of gaps in a semi-evergreen forest in Panama, because the root zones, are clear of roots and free from litter and overhead shade. These factors assist the germination and establishment of pioneer species. In addition in the crown zones 40 % of the original seedlings survived from the logging in the seedling community, increasing competition in these areas. These seedlings also affect the calculated mean growth rates because most of them were damaged or remained suppressed under the branches of the crowns and did not grow during the study period. Seedling mortality in the crown zones decreased significantly from the first to the second year after logging, becoming not-significantly different from the undisturbed forest understorey. It is possible that the high survival was determined by the fact that the seedlings and saplings were already established and were protected by the branches of the crowns.

In the trunk zone, the felling of the tree, conversion of the logs to planks and skidding of the planks killed almost all the original seedlings. In addition, the residues (e.g. sawdust) of the logs interfered with the germination of the seeds and reduced the rate of recruitment. The low mean growth rate of seedlings in this zones is possible

associated with the low exposure to irradiance (in some cases no exposure at all). A high proportion of pioneer species colonised these areas in the first year, probably because of the absence of competition from other plants and the availability of seeds in the seed bank of this group of species. As in the artificial gaps experiment, the density and recruitment of seedlings of commercial species was not affected by gap creation.

4.7 Conclusions

Gaps of small and medium (from 100 to 400 m² or canopy openness from 10 to 20 %) size result in improved regeneration from a forest management point of view than larger gaps. The small gaps possess fewer pioneer plants, a higher diversity of tree seedlings that showed lower mortality rate, although the mean seedling growth rates in the two first years was significantly lower than in the very large gaps.

The size and canopy openness of the gaps affected the growth, recruitment, mortality and composition of the seedling community. Prior classification of gaps by size agreed broadly with the subsequent measurement by canopy openness, but the categories sometimes overlapped. This overlap occurred because of the influence of the surrounding forest on gap formation. The proximity of a natural gap had the potential to increase the canopy openness of a small or medium gap, making their openness more similar to that of larger gaps. This problem represents a limitation of Brokaw's (1982) gap-size definition. The results provided by the canopy openness measurements are more reliable.

The composition of the seedling community in the gaps was determined by processes occurring before gap creation (those leading to establishment in the forest understorey) and those occurring after gap formation such as, the mortality and recruitment rates in the different zones of the gap (or different disturbed areas). This combination of processes might lead in the short-term to differentiation in the species composition of the seedling community within gaps. It is likely that a range of strategies have evolved among the species present leading to differential success in different zones of the gaps.

The seedlings of commercial species were not affected by gap creation in any way other than an increase in growth rates. One explanation for this lack of response might be that there are major physiological and ecological differences within the group of commercial species which mask the expected effects of gap creation on the commercial species that are pioneers.

CHAPTER 5

Effects of small scale forest management on forest dynamics and growth of the residual trees

5.1 Introduction

The effect of forest management on the dynamics and growth of the residual forest, varies as a function of intensity of harvest or basal area extracted (Cannon *et al.* 1994), cycle length (Vanclay, 1989; Appanah, 1990) and skidding techniques (Costa Filho, 1991; Abdul *et al.* 1992; Dykstra and Heinrich, 1992; Pinard and Putz, 1996). Opening of gaps and trails results in increases in the growth rates of the residual trees and changes in the forest dynamics. In general mortality and recruitment rates show a short-term increase after harvesting (Maitre, 1987; Chai and Sia, 1989; Primack *et al.* 1989; Abdul *et al.* 1992; Silva *et al.* 1996). As a result dramatic changes can also be observed in species composition and forest structure (Cannon *et al.* 1994) depending on the harvesting rate and the silvicultural system adopted.

When more severe harvesting rates are applied for example the removal of all emergent trees for commercial or silvicultural reasons a large number of pioneer trees recruit in the felling gaps, which leads to a delay in the development of forest for the next cycle. These sorts of harvesting rates are common in monocyclic systems (e.g. Chai and Udarbe, 1977) which are no longer regarded as suitable for tropical forests (Dawkins and Philip, 1998).

The effect of harvesting on the diameter increment of trees has been reported to start around the second year after harvesting and to persist until around the fifth year (Silva, 1989). In general this effect is restricted to the residual trees surrounding felling gaps, so that the increase in the growth rates in the managed forest as a whole is diluted by the unaffected trees. Hence, the rate of change in the growth rate and the time during which growth will remain significantly different from the natural forest, is a function of the number of harvested, damaged and silviculturally treated trees during logging. Planning of harvesting and skidding activities, and the application of silvicultural treatments (girdling and liana cutting) can reduce significantly the damage produced by forest management (Oliveira and Braz, 1995; Johns *et al.* 1996).

A major concern arising from forest management is whether the silvicultural techniques will be sufficient to maintain a large enough population of the managed species to avoid both local extinction and genetic erosion. Forest exploitation is supposed to act in an analogous way to silvicultural treatments by increasing its

growth rates and maximising regeneration. Felling trees is regarded as a simulation of natural forest gap dynamics (Hilton, 1987). Therefore, the ecological changes that occur after harvesting must be examined in order to identify the appropriated mixture of interventions that optimises cycle length and harvesting intensity.

In the forest management project at the Pedro Peixoto colonisation project, the volume harvested at each cycle (about $10 \text{ m}^3 \text{ ha}^{-1}$) results in a residual standing commercial volume of around $20 \text{ m}^3 \text{ ha}^{-1}$ and an additional standing volume of $150 \text{ m}^3 \text{ ha}^{-1}$ of non-commercial timber. It is important, for management of future cycles, to determine the influence of forest exploitation on tree growth, mortality and recruitment. The behaviour of the managed forest with respect to its composition, growth, recruitment, and mortality was studied using permanent sample plots (PSPs) located inside the managed areas. Permanent sample plots have been widely used for studying natural forest dynamics (Chiew and Garcia 1989; Primack *et al.* 1989; Rai 1989; Silva *et al.* 1996), and to predict production and yields in forest management projects (Weaver and Murphy, 1990; Condit and Hubbell, 1995). Although expensive and time consuming, PSPs play a major role in ecological and management studies; they are and will continue to be one of the main pillars upon which our understanding of tropical forest is built (Sheil, 1995).

Amazonian forests have a high species diversity, which results from the presence of a small number of abundant species and a much greater number of rare species. To study the dynamics of individual species in this environment is not easy whereas to study species within functional groups that possess similar characteristics is more feasible. Therefore, for the study of dynamics, species with common ecological characteristics are usually aggregated in groups.

Many authors have suggested or used different criteria for classifying species, usually related to the size, growth rates, ecology or economic use of the species (e.g. Budowski, 1955; Manokaran and Kochummen, 1987; Silva, 1989; Hubbell and Foster, 1990; Vanclay, 1991). The classification adopted must meet the objectives of the studies and produce practical groups of reasonable size.

According to Swaine and Whitmore (1988), there are two qualitatively distinct groups of tree species, pioneer and climax or non-pioneer species. Subgroups are acceptable, so long as it is realised that they are arbitrary segments of a continuum. For this study I accepted this classification and subgroups were formed for short-lived (small) and large pioneer species (*sensu* Swaine, 1983) and canopy and understorey shade-tolerant species using the diameter distribution of these species (from a previous systematic forest inventory conducted in the area, Chapter 3 – Forest inventory results). The size-class distribution of classical species of each group was

used as a reference e.g. *Cecropia* sp. (short-lived pioneer), *Ceiba pentandra* (large pioneer), *Dipteryx odorata* (canopy tree), *Rheedia floribunda* and *Pansandra trianae* (understorey species). The present division is an approach based on previous studies and characteristics of the species that occur in the study area. Palms were not considered because of their different characteristics and growth patterns (Oldeman, 1990).

In this study, trees on the border of artificial gaps were also studied to identify the influence of the canopy opening and gap size on the growth of these trees. Therefore, this study is a first attempt to provide general information about the dynamics of tropical forest in Acre State by comparing its behaviour in a non-disturbed condition and after harvesting. This study will help to answer some of the questions that still remain in tropical forest research, and will allow us to improve the management systems that exist today and lead to a better understanding of the forest ecosystem.

5.2 Objectives

- To study forest dynamics (growth, recruitment and mortality) in the managed areas.
- To study the growth rate of trees in the borders and neighbourhood of the gaps

5.3 Research questions

- Do forest management activities, performed according the prescriptions of this project, affect species diversity or change significantly the population of the managed species?
- Is the yield of the residual trees significant to sustain wood production, and does the silvicultural system applied increase the productivity of the forest as a whole?
- Do gap size and canopy openness have a significant effect on the growth rate of the residual trees surrounding the gap edge?

5.4 Methods

5.4.1 Permanent sample plots

This study was performed using four permanent sample plots (PSPs) located in the CPAF-ACRE – EMBRAPA experimental area and five PSPs in the PC Peixoto management areas. The distance from CPAF-ACRE to the managed areas in PC Peixoto is approximately 80 km by road.

At CPAF-ACRE the managed area of the project is 20 ha, and was exploited in 1992, at a harvesting rate of $20 \text{ m}^3 \text{ ha}^{-1}$. The forest (*terra-firme*) has a typical well-drained soil, and an average volume of around $180 \text{ m}^3 \text{ ha}^{-1}$ for trees over 10 cm dbh and a basal area ranging from 25 to $30 \text{ m}^2 \text{ ha}^{-1}$. Therefore, it is very similar in structure to the forest at PC Peixoto (see inventory results in Chapter 3). At CPAF-ACRE, the PSPs were distributed across the forest, so that two were in the managed area and two in undisturbed areas on the edge of the managed areas. The two PSPs in the undisturbed forest were about 500 m apart and the PSPs in the managed area around 300 m apart. The minimum distance between any two plots was 300 m. Because of the low number of replicate PSPs in the CPAF-ACRE forest, no statistical comparisons were made with the results from the PSPs at PC Peixoto. In PC Peixoto, the five PSPs were installed in five different management areas, two on the Nabor Junior trail 400 m apart and three on the Granada trail (the first two 400 m from each other and the third one about 800 m from the second). The distance between the two trails is about 10 km.

The PSPs are square plots of 1 ha, sub-divided into 100 sub-plots each of 100 m^2 (10 x 10 m). On them, all trees over 20 cm dbh were tagged, identified and measured. In 20 randomly selected sub-plots in each PSP, all trees > 5 cm dbh were also tagged, identified and measured. The study involved the measurement of tree growth, recruitment, mortality and species richness and diversity. The period of study was 7 years for the PSPs at CPAF-ACRE, with repeated measurements, 3, 5 and 7 years after the PSP establishment. For the PSPs at PC Peixoto, the period of study was 3 years with measurements starting before logging and repeated 1 and 2 years after logging. Tree crown exposure was assessed as following the same classification as Silva *et al.* (1996)

Table 5.1: Crown exposure classification and definitions

Crown exposure class	Definition
1. Full overhead light	The complete tree crown receives direct sunlight
2. Some overhead light	The tree crown receives some direct sunlight
3. Shaded	The tree crown does not receive direct sunlight

5.4.2 Species groups

Species groups were recognised as follows

1. Pioneer species: short-lived pioneers and large pioneers (Appendix 4)
2. Shade tolerant species: understorey trees and canopy trees
3. Commercial species: all species which have been sold in the Rio Branco city market by the farmers (Appendix 2).

5.4.3 Artificial gaps

The study was carried out in the borders of the artificial gaps in CPAF-ACRE (Chapter 4). All trees > 10 cm dbh were identified and measured annually on plots, located in concentric rings 0-5 m and 5-10 m from the edges of the gaps (Figure 5.1). Growth rates on the Permanent Sample Plots in undisturbed forest at CPAF-ACRE were compared with rates in the gap border plots. The species groups and the gap size classes considered were the same as in Chapter 4.

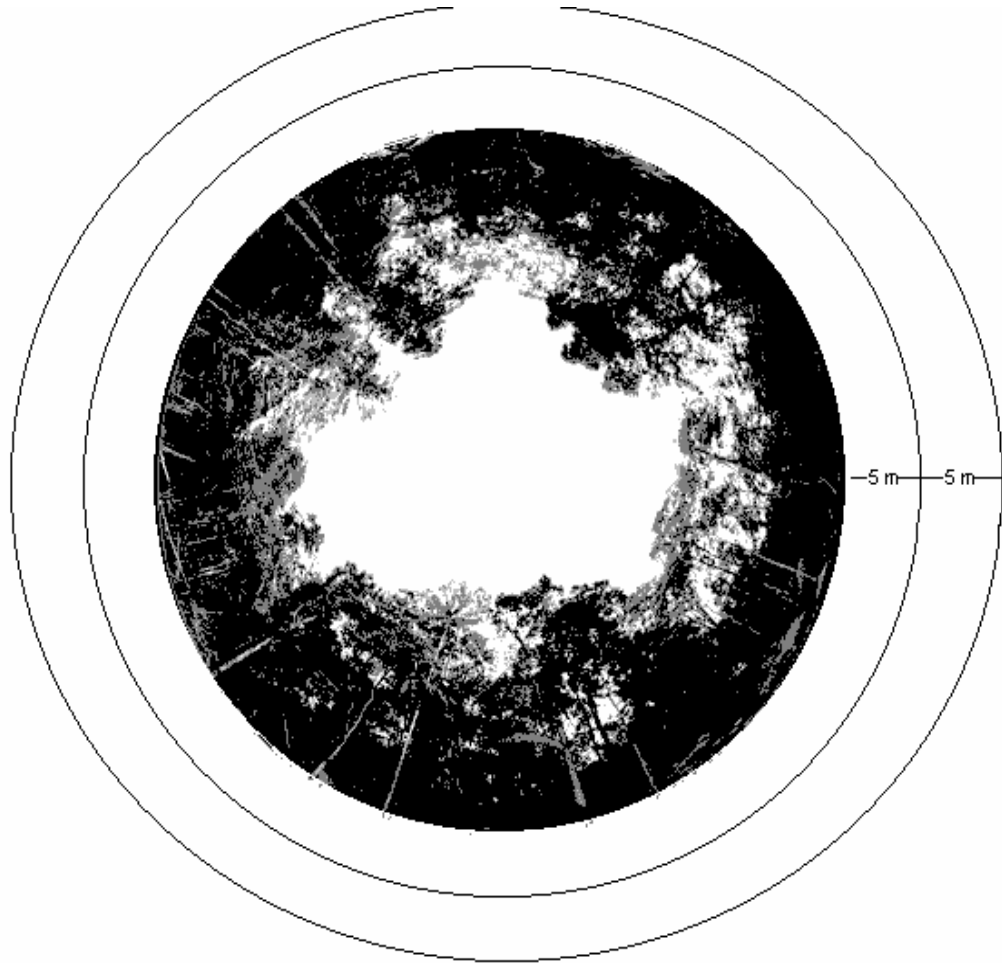


Figure 5.1: Diagram to show the location of the plots surrounding the gap borders of the artificial gaps at distance of 0-5 and 5-10 m from the edge of the gaps.

5.4.4 Data manipulation and analysis

Species richness was defined as the total number of species on plots (Kent and Coker, 1992) and diversity is expressed using Fisher's α . This index was chosen because it is stable to changes in sample sizes and can be used to predict the number of species in larger samples (Condit *et al.* 1996, 1998).

The differences in growth rates were tested statistically using Tukey's test following one way anova for species groups and crown exposure, one way Anova for mean diameter increment in the artificial gaps and t tests for comparison between the mean diameter increment of the PSPs in the undisturbed forest in CPAF-ACRE and the mean diameter increment of the plots in the artificial gaps. Whether was evidence

that the residuals were not normally distributed the data were transformed using the Box Cox transformation (Minitab 12.23). The anova tables are presented in the Appendix 6.

Mortality rates

Mean annual mortality (*AMR*) rates were calculated using the following formula (Sheil *et al.* 1995), by the formula:

$$AMR = 1 - (N_1/N_0)^{1/t}$$

Where N_0 and N_1 are population counts at the beginning and end of the measurement interval, t .

Recruitment rates

The recruitment of all plants which attained the minimum measurement diameter of 5 cm dbh. Recruitment rate was standardised by dividing the total number of recruits in one census by the number of adults in the previous census, then dividing by the census interval (Condit *et al.* 1995).

Growth rates

Growth rates were calculated using the formula

$$(dbh_2 - dbh_1) / t$$

Where dbh_1 and dbh_2 are diameter at the beginning and end of measurement interval t respectively.

5.5 Results

5.5.1 Forest dynamics in the PSPs

5.5.1.1 Mean Diameter growth rate

Species groups

Diameter increment varied from around 2 cm yr⁻¹ (e.g. *Jaracatea spinosa*) to 0.1 cm yr⁻¹ and even less for some understorey species (e.g. *Quaribea guianensis*). Some rare species with only one plant sampled showed negative growth. It is likely that this is a measurement error, and merely means that these plants were not growing. The pioneer and shade-tolerant species groups showed significant differences in mean relative growth (Table 5.2).

Table 5.2: Mean and standard error diameter increment and relative growth rate for species groups of the trees on the permanent sample plots in CPAF-ACRE and in Pedro Peixoto Colonisation Project.

Group	Number of plots	Growth rate (cm yr ⁻¹)	Standard error	Relative growth rate*	Standard error
Short-lived pioneer species	9	0.63	0.25	0.034a	0.014
Big pioneer species	9	0.57	0.29	0.030ab	0.012
All pioneer species group	9	0.61	0.25	0.033a	0.011
Canopy species	9	0.29	0.03	0.017b	0.003
Understorey species	9	0.21	0.03	0.019b	0.002
All tolerant species group	9	0.26	0.28	0.018b	0.002
All trees	9	0.28	0.04	0.019	0.035

* means followed by the same letter are not significantly different (Tukey test, $p < 0.05$)

Crown exposure and diameter classes

Crown exposure had a strong influence on diameter increment. For all trees independent of ecological group, there were significant differences among all crown illumination classes considered. On the PSPs, the variation in mean diameter increment variation due to crown exposure was from 0.47 cm yr⁻¹ (trees with full overhead sunlight) to 0.19 cm yr⁻¹ (shaded trees). Trees which only received some direct sunlight, had a mean growth rate of 0.34 cm yr⁻¹ (Table 5.3). Diameter class did not affect the mean diameter increment of the trees when they were analysed within crown exposure classes.

Table 5.3: Mean annual diameter increment by diameter classes and crown illumination on the nine permanent sample plots at CPAF-ACRE and Pedro Peixoto Colonisation Project.

Diameter classes	Full overhead light		Some overhead light		Shaded	
	Growth rate (cm yr ⁻¹)	Standard error	Growth rate (cm yr ⁻¹)	Standard error.	Growth rate (cm yr ⁻¹)	Standard error
5-10	0.42	0.05	0.29	0.06	0.20	0.02
10-19.9	0.57	0.11	0.43	0.04	0.21	0.01
20-29.9	0.38	0.03	0.32	0.02	0.25	0.02
30-39.9	0.50	0.05	0.30	0.02	0.32	0.04
40-49.9	0.40	0.06	0.37	0.05	0.36	0.10
50-59.9	0.55	0.07	0.34	0.01	0.22	0.08
> 60.0	0.45	0.04	-	-	-	-
Average for all plants*	0.47a	0.06	0.34a	0.06	0.25b	0.03

*Means followed by different letters are significantly different (Tukey test, $p < 0.05$)

5.5.1.2 Stand basal area increment

The permanent sample plots in the mechanised managed areas in CPAF-ACRE showed a higher mean basal area increment than the permanent sample plots in the natural forest. The high impact logging practised in the managed areas at CPAF-ACRE (mechanised logging and removal of 20 m³ ha⁻¹) resulted also in a higher basal area increment (0.35 m² yr⁻¹) in the first three years after logging (Figure 5.2) than that obtained by the low impact management (non-mechanised logging and removal of 8 m³ ha⁻¹) in PC Peixoto (0.28 cm yr⁻¹) two years after logging (Figure 5.3).

The total stand basal area increment in the natural forest in the first seven years of measurement was 0.05 m² yr⁻¹ (0.39 m³ ha⁻¹ yr⁻¹) and in the PSPs in the managed area (mechanised) 0.26 m² yr⁻¹ (2.49 m³ ha⁻¹ yr⁻¹). The commercial species considered were all marketable species in Rio Branco City. The mean annual stand basal area increment of these commercial species seven years after logging was 0.15 m² ha⁻¹ yr⁻¹ (1.36 m³ ha⁻¹ yr⁻¹) and 0.04 m² ha⁻¹ yr⁻¹ (0.30 m³ ha⁻¹ yr⁻¹) in the natural forest. Stand basal area increment showed a tendency to decrease from the beginning to the end of the period in the mechanically managed area (Figure 5.2).

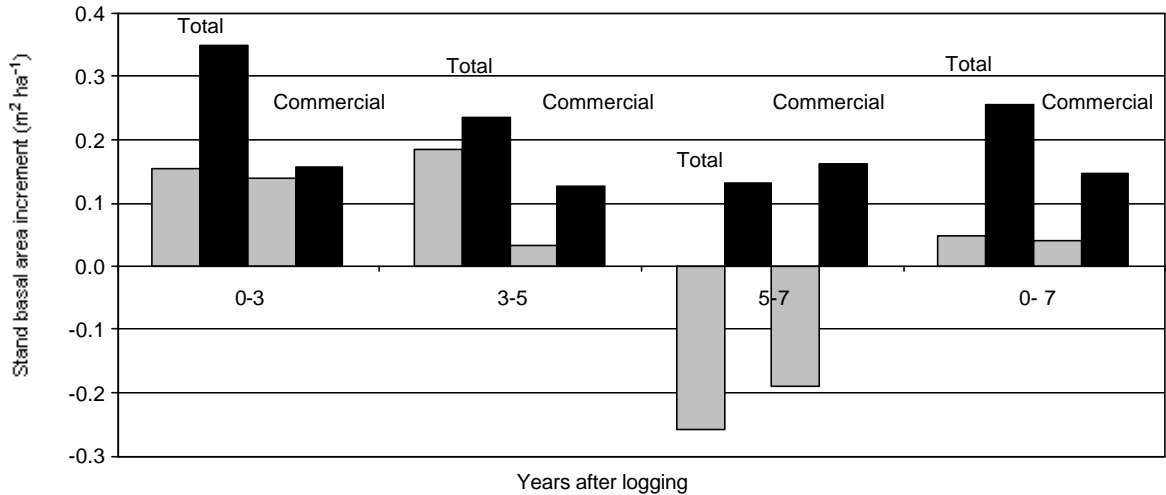


Figure 5.2: Total and commercial species stand basal area increment, calculated as the difference between initial and subsequent stand basal area for each category independently, in the undisturbed (gray columns) and managed areas (black columns) during the first 7 years after logging at CPAF-ACRE.

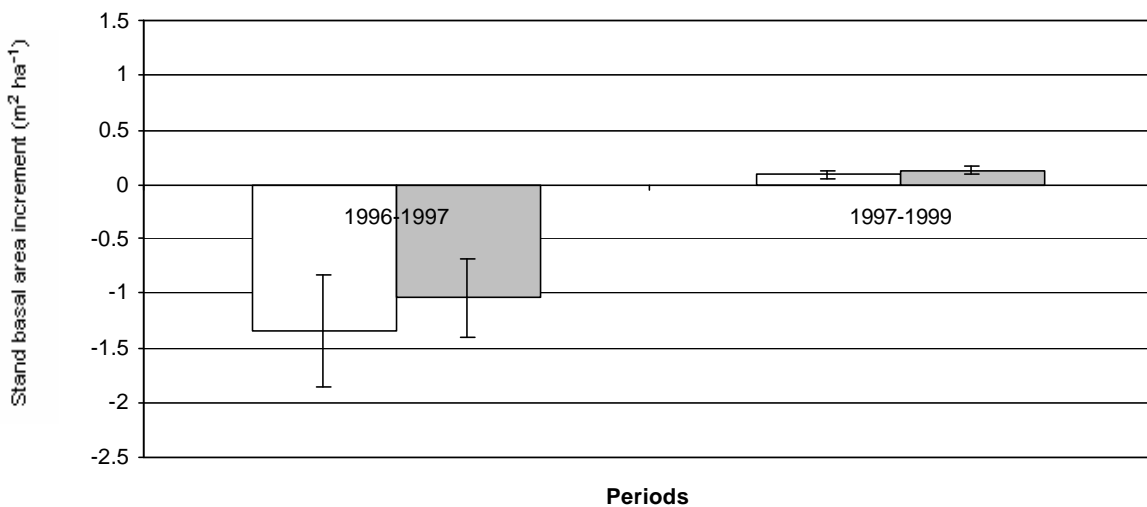


Figure 5.3: Total (white columns) and commercial (gray columns) annual stand basal area increment in the PC Peixoto areas, calculated as in Figure 5.3, in the periods from 1996 to 1997 (one year before logging) and from 1997 to 1999 (two first years after logging). The first period includes losses due to logging. Bars show ± standard error.

In the permanent sample plots in PC Peixoto (non-mechanised logging), the total stand basal area before logging was 24.28 m² ha⁻¹ and the stand basal area of the commercial species 5.96 m² ha⁻¹. The logging of the areas caused a reduction in total stand basal area to 22.93 m² ha⁻¹ and in the stand basal area of the commercial species to 4.89 m² ha⁻¹. Two years after logging the mean stand basal area in these permanent sample plots was 23.12 m² ha⁻¹ and the stand basal area of commercial species 5.33 m² ha⁻¹, which

represent a mean annual increment of $0.09 \text{ m}^2 \text{ ha}^{-1} \text{ yr}^{-1}$ ($0.76 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$) for the total stand basal area and $0.13 \text{ m}^2 \text{ ha}^{-1} \text{ yr}^{-1}$ ($1.06 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$) for the commercial species (Figure 5.3).

5.5.1.3 Mortality rates

As the PSPs in CPAF-ACRE were established after the logging occurred, the measured mortality rates at this site do not represent exactly the effect of the mechanised logging on the forest. However, from the first year after logging to the 7th, mortality was high in these managed areas, showing a mean rate of $4.1 \% \text{ yr}^{-1}$. In the undisturbed areas mortality rates were $2.1 \% \text{ yr}^{-1}$ in the same period. In the site with non-mechanised logging (PC Peixoto), mortality immediately after logging was 3.7% , and two years after, $3.2 \% \text{ yr}^{-1}$. The average for the period was $3.0 \% \text{ yr}^{-1}$. A peak in the mortality was observed from 98-99 (4.0%), which have might be on influenced by the “El Niño” event that year, since one year after logging the mortality was only 2.2% (Figure 5.4).

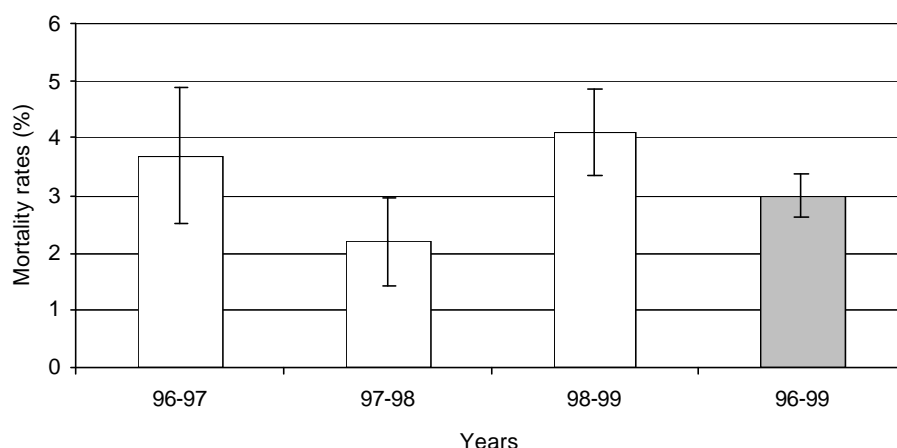


Figure 5.4: Mortality (trees above 5 cm dbh) in the five permanent sample plots in the Pedro Peixoto Colonisation Project (non-mechanised forest management), immediately after logging (96-97), one (97-98), and two (98-99) years after logging, and the mean rate (gray column) for the two years after logging (96-99). Bars show \pm standard error.

5.5.1.4 Recruitment rates

For this study, I used recruitment of trees above 5 cm dbh, which explains the high recruitment rates of 32 (natural forest), 36 (non-mechanised logging) and 50 (mechanised logging) plants $\text{ha}^{-1} \text{ yr}^{-1}$ in the first two years after logging (Table 5.4). Recruitment was higher in the mechanically managed areas and similar in the

undisturbed forest and in the low impact (non-mechanised) forest management (Table 5.4).

Table 5.4: Mean and standard error recruitment rate (stems > 5 cm dbh yr⁻¹ ha⁻¹) in the mechanically managed and undisturbed permanent sample plots in CPAF-ACRE in the first three years after logging and in the non-mechanised logging in the permanent sample plots of Pedro Peixoto Colonisation Project

	Number of plots	Recruitment rate* (ha ⁻¹ yr ⁻¹)	Standard error
Undisturbed areas	2	32	
Managed areas (mechanised)	2	50	
Managed areas (non-mechanised)	5	36	16.6

5.5.1.5 Damage produced by the exploitation and by natural causes in the permanent sample plots in the non-mechanised forest management in Pedro Peixoto Colonisation Project

In the managed areas of PC Peixoto (low impact forest management), the damage caused by the logging operations represented 1.21 m² ha⁻¹ or 5.1% of the stand basal area one year after logging. The damage caused by natural causes (e.g. wind and storms) in the same period was 1.02 m² ha⁻¹ or 4.3 % of the stand basal area. The damage caused by logging was greater in the first years after logging, probably due to the death of damaged trees. Two years after logging there were still some trees dying as a result of the effect of the logging, but the damage caused to the forest by natural causes was higher. The damage produced by natural causes showed a tendency to increase after the harvesting, from 0.61 m² ha⁻¹ one year before to 1.61 m² ha⁻¹ two years after logging (Figure 5.6).

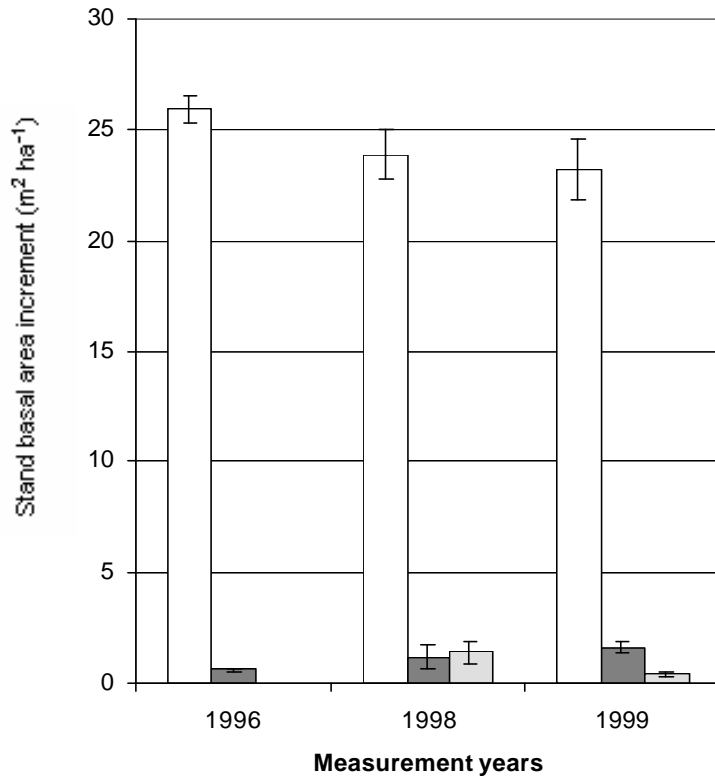


Figure 5.5: Mean and standard error basal area of non damaged (blank columns), damage caused by natural causes (dark gray columns) and damage caused by logging (light gray columns), before logging (1996), one (1998), and two (1999) years after logging. Bars show \pm standard error.

5.5.1.6 Species richness and diversity

Two years after logging the number of species was lower in the managed areas at PC Peixoto colonisation project than before harvesting (235 and 259 respectively). The density of stems of commercial species with dbh > 5 cm was similar before and two years after logging. Fisher's index varied from around 84 before harvesting to 81 after logging (Table 5.5).

Seven years after mechanised logging at CPAF-ACRE there is still a considerable difference in both species diversity and richness compared with the natural forest. However the density of commercial species for trees greater than 5 cm dbh was similar on all samplings occasions (Table 5.5).

Table 5.5 Species richness and diversity in the natural forest, high impact management forest and managed forest in PC Peixoto (non-mechanised low impact management)

	Total number of stems	Number of stems of commercial species	Total number of species	Number of commercial species	Fisher's α based on all species
Natural forest	780	106	164	25	63.3
Managed (mechanised) forest 3 years after logging	703	104	137	19	50.8
Managed (mechanised) forest 7 years after logging	726	103	145	20	54.5
PC Peixoto before logging	1737	265	259	35	84.3
PC Peixoto two years after logging	1390	225	235	32	81.1

5.5.2 Diameter increment around artificial gaps and in adjacent natural forest

The mean growth rate of trees was significantly greater (one way anova, $n = 32$, $p < 0.01$) within the 5 m of the border of the gaps (mean 0.44 cm yr^{-1}) than at the distance of 5-10 m from the border (mean 0.34 cm yr^{-1}). The trees in both locations (0-5 m and 5-10 m from the gap edge) were also significantly greater than the mean for trees in the undisturbed forest (t-test of the mean) in the study period (from 1997 to 1999) (Figure 5.6). Gap size did not affect diameter increment (means test $p < 0.05$) of the trees in the borders around the gaps (Figure 5.7). Canopy openness also did not effect the growth of trees around the gaps. The correlation between diameter increment and canopy openness was insignificant for both sets of measured trees (Figure 5.8).

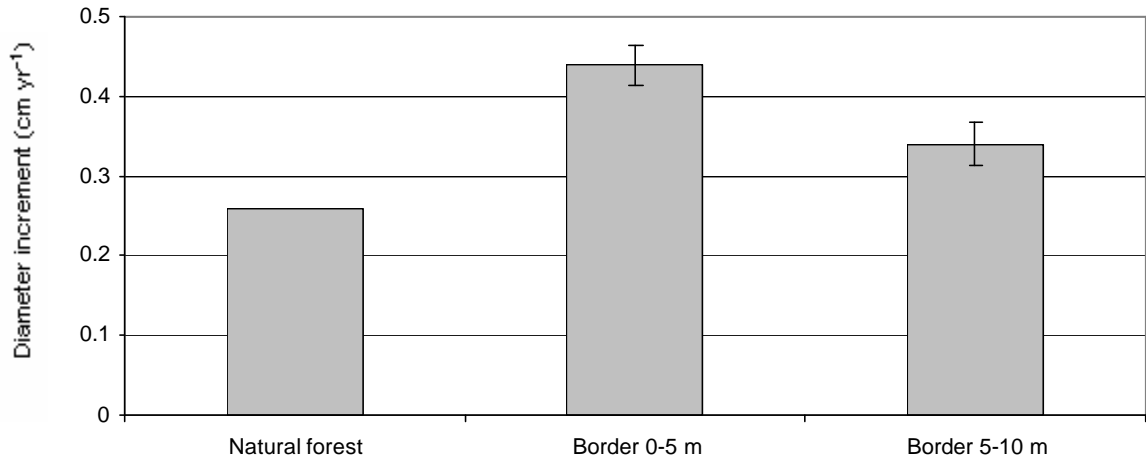


Figure 5.6: Mean annual diameter increment (cm yr⁻¹) of trees located around the 32 artificial gaps at distances of 0 m to 5 m from the gap border and from 5 m to 10 m from the gap border, two years after gap creation, and the mean diameter increment in the two permanent sample plots in the undisturbed forest for the same period. Bars show standard error.

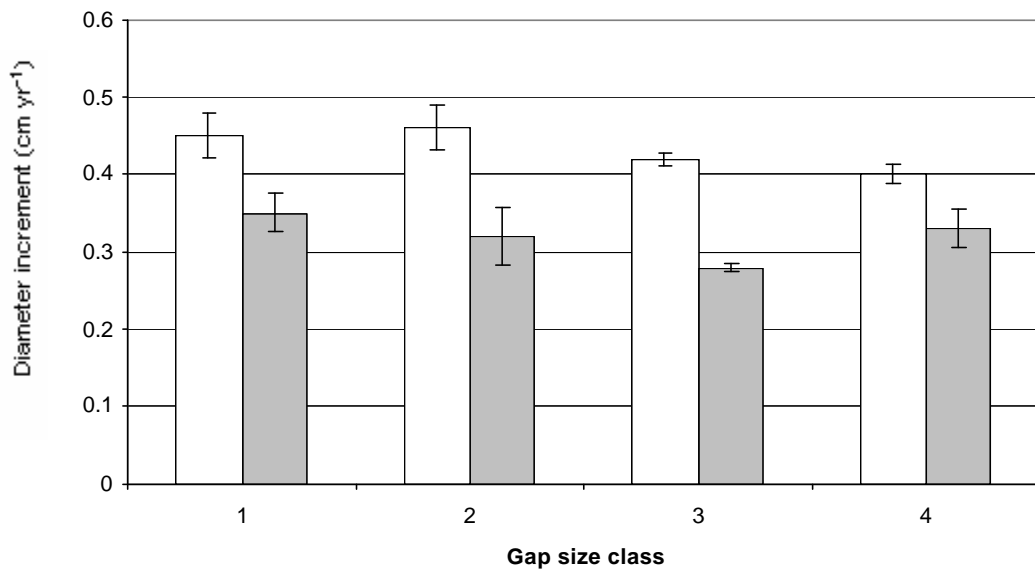


Figure 5.7: Mean annual diameter increment (cm yr⁻¹) in relation to gap size for trees located from 0 m to 5 m from the gap borders (white columns) and from 5 m to 10 m from the gap border (gray columns), two years after gap creation. Bars show \pm standard error. Gap size classes are as follows: 1, 100 m²; 2, 400 m²; 3, 800 m²; 4, 1200 m².

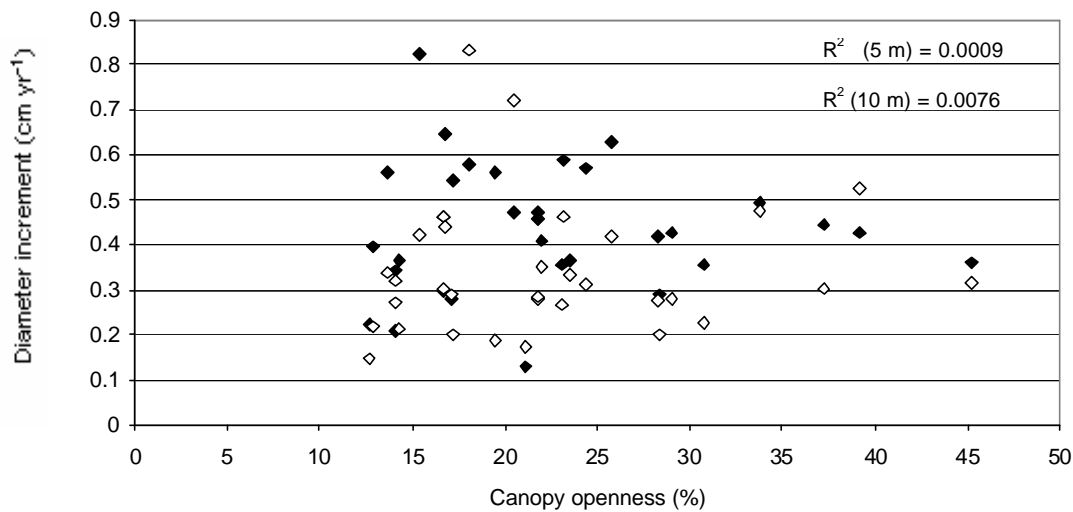


Figure 5.8: Mean annual diameter increment of trees located from 0 m to 5 m from the gap border (closed symbols) and from 5 m to 10 m from the gap border (open symbols) in relation to canopy openness of the adjacent gap, two years after gap creation.

5.6 Discussion

Tree diameter increment

The periodic annual diameter increments recorded here were similar to other values obtained in tropical forests (e.g. Okali and Ola-Adams 1987; Chiew and Garcia 1989; Primack *et al.* 1989; Rai 1989; Silva *et al.* 1996) showing an average of 0.27 cm yr⁻¹ for the plants measured on all PSPs in the period (CPAF-ACRE and PC Peixoto).

Differences in crown exposure had a highly significant effect on the growth of the trees. This effect is well known and has been reported before (e.g. Silva, 1989, 1995). However, the results presented in this thesis demonstrate that a considerable increase (of up to 100 %) in the mean annual diameter increment can be expected following a change of the crown exposure of a tree (Table 5.3). This finding provides strong support for the application of silvicultural treatments in the region.

Different species groups also showed significant differences in their relative diameter increments. The pioneer species group presented a significantly higher diameter increment than the shade-tolerant species, although the sub-groups did not possess significantly different relative growth rates. However, the considerable difference in the mean diameter increment of canopy species and understorey species can be indicates that even after grouping into shade-tolerant and pioneers species, there are still species with very different growth patterns within the groups.

These species could cause misinterpretation of growth data when all species are pooled together for analysis. Thus, it is expected that big trees such as *Bertholletia excelsa* will continue to grow fast in diameter classes over 1 m dbh, because this species can reach diameters greater than 2 m dbh, while small trees such as *Gustavia augusta* will grow slowly after they reach 20 cm dbh, because this is the approximate maximum diameter of these species.

Diameter increment was not affected by diameter class when analysed within crown exposure classes. Diameter increment in this study was affected only by crown exposure to sunlight. There is an expectation in the literature that diameter increment increases with tree size (e.g. Swaine *et al.* 1987) possibly because most of the slow-growing trees die when they are small and because the big tree class includes no understorey species. The study of diameter increment in big trees is often difficult because of the need to survey large areas to obtain a significant sample of their populations (Clark and Clark, 1996). In this study, for statistical reasons, trees larger than 60 cm dbh were concentrated in a single diameter class. Therefore it is debatable whether the diameter increments of big trees tend to decline or not. Clark and Clark (1996) found that annual diameter increment was negatively correlated with diameter in four out of the five species they studied in Costa Rica. There is a general belief (e.g. Vanclay, 1989) that this decline is a consequence of the increase of respiratory demands relative to the effective photosynthetic area in large trees. However, other studies have showed a linear increase in diameter increment from the first to the last diameter classes considered (e.g. Alder, 1990; Wong, 1997). This pattern seems to vary among species, but might be expected that the death of a tree does not occur only by accident (e.g. storms) and that it is a side-effect of a physiological process that is also manifested in diameter increment decline (senescence).

Stand basal area increment

The stand basal area increment in the first two years after exploitation in PC Peixoto was similar to the stand basal area increment in the undisturbed areas in CPAF-ACRE, possibly because of the residual effects of the damage produced by the logging operations, and the short period of measurement. The greater stand basal area increment in the areas subjected to high impact management (mechanised logging) during the period is an effect of the greater canopy opening during the harvesting and skidding operations. This difference in increment is significant

considering that only around 20 % of the sub-plots in the PSPs in these areas were actually affected by exploitation.

The greater volume increment of the commercial species ($1.06 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$) in the PSPs at Pedro Peixoto colonisation project compared with the total volume increment ($0.76 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$) can be interpreted as an increase in the population of the commercial species in the total volume in the forest. This might be an effect of directional felling, which aimed to reduce the environmental impact of logging and the protection of residual trees of commercial and potential species.

Mortality

Mortality rates (mean 2.1 \% yr^{-1}) in the undisturbed natural forest were similar to the values obtained in other studies in tropical forests (Lieberman and Lieberman, 1987; Swaine *et al.* 1987; Rankin-de-Merona, 1990) of between 1 % and 2 % yr^{-1} . The proximity of the mean in my study to the upper limit may be an effect of natural disturbances in the plots during the measurement period.

The greater increment and mortality in CPAF-ACRE during the last measurement interval (1997-1999), even in the natural forest, was probably a consequence of a higher occurrence of winds and storms in this period caused by the “El Niño” event. To some extent, these effects were also observed in the forest management using non-mechanised methods, where the losses of basal area from natural causes increased during the same period. The effect of harvesting in those areas on tree mortality were still being observed two years after harvesting, but decreased sharply during the period. Tree mortality in the forest management using mechanised methods was probably underestimated, because the first measurement was carried out one year after logging. Nevertheless, the heavier logging practised there and the use of tractors (a Skidder) to skid the logs resulted in a higher mortality in the residual trees than at the other study site.

Recruitment

Recruitment in the areas managed by the farmers in PC Peixoto (non-mechanised logging), was similar to the natural forest. The canopy opening caused by the harvesting operations was minimised by the low number of trees extracted (around two trees ha^{-1}) and by the use of oxen to skid the planks. However, as recruitment considered only trees with a dbh greater than 5 cm, the period of time covered by the study was not sufficient to incorporate the cohort of trees which germinated

immediately after the logging. Thus, an increase in the recruitment rates in those areas may be expected in the next few years.

In the mechanised forest management system, the recruitment rate was higher than the undisturbed forest even seven years after harvesting. The damage produced by felling the trees ($20 \text{ m}^3 \text{ ha}^{-1}$ or around 4 trees ha^{-1}) and skidding the logs produced an opening in the forest canopy around 15 % of the total managed area (Oliveira and Braz, 1995). The creation of large gaps allowed the higher recruitment rates. The high harvesting intensity used in the mechanised logging was the responsible for the difference in the basal areas between the natural forest and the managed areas, one year after logging.

Damage

In this study logging damage for all trees was estimated from the basal area of trees which fell or had their crowns destroyed in or around felling gaps. Therefore even those trees that fell as a result of natural causes (e.g. high winds and storms) after the logging operations were considered as having been damaged by exploitation, because the increase in tree's crown exposure was caused by non-natural causes.

The damage resulting from natural causes in the managed areas at PC Peixoto, increased from the first to the last measurement, and was associated with the logging impact. However, the increase in the damage resulting from natural causes probably occurred because 1998 was an atypical year, with more frequent and stronger storms in the area.

Species diversity and richness

The variation in species richness and diversity in the PSPs in PC Peixoto before and after logging was too low to be considered significant. It is possible that before the end of the felling cycle (10 years) this area will show an even higher diversity than before management started because of the opportunities for invasion by pioneer species given by canopy opening. The density of commercial species apparently did not change following the removal of one or two trees per hectare (in low impact forest management). The mechanised forest management, at least in the short-term, produced a significant variation in the composition of the forest. However, once more, the density of commercial species did not change significantly.

Tree diameter increment in the borders of the gaps

The significantly higher diameter increment of the trees near the gap borders was an expected effect of decreased competition for light and nutrients. That this increment remained significant in the trees 5 to 10 m from the border supports the theory of the extended gap (Canham *et al.* 1990) and suggests that as gap size increases, light can penetrate even greater distances into the understorey. However, no significant differences could be found in the increment of these trees with differences in gap size or canopy openness.

5.7 Conclusions

The increase in diameter increment in a tree is produced by a change in the status of its crown exposure to sunlight. Thus, the increase is only observed in the residual trees surrounding natural gaps or felling gaps, while the average growth rates of trees in managed forest as a whole is lower, as a consequence of dilution by the unaffected trees. Hence the rate of change in growth and the time during which it will remain significantly different from the natural forest is correlated with the number of trees surrounding the gaps produced by logging.

The influence of mechanised management was positive in terms of basal area increment. For the forest management at PC Peixoto, although the harvesting effect was not observed effectively, the expectation is that the effects will be determined at the next measurement of the permanent sample plots and that the short felling cycles will be shown to have contribute to preventing stagnation of growth by frequent gaps creation. For management using long cycles, although the diameter growth enhancement still exists after seven years, the influence of the opening is unlikely to continue throughout the entire cycle (e.g. Silva 1989), and extra silvicultural treatments would be necessary before the next logging to maintain growth rates.

Maintenance of the volume increment of commercial species in both forest management systems was compatible with the logging intensity and cycle length proposed. The density and recruitment of commercial species were not significantly affected by management.

CHAPTER 6

Modelling growth, yield and the selection harvesting

6.1 Introduction

The long-term management of forests for wood production is a primary objective of forestry. To achieve this in natural forests, information is required about the growth, mortality and recruitment rates of trees of different species. There are three techniques for acquiring this growth rate information: stem analysis, time series data and permanent plots (Alder, 1990).

Timber production based on growth and yield studies has never been practised in the Brazilian Amazon (Silva *et al.* 1996). The determination of sustainable cuts for long-term timber production is practised empirically. There is not enough information from the forest with the result that cycle lengths and harvesting intensities are defined by the IBAMA (Brazilian Institute for the Environment and Natural Resources). EMBRAPA (Brazilian Agriculture Research Corporation) and INPA (Amazonian National Research Institute) have been monitoring PSPs in Tapajós National forest (Pará State, east Amazon) and ZF2 Reserve (Amazonas State, central Amazon) since the 1980s (Silva *et al.* 1989, 1995 and 1996, Higuchi *et al.* 1995). Most of these data have been published recently especially in scientific reviews, but access to it for people working in the field is still very limited.

The Brazilian forest code was prepared in 1965, and established that the pristine forests of the Amazon basin could only be used under forest management plans. The technical requirements for these plans, however, were only defined in 1991 (Silva, 1992). These new regulations establish criteria for logging operations, silvicultural treatments, cycle length, harvesting and monitoring. The monitoring rules determine that the managed forest must be evaluated in intervals between cuttings to assess growth, natural regeneration and to determine the necessity for silvicultural interventions (Silva, 1982).

Considerable improvements in forest management are expected to arise from these forest regulations, but sustainable forest management will only be implemented with adequate policies for land use, training for the technicians of the region and the availability of information on forest growth and yield. The Amazon is the largest continuous tropical forest in the world, and its management will depend on ecological, economic and social factors acting together. The silvicultural systems and

regulations must to be flexible to be applicable and to adjust to different circumstances.

This year (1999) IBAMA officially recognised the possibility of forest management in short cycles establishing the basic rules for its application in Amazon, as a form of low impact forest management, with low cutting rates and non-mechanised logging (Oliveira *et al.* 1998). This new view of forest management implies a different strategy for forest intervention, resulting in forest dynamics different from those produced by the high impact forest management practised nowadays. The only way to guarantee the sustainability of timber production by this system is through long-term studies of the dynamics and responses of the forests under this kind of management. These studies will lead to the definition of the most suitable cycle length, harvesting rates and silvicultural treatments.

Acquisition of data from Permanent Sample Plots (PSPs) will make possible the determination of cutting rates and felling cycle, using modelling studies which allow predictions about the standing volume of the forest in the future.

Sustained yield management of natural forests requires growth models and harvesting models to enable the reliable estimation of yields, and to enable the long-term effects of repeated logging to be evaluated. Growth models, when combined with inventory, provide a reliable way to examine harvesting options, to determine the sustainable timber yield and to examine the impacts on other values of the forest (Vanclay, 1991). Although harvesting models have not received the same attention as growth models they are an equally important component of the yield calculation (Vanclay, 1989).

In the last decades several models have been developed to simulate tropical forest dynamics using parameters and functions obtained from plots in managed forests (e.g. Nor, 1978; Vanclay, 1989; Bossel *et al.* 1989; Appanah *et al.* 1990; Boucher *et al.* 1994; Boscolo and Bongiorno, 1997), and in forests disturbed by natural causes (Burslem *et al.* 1996). This study will use the Cohort Model, in which the forest is classified in cohorts (groups of trees of the same species group and size class) and growth is simulated by updating the parameters defining a cohort over increments of simulated time (Alder, 1995b).

The aim of this study is to do a first approach in forest dynamics simulation in a tropical forest in Acre State West Amazon, under a low impact forest management without the use of heavy machinery (as described in Chapter 3), trying to identify the best possible combinations of cycle length, harvesting rates and silvicultural treatments for sustainable small-scale timber production.

6.2 Objectives

- Compare growth functions for forest trees in the East and West Amazon
- Modify a simulation model to estimate the growth and yield in the managed forest (diameter or basal area increment, mortality and ingrowth and natural regeneration modelling)
- Study simulation-harvesting models to estimate the logging yields and the impact of the management in the residual stand.
- Determine the ideal harvesting rate and cycle length for the proposed forest management system

6.3 Research question

Is the management system as practised today (as described in Chapter 3) sustainable for wood production?

6.4 Methods

For this study, the growth, mortality and recruitment functions were generated by the CAFOGROM (CPATU Amazon Forest Growth Model) software (Alder, 1995a, 1995b; Alder and Silva, 1999). CAFOGROM version 2.03 incorporates both growth models and harvesting models.

6.4.1 Model description

This system works through an interface with the two programs: SFC – Sistema de Inventário Florestal Contínuo – Manejo Operacional (Korsgaard, 1993) and CIMIR – Compilation of Increment, Mortality and Ingrowth for Regression (Alder, 1995b, Alder, 1996b). SFC generates the data files to be used by CIMIR and CIMIR generates the files CAFOGROM needs to work. Thus, CIMIR does an interface between SFC and CAFOGROM using the SFC data files to calculate increments, mortality and ingrowth from the PSPs, form the species groups and generate a basis for simulation, to be used by CAFOGROM to produce the functions for simulations and the simulation outputs (Alder, 1996a). The species groups are separated by tree size, growth rate and commercial status according to Table 6.1.

Table 6.1. Species groups generated by CIMIR.

Indicator	Description
Tree size	
A	Largest 1 % of trees > 90 cm dbh
B	Largest 1 % of trees > 60 cm but less than 90 cm dbh
C	Trees > 30 cm dbh, but less than 1 % are > 60 cm dbh
D	No trees > 30 cm dbh
P	Palm trees
X	No diameter data, typical size unknown
Mean increment	
0	No increment data available
1	Mean growth rates less than 2 mm yr ⁻¹
2	Mean growth rates 2-4 mm yr ⁻¹
3	Mean growth rates 4-8 mm yr ⁻¹
4	Mean growth rate 8 mm yr ⁻¹ or more
Commercial status	
+	Commercial species
-	Non commercial species

From Alder, 1996a

Functions in CAFOGROM

CAFOGROM uses the following functions as a basis for estimating growth, mortality and recruitment (Alder, 1996a):

1. Tree diameter increment prediction CAFOGROM uses a quadratic regression in the form

$$\Delta d = a + b_1 \cdot d + b_2 \cdot d^2 \text{ (eq. 1)}$$

Where Δd is diameter increment in cm yr⁻¹, d is diameter in cm and a , b_1 and b_2 regression coefficients, which vary between species group and for understorey (shaded) or canopy species.

2. Tree mortality is calculated as annual mortality rates (AMR) (Sheil *et al.* 1995) for each species group, and separately for damaged or malformed trees, understorey trees and canopy trees (Alder and Silva, 1999).

$$AMR = 1 - ((N_0 - N_1) / N_0)^{1/t} \text{ (eq. 2)}$$

Where t is the measurement interval in years and N_0 and N_1 are populations counts at the beginning and end of the measurement interval, excluding the recruitment.

3. Recruitment in CAFOGROM is controlled by two kinds of models. At the stand level the total basal area of recruits is calculated by a function relating recruitment basal area to stand basal area. This is referred to as the general recruitment model. The recruitment is calculated using the function

$$RBA = \alpha \cdot \exp(-\beta \cdot SBA) \text{ (eq. 3)}$$

Where RBA is the recruitment basal area, SBA is the standing basal area. The α coefficient represents the annual recruitment rate expected at zero basal area and β represents a slope factor.

The total recruitment is then allocated to species groups and to commercial and non-commercial components of each species groups, via a table of recruitment proportions that depends on disturbance class. The disturbance class is defined in terms of recruitment basal area. If recruitment is less than $0.3 \text{ m}^2 \text{ yr}^{-1} \text{ ha}^{-1}$ then disturbance is class 1. If recruitment is more than $0.3 \text{ m}^2 \text{ yr}^{-1} \text{ ha}^{-1}$ but less than $0.7 \text{ m}^2 \text{ yr}^{-1} \text{ ha}^{-1}$ then disturbance is class 2. When recruitment is greater than $0.7 \text{ m}^2 \text{ yr}^{-1} \text{ ha}^{-1}$, then disturbance is class 3.

4. Crown class allocation of trees. Trees are allocated to crown classes on the basis of standing basal area. Two crown classes are considered in the model: understorey trees and canopy trees. The proportion of understorey as a component of basal area is given by the function

$$UBA = \alpha \cdot \ln(SBA) - \beta \text{ (eq. 4)}$$

Where UBA is understorey basal area and SBA the standing basal area, both in $m^2 ha^{-1}$. Negative values of understorey basal area are given by this equation when standing basal area is below $??$ and are assumed to be zero in the model.

5. Logging damage is modelled in CAFOGROM by relating severe tree damage and direct mortality following logging to the absolute basal area extracted. The damaged trees are tracked as separate cohorts to the healthy ones, and have higher subsequent mortality. Both logging mortality and logging damage are indicated by equations with the form

$$DBA = ?HBA^? \text{ (eq. 5)}$$

Where DBA is the basal area of damaged or dead trees, and HBA is the basal area extracted in harvesting. $?$ and $?$ are regression coefficients.

6. It is necessary to limit basal area increment to avoid overestimating growth for stands at high densities. CAFOGROM uses a function of stand basal area increment to constrain total increment

$$SBAI = ? \cdot \text{Exp}(-? \cdot SBA) \text{ (eq. 6)}$$

Where SBA is the standing basal area $SBAI$ is basal area increment per annum and $?$ and $?$ coefficients.

For the analysis two sets of simulation functions were used, one generated using data from the PSPs in Acre and other taken from in Alder (1996a) and Alder and Silva (1999) using data from CPATU (East Amazon Humid Tropic Research Centre, in Pará State, East Amazon). The models of CPATU were used because of the similarities between the sites in terms of forest structure, forest dynamics, climate and latitude. Thus the greater size and age of the data sets (136 PSPs established in the field and measured from 1980 to 1994) and the sites similarities combined are a good reference to parameterise the functions of CPAF-ACRE. In addition, the CPATU work is the only experience with forest management simulation modelling in the Brazilian Amazon. Therefore the increment models developed using the CPATU PSPs act as a reference for comparison with my results. The study of PSPs in

CPATU follows the same methodology described in Chapter 5 for the PSPs in CPAF-ACRE (see Silva, 1989).

6.4.2 CAFOGROM functions generated with data from the Pará (CPATU) PSPs

The coefficients and demographic rates generated by CAFOGROM with data from the PSP in CPATU (Alder, 1996a) are shown in Table 6.2.

Table 6.2 Coefficients and rates generated by the data from CPATU

1. Tree diameter increment (eq. 1)

Increment models	Canopy trees					Understorey trees				
	Na	Nc	??	???	???	Na	Nc	??	???	???
A1	24	9	0.10989	0.00206	-0.00002	38	6	0.09958	0.00086	-0.00001
A2	3009	17	0.29189	0.00701	-0.00007	2703	18	0.10980	0.01095	-0.00017
A3	527	17	0.30365	0.01783	-0.00014	485	16	0.11953	0.01869	-0.00023
A4	361	14	0.01535	0.05965	-0.00056	358	14	0.05097	0.03725	-0.00034
B1	1126	15	0.16465	0.00503	-0.00006	1999	15	0.07510	0.00905	-0.00019
B2	5343	16	0.21351	0.00945	-0.00011	7837	17	0.11895	0.01022	-0.00016
B3	2134	15	0.30446	0.03452	-0.00043	3398	16	0.20725	0.02736	-0.00047
B4	28	10	0.19420	0.07168	-0.00082	37	5	0.23804	0.03731	-0.00070
C1	3917	13	0.02044	0.01236	-0.00016	21410	12	0.05056	0.01099	-0.00022
C2	4668	15	0.26315	0.01457	-0.00022	21414	15	0.17512	0.01444	-0.00035
C3	2858	13	0.42921	0.04824	-0.00096	10217	14	0.49032	0.02275	-0.00084
C4	1463	6	1.96588	0.02504	-0.00173	2676	7	0.75317	0.07960	-0.00297
D1	591	5	0.06244	0.01413	-0.00043	11363	8	0.02852	0.01377	-0.00049
D2	311	8	0.10063	0.02907	-0.00096	1561	10	0.07048	0.03106	-0.00120
D3	41	5	0.06260	0.13402	-0.00459	112	7	0.03540	0.06872	-0.00233
D4	17	4	0.25675	0.17045	-0.00598	76	4	-0.21628	0.21837	-0.00770
X0	2911	8	0.18822	0.00924	-0.00011	9892	9	0.07243	0.01223	-2.11E-04

Where: Na = number of trees in the groups and Nc = number of species in the group

2. Annual mortality rates (eq. 2)

Species groups	CPATU- annual mortality rate (%)			Number of trees in the samples		
	Damaged	Understorey	Canopy	Damaged	Understorey	Canopy
A1	3.90	3.79	1.62	7	40	35
A2	3.44	2.55	0.73	783	2645	2973
A3	2.30	2.83	1.81	331	394	377
A4	3.90	4.65	3.32	62	355	361
B1	2.23	2.15	0.86	472	1977	1108
B2	1.85	2.21	1.33	4484	5986	4348
B3	3.81	2.88	1.92	657	3348	2110
B4	3.90	3.79	1.62	1	37	28

Table 6.2 (continued)

C0	3.90	3.79	1.62	0	1	0
C1	4.23	3.49	1.35	3944	20809	3657
C2	5.47	4.51	1.94	2926	20989	4422
C3	5.86	3.96	2.74	1246	10073	2741
C4	9.30	9.52	1.63	135	2703	1436
D0	3.90	3.79	1.62	0	4	0
D1	4.84	3.74	1.60	1332	10955	527
D2	5.75	3.29	1.65	209	1530	299
D3	3.90	3.26	1.62	28	109	39
D4	3.90	3.79	1.62	5	74	17
X0	3.86	3.23	1.60	1929	9613	2761

3. Recruitment (eq. 3)

$$RBA = 12.558e^{-0.148 \text{ SBA}}$$

$$R^2 = 0.32$$

4. Crown class allocation of trees (eq. 4)

$$UBA = 12.531 \text{ Ln (SBA)} - 33.113$$

$$R^2 = 0.63$$

5. Logging damage (eq. 5)

$$DBA = 4.377 \text{ HBA}^{0.3763}$$

$$R^2 = 0.29$$

6. Basal area dynamics

$$ISBA = 1.6603 e^{-0.0346 \text{ SBA}}$$

6.4.3 Sensitivity analysis

The usefulness of models depends on their sensitivity to errors in parameter estimation (Pinard, 1993). A sensitivity analysis was performed in the mortality and recruitment functions of CAFOGROM to verify the effect in changing the values estimated in the volume of commercial species dbh > 50 cm (mortality) and in the volume of non-commercial species dbh > 5 cm. The volume of commercial species

above 50 cm dbh was chosen because of the interest in this variable for the predictions, and the volume of trees above 5 cm dbh because recruits are small trees which are included in the permanent sample plot measurements when they reach 5 cm dbh. The technique used was to increase and decrease by 10 % the originally estimated recruitment and mortality rates. The changes in the annual mortality rates were carried out by increasing or decreasing in 10 % the calculated annual mortality rates of each species group. The change in the recruitment rates was achieved by increasing or decreasing by 10 % the coefficient λ in the function for calculating recruitment (RBA).

$$RBA = \lambda \cdot \exp(-\lambda \cdot SBA)$$

6.4.4 Development of the simulations

Forest management simulations were tested for cycles of 5, 10, 15, 20 and 30 years over a simulation time course of 70 years. The harvesting rates varied from 0.5 to 2 $\text{m}^2 \text{ha}^{-1} \text{cycle}^{-1}$ and silvicultural treatments (ST) from zero to 2 $\text{m}^2 \text{ha}^{-1} \text{cycle}^{-1}$.

The parameters used to compare the simulations were:

- Total volume production: sum of all harvested volume ($\text{m}^3 \text{ha}^{-1}$) in the simulation time course
- Final commercial volume: the stand volume of commercial species (Appendix 2) at the end of the simulation time course ($\text{m}^3 \text{ha}^{-1}$)
- Final volume ($\text{m}^3 \text{ha}^{-1}$) of non-commercial species (dbh > 50 cm and dbh > 5 cm) at the end of the simulation time course
- Mean volume production: the mean of harvested volume per cycle ($\text{m}^3 \text{ha}^{-1} \text{yr}^{-1}$) during the simulation time course
- Coefficient of variation of the harvested volume per cycle during the simulation time course

6.5 Results

6.5.1 CAFOGROM coefficients

The coefficients and rates generated by CAFOGROM using data from ACRE PSP for diameter increment, to be compared with those from CPATU (Table 6.1) are shown in Table 6.3.

Table 6.3 Coefficients and demographic rates generated by CAFOGROM with the data from CPAF-ACRE

1. Tree diameter increment (eq. 1)

Increment models	Canopy trees					Understorey trees				
	Species group	Na	Nc	??	???	???	Na	Nc	??	???
A2	132	17	0.21299	0.00729	-0.00005	65	11	0.06293	0.01045	-0.00007
A3	73	13	0.35934	0.00631	-0.00004	24	5	0.06956	0.01252	0.00000
B1	43	5	-0.11459	0.02015	-0.00023	48	7	-0.05109	0.01336	-0.00020
B2	250	14	-0.01336	0.01913	-0.00021	209	13	0.04477	0.02272	-0.00042
B3	88	10	0.27082	0.01760	-0.00019	58	11	0.22330	0.02332	-0.00040
B4	36	9	-0.15920	0.06889	-0.00066	25	8	-0.22937	0.22046	-0.00663
C1	476	13	0.02562	0.01048	-0.00016	944	13	0.03817	0.00913	-0.00014
C2	795	15	0.06262	0.01777	-0.00025	1181	13	0.15766	0.00938	-0.00019
C3	111	11	0.17172	0.01470	-0.00012	78	10	0.38327	0.02273	-0.00057
C4	30	4	-0.01621	0.05168	-0.00090	14	4	0.44548	0.02473	-0.00011
D1	107	4	0.03887	0.01899	-0.00056	841	8	0.01474	0.01613	-0.00055
D2	109	5	0.25832	0.00735	-0.00020	420	7	0.13802	0.02766	-0.00103
D3	36	5	0.10855	0.06741	-0.00244	80	7	0.07919	0.12466	-0.00549
D4	2	2				9	1	1.28000		

2. Tree mortality rates (eq.2)

Species	Annual mortality rate (%)			Number of trees in sample		
	Damaged	Understorey	Canopy	Damaged	Understorey	Canopy
A2	6.16	2.69	2.64	4	70	134
A3	6.16	2.69	2.19	2	26	74
B1	6.16	2.69	2.19	7	56	48
B2	6.16	1.06	2.30	9	222	262
B3	6.16	2.69	2.19	2	60	92
B4	6.16	2.69	2.19	-	25	38
C1	6.16	2.74	1.87	38	984	486
C2	6.16	3.15	1.95	39	1243	811
C3	6.16	2.69	2.19	6	82	113
C4	6.16	2.69	2.19	-	17	26
D0	6.16	2.69	2.19	-	7	1
D1	6.16	2.02	2.15	19	866	119

Table 6.3 (continued)

D2	6.16	2.27	2.06	23	434	115
D3	6.16	2.69	2.19	4	79	35
D4	6.16	2.69	2.19	-	11	1

3. Recruitment (eq. 3)

$$RBA = 0.0055e^{0.1833SBA}$$

$$R^2 = 0.39$$

4. Crown class allocation (eq.4)

$$UBA = 6.1709 \ln(SBA) - 10.754$$

$$R^2 = 0.071$$

5. Logging damage (eq. 5)

$$DBA = 0.8167 * HBA^{0.7757}$$

$$R^2 = 0.65$$

6. Basal area dynamics

$$ISBA = 1.8344 e^{-0.0462 SBA}$$

$$R^2 = 0.18$$

Basal area increment function

The models generated using data from PSPs from CPATU and CPAF produced similar simulated outcomes. The CPATU model always generated a greater increment (differences varying from 0.2 m² to 0.5m² ha⁻¹ 5 yr⁻¹). These results represent a growth difference below 0.1 m² ha⁻¹ yr⁻¹ between the two sets of functions which is an indication that the studied forests from Pará and Acre State have a similar behaviour (Figure 6.1).

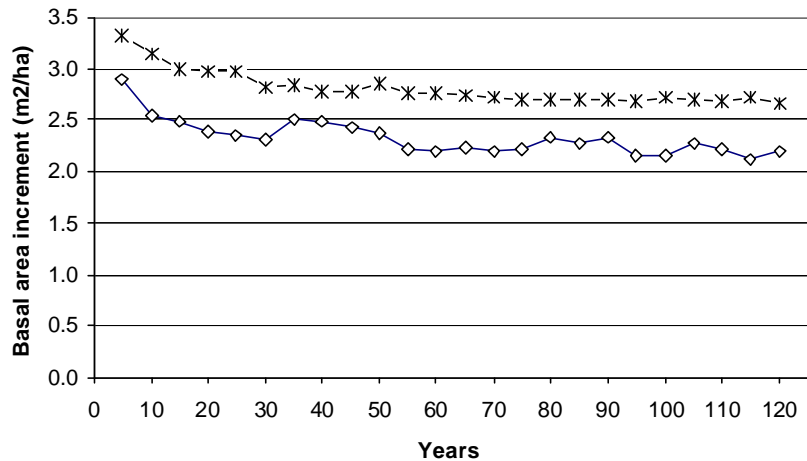


Figure 6.1: Time course of simulated basal area increment in undisturbed forest using functions derived from data from CPATU (closed symbols) and CPAF-ACRE (open symbols)

Mortality rates

The mortality rates obtained using data from CPAF-ACRE for most of the species groups were the same in the same class (e.g. damaged trees). The reason for that is that CAFOGROM replaces weak estimates by the class mean. Assuming that there are no differences between mortality rates among diameter class or species groups the use of class means cannot significantly affect the simulations. The results for CPATU and CPAF-ACRE simulated mortality rates were also similar for undisturbed forest (Figure 6.2).

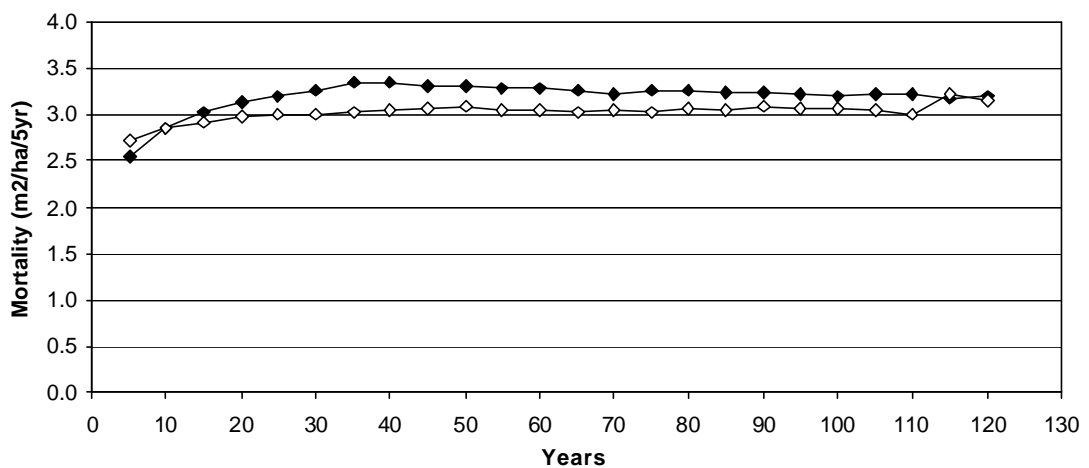


Figure 6. 2: Time course of simulated mortality rates (%) in undisturbed forest using rates obtained from data from CPATU (closed symbols) and CPAF-ACRE (open symbols)

Recruitment

Good recruitment predictions are usually difficult to obtain and demand long-term studies in a large number of PSPs. Even with the CPATU database, a low R^2 (0.32) was obtained for this function. The function generated with the data from CPAF-ACRE was unrealistic because the results presented the contrary of the natural tendency that recruitment has in tropical forest to decline with increasing stand basal area (Figure 6.3) and will not be used in this work. On the other side, despite the low R^2 , the CPATU function produced reasonable results, which was assumed to be adequate to represent the forest in Acre State.

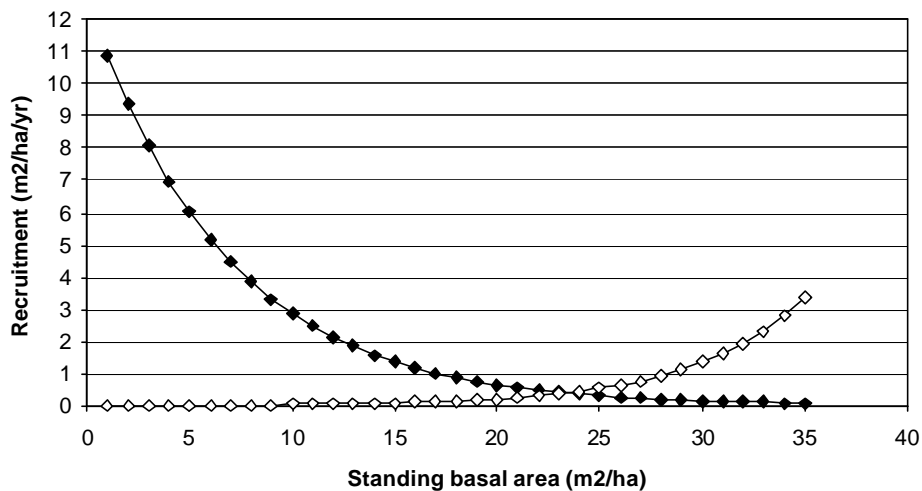


Figure 6.3: Estimated recruitment (m2/ha) using the CPAF-ACRE (open symbols) and CPATU (closed symbols) functions

Crown class allocation

The results obtained with the two data sets showed large differences especially for understorey basal areas estimated in very low standing basal areas. However there was a tendency for both estimates to become similar for greater standing basal areas (Figure 6.4).

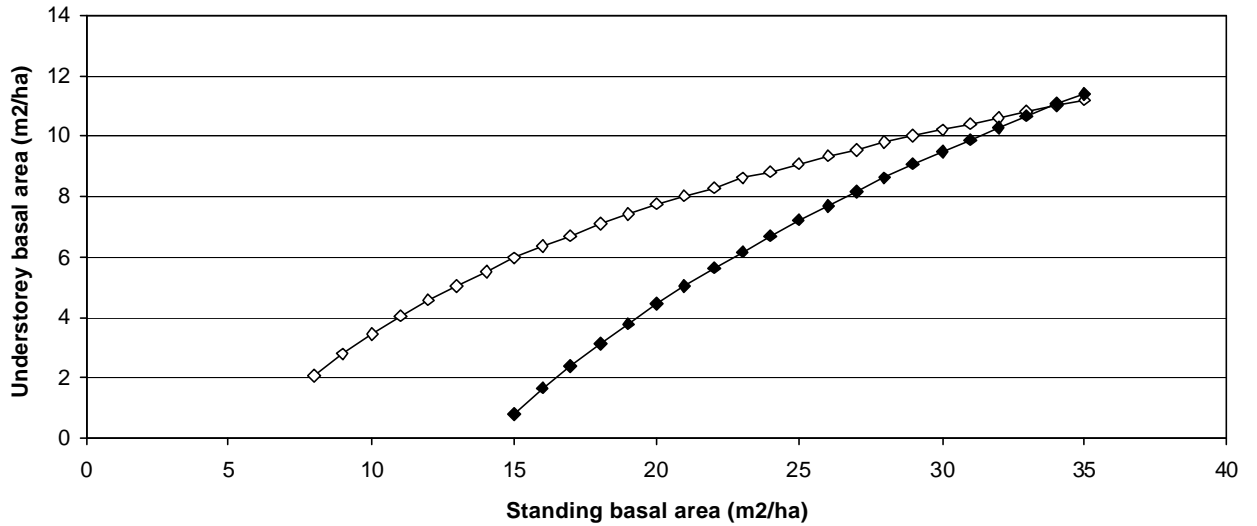


Figure 6.4: Estimated Understorey basal area using the CPAF-ACRE (open symbols) and CPATU (closed symbols) functions

Logging damage

Comparing the coefficients from CPATU and CPAF the result was according to expectation and the low logging damaged produced by the CPAF-ACRE coefficients was a result of the non-mechanised exploitation and the low harvesting intensity practised in the managed areas (Figure 6.5).

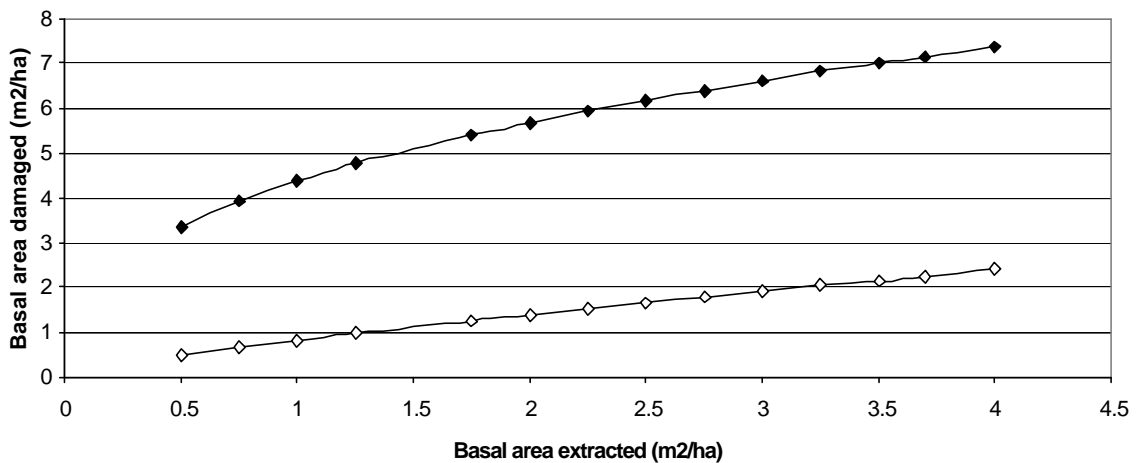


Figure 6.5: Estimated logging damage using functions from data from CPAF-ACRE (open symbols) and CPATU (closed symbols)

Basal area dynamics

Despite the low R^2 of the equation generated by the CPAF-ACRE data set, it presented very similar results for standing basal areas to the equation from CPATU. Both equations generate realistic curves limiting the increment to around $0.5 \text{ m}^2 \text{ ha}^{-1} \text{ yr}^{-1}$ when the standing basal area reaches $35 \text{ m}^2 \text{ ha}^{-1}$ (Figure 6.6).

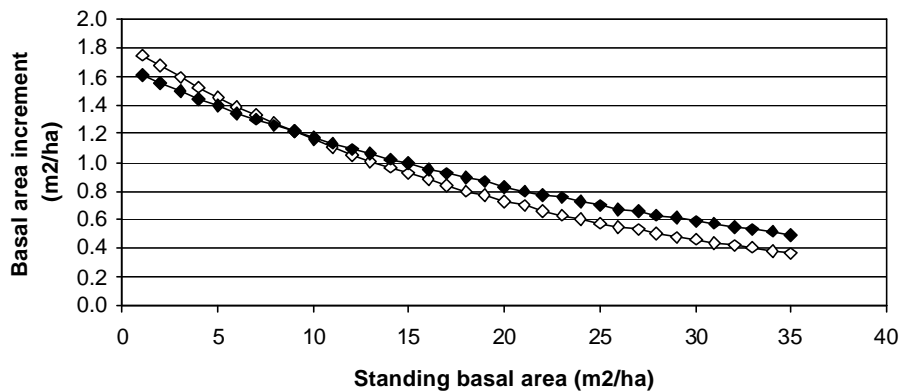


Figure 6.6: Estimated basal area increment using the CPAF-ACRE (open symbols) and CPATU (closed symbols) functions

6.5.2 Sensitivity analysis

Mortality

The volume of commercial species ($\text{dbh} > 50 \text{ cm}$) in the undisturbed forest during the time course of the simulation varied from around $28 \text{ m}^3 \text{ ha}^{-1}$ to $22 \text{ m}^3 \text{ ha}^{-1}$. The reduction of the mortality rates by 10 % produced an increase of the volume of commercial species ($\text{dbh} > 50 \text{ cm}$) at the end of the simulation course from $22 \text{ m}^3 \text{ ha}^{-1}$ (using the calculated mortality rates) to $28 \text{ m}^3 \text{ ha}^{-1}$, a volume equivalent to that observed at the beginning of the simulation course. Increasing the mortality rates by 10 % resulted in a final volume of commercial species ($\text{dbh} > 50 \text{ cm}$) of $18 \text{ m}^3 \text{ ha}^{-1}$.

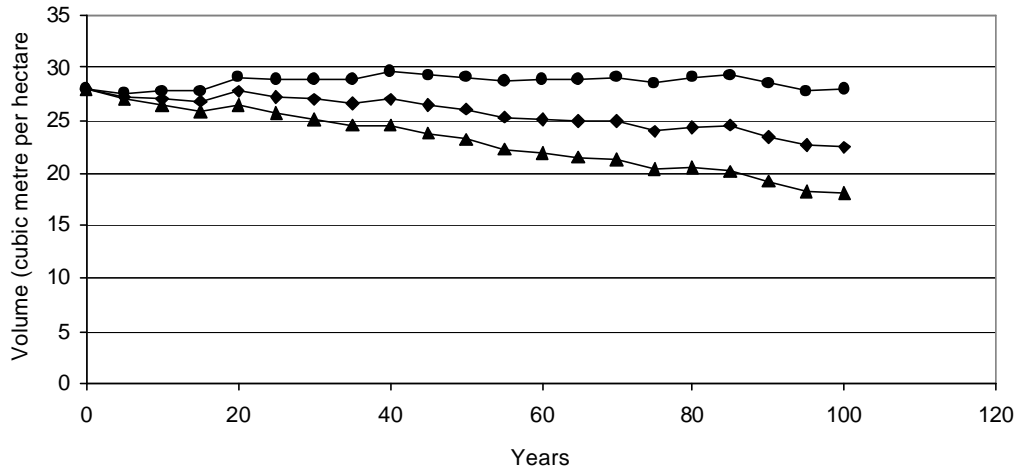


Figure 6.7: Volume of commercial species (dbh >50 cm) simulation course for the calculated mortality rates (diamonds) the calculated mortality rates plus 10 % (triangles) and the calculated mortality rates less 10% (circles)

Recruitment

In the first 40 years of the simulation course the variation in the recruitment rates did not promote great variation in the volume of the non-commercial species (dbh > 5 cm). The effect of increase the recruitment rates starts to be clear around the 60th year of the simulation course because of the accumulated volume of recruits and the gradual passage of the early recruited trees to greater diameter classes. The initial volume of the non-commercial tree species (dbh > 5 cm) was 107 m³ ha⁻¹ and the final volume at the end of the simulation course using the calculated recruitment rate was around 132 m³ ha⁻¹. The use of a 10 % higher recruitment rate increased the volume of non-commercial species at the end of the simulation to 144 m³ ha⁻¹ and the use of a 10 % lower recruitment rate reduced this volume to 125 m³ ha⁻¹.

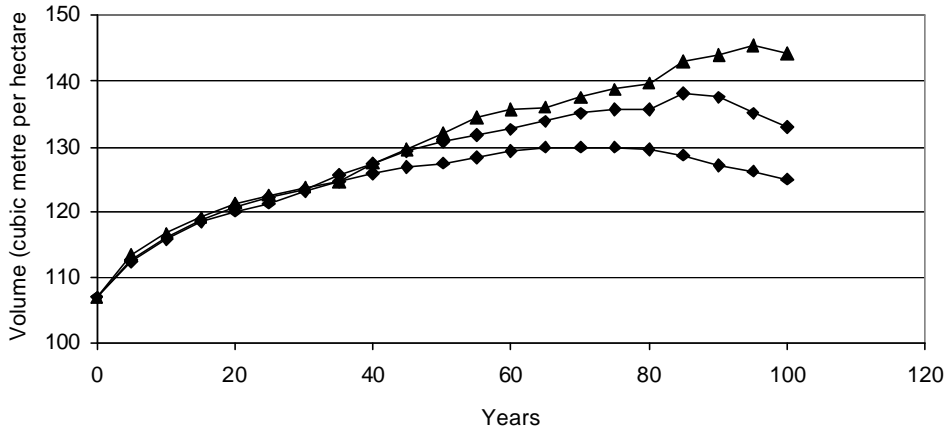
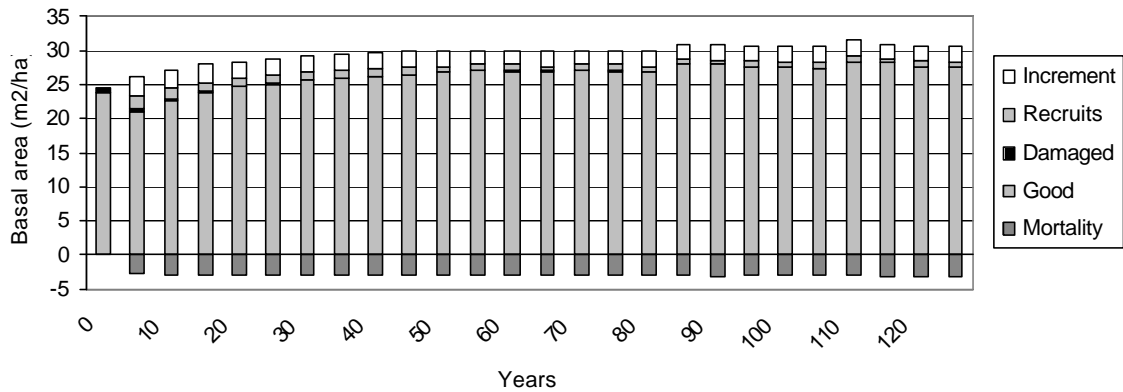


Figure 6.8: Volume of non-commercial species (dbh > 5 cm) simulation course for the calculated recruitment (diamonds) the calculated recruitment plus 10 % (triangles) and the calculated recruitment less 10% (circles)

6.5.3 Simulation of Undisturbed forest dynamics

The growth of the undisturbed forest stabilised around the 50th year of the simulation course with a basal area around 28 m² ha⁻¹. At this point the sum of the forest increment (2.4 m² ha⁻¹) and the ingrowth (0.9 m² ha⁻¹) were still greater than the mortality (3.1 m² ha⁻¹) allowing the basal area to increase at a slow rate until the 90th year of the simulation course when it began to oscillate around 30 m² ha⁻¹ (Figure 6.9 a). The volume components for commercial and non-commercial species of trees with dbh > 5 cm, showed a similar tendency of the basal area, growing fast until around the 50th year when the increment rates decrease tending to stabilising around the 80th year. The volume of non-commercial species varied from 110 to 140 m³ ha⁻¹ during the simulation course and the volume of commercial species presented a variation from 47 m³ ha⁻¹ in the beginning of the simulation course, to 67 m³ ha⁻¹ at the end in the 130th year.

a) Basal area components



b) Volume components in undisturbed forest for commercial species (open symbols, diamonds dbh > 50cm and circle dbh > 5cm) and non-commercial species (closed symbols, diamonds dbh > 50 cm and circles dbh > 5 cm)

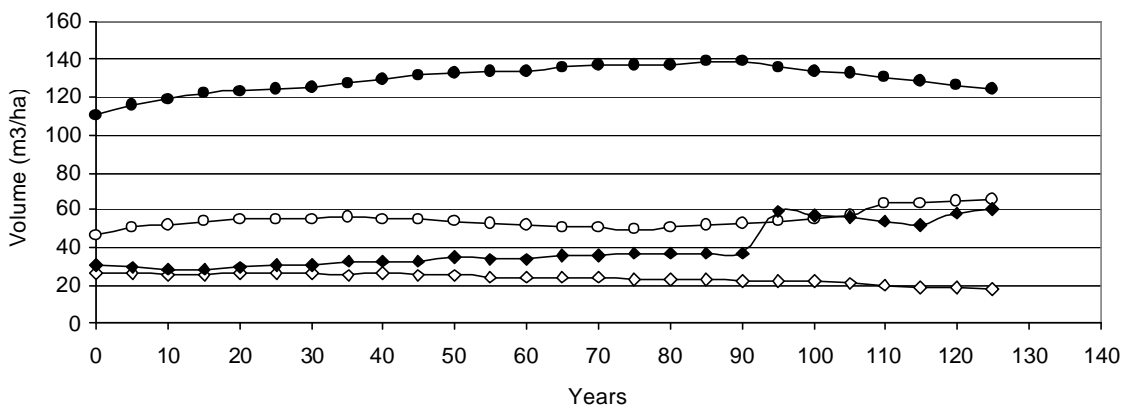


Figure 6.9: Time courses of simulated basal area (a) and volume components (b) for undisturbed forest

6.5.4 Five year cycles

The results of simulation with 5-yr cycles are shown in Figure 6.10. The total production (Figure 6.10a) varied according to the silvicultural treatment (ST) applied, from 35 m³ ha⁻¹ without to 41 m³ ha⁻¹ with a very light ST (0.5 m² ha⁻¹ cycle⁻¹ removed) respectively and from around 40 to 98 m³ ha⁻¹ cycle⁻¹ when more heavy STs were applied (1 or 2 m² ha⁻¹ cycle⁻¹ removed). The commercial standing volume (Figure 6.10b) showed a sharp decrease in all simulations even when heavy STs were used. Usually, at the end of the course of the simulation it was around zero, the two

exceptions being the simulation with $0.5 \text{ m}^2 \text{ ha}^{-1}$ of basal area extracted (BAE) and an ST removing 1 and $1.5 \text{ m}^2 \text{ ha}^{-1}$, when it was 17 and $10 \text{ m}^3 \text{ ha}^{-1}$ at the end of the simulation.

The volume of non-commercial species (Figure 6.10c) increased to around $50 \text{ m}^3 \text{ ha}^{-1}$ when no silvicultural treatments were applied in all harvesting intensities. Low intensity harvesting (0.5 and $1.0 \text{ m}^3 \text{ ha}^{-1}$ BAE) can act as a ST for the non-commercial species increasing its proportion in the forest population. The use of ST removing $0.5 \text{ m}^2 \text{ ha}^{-1}$ resulted in a final volume of non-commercial species similar to the natural forest varying from 22 to $38 \text{ m}^3 \text{ ha}^{-1}$. Silvicultural treatments removing more than $0.5 \text{ m}^2 \text{ ha}^{-1}$ removed combined with a harvesting intensity of $0.5 \text{ m}^2 \text{ ha}^{-1}$ resulted in the almost total extinction of non-commercial species with dbh > 50 cm. Harvesting intensities superior to $0.5 \text{ m}^2 \text{ ha}^{-1}$ BAE can keep the population of non-commercial species in a similar condition to that of the natural forest or even make it increase (e.g. combination of $1.0 \text{ m}^2 \text{ ha}^{-1}$ BAE and $1.0 \text{ m}^2 \text{ ha}^{-1}$ ST). Silvicultural treatments removing more than $1.0 \text{ m}^2 \text{ ha}^{-1}$ resulted in the reduction of the trees of non-commercial species with dbh > 50 to near zero except when combined with the highest simulated harvesting intensity ($2.0 \text{ m}^2 \text{ ha}^{-1}$ BAE) when it remained around $18 \text{ m}^3 \text{ ha}^{-1}$. In general the simulations for 5 year cycles presented very high variance. The total volume of the non-commercial species (Figure 6.10d) showed a tendency to increase with the harvesting intensity from $128 \text{ m}^3 \text{ ha}^{-1}$ to $147 \text{ m}^3 \text{ ha}^{-1}$ and to decrease when STs removing more than $1.0 \text{ m}^2 \text{ ha}^{-1}$ were applied.

The average of logged volume per cycle per hectare (Figure 6.11e) was around 2 to $3 \text{ m}^3 \text{ ha}^{-1} \text{ cycle}^{-1}$ for simulations without or with light ST and 4 to $6 \text{ m}^3 \text{ ha}^{-1} \text{ cycle}^{-1}$ when the heaviest STs were applied in simulations with harvesting rates between 0.5 to $1.0 \text{ m}^2 \text{ ha}^{-1} \text{ cycle}^{-1}$. Harvesting rates above $1.0 \text{ m}^3 \text{ ha}^{-1} \text{ cycle}^{-1}$ produced a series of very low harvests, near or even equal to zero, which eliminates any possibility of further analysis. In all simulations the coefficient of variation (Figure 6.10f) was very high and showed a tendency to increase when the limit for basal area extracted increases.

The best results obtained with this cycle length, was the combination of a harvesting rate of $0.5 \text{ m}^2 \text{ ha}^{-1} \text{ cycle}^{-1}$ with a ST removing $1 \text{ m}^2 \text{ ha}^{-1} \text{ cycle}^{-1}$. The total production was $98 \text{ m}^3 \text{ ha}^{-1}$ and despite some variance, the harvests in the simulation course were regular varying from 5 to $6 \text{ m}^3 \text{ ha}^{-1} \text{ cycle}^{-1}$.

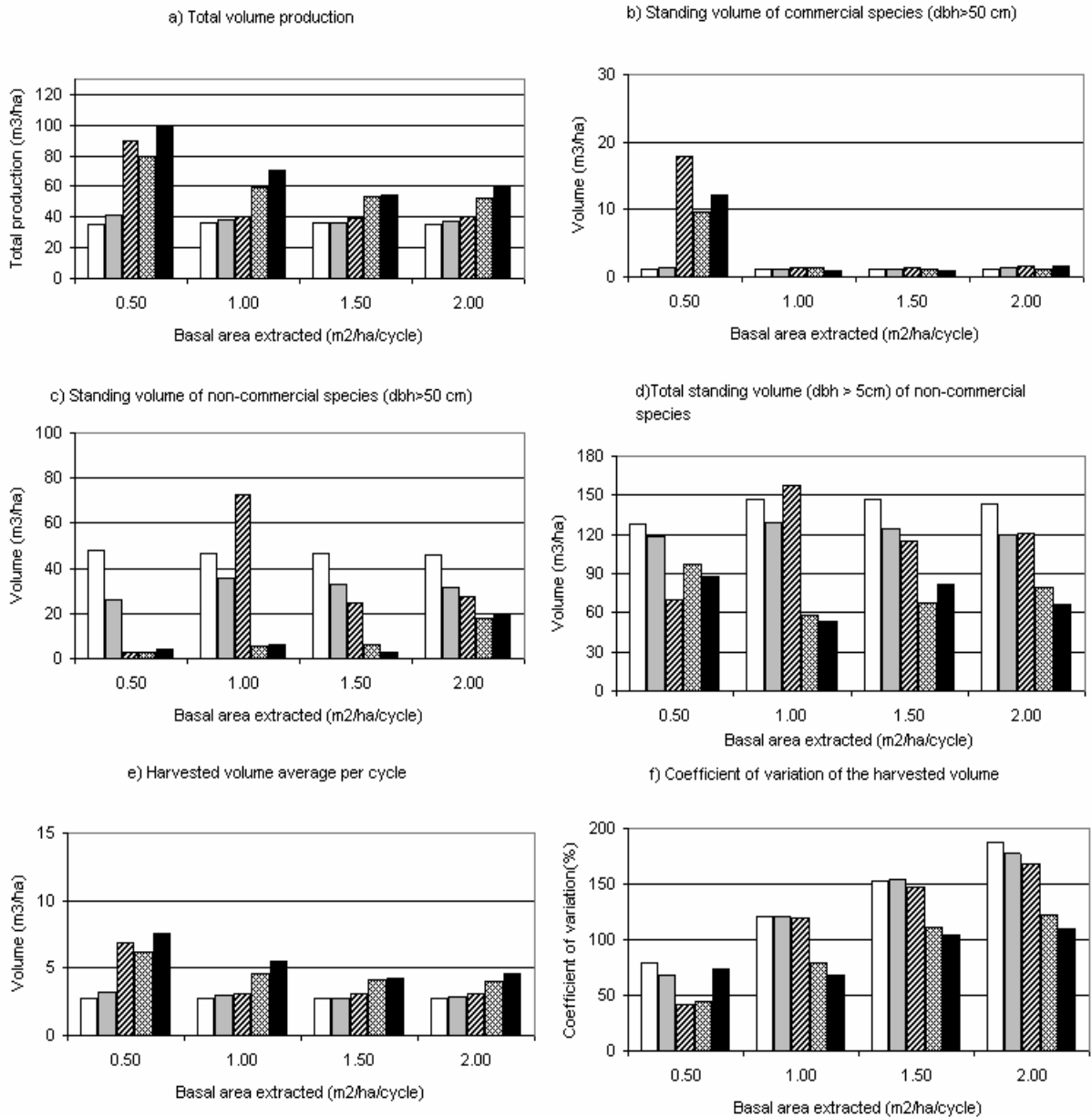


Figure 6.10: Five year cycle simulation components in a 70 year simulation course with different harvesting intensities (basal area extracted) and Silvicultural treatments – ST (no ST- white columns, ST removing 0.5 m² ha⁻¹ – grey columns, ST removing 1 m² ha⁻¹ – white columns with diagonal lines; ST removing 1.5 m² ha⁻¹ white columns with crossed lines and ST removing 2 m² ha⁻¹ – black columns): a- total harvested volume (m³ ha⁻¹), b - standing volume of commercial species dbh > 50 cm (m³ ha⁻¹), c- standing volume of non-commercial species dbh > 50 cm (m³ ha⁻¹), d- total volume of non-commercial species e- mean harvested volume per cycle (m³ ha⁻¹) and f- coefficient of variation of the harvested volume.

6.5.5. Ten year cycles

Production at the end of the simulation course does not change too much without silvicultural treatment or with soft silvicultural treatments (removing $0.5\text{m}^2\text{ ha}^{-1}\text{ cycle}^{-1}$), varying from 32 to $40\text{ m}^3\text{ ha}^{-1}\text{ cycle}^{-1}$ even when different limits for basal area extraction (from 0.5 to $2.0\text{ m}^2\text{ ha}^{-1}\text{ cycle}^{-1}$) were tested (Figure 6.11a). Production increased significantly when ST removing more than $1.0\text{ m}^2\text{ ha}^{-1}$ basal area were applied in less intensive harvesting rates (BAE per hectare varying from 0.5 to $1.0\text{ m}^2\text{ ha}^{-1}\text{ cycle}^{-1}$) showing the peak of the production ($77\text{ m}^3\text{ ha}^{-1}$) with the combination of $1.0\text{ m}^2\text{ ha}^{-1}$ BAE and $2.0\text{ m}^2\text{ ha}^{-1}$ ST (Figure 6.11a). Total production became about constant for superior harvesting intensities (1.5 and $2.0\text{ m}^2\text{ ha}^{-1}$ BAE). The standing commercial volume (dbh > 50 cm) was about zero at the end of the simulation course with the exception of harvesting intensity of $0.5\text{ m}^2\text{ ha}^{-1}$ combined with ST removing more than $1.0\text{ m}^2\text{ ha}^{-1}$ or harvesting intensity of $1.0\text{ m}^2\text{ ha}^{-1}$ combined with ST removing $2.0\text{ m}^2\text{ ha}^{-1}$ (Figure 6.11b). The volume of non-commercial (Figure 6.11c) species with dbh superior to 50 cm decreased sharply when heavier STs are applied together with low intensity harvesting (0.5 and $1.0\text{ m}^2\text{ ha}^{-1}$ BAE). The use of superior harvesting intensities still can produce a decrease in the total volume of this class of species, whilst keeping its volume above $20\text{ m}^3\text{ ha}^{-1}$. The total volume of non-commercial species (Figure 6.11d) did not change significantly except when a harvesting of $0.5\text{ m}^2\text{ ha}^{-1}$ BAE was applied, without ST. In this case it seems that the harvesting itself acted as a ST for the non-commercial species. The harvesting average per cycle (Figure 6.11e) was always around 5 to $6\text{ m}^3\text{ ha}^{-1}\text{ cycle}^{-1}$, except with a combination of $1.0\text{ m}^2\text{ ha}^{-1}$ BAE harvesting and ST removing $2.0\text{ m}^2\text{ ha}^{-1}$ when the harvesting average was $11\text{ m}^3\text{ ha}^{-1}\text{ cycle}$. The variance (Figure 6.11f) showed an almost linear tendency to increase when more intensive harvesting rates were applied and to decrease when more intensive STs were applied.

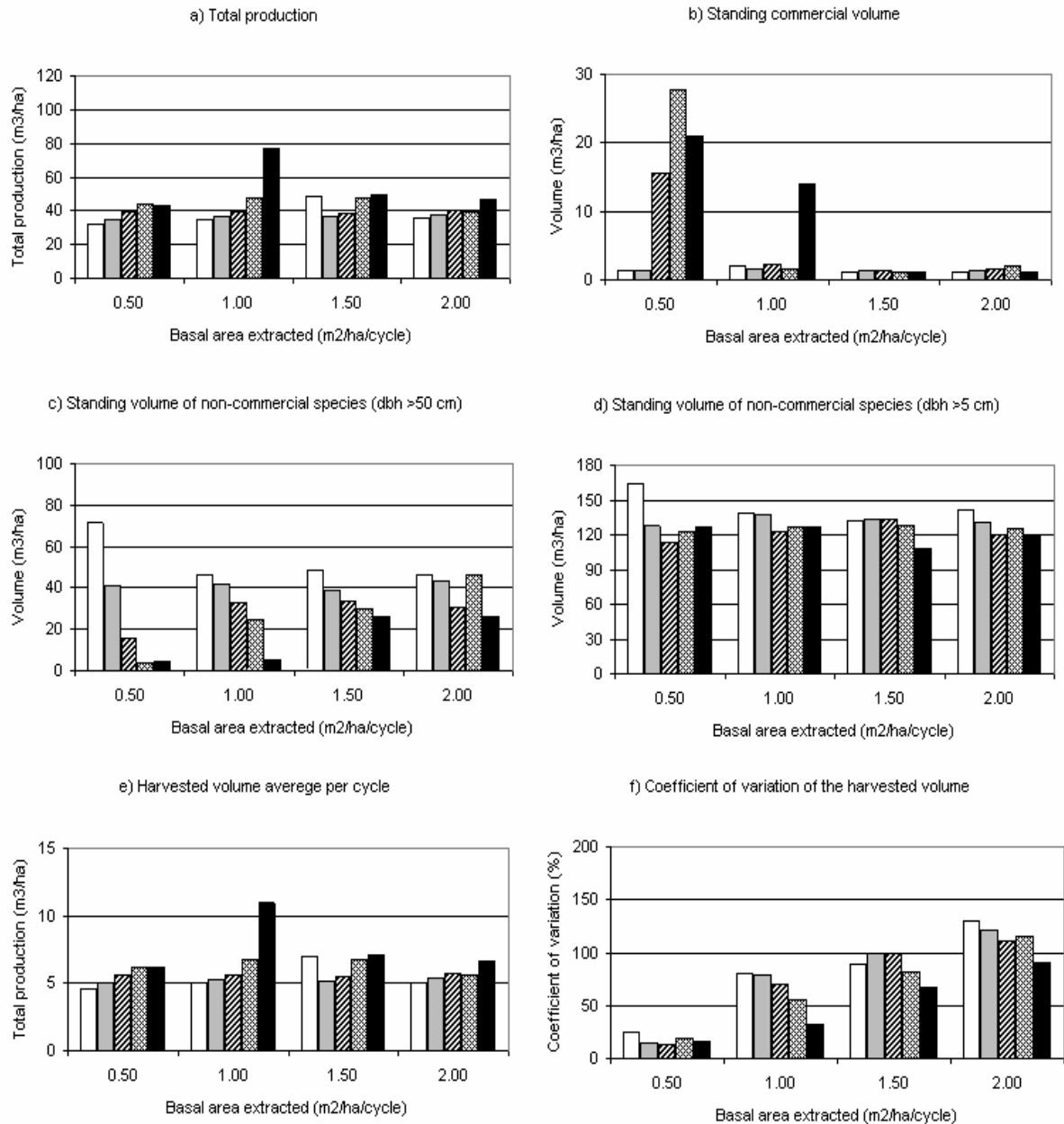


Figure 6.11: Ten year cycle simulation components in a 70 years simulation course with different harvesting intensities (basal area extracted) and Silvicultural treatments – ST (no ST- white columns, ST removing 0.5 m² ha⁻¹ – grey columns, ST removing 1 m² ha⁻¹ – white columns with black dots; ST removing 1.5 m² ha⁻¹ black columns with white dots and ST removing 2 m² ha⁻¹ – black columns): a- total harvested volume (m³ ha⁻¹), b - standing volume of commercial species dbh > 50 cm (m³ ha⁻¹), c- standing volume of non-commercial species dbh > 50 cm (m³ ha⁻¹), d- total volume of non-commercial species e- mean harvested volume per cycle (m³ ha⁻¹) and f- coefficient of variation of the harvested volume.

6.5.6 Fifteen year cycles

The total production (Figure 6.12a) did not vary much with the use of different intensities of ST, however it showed a tendency to increase when more intense ST were applied. The production only increased from 0.5 to 1.0 m² ha⁻¹ cycle⁻¹ BAE, becoming constant for higher harvesting intensities. The peak of total production at the end of the simulation course (48 m³ ha⁻¹) was a combination of 1.0 m² ha⁻¹ BAE harvesting and ST removing 2.0 m² ha⁻¹ cycle⁻¹. The standing commercial volume (Figure 6.12b) at the end of the simulation course increased when STs removing more than 1.0 m² ha⁻¹ were applied with a harvesting intensity of 0.5 m² ha⁻¹. With the exception of the simulation with 1.0 m² ha⁻¹ BAE harvesting and ST removing 2.0 m² ha⁻¹, all other simulations finished with standing commercial volume below 5 m³ ha⁻¹. The standing volume of non-commercial species (dbh > 50 cm and dbh > 5 cm) decreased sharply with the ST intensity at a harvesting intensity of 0.5 m² ha⁻¹ BAE (Figure 6.12c and 6.12d). This effect tends to diminish with the use of heavier harvesting and in the simulation with 2.0 m² ha⁻¹ BAE it was null. The average of harvested wood per cycle (Figure 6.12e) was around 5 m³ ha⁻¹ cycle⁻¹ for harvesting intensity of 0.5 m² ha⁻¹ cycle⁻¹ BAE and almost constant, varying from 6 to 8 m³ ha⁻¹ cycle⁻¹, for the rest of the simulations. The highest harvesting average was obtained with the combination of a ST removing 2.0 m² ha⁻¹ cycle⁻¹ and a limit for BAE of 1.0 m² ha⁻¹ cycle⁻¹ which produced a harvesting average of 12 m³ ha⁻¹ cycle⁻¹. The variance (Figure 6.12f) followed the same pattern as the 10 year cycle with a tendency to increase almost linearly when the limit for BAE increased from 0.5 to 2 m² ha⁻¹ cycle⁻¹ and to decrease with ST especially in the simulation using 1.0 m² ha⁻¹ cycle⁻¹ harvesting.

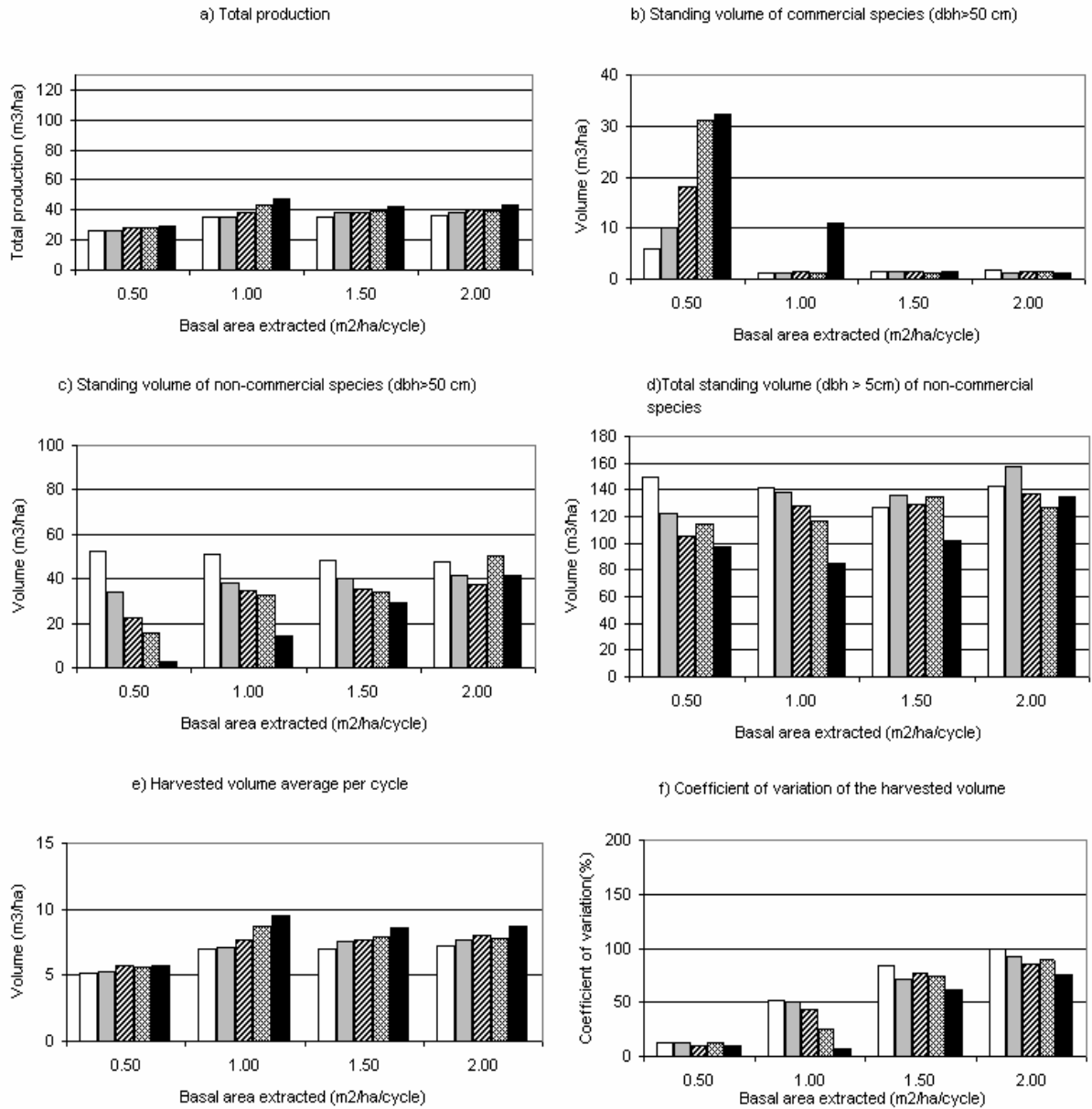


Figure 6.12: Fifteen year cycle simulation components in a 70 years simulation course with different harvesting intensities (basal area extracted) and Silvicultural treatments – ST (no ST- white columns, ST removing 0.5 m² ha⁻¹ – grey columns, ST removing 1 m² ha⁻¹ – white columns with diagonal lines; ST removing 1.5 m² ha⁻¹ white columns with crossed lines and ST removing 2 m² ha⁻¹ – black columns): a- total harvested volume (m³ ha⁻¹), b - standing volume of commercial species dbh > 50 cm (m³ ha⁻¹), c- standing volume of non-commercial species dbh > 50 cm (m³ ha⁻¹), d- total volume of non-commercial species e- mean harvested volume per cycle (m³ ha⁻¹) and f- coefficient of variation of the harvested volume

6.5.7 Twenty year cycle

The total production is about constant for all the different ST applied and varied from around $20 \text{ m}^3 \text{ ha}^{-1}$ using the $0.5 \text{ m}^2 \text{ ha}^{-1} \text{ cycle}^{-1}$ BAE harvesting to $40 \text{ m}^3 \text{ ha}^{-1}$ for the other harvesting intensities studied (Figure 6.13 a). The standing volume of commercial species (Figure 6.13b) showed a strong increase with the use of ST and $0.5 \text{ m}^2 \text{ ha}^{-1}$ BAE harvesting with a maximum of $36 \text{ m}^3 \text{ ha}^{-1}$ when combined with ST removing $2.0 \text{ m}^2 \text{ ha}^{-1} \text{ cycle}^{-1}$. For the rest of the simulations it was always below $5 \text{ m}^3 \text{ ha}^{-1}$ with the exception of the combination of $1.0 \text{ m}^2 \text{ ha}^{-1}$ BAE harvesting and ST removing $2.0 \text{ m}^2 \text{ ha}^{-1}$ when it was $16 \text{ m}^3 \text{ ha}^{-1}$ at the end of the simulation time course. The effect of the harvesting and ST in the non-commercial ($\text{dbh} > 50 \text{ cm}$ and $\text{dbh} > 5 \text{ cm}$) species was similar to that observed in the 15-year cycle decreasing with the ST intensity with harvesting intensity of $0.5 \text{ m}^2 \text{ ha}^{-1}$ BAE (Figure 6.13c and 6.13d). Again, this effect tended to diminish with the use of heavier harvesting. The average harvested wood per cycle (Figure 6.13e) was $5 \text{ m}^3 \text{ ha}^{-1} \text{ cycle}^{-1}$ for a harvesting intensity of $0.5 \text{ m}^2 \text{ ha}^{-1} \text{ cycle}^{-1}$ BAE and almost constant varying, from 8 to $11 \text{ m}^3 \text{ ha}^{-1} \text{ cycle}^{-1}$, for the rest of the simulations. The highest harvesting average was obtained with the combination of a ST removing $2.0 \text{ m}^2 \text{ ha}^{-1} \text{ cycle}^{-1}$ and a limit for BAE of $2.0 \text{ m}^3 \text{ ha}^{-1} \text{ cycle}^{-1}$ which produced a harvesting average of $11 \text{ m}^3 \text{ ha}^{-1} \text{ cycle}^{-1}$. The variance showed a tendency to increase in an almost linear way when the limit for BAE increased from 0.5 to $2 \text{ m}^2 \text{ ha}^{-1} \text{ cycle}^{-1}$ and to decrease with ST (Figure 6.13f).

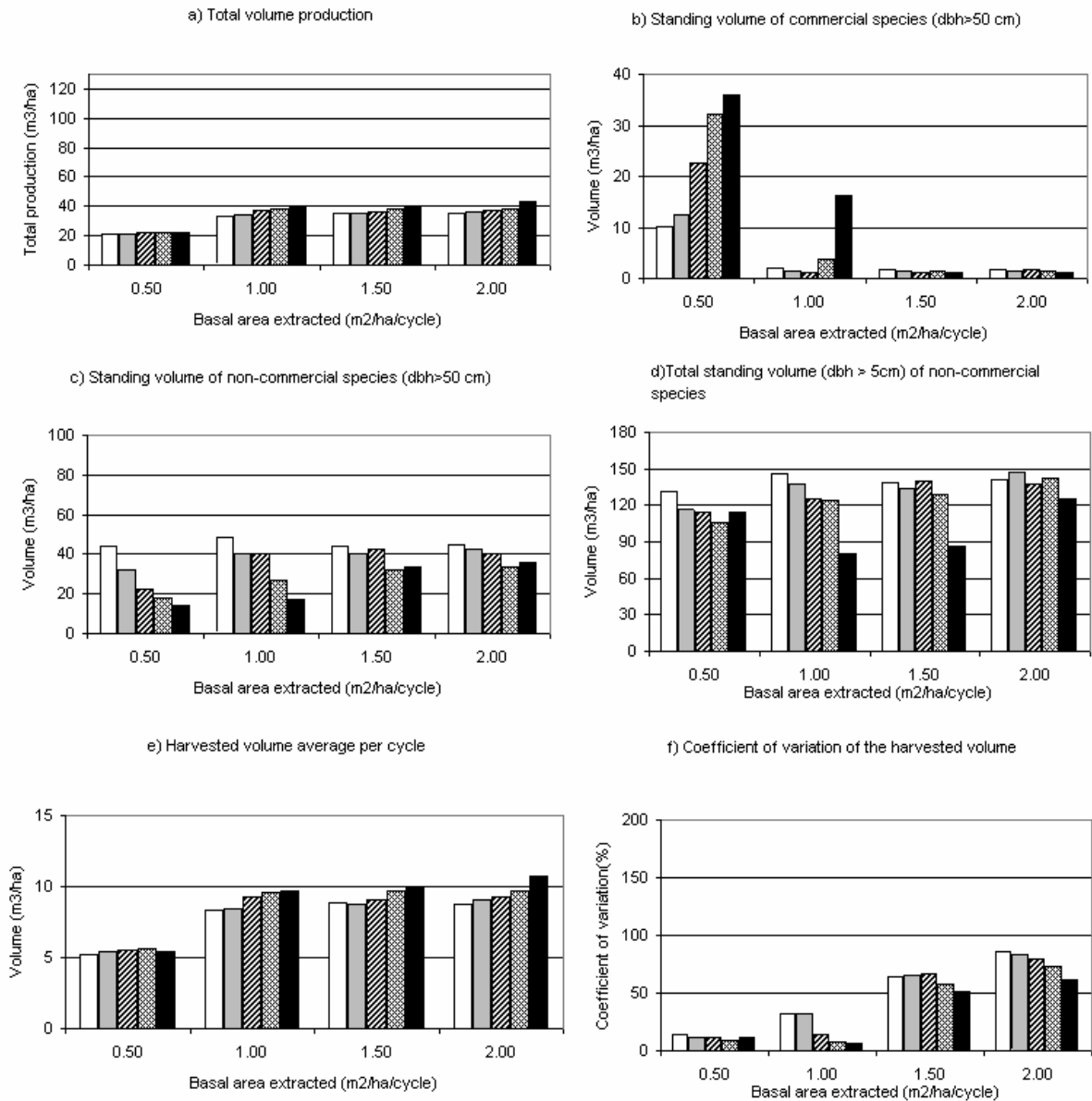


Figure 6.13: Twenty year cycle simulation components in a 70 years simulation course with different harvesting intensities (basal area extracted) and Silvicultural treatments – ST (no ST- white columns, ST removing 0.5 m² ha⁻¹ – grey columns, ST removing 1 m² ha⁻¹ – white columns with diagonal lines; ST removing 1.5 m² ha⁻¹ white columns with crossed lines and ST removing 2 m² ha⁻¹ – black columns): a- total harvested volume (m³ ha⁻¹), b- standing volume of commercial species dbh > 50 cm (m³ ha⁻¹), c- standing volume of non-commercial species dbh > 50 cm (m³ ha⁻¹), d- total volume of non-commercial species e- mean harvested volume per cycle (m³ ha⁻¹) and f- coefficient of variation of the harvested volume

6.6 Discussion

Sensitivity analysis

The model proved to be sensitive to both functions tested. The results from the variation in mortality rates were apparent early during the simulation course because of its direct influence on the tree population. This is in contrast with recruitment, which represents small trees entering in the tree population contributing of small volume around 0.2 to 0.4 m³ ha⁻¹ yr⁻¹. Thus it was to be expected that in the first 40 years of the simulation course the difference among recruitment rates used had little effect compared with the case of the mortality rates.

Mortality rates can be calculated directly which gives to this function a high precision. However, recruitment rates are calculated through a regression between stand basal area and the number of plants recruited in the period. It is to be expected that sites with lower stand basal area should have a higher area of gaps that should provide a better environment for the establishment of new recruits in the forest. However, in this study, probably because of the short time of the measurements in the permanent sample plots and also that the logging was a relatively recent event, the inverse occurred and recruitment was higher where basal area was higher. A potential problem with this function is that there is the possibility to have in a disturbed site a high basal area (e.g. a logged area that possesses very big residual trees), and in the same way in an undisturbed site (sites without natural or human disturbance) a closed canopy and low basal area. In these situations the recruitment probably will be higher in the site with the higher basal area than in the site with the lower basal area. The same effect could be verified in the basal area increment, considering the above described situation, a higher basal area increment could be expected in the site with the higher basal area than in the other one.

The fact that the model produced reasonable outputs when running this set of simulations with a relatively young and small data set, and that the functions generated by two data sets (from CPATU and CPAF-ACRE) also produced (with exception of recruitment function for the CPAF-ACRE data set) reasonable results, are a good indication of its robustness. For the same reason is difficult to recognise and point out its potential weaknesses. As other models, CAFOGROM requires a large amount of data to produce good predictions, so that more information that is accumulated from the past the better will be the vision of the future. In an evaluation of the model's performance comparing observed and estimated values over a period of 16 years (Alder and Silva, 1999), the system presented a tendency to overestimate

growth (e.g. for all species with diameter > 45 cm dbh the observed was $2.56 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ and the estimated $3.13 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$)

Silvicultural treatments

For all forest management simulations tested, the volume produced over the 70-year simulations using silvicultural treatments was greater than in the equivalent forest management simulations without silvicultural treatments. In addition, the harvested volume becomes more constant when silvicultural treatments are used. The managed forest without silvicultural treatments, in all tested simulations, showed a sharp decrease in the standing volume of commercial species at the end of the simulation time course.

In short cycles the silvicultural treatments can cause a drastic reduction in the population of non-commercial species > 50 cm dbh. In the simulations a sort of equilibrium can be obtained between commercial and non-commercial species by combining intensive ST with harvesting equal or superior to $1 \text{ m}^2 \text{ ha}^{-1} \text{ cycle}^{-1}$ basal area extracted.

Silvicultural treatments must be carried out very carefully to avoid the removal of “potential” species, which could in future become commercial and a tree should be eliminated only if it is directly competing with a more valuable one (Schmidt, 1987). In this case it is important to note that the commercial species list was not changed during the simulation (which is in fact very likely to happen in the real life). In addition, when the system is designed for small farmers, some species (e.g. *Ceiba* spp) will not be considered as commercial because of difficulties in the extraction of such large logs and because of the low prices offered by the industry for collecting the logs in the forest, but these species are commercial and some time in the future its use will be possible by small farmers.

Harvesting rates (Basal area limit for extraction – BAE)

The limit for basal area (hence volume) extraction for cycles of 5 years cannot exceed $0.5 \text{ m}^2 \text{ ha}^{-1}$. The other studied cycles obtained their peak production around $1.0 \text{ m}^2 \text{ ha}^{-1}$ and when the heaviest extractions were tested the standing commercial volume decreased sharply and the system becomes unsustainable for wood production.

A light harvesting intensity combined with light ST usually resulted in a treatment that promoted the non-commercial species, making the volume of these species increase while the volume of commercial species decrease until near zero.

In short cycles of 5 and 10 years there were a general tendency for the production to decrease when more intensive harvesting was applied due the total extinction of the commercial species during the simulation time course. The other two cycles presented an increase in the production when the harvesting intensity was increased from 0.5 to 1.0 m² ha⁻¹ cycle⁻¹ BAE, after that it showed a tendency to stay constant. The cycles of 15 and 20 year harvesting intervals allowed the forest to grow in a way which kept the production constant, despite the high variability among the harvests. Probably better results can be obtained from these cycles but intermediate ST must be applied to keep the forest productivity high.

Some harvests exceed the established limit for basal area extraction when the harvesting limit was 0.5 and 1.0 m³ ha⁻¹ cycle⁻¹. It probably was because these low harvesting rates did not allow big trees (with more than 0.5m² of basal area which means greater than 80 cm dbh) to cut. Thus, the program selected smaller trees for harvesting, while they are available in the database, in a way to avoid exceeding the determined limit for basal area extraction. However when these options finished harvesting higher than the limit were observed sometimes increasing the total production and always increasing the coefficient of variance. In practice this problem can be avoided when the forester is taking the decision of which trees will be logged in the compartment, by reducing the number of trees to be logged per hectare, hence reducing the harvested volume and keeping some standing commercial volume for the next harvest.

5 year cycles

Some reasonable simulations could be produced with a 5-yr cycle which gave regular harvesting around 4 to 5 m³ ha⁻¹ cycle⁻¹. However these results were obtained through a combination of low harvesting rates with intensive ST, resulting in a sharp decrease in both the volume of commercial and non-commercial species. The reduction of the commercial volume after harvesting is not a big problem and is even expected on longer cycles, but for very short cycles some reserves must be present to guarantee the following harvests. In addition, the variance was usually too high to be acceptable (e.g. when harvesting is near zero in the cycle, the farmers receive no income).

Also, the low productivity and the greater area of the compartments increases costs and labour demand and must be considered as strong economic limitation for the use of 5 year cycles and, due the need for annual and regular incomes longer cycles are recommended.

10 year cycle

Harvesting without the use of silvicultural treatments, even in the lowest intensity ($0.5 \text{ m}^2 \text{ ha}^{-1} \text{ cycle}^{-1}$) promoted a decrease in the volume of commercial species in diameter classes above 50 cm dbh and hence a decrease in the harvested volume in the later cycles. The management without ST allow the maintenance of a high volume in the forest but a low volume of commercial species, because the forest remain dominated by non-commercial species.

The best results obtained were with the use of harvesting intensities from 0.5 to $1.0 \text{ m}^2 \text{ ha}^{-1} \text{ cycle}^{-1}$ allied with intense silvicultural treatments. Silvicultural treatments removing 1.0 and $2.0 \text{ m}^2 \text{ ha}^{-1} \text{ cycle}^{-1}$ resulted in uniform harvests and allowed the maintenance of the commercial volume after the last harvesting between 17 and $30 \text{ m}^3 \text{ ha}^{-1}$. The intensive ST promoted a reduction in the volume of trees of non-commercial species with $\text{dbh} > 50 \text{ cm}$.

There is a strong response from the managed species when ST are applied with $1.0 \text{ m}^2 \text{ ha}^{-1} \text{ cycle}^{-1}$ basal area extracted harvesting, but still a high decrease in the volume of non-commercial species due the repetition of intensive ST. The use of repeated ST is a decision which must be taken by the forester so that the development of the forest keeps the productivity of the managed species high and at the same time protecting the biodiversity and the potential species (Appendix 3).

Among all simulations, the forest management using a 10 yr-cycle, $1.0 \text{ m}^2 \text{ ha}^{-1}$ BAE harvesting and ST removing $2.0 \text{ m}^2 \text{ ha}^{-1}$ basal area, produced a high and uniform harvests (from $8 \text{ m}^3 \text{ ha}^{-1}$ to $10 \text{ m}^3 \text{ ha}^{-1}$).

15 year cycle

Longer cycles demand more intensive harvesting rates as a way to compensate the smaller number of harvests in the period. More intensive harvesting can produce higher yields in the short-term, but the standing volume of commercial species has a tendency to decrease sharply during the course of the simulation. For the 15-yr cycles the need of a high standing commercial volume at the end of simulation is not as important as for shorter cycles, because the forest will have more time to recover. Thus a standing commercial volume from 10 to $20 \text{ m}^3 \text{ ha}^{-1}$ at the end of the simulation can be considered enough to guarantee the sustainability of the production.

The ST removing $1.0 \text{ m}^2 \text{ ha}^{-1} \text{ cycle}^{-1}$, produced similar results to the equivalent simulation for 10 year cycle, but with lower total volume production over the course of a 70 year simulation due a smaller number of harvests. With the heaviest silvicultural

treatments, removing $2.0 \text{ m}^2 \text{ ha}^{-1} \text{ cycle}^{-1}$ and a limit for BAE of $1.0 \text{ m}^2 \text{ ha}^{-1} \text{ cycle}^{-1}$, 15-yr cycles obtained a total volume production around $50 \text{ m}^3 \text{ ha}^{-1}$. In this case the variance was low, and standing commercial volume at the end of the simulation was high, around $30 \text{ m}^3 \text{ ha}^{-1}$ and the harvests presented an average of $10 \text{ m}^3 \text{ ha}^{-1} \text{ cycle}^{-1}$. These cycles can be considered for larger areas and a larger set of commercial species, but the 10-yr. cycles are preferred from an economic point of view for the present purpose.

20 year cycle

Twenty-yr. cycles are much more recommended for big areas and forest management techniques involving the use of high technology for logging, skidding and processing the wood.

The low response of the forest to ST probably has two main causes, the need of an intermediate ST, for example around the 5th year after the forest exploitation, and the low number of commercial species.

For this cycle length, the heaviest harvesting rates must to be applied to compensate the smaller number of harvests. Higher harvesting rates produced harvests about that which could be expected from a 20 year harvesting cycle, but only in the two first cycles. After that the forest could no longer support the intervention and both standing commercial volume and harvested volume fell to around zero. The final volume of commercial species does not have the same importance which it has for short cycles due the longer period which the forest has to recover. However, the maintenance of the commercial volume around 10 to $20 \text{ m}^3 \text{ ha}^{-1}$ will guarantee the next cycle.

The decision whether to use longer cycles is related not only to ecological and economic matters, but also to social and political aspects. The pressure for land tenure in Amazon is becoming stronger and the risk that the forest may be used for different activities in the intervals between cycles is considerable, and have been one of the most common reasons for the failure of forest management in the tropics.

6.7 Conclusions

1- Without silvicultural treatment the total production is about constant in short cycles (from 5 to 15 year cycles). The need for ST is due the small number of commercial species competing with a large number of non-commercial or potential species. With a larger set of commercial species the harvesting itself should produce the same effect as ST, eliminating the need to use it. The low and about constant production presented in the simulations without silvicultural treatments indicate the need to provide competitive benefits to the managed species.

2- Strong silvicultural treatments ($2.0 \text{ m}^2 \text{ ha}^{-1}$) must be applied with care especially in short cycles, because they are expensive, they affect negatively the population of potential species (verified by the sharp decrease in volume of these species) and increase the risks of biodiversity losses.

3- The variance increases when the extracted basal area increases, in all the studied cycles with the exception of 5-yr cycles, in which the variance was always high. It means that more intensive harvesting rates produce irregular harvests among cycles due the absence of commercial species to be logged.

4- Ten-yr. cycles seem to be the best option for sustainable forest management in the conditions presented in this work. Regular harvests from 8 to $10 \text{ m}^3 \text{ ha}^{-1} \text{ cycle}^{-1}$ can be expected with the combination of a harvesting intensity around $1.0 \text{ m}^2 \text{ ha}^{-1} \text{ cycle}^{-1}$ and ST removing around $2.0 \text{ m}^2 \text{ ha}^{-1} \text{ cycle}^{-1}$.

4- 20-yr. cycles are not applicable to small farms, because they demand much larger areas. The alternative for use of these cycles in small farms should be a two-year interval between harvesting, which is usually not suitable due the need for annual incomes from the forest. In addition the total production (using the conditions of this study) was below that of the short cycles, probably because of the need for more than one ST (few species competing with a much larger population) and a larger set of commercial species to allow more intensive harvesting rates. Alternatively, ST five years after logging can be tried. The use of heavy machines (Skidders) must be considered for these cycles for harvesting rates of $2 \text{ m}^2 \text{ ha}^{-1} \text{ cycle}^{-1}$ and above. Longer cycles might be suitable for small properties where forest management is not considered as a main activity, or where the calendar of activities other than forest management has more economic importance or labour demand.

5- The results of the simulations must be interpreted as tendencies presented by the forest for different interventions. In general, simulations have the tendency to produce better predictions as time passes and the management system must be flexible enough to assimilate the necessary changes. Thus the predictions produced by the

simulations are important for planning but they cannot replace the field experience of the foresters. This is especially important in a scenario where the set of commercial species is constantly changing, making delicate decisions such as which plants can be removed as silvicultural treatment.

6- The improvement of the model performance demands more data. Additional permanent sample will be established in the area in the year 2000.

CHAPTER 7

Summary and General Conclusions

7.1 Introduction

Despite pressure from conservationists and the efforts of most governments from tropical countries, tropical forests are still being slashed and burned on a considerable scale. The reason for this is usually that the land is needed to sustain the people who live there and, although cattle breeding and shifting cultivation have a low profitability in the tropics, there are no economic alternatives to these activities. The obvious conclusion from this is that to preserve tropical forests it is necessary to give them a value. As long as tropical forests are no more than an obstacle to the cultivation of crops and pasture, all the possible arguments of conservationists such as biodiversity protection, global warming, reduction in carbon emission and the protection of the ozone layer, will not produce the desired effect of reducing deforestation rates.

Forest management has been tried, very often without success, in several tropical countries. The most common reasons for its failure were the long felling cycles required and the non-involvement of the local populations. As a result of this relatively unsuccessful history, the concept of forest management has become misunderstood, and what was actually a socio-economic problem (demographic pressure and the need to produce food from the land) was interpreted as a technical problem (the systems were not working because they were inadequate for the forests). It also gave forest management the reputation for being the first step to deforestation and this infamy has persisted until today being used frequently to demonstrate how impracticable the management of tropical forest is (Poore, 1989; Dawkins and Philip, 1998).

Alternative traditional extractivism practices have been recommended (e.g. Fearnside, 1989). However, because of the low density of the marketable species (e.g. *Hevea brasiliensis* and *Bertholletia excelsa*), and the competition from plantations, this activity is nowadays economically impracticable in Brazil (Homma, 1997). Agricultural techniques have been developed to improve traditional shifting cultivation practices, the establishment of pastures (e.g. Valentim, 1989) and agroforestry systems (e.g. Fernandez *et al.* 1999). All these techniques are indeed very good, but alone they just emphasise the idea that the forest is an obstacle that must be replaced, for the implementation of these alternative land uses.

This thesis had the aim of presenting a forest management system to be applied on small farms, especially in the settlement projects of the Brazilian Amazon, and to initiate the debate about its sustainability by investigating the responses of the forest to the forest management interventions in terms of changes in natural regeneration in the felling gaps and the dynamics of the residual trees. Using the program CAFOGROM, an additional aim was to simulate the forest responses to different cycle lengths, harvesting intensities and silvicultural treatments to determine the theoretical optimum combination of these parameters for sustainable timber production.

The reason to provide an alternative forest management system for small farmers came from two main sources. First, the total population of Acre State is 483,593 inhabitants; 168,322 of them live in the countryside (IBGE, 1997). There are around 20,000 families living in settlement projects in Acre (INCRA, 1998). Considering that the average size of a family in Acre is around five people there is a total number of 100,000 inhabitants or around 60 % of the population in rural areas. These people are occupying an area of 1,5000,000 ha, which represents 10 % of the total area of Acre State (152.598 km²) and a total area of legal forest reserves of around 750,000 ha. So the potential problems which can arise from land use (e.g. deforestation) in Acre State is strongly concentrated in settlement projects and small properties.

Secondly, although the Brazilian forest code specifies the conservation of 50 % of the area of properties as forest cover in Amazon, the mean area deforested in these farms in 1994 (PC Peixoto in Acre State and PC Theobroma in Rondônia State (Witcover, 1994)) was 40 % of the total area, with a mean deforestation rate of 2.4 ha yr⁻¹. As the size of these farms is around 100 ha, and assuming the same deforestation rate as 1994, this year (1999), on average, the farmers of settlement projects in Acre and Rondônia States, are reaching the limit of 50 % of their properties which they can legally slash and burn for shifting cultivation or pasture establishment. Therefore it is likely that they will not stop, or even reduce, the deforestation rate on their properties unless they can find an economic use for their forests.

7.2 The forest management system

The proposed forest management system was designed for small farmers and aimed to generate a new source of family income whilst maintaining the structure and biodiversity of the legal forest reserves. The expectation is that small-scale harvesting can change the emphasis of production in Brazilian Amazon properties (by

incorporating a much broader range of legal forest reserves into the production system) and create new models of rural development for the region.

There is a long history of forest exploitation in the Amazon based on traditional 'low technology' methods. These methods require low inputs and have a relatively benign environmental impact, but production and profit margins are also low (Oliveira 1989). The extraction of timber by small producers is a seasonal activity. This permits them to continue other essential activities (hunting, fishing, non-timber product extractivism and subsistence agriculture).

The proposed model is a formalisation of these traditional methods. It is a polycyclic forest management system similar to the traditional selection system (Jonkers, 1987). Selective logging in many respects creates disturbances akin to natural tree falls and results in canopy openings that stimulate the growth of advance regeneration (Uhl *et al.* 1990). I suggest that low-impact disturbance at short intervals, combined with silvicultural treatments, will create a gap mosaic of different ages and permit the maintenance of a forest with a similar structure and biodiversity to that of the original natural forest, and that canopy openings will allow young trees to grow faster. The short rotation cycle substitutes the larger impact caused by heavier interventions distributing it over time. The property's legal forest reserve area (50 % of the total area) was considered as the production unit for the implementation of forest management. The number of annual harvesting coupes was determined on the basis of a minimum felling cycle of ten years and an annual harvest of 5-10 m³ of timber per hectare, through the following sequence of operations for the evaluation of the production capacity of the forest, planning of exploitation activities, and monitoring.

- Forest inventory, 1 - 2 years before harvesting. The inventory determines the potential of the forest for forest management and the length of the cutting cycle.
- Compartmentalisation and permanent sample plot establishment.
- 100 % prospective inventory of trees > 50 cm dbh and tree mapping.
- Preparation of the exploitation plan, marking trees for felling and establishment and measurement of permanent sample plots for growth and yield studies one year before logging.
- Species selection and felling rate determination based on the species diameter distribution, growth rates and seed dispersal.
- Logging, observing directional felling wherever possible. A logging intensity of 5-10 m³ ha⁻¹ and felling diameter limit of 50 cm dbh should be observed.
- Artificial regeneration of commercial species in the felling gaps if necessary, immediately after logging.

- Measurement of the PSPs one year after logging to estimate logging damage and stocking of the residual stand.
- Measurement of the PSPs three years after logging.
- Measurement of the PSPs five years after logging.
- Refinement to assist growth of the residual commercial trees and artificial regeneration of noble species if necessary.
- Measurement of the PSPs 10 years after logging.
- Redefinition of the cutting cycle, cutting rate and silvicultural treatments according to data provided by the PSPs before the beginning of the next cycle (ten years).

The system is new in three main characteristics: the use of short cycles in the management of tropical forest, the low harvesting intensity and environmental impact and the direct involvement of the local population in all forest management activities.

From the previous experience with forest management, even though it is known that the short cycle can provide for continuing benefits of enhanced growth in the residual trees, it is expected that additional silvicultural treatments will be necessary between harvests to maintain forest productivity at a high level (e.g. De Graaf, 1986). The application of silvicultural treatments will be facilitated by the fact that small farmers regularly enter or cross the management area during the working day for hunting, fishing and rubber tree tapping. The silvicultural treatments that have been applied already, such liana cutting and directional felling were effective at reducing the damage promoted by the logging and to protect the residual trees of commercial and potential species.

The harvesting intensity proposed is a reasonable first approximation. It allowed the maintenance of populations of the managed species and a considerable income for the farmers. However, in the future, with more information about forest dynamics and the entrance of some of the potential species onto the timber markets, more intensive harvesting could be applied to maximise forest use. The price of the timber is likely to increase in the future because of the rise in the demand for tropical timber worldwide and the restriction in supply, especially of the more valuable timbers (e.g. Mahogany). Therefore the current standing stock of timber represents an investment rather like a savings account. This may be true even for stems of species that are not highly valued at present, because new species become marketable over time.

The conversion of the logs to planks was the most expensive, labour demanding and probably also the most dangerous operation, although the conversion

yields of around 50 % were above expectation. The project has received some support from the ASB (Alternatives to Slash and Burn project), which involved the acquisition of a one-man sawmill. This is a portable sawmill that can be transported to the felling gaps. The expectation is that with the use of this equipment the conversion of the logs will become easier and cheaper, and that not only will the yields increase but also the quality of the final product will increase.

The use of the “zorra” over distances in the forest reduced the productivity of the skidding phase. The alternative use of a wagon pulled by one ox to skid the planks from the main skid trail to the border of the secondary roads, was successfully applied this year, limiting the skidding by the “zorra” from the felled tree to the main skid trail or a maximum distance of 200 m. This combination of methods made this phase easier for both man and ox.

The short period of time the forest management system has been applied in PC Peixoto (from 1996 to 1999) prevents definitive conclusions and it is possible that in a few years some modifications might be necessary. In this sense, possibly the greatest advantage of the short cycles is the flexibility to change interventions such as harvesting intensity, silvicultural treatment, cycle length, the set of managed species, etc. over a relatively short time scale and to adjust the system when necessary.

7.3 Natural regeneration

Artificial gaps

The higher diversity of seedlings in small and medium gaps than in the forest understorey in the second year confirmed the expectation of higher species diversity in the gaps. It is likely that diversity will continue to increase in the gaps, although slower in gaps larger than 1000 m² or with canopy openness greater than 25 %.

The increase in the relative density of pioneer species with increasing gap size and canopy openness supports the work of Barton (1984) who showed that pioneer species density is higher in larger gaps, but no evidence could be found for the hypothesis that pioneer species regenerate more effectively in the gap centre and shade-tolerant species in the gap edges. However, there was a significant difference in the relative density of the pioneer species in the gap border and in the gap centre at this site. There was also a tendency for the relative density of pioneer species to decrease in the smaller gaps and to increase in the larger ones from the first to the second year after gap creation.

Differences in gap size and canopy openness produced significant differences in the growth rates of seedlings, but no statistically significant differences could be determined according to the position of the quadrats in the gaps. Mortality rates increased with gap size and recruitment rates decreased. One possible interpretation for the low recruitment in the larger gaps could be because of the high mortality there, the potential recruit (seedlings which could reach 1 m in height during the period between the census) died between the first and the last measurement. It also can be interpreted as an effect of the short time of the measurement and the natural tendency is that the larger gaps will be filled in the future and a higher seedling density is expected in these gaps.

The density and recruitment of seedlings of commercial species was not different between gap sizes, but gap creation increased the growth rate of the seedlings of these species.

Felling gaps

The gaps produced by logging in PC Peixoto can be classified as small or less often medium sized (canopy openness from 10 % to 25 %). The richness and diversity of seedlings in these areas one year before logging and two years after logging were similar. The logging produced a sharp decrease in the richness and diversity of both gap zone areas, but two years after logging they were similar to the understorey forest. It is probable that diversity will become higher in the crown zone than in the natural forest understorey over time. The relative density of pioneers, two years after logging, was similar in both gap zones at around 35 %, which is also similar to that observed in the small gaps in the artificial gaps experiment.

The low growth rate of seedlings in the felling gaps might be associated with the low canopy openness in the trunk zone, and the intense competition from the seedlings that survived the logging as well as the felled tree crowns acting as a barrier, in the crown zone.

Mortality of seedlings in the gap zones decreased significantly from the first to the second year and did not differ significantly from that in the understorey. In the trunk zone, felling the tree, conversion of the logs to planks and skidding the planks resulted in complete mortality. In addition, the residues of the logs interfered with the germination of seeds (personal observation) and reduced the recruitment of new seedlings.

The felling gaps do not affect the density and recruitment of commercial species, and again a significant increment in growth rates was observed. Small and

medium gaps, or gaps with less than 25 % canopy openness resulted in improved regeneration from the forest management point of view, with fewer pioneer plants higher species diversity and lower mortality, although the growth rates in the two first years was significantly lower than in the larger gaps.

Consequences and recommendations for the management system

In general the results from the artificial gaps experiments also support Hawthorne (1993) who found that larger gaps are undesirable for almost every reason except the convenience of the loggers. Therefore regulations must be applied to limit the total number of trees felled in a compartment, as well as the number of adjacent trees which can be felled, so that gap sizes will be small.

Most of the gaps produced by the felling of trees in Pedro Peixoto Colonisation Project can be classified as small (considering the categories used in this study). Small and medium gaps in the artificial gap experiment showed the optimum results for natural regeneration from the perspective of forest management. Despite some differences arising during the creation of artificial gaps (destruction of the original seedling community and removal of large branches) and felling gaps, the environmental conditions (e.g. temperature, humidity and water availability) were similar. Thus, the continuation of the study in both conditions (artificial and felling gaps) will probably emphasise these similarities. Studies of artificial gaps have the advantage of controlling important characteristics of gaps, such as size, topographic position and orientation and they are a tool to help forecast regeneration dynamics in the felling gaps where the control of such characteristics are usually difficult.

The distribution of the impacts in space and time as proposed by the studied silvicultural system coincides, with these principles. The low harvesting rates and short cycles used reduces the number of gaps and distributes the impacts among the following harvesting cycles, in contrast to what happens with conventional forest management where the impacts occur at one time. In addition, the potential benefits of canopy opening are repeated at shorter intervals, which avoids stagnation of forest production. The felling of the trees in the compartments produced gaps which could be classified as small gaps in the artificial gaps experiment. The fact that all seedlings were removed during the creation of artificial gaps can be used to explain differences in growth rates and recruitment in the first two years. However, the species composition, richness and diversity of seedling communities were similar.

More frequent logging has the disadvantage of producing more damage to the residual trees. Special care must be taken during the harvesting operations, through

the use of directional felling and liana cutting. In addition, the extraction of the logs by animal traction significantly reduces this damage.

7.4 Forest dynamics

The mean periodic annual diameter increment (0.28 cm yr^{-1}) was similar to that found by other work in the tropics. Differences in crown exposure produced a highly significant effect on the growth of the trees. The sub-groups of species also possess different growth rates, probably because of different growth patterns shown by those species (e.g. *Bertholletia excelsa* – big pioneers and *Gustavia augusta* – understory species). The increase in diameter increment from small trees to big trees is also correlated with increase in crown exposure and growth patterns. The influence of management was positive in terms of diameter increment increase in both mechanised and non-mechanised logging. Diameter increment immediately after logging in PC Peixoto was slower than in the undisturbed forest possibly because the short time between logging and measurement did not allow the effect of canopy openness to be observed.

Mortality rates in the natural forest were similar to other studies in tropical forests i.e. between 1 % and 2 % yr^{-1} . The higher mortality recorded at the last measurement (1999), can be a consequence of higher occurrence of winds and storms in this period ("El Niño" event). Although mortality caused by mechanised management was underestimated, it is still higher than in the natural forest.

Recruitment in the areas managed by the farmers in PC Peixoto (using non-mechanised methods), was not significantly higher than in the natural forest probably because the canopy opening caused by the harvesting operations was minimised by the low harvesting intensity. However, as recruitment considered plants with dbh greater than 5 cm, the period covered by the study was not enough to include some of the plants that germinated after the logging. Thus, an increase in the recruitment rates in those areas may be expected in the next few years.

The increase in the damage from natural causes from the first to the last measurement might be associated with the logging, but it is also possible that 1998 was an atypical year, with more frequent strong storms in the area.

The difference in species richness and diversity in the low impact management system before and after logging was low, and it is probable that before the end of the cycle diversity will increase in this area. The high impact management system, at least in the short-term, produced a high variation in the composition of the forest, but the density of commercial species did not change.

An acceptable volume increment of commercial species was compatible with the logging intensity and cycle length proposed for both forest management systems examined. The high volume increment of commercial species might be an effect of the practice of the directional felling, protecting residual trees of commercial and potential species.

7.5 The simulations

Sensitivity analysis and the weakness and limitation of the application of the model in this study

The model was demonstrated, when tested, to be sensible for both recruitment and mortality. This is important in the sense that the precision of the predictions come from the capacity of the model to show in their outputs the difference caused by small changes in the forest dynamics (Pinard, 1993). Functions generated from the data from CPATU were compared with those using the data set of the permanent sample plots in CPAF-ACRE and in Pedro Peixoto Colonisation Project. Although generated in different regions of Amazon, these two forests have similar characteristics in terms of climate (temperatures around 25^o C, rainfall around 2000 mm yr⁻¹, mean relative humidity over 80 % and a not very pronounced dry season concentrated between August and September), geographical position (from 2^o to 6^o S), soil (dystrophic yellow latosol), forest structure (*terra-firme* forest, with emergent species such as *Bertholletia excelsa* and *Couratari* sp. and basal area around 25 to 30 m² ha⁻¹) and forest dynamics (mortality rates in the undisturbed forest around 2 % year⁻¹ and mean diameter increment around 0.25 cm year⁻¹). All data from Tapajós National Forest are in Silva (1989); Silva *et al.* (1989); Silva *et al.* (1996) and for PC Peixoto and CPAF-ACRE in this work (Chapter 2 (site description), Chapter 3 (forest inventory results) and Chapter 5). Thus, the use of the functions generated by the CPATU data set is a reasonable approach to parameterising the functions generated by the CPAF-ACRE data. In general the functions generated with my data set produced realistic outputs and the differences from those using CPATU data (e.g. logging damage, mortality rates and diameter increment) were expected as a result of the different management techniques and harvesting intensities applied for these two sites. These differences also emphasises the need for the development of different functions for the proposed forest management system.

The unexpected equation generated for recruitment probably arose because the recruitment in the managed areas was low. Thus, because of the lack of

recruitment in the managed areas, which presumably have a lower basal area than the undisturbed areas, the regression showed a tendency for recruitment to increase with basal area. The natural tendency is that these areas will have a higher recruitment in future years and the basic assumption of the recruitment function, that sites with lower basal areas will have a higher probability of higher recruitment, is correct.

In addition there is a possibility for a disturbed site to have a high basal area (e.g. a logged area that possesses very big residual trees), and for an undisturbed site (sites without natural or human disturbance) to have a closed canopy and low basal area. In these situations the recruitment will probably be higher in the site with the higher basal area than in the site with the lower basal area. The same effect might be found for basal area increment, considering the situation described above whereby, a higher basal area increment is expected in the site with the higher basal area than in the other one.

A similar effect for recruitment was observed in the artificial gaps, probably associated with climatic conditions during the period of this study. Larger gaps, which in a forest management condition could be associated with higher harvesting intensities and as consequence lower basal areas, showed lower recruitment rates. On the other side, the growth of the residual tree, in terms of stand basal area, was according to the assumption of the model and the managed areas showed higher basal area increment in the studied period.

However, it must be pointed out that the data available in CPAF-ACRE for this work is not robust and better predictions are expected in the future from the new permanent sample plots already established in new areas where the proposed forest management system was implemented in 1998 (Antimari Forest, FUNTAC, 1989).

Silvicultural treatments

Without silvicultural treatment, total production is almost constant in short felling cycles (i.e. from 5 to 15 years). The need for silvicultural treatments is due to the small number of commercial species competing with a large number of non-commercial or potential species. With a larger set of commercial species, higher harvesting intensity could be practised and the harvesting itself should produce the same effect as silvicultural treatments, eliminating the need to use them. On the other hand, heavy silvicultural treatments must be applied with care because they can affect negatively the population of potential species and increase the risks of biodiversity loss.

Cycle length, harvesting intensity and timber production

The variance in the average harvested volume increased when the harvesting intensity increased in all the cycles examined, this suggests that heavy harvesting might result in the extinction of commercial species, or a lowering their density if more intensive silvicultural treatments are applied.

Five year cycles always showed a high variance in the harvested timber per cycle. The high final production values obtained in some simulations resulted from a combination of low harvesting rates with intensive silvicultural treatments, resulting in a sharp decrease in the standing volume of the forest as a whole. The reduction in the commercial volume after harvesting is not a major problem, and is even expected on longer cycles, but for very short cycles some residual trees of commercial species must be present to guarantee the following harvests. In addition, the low productivity and the greater area of the compartments increases costs and labour demand, and must be considered as strong economic limitations on the use of five year cycles. Therefore, because of the need for annual and regular incomes, longer cycles are recommended.

Twenty and 15 year cycles are not applicable on small farms, because they demand much larger areas to be economically viable. In addition, the total production (using the conditions of this study) was less than in the short cycles. The lower production is caused by the need for more than one silvicultural treatment and a larger set of commercial species to allow more intensive harvesting rates.

Ten year cycles are the most appropriate compromise for sustainable forest management under the conditions examined in this study. A regular harvesting of 8 to 10 m³ ha⁻¹ cycle⁻¹ can be expected with the combination of a harvesting intensity of around 1.0 m² ha⁻¹ cycle⁻¹ and silvicultural treatments removing around 1.5 m² ha⁻¹ cycle⁻¹.

Implications for the forest management system

The results of the simulations must be interpreted as qualitative responses of presented by the forest to different interventions. Thus, the predictions produced by the simulations are important for planning but they cannot replace the field experience of foresters. This qualification is especially important in a scenario where the set of commercial species is constantly changing, resulting in delicate decisions such as which trees can be removed during silvicultural treatments.

The initial choice of ten year cycles and harvesting rates of around $10 \text{ m}^3 \text{ ha}^{-1} \text{ cycle}^{-1}$ were consistent with the results of the simulations. There is a clear need for silvicultural treatments to increase forest production. In the forest dynamics study, it was observed that the changes in the crown illumination status of the trees produced an increase in their growth rates, therefore it is reasonable to apply a competitive advantage to a particular group of species being affected by the forest management.

The model will be also a tool to simulate different forest management scenarios during harvesting intervals, not only using new data from the forest dynamics studies but also variations in the set of commercial species during this period.

7.6 The way ahead: constraints, opportunities and future research

The project will continue as a part of the EMBRAPA research programme. Additional support has been provided by the ASB (alternative to slash and burn) project that has PC Pedro Peixoto as one of its chosen sites for research. In addition the project was submitted to the “Pro-manejo” project which is administered by the Brazilian Institute of Environment and Natural Resources (IBAMA) and supported by the G-7 Nations and the GTZ. This project aims to identify and to give support for the implementation of “promising initiatives” for forest management in the Amazon. The continuation of the project will allow the continuation of research on forest dynamics and plant succession in the felling and artificial gaps, which demand long term studies (Whitmore and Brown, 1996).

The system is also being implemented in the Antimari forest management project. This project has the aim of sustainable timber and non-timber production and research. It has the support of ITTO and is being conducted by FUNTAC (Acre State Technology Foundation). Fifteen permanent sample plots have already been established there and all the studies will be conducted through a partnership between EMBRAPA and FUNTAC teams.

Some opportunities have been created for the implementation of forest management for small farmers in the Amazon. A specific legislative framework covering implementation and inspection of management plans on small properties was approved in 1998, establishing the use of short cycles and animal traction by IBAMA (Brazilian Institute for Environment and Natural Resources) agencies. In addition, BASA (the Amazonian Bank) has implemented a scheme that allows farmers access to a specific account to finance forest management following this model.

Some outstanding problems must still be solved, such as the lack of control of the trade in illegal timber, and the entrance onto the market of royalty-free timber from areas being converted from forests to agriculture. These problems make it difficult for legally produced timber to compete on an equal basis. In addition, the extension services that already exist in Brazil (EMATER) are only for technical support in activities related to agriculture. They cannot act in the same way for forest management activities. Their support will be necessary in the future to help the small farmers with technical activities such as prospective forest inventories and harvesting intensity determination, tasks which are now being performed by CPAF-ACRE.

The wide application of the system proposed here in tropical forests will be limited by the size of the properties. The size of the small farms in the Brazilian Amazon (from 80 to 100 ha) are, very probably, an exception in the world and the forest management proposed in this thesis will not be applicable to forest areas much smaller than 40 ha.

In general, new activities and technologies are difficult to implement, especially in a complex socio-economic and ecological environment. However, there is a need for economic and ecologically sound technologies to be implemented in the Amazon and the small scale forest management proposed in this thesis has been demonstrated to be viable in these respects.

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Appendix 1

Species list of PC Peixoto Forest Management Areas (Based on FUNTAC, 1989, 1992)

Scientific name	Family	Common name
<i>Acacia pollyphylla</i> A. DC.	Mimosaceae	Espinheiro vermelho
<i>Agonandra brasiliensis</i> Benth. & Hook	Opiliaceae	Marfim de veado
<i>Aiouea</i> sp.	Lauraceae	Louro rosa
<i>Alibertia edulis</i> (L. Rich.) A. Rich.	Rubiaceae	Apurui
<i>Allophylus pilosus</i> (P. & E.) Radlk.	Sapindaceae	Jitozinho
<i>Allophylus</i> sp.	Sapindaceae	Seringuinha
<i>Alseis</i> sp.	Rubiaceae	Pau de remo
<i>Alseis</i> sp.	Rubiaceae	Tamanqueiro
<i>Amaioa</i> sp.	Rubiaceae	Canela de veado
<i>Ampelocera edentula</i> Kuhlmann	Ulmaceae	Envira iodo
<i>Anacardium gigantum</i> Hancock	Anacardiaceae	Cajui
<i>Anaxegorea dalichocarpa</i> S. & Sandwith	Annonaceae	Envira porco
<i>Angoustura ucayalina</i> (Hub.) Albuquerque	Rutaceae	Envira nambú
<i>Aniba canelina</i> (H.B.K.) Mez.	Lauraceae	Casca preciosa
<i>Antrocaryon amazonicum</i> Ducke	Anacardiaceae	Almeixa
<i>Aparisthium cordatum</i> (Juss.) Baillon	Euphorbiaceae	Marmeleiro da mata
<i>Apeiba echinata</i> Gaertner	Tiliaceae	Envira pente de macaco
<i>Apeiba timbourbou</i> Aublet	Tiliaceae	Malva pente de macaco
<i>Apuleia molares</i> Spruce ex Benth.	Caesalpiniaceae	Cumarú cetim
<i>Aspidosperma auriculatum</i> H.E.F.	Sapotaceae	Carapanauba amarela
<i>Aspidosperma oblongum</i> A. DC.	Sapotaceae	Carapanauba preta
<i>Aspidosperma vargasii</i> A. DC.	Sapotaceae	Amarelo
<i>Astrocaryum murmurum</i> Mart.	Arecaceae	Murmuru
<i>Astronium leicotei</i> Ducke	Anacardiaceae	Gonçalo alvez
<i>Banara nitida</i> Spruce ex Benth.	Flacourtiaceae	Cabelo de cutia
<i>Batocarpus</i> sp.	Moraceae	Guariuba branca
<i>Bauhinia</i> sp.	Caesalpiniaceae	Mororo
<i>Bauhinia</i> sp.	Caesalpiniaceae	Mororo branco
<i>Bauhinia</i> sp.	Caesalpiniaceae	Mororo preto
<i>Bertholletia exelsa</i> (H.B.K.)	Lecythidaceae	Castanha do Brasil
<i>Brosimum acutifolium</i> Hubert	Moraceae	Mururu
<i>Brosimum alicastrum</i> Swartz	Moraceae	Inhare
<i>Brosimum guianense</i> (Aubl.) Hubert	Moraceae	Inhare mole
<i>Brosimum parinarioides</i> Ducke	Moraceae	Amapa
<i>Brosimum rubescens</i> Taubert	Moraceae	Falsa rainha
<i>Brosimum uleanum</i> Mildbr.	Moraceae	Manite
<i>Brosimum</i> sp.	Moraceae	Inhare amarelo
<i>Buchenavia</i> sp.	Combretaceae	Imbirindiba roxa
<i>Byrsonima chrysophylla</i> H.B.K.	Malpighiaceae	Murici amarelo
<i>Callycophyllum acreanum</i> Ducke	Rubiaceae	Mamalu
<i>Carapa guianensis</i> Aublet	Meliaceae	Andiroba
<i>Cariniana</i> sp.	Lecythidaceae	Jequitiba
<i>Caryocar glabrum</i> (Aubl.) Pers.	Cariocaraceae	Piquiarana
<i>Casearea</i> sp.	Flacourtiaceae	Sardinheiro
<i>Casearia gossypiosperma</i> Briquet	Flacourtiaceae	Laranjinha
<i>Casearia</i> sp.	Flacourtiaceae	Caferana
<i>Casearia</i> sp.	Flacourtiaceae	Caferana vermelha

<i>Cassia lucens</i> Vog.	Caesalpiniaceae	Flor de São João
<i>Cassia</i> sp.	Caesalpiniaceae	Bajão
<i>Cassipourea</i> sp.	Rhizophoraceae	Angelca preta
<i>Castilla ulei</i>	Moraceae	Caucho amarelo
<i>Cathedra acuminata</i> (Benth.) Miers.	Anacardiaceae	Cajuzinho
<i>Catoblastus</i> sp.	Arecaceae	Paxiubarana
<i>Cecropia leucoma</i> Miq.	Cecropiaceae	Imbauba branca
<i>Cecropia sciadophylla</i> Mart.	Cecropiaceae	Imbauba gigante
<i>Cecropia</i> sp.	Cecropiaceae	Imbauba
<i>Cedrela odorata</i> L.	Meliaceae	Cedro vermelho
<i>Ceiba pentandra</i> (L.) Gaertn.	Bombacaceae	Sumauma
<i>Ceiba samauma</i> (Mart.) K. Schum.	Bombacaceae	Sumauma preta
<i>Celtis</i> sp.	Ulmaceae	Farinha seca
<i>Chorizia speciosa</i> St. Hill.	Bombacaceae	Sumauma barriguda
<i>Chrysophyllum auratum</i> Miq.	Sapotaceae	Abiurana da folha cinzenta
<i>Chrysophyllum prieurii</i> A. DC.	Sapotaceae	Abiurana vermelha
<i>Chrysophyllum</i> sp.	Sapotaceae	Abiurana bacuri
<i>Chrysophyllum</i> sp.	Sapotaceae	Maparajuba branca
<i>Cibianthus</i> sp.	Myrcinaceae	Casca grossa
<i>Clarisia racemosa</i> Ruiz & Pav.	Moraceae	Guariuba vermelha
<i>Clinostemon mahuba</i> Kuhlm.	Lauraceae	Mauba
<i>Clitoria</i> sp.	Fabaceae	Feijãozinho
<i>Cocholospermum orinocense</i> Stend	Cocholospermaceae	Pacote
<i>Cocoloba paniculata</i> Meissn.	Polygonaceae	Coacu
<i>Copaifera multijuga</i> Hayne	Caesalpiniaceae	Copaiba
<i>Cordia alliodora</i> (R. F.) Chaw	Boraginaceae	Frei jorge
<i>Cordia goeldiana</i> Hub.	Boraginaceae	Frei jorge preto
<i>Cordia</i> sp.	Boraginaceae	Frei jorge branco
<i>Couratari macrosperma</i> A. S. Smith	Lecythidaceae	Tauari vermelho
<i>Couratari</i> sp.	Lecythidaceae	Tauari roxo
<i>Couroupita guianensis</i> Aubl.	Lecythidaceae	Coite de macaco
<i>Cupania</i> sp.	Sapindaceae	Breu de tucano
<i>Dailium guianensis</i> (Aubl.) Sandwith	Caesalpiniaceae	Tamarina
<i>Dalbergia amazonica</i> (Radlk. Ex Köpff) Ducke	Fabaceae	Jacarandá
<i>Diclinanona</i> sp.	Annonaceae	Manga de anta
<i>Diploptropis purpurea</i> (Rich.) Amsh.	Fabaceae	Sucupira preta
<i>Dipteryx odorata</i> (Aubl.) Willd	Fabaceae	Cumaru ferro
<i>Dipteryx polyphylla</i> Huber.	Fabaceae	Cumarurana
<i>Drypetes</i> sp.	Euphorbiaceae	Sernambi de índio
<i>Drypetes variabilis</i> Vitt.	Euphorbiaceae	Angelca
<i>Duguetia macrophylla</i> R.E. Fr.	Annonaceae	Envira conduru
<i>Ecclinusa</i> sp.	Sapotaceae	Abiurana cagaça
<i>Ecclinusa</i> sp.	Sapotaceae	Abiurana casca fina
<i>Ecclinusa</i> sp.	Sapotaceae	Abiurana casca grossa
<i>Ecclinusa</i> sp.	Sapotaceae	Abiurana preta
<i>Enterolobium schomburgkii</i> Benth.	Mimosaceae	Fava orelinha
<i>Ephedranthus guianensis</i> R.E. Fr.	Annonaceae	Envira preta
<i>Erythryna glauca</i> Willd.	Fabaceae	Mulungu
<i>Eschweilera grandifolia</i> (Aubl.) Sandwith	Lecythidaceae	Mata-mata branco
<i>Eschweilera odorata</i> (Poepp.) Miers.	Lecythidaceae	Mata-mata roxo
<i>Eschweilera</i> sp.	Lecythidaceae	Mata-mata amarelo
<i>Eugenia</i> sp.	Myrtaceae	Araca brabo
<i>Eugenia</i> sp.	Myrtaceae	Goiabinha
<i>Euterpe precatoria</i> M.	Arecaceae	Acai

<i>Ficus dusiaefolia</i> Schett.	Moraceae	Apui branco
<i>Ficus frondosa</i> Standl.	Moraceae	Apui amarelo
<i>Ficus maxima</i> Miller	Moraceae	Caxinguba
<i>Ficus</i> sp.	Moraceae	Apui
<i>Ficus</i> sp.	Moraceae	Apui preto
<i>Ficus</i> sp.	Moraceae	Gameleira
<i>Galipea trifoliata</i> Aubl.	Bignoniaceae	Pau d'arquinho
<i>Geissospermum reticulatum</i> A.H. Gentry	Apocynaceae	Quina-quina amarela
<i>Glycidendron amazonicum</i> Ducke	Euphorbiaceae	Castanha de porco
<i>Goupia glabra</i> Aubl.	Celastraceae	Capoeiro
<i>Guarea kunthiana</i> A. Juss.	Meliaceae	Jito preto
<i>Guarea pterorachis</i> Harms.	Meliaceae	Jito da terra firme
<i>Guarea purusiana</i> C. DC.	Meliaceae	Jito vermelho
<i>Guarea</i> sp.	Meliaceae	Jito branco
<i>Guatteria</i> sp.	Annonaceae	Envira fofa
<i>Guatteria</i> sp.	Annonaceae	Envira mole
<i>Guazuma ulmifolia</i> L.	Sterculiaceae	Mutamba preta
<i>Guazuma</i> sp.	Sterculiaceae	Mutamba
<i>Guettarda</i>	Rubiaceae	Quina-quina
<i>Gustavia augusta</i> L.	Lecythidaceae	Castanha fedorenta
<i>Heisteria ovata</i> Benth.	Olacaceae	Itaubarana
<i>Heliocarpus</i> sp.	Tiliaceae	Malva branca
<i>Hevea brasiliensis</i> Muell. Arg.	Euphorbiaceae	Seringa real
<i>Hevea guianensis</i> Aubl.	Euphorbiaceae	Seringa vermelha
<i>Himatanthus sucuuba</i> (Spruce) Woodson	Apocynaceae	Sucuuba
<i>Hirtella</i> sp.	Chrysobalanaceae	Caripe branco
<i>Hirtella</i> sp.	Chrysobalanaceae	Macucu vermelho
<i>Huberodendron swietenioides</i> Ducke	Bombacaceae	Munguba da mata
<i>Hyeronima laxiflora</i> Muell. Arg.	Euphorbiaceae	Pau pedra
<i>Hymenolobium excelsum</i> Ducke	Fabaceae	Angelim da mata
<i>Hymenolobium</i> sp.	Fabaceae	Angelim
<i>Hymenolobium</i> sp.	Fabaceae	Angelim amarelo
<i>Hyminaea courbaril</i> L.	Caesalpiniaceae	Jatoba
<i>Hyminaea oblongifolia</i> Hub.	Caesalpiniaceae	Jutai
<i>Inga marginata</i> Willd.	Mimosaceae	Inga facao
<i>Inga thibaudiana</i> DC.	Mimosaceae	Inga vermelha
<i>Inga tomentosa</i> Benth.	Mimosaceae	Inga branca
<i>Inga veludina</i> Willd.	Mimosaceae	Inga peluda
<i>Inga</i> sp.	Mimosaceae	Inga copaiba
<i>Inga</i> sp.	Mimosaceae	Inga de varzea
<i>Inga</i> sp.	Mimosaceae	Inga ferro
<i>Inga</i> sp.	Mimosaceae	Inga mirim
<i>Inga</i> sp.	Mimosaceae	Inga preta
<i>Iryanthera juruensis</i> Warb.	Myristicaceae	Ucuuba sangue
<i>Iryanthera triconis</i> Warb.	Myristicaceae	Ucuuba punã
<i>Jacaranda copaia</i> (Aubl.) D. Don.	Bignoniaceae	Marupa
<i>Jacaranda</i> sp.	Bignoniaceae	Fava roxa
<i>Jaracatea spinosa</i> Aubl.	Caricaceae	Jaracatia
<i>Laetia procera</i> (Poepp.) Eichl.	Flacourtiaceae	Pau jacare
<i>Leonia glycyarpa</i> Ruiz & Pav.	Violaceae	Gogo de guariba
<i>Licania apetala</i> Fritsch.	Chrysobalanaceae	Caripe vermelho
<i>Licania arborea</i> Sum.	Chrysobalanaceae	Caripe roxo
<i>Licania latifolia</i> Benth.	Chrysobalanaceae	Macucu sangue
<i>Licania</i> sp.	Chrysobalanaceae	Macuco chiador

<i>Licaria aritu</i> Ducke	Lauraceae	Louro aritu
<i>Licaria</i> sp.	Lauraceae	Louro chumbo
<i>Luehea</i> sp.	Tiliaceae	Mutamba preta
<i>Luhea</i> sp.	Tiliaceae	Acoita cavalo
<i>Luhea</i> sp.	Tiliaceae	Urucurana cacau
<i>Mabea caudata</i> Pax. ex K. Hoffm.	Euphorbiaceae	Seringai
<i>Mabea</i> sp.	Euphorbiaceae	Taquari
<i>Macrobium acaceiphollium</i> Benth.	Caesalpiniaceae	Fava arapari
<i>Manilkara</i> sp.	Sapotaceae	Macaranduba branca
<i>Manilkara</i> sp.	Sapotaceae	Maparajuba
<i>Manilkara surinamensis</i> (Miq.) Dub.	Sapotaceae	Macaranduba
<i>Martiodendron elatum</i> (Ducke) Gleas	Caesalpiniaceae	Pororoca
<i>Matayba arborescens</i> (Aubl.) Radlk.	Sapindaceae	Pitombarana
<i>Maytenus</i> sp.	Celastraceae	Xixua
<i>Metrodora flavida</i> K. Krause	Rutaceae	Pirarara
<i>Mezilaurus itauba</i> (Meissn.) Taub.	Lauraceae	Itauba
<i>Miconia</i> sp.	Melastomataceae	Buxixu liso
<i>Miconia</i> sp.	Melastomataceae	Tinteiro
<i>Miconia</i> sp.	Melastomataceae	Buxixu canela de velho
<i>Micropholis venulosa</i> (Mart. & Eichler) Pierre	Sapotaceae	Abiurana rosa
<i>Micropholis</i> sp.	Sapotaceae	Abiurana abiu
<i>Minquartia guianensis</i> Aubl.	Olacaceae	Aquariquara
<i>Minquartia</i> sp.	Olacaceae	Acapu
<i>Mouriri nervosa</i> Pilger	Melastomataceae	Gurgui
<i>Myrcia</i> sp.	Myrtaceae	Araçazinho
<i>Myroxilom balsamum</i> Harms	Fabaceae	Balsamo
<i>Naucleopsis caloneura</i> Ducke	Moraceae	Muiratinga
<i>Nectandra rubra</i> Mez.	Lauraceae	Louro gamela
<i>Nectandra</i> sp.	Lauraceae	Louro amarelo
<i>Neea glomerulifolia</i> Heimerl	Nyctaginaceae	Joao mole folha pequena
<i>Neea</i> sp.	Nyctaginaceae	Joao mole
<i>Neea</i> sp.	Nyctaginaceae	Joao mole da folha grande
<i>Ochroma pyramidalis</i> Urb.	Bombacaceae	Pau de balsa
<i>Ocotea myriantha</i> (Meissn.) Mez.	Lauraceae	Louro abacate
<i>Ocotea neesiana</i> (Miq.) Kosterm.	Lauraceae	Louro preto
<i>Ocotea opifera</i> Mart.	Lauraceae	Louro de tucano
<i>Ocotea</i> sp.	Lauraceae	Louro bosta
<i>Ocotea</i> sp.	Lauraceae	Louro branco
<i>Onochopetallum lucidum</i> R. E. Fries	Annonaceae	Envira caju
<i>Ormosia</i> sp.	Fabaceae	Feijao bravo
<i>Ormosia</i> sp.	Fabaceae	Muirapiranga
<i>Osteopholeum platyspermum</i> (A. DC.) Mart.	Myristicaceae	Ucuuba branca
<i>Otoba parviflora</i> (M.G.F.) Gentry	Myristicaceae	Ucuuba vermelha
<i>Oxandra</i> sp.	Annonaceae	Envira ferro
<i>Pachira</i> sp.	Bombacaceae	Munguba
<i>Palicourea guianensis</i> Aubl.	Rubiaceae	Capança
<i>Panopsis rubescens</i> (Pohl.) Rusby	Proteaceae	Bofe de jabuti
<i>Parkia pendulo</i> Benth. ex Walp.	Mimosaceae	Angelim saio
<i>Parkia</i> sp.	Mimosaceae	Angelim pedra
<i>Parkia</i> sp.	Mimosaceae	Fava pe de arara
<i>Pausandra trianae</i> (Muell. Arg.) Baill.	Euphorbiaceae	Orelha de burro
<i>Peltogyne</i> sp.	Caesalpiniaceae	Roxinho
<i>Perebea mollis</i> (P.G.) Hub.	Moraceae	Paima caucho
<i>Phyllocarpus reidellii</i> Tul.	Caesalpiniaceae	Guaribeiro

<i>Physocalymma</i> sp.	Lythraceae	Itaubarana de capoeira
<i>Picramnia</i> sp.	Fabaceae	Anilina
<i>Piptadenia suaveolens</i> Miq.	Mimosaceae	Fava da folha fina
<i>Piptadenia</i> sp.	Mimosaceae	Fava branca
<i>Pithecellobium</i> sp.	Mimosaceae	Inga dura do Igapó
<i>Pithecellobium</i> sp.	Mimosaceae	Ingazinha verde
<i>Platonia insignis</i> Mart.	Clusiaceae	Bacuri de serra
<i>Platymiscium duckei</i> Hub.	Fabaceae	Violeta
<i>Platypodium</i> sp.	Sapotaceae	Abiurana de quina
<i>Poeppigia procera</i> Presl.	Caesalpiniaceae	Pintadinho
<i>Pourouma aspera</i> Trécul.	Cecropiaceae	Torem de lixa
<i>Pourouma</i> sp.	Cecropiaceae	Torem imbauba
<i>Pourouma</i> sp.	Cecropiaceae	Torem abacate
<i>Pouteria</i> sp.	Sapotaceae	Abiu brabo
<i>Pradosia</i> sp.	Sapotaceae	Pau garrote
<i>Protium apiculatum</i> Swartz	Burceraceae	Breu vermelho
<i>Protium hebetatum</i> D. Daly	Burceraceae	Breu branco
<i>Protium tenuifolium</i> (Engl.) Engl.	Burceraceae	Breu manga
<i>Pseudobombax</i> sp.	Bombacaceae	Embiratanha
<i>Pseudolmedia laevis</i> (Ruiz & Pav.) Macbr.	Moraceae	Paima preta
<i>Pseudolmedia murure</i> Standl.	Moraceae	Paima amarela
<i>Pseudolmedia</i> sp.	Moraceae	Paima folha grande
<i>Psychotria</i> sp.	Rubiaceae	Taboquinha
<i>Pterocarpus rohrii</i> Vahl.	Fabaceae	Pau sangue
<i>Pterocarpus</i> sp.	Fabaceae	Pau sangue casca grossa
<i>Qualea grandiflora</i> Mart.	Volchysiaceae	Catuaba roxa
<i>Qualea tesmanni</i> Milldr.	Volchysiaceae	Catuaba
<i>Quararibea guianensis</i> Aubl.	Bombacaceae	Envira sapatinha
<i>Quiina juruana</i> Ule.	Quinaceae	Murici azedo
<i>Rauwolfia</i> sp.	Apocynaceae	Marfim fedorento
<i>Rheedia acuminata</i> Tr. & P.I.	Clusiaceae	Bacuri de espinho
<i>Rheedia brasiliensis</i> Mart.	Clusiaceae	Bacuri liso
<i>Rinorea pubiflora</i> (Benth.) Sprang & Sandwith	Violaceae	Canela de velho
<i>Rinoreocarpus</i> sp.	Violaceae	Pau estalador
<i>Rollinia exsucca</i> (Dun.) DC.	Annonaceae	Ata braba
<i>Roupala montana</i> Aubl.	Proteaceae	Pau conserva
<i>Ruizodendrom</i> sp.	Annonaceae	Envira orelha de onça
<i>Sambucus</i> sp.	Caprifoliaceae	Sabugueira brava
<i>Sapindus saponaria</i> L.	Sapindaceae	Sabonete
<i>Sapium glandulatum</i> (Vell.) Pax.	Euphorbiaceae	Burra leiteira folha pequena
<i>Sapium marmiere</i> Hub.	Euphorbiaceae	Burra leiteira
<i>Sapium</i> sp.	Euphorbiaceae	Seringarana
<i>Schefflera morototoni</i> Dcne. & Planch.	Araliaceae	Morototo
<i>Schyzollobium amazonicum</i> Hub.	Caesalpiniaceae	Fava canafístula
<i>Sclerolobium</i> sp.	Caesalpiniaceae	Taxi vermelho
<i>Sickingia tinctoria</i> (H.B.K.) K. Sch.	Rubiaceae	Pau brasil
<i>Sickingia</i> sp.	Rubiaceae	Pau arara
<i>Simaruba amara</i> Aubl.	Simarubaceae	Marupa preto
<i>Siparuna</i> sp.	Monimiaceae	Aquariquara de igapo
<i>Siparuna</i> sp.	Monimiaceae	Capitiu branco
<i>Sloanea nitida</i> Benth.	Elaeocarpaceae	Urucurana
<i>Sorocea guilleminiana</i> Gad.	Cecropiaceae	Jaca brava
<i>Sparattosperma leucanthum</i> K. Schu.	Bignoniaceae	Pau d'arco branco
<i>Spondias testudines</i> Mitchell & Daly	Anacardiaceae	Cajarana da mata

<i>Sterculia elata</i> Ducke	Sterculiaceae	Xixa da casca dura
<i>Sterculia pruriens</i> (Aubl.) K. Schum.	Sterculiaceae	Xixa da casca mole
<i>Sterculia</i> sp.	Sterculiaceae	Xixa
<i>Stryphnodendron</i> sp.	Mimosaceae	Bajinha
<i>Swartzia platygyne</i> Ducke	Caesalpiniaceae	Pitaica
<i>Swartzia ulei</i> Harms.	Caesalpiniaceae	Muiragiboia
<i>Swartzia</i> sp.	Caesalpiniaceae	Muiragiboia preta
<i>Swietenia macrophylla</i> King.	Meliaceae	Aguano
<i>Symphonia globulifera</i> L.F.	Clusiaceae	Anani da terra'firme
<i>Tabebuia impetiginosa</i> (Mart.) Tol.	Bignoniaceae	Pau d'arco roxo
<i>Tabebuia serratifolia</i> (Vahl.) Nichols.	Bignoniaceae	Pau d'arco amarelo
<i>Tabernaemontana heterophylla</i> Vahl	Apocynaceae	Grao de galo
<i>Tachigalia paniculata</i> Aubl.	Caesalpiniaceae	Taxi preto
<i>Talisia</i> sp.	Sapindaceae	Pitomba folha dura
<i>Tapirira guianensis</i> Aubl.	Anacardiaceae	Pau pombo
<i>Tapura jurana</i> (Ule.) Rizz.	Dichapetalaceae	Pau ferrugem
<i>Terminalia</i> sp.	Combretaceae	Imbirindiba amarela
<i>Tetragastris</i> sp.	Burceraceae	Breu de campina
<i>Tetragastris</i> sp.	Burceraceae	Breu mescla
<i>Tetrastylidium</i> sp.	Olacaceae	Pau embua
<i>Theobroma microcarpum</i> M.	Sterculiaceae	Cupuaçu branco
<i>Theobroma obovatum</i> Klotzch ex Ber. N.	Sterculiaceae	Cupuaçu da mata
<i>Theobroma silvestris</i> Mart.	Sterculiaceae	Cacauí
<i>Thyrsodium herrerences</i> D. Daly	Anacardiaceae	Breu de leite
<i>Torresia acreana</i> Ducke	Caesalpiniaceae	Cerejeira
<i>Trichilia pallida</i> Sw.	Meliaceae	Marachimbe vermelho
<i>Trichilia poeppigiana</i> C.DC.	Meliaceae	Papo de mutum
<i>Trichilia poeppigii</i> C. DC.	Meliaceae	Marachimbe branco
<i>Trichilia</i> sp.	Meliaceae	Breu maxixe
<i>Trichillia</i> sp.	Meliaceae	Murici vermelho
<i>Urbanella</i> sp.	Sapotaceae	Abiurana massa
<i>Urera</i> sp.	Urticaceae	Urtiga branca
<i>Vatairea sericea</i> Ducke	Fabaceae	Sucupira amarela
<i>Vatairea</i> sp.	Fabaceae	Angelim amargoso
<i>Virola multiflora</i> (Standl.) A.C. Sm.	Myristicaceae	Ucuuba folha miúda
<i>Vismia cayennensis</i> (Jacq.) Pers.	Clusiaceae	Lacre branco
<i>Vismia guianensis</i> Pers.	Clusiaceae	Lacre
<i>Vismia</i> sp.	Clusiaceae	Lacrinho preto
<i>Vitex trifolia</i> Vahl.	Verbenaceae	Taruma
<i>Vochysia</i> sp.	Vochysiaceae	Quaruba
<i>Vochysia</i> sp.	Vochysiaceae	Quaruba branca
<i>Volchysia</i> sp.	Volchysiaceae	Cedrinho
<i>Xylopia</i> sp.	Annonaceae	Envira vassorinha
<i>Zanthoxylum rhoifolium</i> Lam.	Rutaceae	Limaozinho

Appendix 2

List of the commercial species in Rio Branco

(Based on FUNTAC, 1989, 1992)

Scientific name	Family	Vernacular name
<i>Aniba canelila</i> (H.B.K.) Mez.	LAURACEAE	Casca preciosa
<i>Apuleia molaris</i> Spruce ex Benth.	CAESALPINIACEAE	Cumaru cetim
<i>Aspidosperma vargasii</i> A. DC.	SAPOTACEAE	Amarelao
<i>Aspidosperma</i> sp.	SAPOTACEAE	Amarelinho pereiro
<i>Aspidosperma macrocarpon</i> Mart.	SAPOTACEAE	Pereiro
<i>Astronium leicotei</i> Ducke	ANACARDIACEAE	Aroeira/Maracatiara
<i>Buchenavia</i> sp	COMBRETACEAE	Imbirindiba roxa
<i>Calycophyllum spruceanum</i> Benth.	RUBIACEAE	Mulateiro
<i>Carapa guianensis</i> Aubl.	MELIACEAE	Andiroba
<i>Caryocar glabrum</i> (Aubl.) Pers.	CARIOCARACEAE	Piquiarana
<i>Cariniana</i> sp.	LECYTHIDACEAE	Jequitiba
<i>Cedrela odorata</i> L.	MELIACEAE	Cedro/Cedro vermelho
<i>Copaifera multijuga</i> Hayne	CAESALPINIACEAE	Copaiba
<i>Cordia alliodora</i> (R.F.) Chaw	BORAGINACEAE	Freijo
<i>Cordia goeldiana</i> Hub.	BORAGINACEAE	Freijo preto
<i>Cordia</i> sp	BORAGINACEAE	Freijo branco
<i>Couratari macrosperma</i> A.S. Smith	LECYTHIDACEAE	Tauari/Toari vermelho
<i>Diplostropis purpurea</i> (Rich.) Amsh.	FABACEAE	Sucupira preta
<i>Dipteryx odorata</i> (Aubl.) Willd	FABACEAE	Cumaru ferro
<i>Enterolobium schomburskii</i> Benth.	MIMOSACEAE	Orelha de macaco
<i>Goupia glabra</i> Aubl.	CELASTRACEAE	Capoeiro
<i>Guarea purusiana</i> C. DC.	MELIACEAE	Jito terra firme
<i>Guarea kunthiana</i> A. Juss.	MELIACEAE	Jito preto
<i>Guarea pterorachis</i> Harms	MELIACEAE	Jito-vermelho
<i>Heisteria ovata</i> Benth.	OLACACEAE	Itaubarana
<i>Hymenaea courbaril</i> L.	CAESALPINIACEAE	Jatoba
<i>Hymenaea oblongifolia</i> Hub.	CAESALPINIACEAE	Jutai
<i>Hymenolobium excelsum</i> Ducke	FABACEAE	Angelim da mata
<i>Hymenolobium</i> sp.	FABACEAE	Angelim amarelo
<i>Hymenolobium</i> sp.	FABACEAE	Angelim rajado
<i>Macrolobium acaceifolium</i> Benth.	CAESALPINIACEAE	Arapari
<i>Manilkara surinamensis</i> (Miq.) Dub.	SAPOTACEAE	Macaranduba
<i>Mezilaurus itauba</i> (meissn.) Taub.	LAURACEAE	Itauba
<i>Myroxylon balsamum</i> Harms	FABACEAE	Balsamo
<i>Parkia pendula</i> Benth. ex Walp.	MIMOSACEAE	Angelim pedra
<i>Peltogyne</i> sp	CAESALPINACEAE	Roxinho
<i>Protium apiculatum</i> Swartz	BURSERACEAE	Breu vermelho
<i>Qualea grandiflora</i> Mart.	VOLCHISYACEAE	Catuaba roxa
<i>Qualea tesmannii</i> Milldbr.	VOCHYSIACEAE	Catuaba
<i>Swietenia macrophylla</i> King.	MELIACEAE	Aguano
<i>Tabebuia impetiginosa</i> (Mart.) Tol.	BIGNONIACEAE	Pau d'arco roxo
<i>Tabebuia serratifolia</i> (Vahl.) Nichols.	BIGNONIACEAE	Pau d'arco amarelo
<i>Terminalia</i> sp.	COMBRETACEAE	Imbirindiba amarela
<i>Torresea acreana</i> Ducke	CAESALPINACEAE	Cerejeira
<i>Vatairea sericea</i> Ducke	FABACEAE	Sucupira amarela
<i>Vatairea</i> sp.	FABACEAE	Angelim amargoso

Appendix 3

List of the potential species in PC Peixoto

(Based on FUNTAC, 1989, 1992)

Scientific name	Family	Common name
<i>Agonandra brasiliensis</i> Bent. & Hook	OPILIACEAE	Pau marfim
<i>Anacardium giganteum</i> Hancock	ANACARDIACEAE	Cajui
<i>Batocarpus</i> sp.	MORACEAE	Guariuba branca
<i>Bertholletia excelsa</i> (H.B.K.)	LECYTHIDACEAE	Castanheira
<i>Brosimum acutifolium</i> Hub.	MORACEAE	Murure
<i>Brosimum guianensis</i> (Aubl.) Huber	MORACEAE	Inhare mole
<i>Brosimum</i> sp.	MORACEAE	Inhare (amarelo,preto)
<i>Casearia</i> sp.	FLACOURTIACEAE	Caferana
<i>Clarisia racemosa</i> Ruiz & Pav.	MORACEAE	Guariuba(amarela,vermelha)
<i>Dialium guianensis</i> (Aubl.) Sandwith	CAESALPINACEAE	Tamarina
<i>Enterolobium maximum</i> Ducke	MIMOSACEAE	Taninbuca
<i>Erisma</i> sp.	VOLCHYSIACEAE	Quaruba-vermelha
<i>Eschweilera odorata</i> (Poepp.) Miers	LECYTHIDACEAE	Mata-mata
<i>Eschweilera grandiflora</i> (Aubl.) Sandwith	LECYTHIDACEAE	Mata-mata branco
<i>Eschweilera</i> sp.	LECYTHIDACEAE	Mata-mata amarelo
<i>Guazuma ulmifolia</i> L.	STERCULIACEAE	Mutamba preta
<i>Hyeronima laxiflora</i> Muell. Arg.	EUPHORBIACEAE	Pau pedra
<i>Licaria</i> sp.	LAURACEAE	Louro chumbo
<i>Matisia cordata</i> (Hum. & Bonpl.) Vich.	BOMBACACEAE	Sapota
<i>Micropholis</i> sp.	SAPOTACEAE	Abiurana rosa
<i>Micropholis venulosa</i> (Mart. & Eichler) Pierre	SAPOTACEAE	Abiurana branca
<i>Nectandra</i> sp.	LAURACEAE	Louro amarelo
<i>Nectandra rubra</i> Mez.	LAURACEAE	Louro itauba
<i>Nectandra</i> sp.	LAURACEAE	Louro inhamui
<i>Ocotea neesiana</i> (Miq.) Kosterm.	LAURACEAE	Louro preto
<i>Ocotea miriantha</i> (Meissn.) Mez.	LAURACEAE	Louro abacate
<i>Ocotea</i> sp.	LAURACEAE	Louro bosta
<i>Ormosia</i> sp.	FABACEAE	Feijao bravo/Jito fava
<i>Ormosia</i> sp.	FABACEAE	Tento
<i>Otoba parviflora</i> (M.G.F.) Gentry	MYRISTICACEAE	Ucuuba-vermelha
<i>Peltogine</i> sp.	CAESALPINACEAE	Escorrega macaco
<i>Phyllocarpus riedellii</i> Tul.	CAESALPINIACEAE	Guaribeiro
<i>Platonia insignes</i> Mart.	CLUSIACEAE	Bacuri de serra
<i>Platymiscium duckei</i> Hub.	FABACEAE	Violeta/ Macacauba
<i>Poeppigia procera</i> Presl.	CAESALPINACEAE	Pintadinho
<i>Pouteria</i> sp.	SAPOTACEAE	Abiu bravo
<i>Pouteria</i> sp.	SAPOTACEAE	Maparajuba
<i>Pradosia</i> sp.	SAPOTACEAE	Pau garrote
<i>Pterocarpus rohrii</i> Vahl.	FABACEAE	Pau-sangue
<i>Sickingia tinctoria</i> (H.B.K.) K. Sch.	RUBIACEAE	Pau brasil
<i>Sickingia</i> sp.	RUBIACEAE	Pau arara
<i>Symphonia globulifera</i> L.F.	CLUSIACEAE	Anani da terra firme

Appendix 4
List of pioneer species
(Based on FUNTAC, 1989, 1992)

Scientific name	Family	Common name
<i>Acacia pollyphylla</i> A. DC.	MIMOSACEAE	Espinheiro vermelho
<i>Acalypha</i> sp.	EUPHORBIACEAE	Maria preta
<i>Acalypha</i> sp.	EUPHORBIACEAE	Pirarucu
<i>Apeiba echinata</i> Gaertn.	TILIACEAE	Envira pente de macaco
<i>Apeiba timbourbou</i> Aubl.	TILIACEAE	Malva pente de macaco
<i>Calycophyllum spruceanum</i> Benth.	RUBIACEAE	Mulateiro
<i>Cavanilezia</i> sp.	BOMBACACEAE	Butijao
<i>Cecropia</i> spp	CECROPIACEAE	Embauba
<i>Cedrela odorata</i> L.	MELIACEAE	Cedro vermelho
<i>Ceiba pentandra</i> (L.) Gaertn.	BOMBACACEAE	Samauma branca
<i>Ceiba samauma</i>	BOMBACACEAE	Sumauma preta
<i>Chorizia speciosa</i> St. Hill.	BOMBACACEAE	Samauma barriguda
<i>Cordia alliodora</i> (R.F.) Chaw	BORAGINACEAE	Freijo
<i>Cordia goeldiana</i> Hub.	BORAGINACEAE	Freijo preto
<i>Cordia</i> sp.	BORAGINACEAE	Freijo branco
<i>Erythrina glauca</i> Willd.	FABACEAE	Mulungu
<i>Goupia glabra</i> Aubl.	CELASTRACEAE	Capoeiro
<i>Heliocarpus</i> sp.	TILIACEAE	Malva branca
<i>Jacaranda copaia</i> (Aubl.) D. Don.	BIGNONIACEAE	Marupa
<i>Jaracatia espinosa</i> Aubl.	CARICACEA	Jaracatia
<i>Maclura tinctoria</i> (L.) D. Don. ex Steud.	MORACEAE	Tatajuba
<i>Ochroma pyramidalis</i> Urb.	BOMBACACEAE	Pau balsa
<i>Pachira</i> sp.	BOMBACACEAE	Paineira
<i>Piptadenia suaveolens</i> Miq.	MIMOSACEAE	Angico amarelo
<i>Pourouma aspera</i> Trécul.	CECROPIACEAE	Torem lixa
<i>Sapium marmiere</i> Hub.	EUPHORBIACEAE	Burra leiteira folha grande
<i>Sapium glandulatum</i> Pax.	EUPHORBIACEAE	Burra leiteira folha miuda
<i>Schyzollubium amazonicum</i> Hub.	CAESALPINIACEAE	Canafistula
<i>Solanum</i> sp.	SOLANACEAE	Jurubeba
<i>Tabebuia impetiginosa</i> (Mart.) Tol.	BIGNONIACEAE	Pau d'arco roxo
<i>Tabebuia serratifolia</i> (Vahl.) Nichols.	BIGNONIACEAE	Pau d'arco amarelo
<i>Trema micrantha</i> (L.) Blume	ULMACEAE	Piriquiteira
<i>Urera</i> sp.	URTICACEAE	Urtiga branca
<i>Zanthoxylum rhoifolium</i> Lam.	RUTACEAE	Limaozinho (amarelo)

Appendix 5

Anova tables generated by the data analysis in Chapter 4

1. Artificial gaps experiment

Analysis of Variance for Growth (Table 4.3 and 4.4)

Effect of position and size using three positions present in all four sizes (Table 4.4)

Factor	Type	Levels	Values
Line	fixed	4	1 2 3 4
Size	fixed	4	1 2 3 4
position	fixed	3	1 2 3

Analysis of Variance for Growth, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Critical value						
Line	3	0.47124	0.22828	0.07609	1.41	
3.86	n.s.					
Size	3	0.22272	0.22272	0.07424	1.38	
3.86	n.s.					
Main plot error	9	0.48534	0.48534	0.05393		
position	2	15.74819	14.38672	7.19336	161.00	0.000
Size*position	6	0.84899	0.84899	0.14150	3.17	0.008
Error	72	3.21699	3.21699	0.04468		
Total	95	20.99347				

Least Squares Means for Growth

Line	Mean	StDev
1	0.5829	0.05059
2	0.7112	0.05059
3	0.5744	0.05059
4	0.6648	0.05059
Size		
1	0.5762	0.03051
2	0.6671	0.04315
3	0.5933	0.06102
4	0.6967	0.06102
position		
1	0.2745	0.04382
2	0.3517	0.04382
3	1.2737	0.04382
Size*position		
1 1	0.2794	0.05284
1 2	0.4131	0.05284
1 3	1.0362	0.05284
2 1	0.3738	0.07473
2 2	0.3363	0.07473
2 3	1.2912	0.07473
3 1	0.2325	0.10569
3 2	0.3050	0.10569
3 3	1.2425	0.10569
4 1	0.2125	0.10569
4 2	0.3525	0.10569
4 3	1.5250	0.10569

Analysis of Variance for growth (**transformed data**), using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Critical value						
Line	3	0.29367	0.14677	0.04892	2.21	
3.86 n.s.						
Size	3	0.08318	0.08318	0.02773	1.25	
3.86 n.s.						
Main plot error	9	0.19873	0.19873	0.02208	1.06	0.400
position	2	6.15734	5.33131	2.66566	128.40	0.000
Size*position	6	0.23223	0.23223	0.03871	1.86	0.099
Error	72	1.49471	1.49471	0.02076		
Total	95	8.45986				

Effects of within-gap position using the three largest size classes (Table 4.4)

Factor	Type	Levels	Values
line	fixed	4	1 2 3 4
size	fixed	3	2 3 4
position	fixed	2	3 4

Analysis of Variance for growth, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Critical value						
Line	3	0.03156	0.09698	0.03233	0.20	
4.76 n.s.						
Size	2	0.38840	0.38840	0.19420	1.19	
4.76 n.s.						
Main plot error	6	0.98066	0.98066	0.16344		
position	1	0.07125	0.06105	0.06105	1.97	0.178
size*position	2	0.00240	0.00240	0.00120	0.04	0.962
Error	17	0.52667	0.52667	0.03098		
Total	31	2.00095				

Least Squares Means for growth

line	Mean	StDev
1	1.213	0.06560
2	1.299	0.06560
3	1.359	0.06560
4	1.351	0.06560
size		
2	1.252	0.04400
3	1.187	0.06223
4	1.478	0.06223
position		
3	1.260	0.04638
4	1.352	0.04638
size*position		
2 3	1.201	0.06223
2 4	1.302	0.06223
3 3	1.132	0.08801
3 4	1.243	0.08801
4 3	1.445	0.08801
4 4	1.510	0.08801

Positions forest edge 1 and 2 (Table 4.4)

Factor	Type	Levels	Values
line	fixed	4	1 2 3 4
size	fixed	4	1 2 3 4
position	fixed	2	1 2

Analysis of Variance for growth, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Critical value						
line	3	0.55467	0.27187	0.09062	3.02	
3.86	n.s.					
size	3	0.06647	0.06647	0.02216	0.72	
3.86	n.s.					
Main plot error	9	0.27525	0.27525	0.03058		
position	1	0.11306	0.06933	0.06933	1.63	0.208
size*position	3	0.08539	0.08539	0.02846	0.67	0.575
Error	44	1.86863	1.86863	0.04247		
Total	63	2.96346				

Least Squares Means for growth

	Mean	StDev
1	0.2991	0.06041
2	0.4403	0.06041
3	0.2394	0.06041
4	0.2738	0.06041
size		
1	0.3463	0.03643
2	0.3550	0.05152
3	0.2687	0.07286
4	0.2825	0.07286
position		
1	0.2745	0.04272
2	0.3517	0.04272
size*position		
1 1	0.2794	0.05152
1 2	0.4131	0.05152
2 1	0.3738	0.07286
2 2	0.3363	0.07286
3 1	0.2325	0.10304
3 2	0.3050	0.10304
4 1	0.2125	0.10304
4 2	0.3525	0.10304

Analysis of Variance for growth (**transformed data**), using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Critical value						
line	3	0.18374	0.11585	0.03862	3.36	
3.86	n.s.					
size	3	0.03024	0.03024	0.01008	0.88	
3.86	n.s.					
Main plot error	9	0.10325	0.10325	0.01147		
position	1	0.03951	0.02892	0.02892	2.52	0.120
size * position	3	0.04046	0.04046	0.01349	1.17	0.330
Error	44	0.50505	0.50505	0.01148		

Total 63 0.90226

Gaps only (Table 4.3)

Factor	Type	Levels	Values
line	fixed	4	1 2 3 4
size	fixed	4	1 2 3 4

Analysis of Variance for growth, using Adjusted SS for Tests							
Source	DF	Seq SS	Adj SS	Adj MS	F	P	
line	3	0.11151	0.11151	0.03717	0.68	0.572	
size	3	0.91985	0.91985	0.30662	5.62	0.004	
Error	25	1.36353	1.36353	0.05454			
Total	31	2.39489					

Least Squares Means for growth

line	Mean	StDev
1	1.231	0.08635
2	1.284	0.08635
3	1.214	0.08635
4	1.366	0.08635
size		
1	1.036	0.05839
2	1.291	0.08257
3	1.242	0.11677

Tukey 95.0% Simultaneous Confidence Intervals
 Response Variable growth
 All Pairwise Comparisons among Levels of size

size = small subtracted from:

size	Lower	Center	Upper	
medium	0.0051	0.2550	0.5049	(-----*-----)
big	-0.1164	0.2062	0.5289	(-----*-----)
very big	0.1661	0.4887	0.8114	(-----*-----)

--+-----+-----+-----
 +----
 -0.35 0.00 0.35
 0.70

size = medium subtracted from:

size	Lower	Center	Upper	
big	-0.4022	-0.04875	0.3047	(-----*-----)
very big	-0.1197	0.23375	0.5872	(-----*-----)

--+-----+-----+-----
 ---+----
 -0.35 0.00 0.35
 0.70

size = big subtracted from:

size	Lower	Center	Upper	
------	-------	--------	-------	--

--+-----+-----+-----
 ---+----


```

very big    -0.1256    0.2825    0.6906    (-----*-----
---)
---+-----+-----+-----
---+-----
0.70                                -0.35    0.00    0.35

```

Tukey Simultaneous Tests
Response Variable growth
All Pairwise Comparisons among Levels of size

size = small subtracted from:

Level size	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
medium	0.2550	0.08727	2.922	0.0445
big	0.2062	0.11267	1.831	0.2957
very big	0.4887	0.11267	4.338	0.0026

size = medium subtracted from:

Level size	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
big	-0.04875	0.1234	-0.3950	0.9784
very big	0.23375	0.1234	1.8939	0.2693

size = big subtracted from:

Level size	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
very big	0.2825	0.1425	1.982	0.2353

Analysis of variance for Recruitment (Table 4.6)

Effects of position and size using three positions present in all four gap sizes

Factor	Type	Levels	Values
Line	fixed	4	1 2 3 4
Size	fixed	4	1 2 3 4
position	fixed	3	1 2 3

Analysis of Variance for recruitment, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
critical value						
line	3	7967652	5539671	1846557	1.93	
3.86	n.s.					
Size	3	2938651	2938651	979550	1.03	
3.86	n.s.					
Main plot error	9	8588534	8588534	954282		
position	2	29378306	13345619	6672809	9.79	0.000
Size*position	6	7561552	7561552	1260259	1.85	0.102
Error	72	49093683	49093683	681857		
Total	95	105528378				

Least Squares Means for recruitment

Line	Mean	StDev
1	508.3	197.6

2		1303.6	197.6
3		902.2	197.6
4		943.6	197.6
Size			
1		1183.3	119.2
2		903.6	168.6
3		811.1	238.4
4		759.7	238.4
position			
1		343.7	171.2
2		993.8	171.2
3		1405.8	171.2
Size*position			
1	1	325.0	206.4
1	2	975.0	206.4
1	3	2250.0	206.4
2	1	450.0	291.9
2	2	1000.0	291.9
2	3	1260.8	291.9
3	1	500.0	412.9
3	2	800.0	412.9
3	3	1133.3	412.9
4	1	100.0	412.9
4	2	1200.0	412.9
4	3	979.2	412.9

Effects of within-gap position using the three largest size classes

Factor	Type	Levels	Values
Line	fixed	4	1 2 3 4
Size	fixed	3	2 3 4
position	fixed	2	3 4

Analysis of Variance for recruitment, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
critical value						
Line	3	343611	384375	128125	0.27	
4.76	n.s.					
Size	2	2216875	2216875	1108438	2.32	
4.76	n.s.					
main plot error	6	2868681	2868681	478113	0.60	0.727
position	1	2761250	3570125	3570125	4.48	0.049
size*position	2	5495625	5495625	2747812	3.45	0.055
Error	17	13546736	13546736	796867		
Total	31	27232778				

Least Squares Means for recruitment

Line	Mean	StDev
1	1638.9	332.7
2	1322.2	332.7
3	1522.2	332.7
4	1441.7	332.7
size		
2	1206.3	223.2
3	1850.0	315.6
4	1387.5	315.6
position		
3	1129.2	235.2

4		1833.3	235.2
size*position			
2	3	1087.5	315.6
2	4	1325.0	315.6
3	3	850.0	446.3
3	4	2850.0	446.3
4	3	1450.0	446.3
4	4	1325.0	446.3

Positions forest edge 1 and 2

Factor	Type	Levels	Values
line	fixed	4	1 2 3 4
size	fixed	4	1 2 3 4
position	fixed	2	1 2

Analysis of Variance for recruitment, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Critical value						
line	3	4407500	2300000	766667	1.72	
3.86	n.s.					
size	3	67500	67500	22500	0.05	
3.86	n.s.					
Main plot error	9	4022500	4022500	446944		
position	1	6502500	4916364	4916364	9.13	0.004
size*position	3	687500	687500	229167	0.43	0.736
Error	44	23690000	23690000	538409		
Total	63	39377500				

Least Squares Means for recruitment

	Mean	StDev
1	412.5	215.1
2	1025.0	215.1
3	625.0	215.1
4	612.5	215.1
size		
1	650.0	129.7
2	725.0	183.4
3	650.0	259.4
4	650.0	259.4
position		
1	343.7	152.1
2	993.8	152.1
size*position		
1 1	325.0	183.4
1 2	975.0	183.4
2 1	450.0	259.4
2 2	1000.0	259.4
3 1	500.0	366.9
3 2	800.0	366.9
4 1	100.0	366.9
4 2	1200.0	366.9

Gaps only

Factor	Type	Levels	Values
line	fixed	4	1 2 3 4

size fixed 4 1 2 3 4

Analysis of Variance for recruitment, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
line	3	6529873	6529873	2176624	2.02	0.137
size	3	9745202	9745202	3248401	3.01	0.049
Error	25	26999996	26999996	1080000		
Total	31	43275072				

Least Squares Means for recruitment

line	Mean	StDev
1	695.3	384.3
2	1425.7	384.3
3	1941.6	384.3
4	1560.7	384.3
size		
1	2250.0	259.8
2	1260.8	367.4
3	1133.3	519.6
4	979.2	519.6

Analysis of Variance for recruitment (**transformed data**) using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
line	3	871.7	1023.7	341.2	2.77	0.075
size	3	1557.6	1557.6	519.2	4.22	0.022
line * size	9	1842.1	1842.1	204.7	1.66	0.180
Error	16	1970.4	1970.4	123.2		
Total	31	6241.8				

Analysis of Variance for Mortality (Table 4.7)

Effects of position and size using three positions present in all four sizes

Factor	Type	Levels	Values
Line	fixed	4	1 2 3 4
Size	fixed	4	1 2 3 4
position	fixed	3	1 2 3

Analysis of Variance for Mortality, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Critical value						
Line	3	0.010225	0.002701	0.000900	0.35	
3.86	n.s.					
Size	3	0.032456	0.032456	0.010819	4.22	
3.86	< 0.05					
Main plot error	9	0.023061	0.023061	0.002562	0.26	0.983
position	2	0.196774	0.143428	0.071714	7.26	0.001
Size*position	6	0.027664	0.027664	0.004611	0.47	0.831
Error	72	0.711006	0.711006	0.009875		
Total	95	1.001187				

Least Squares Means for Mortality

Line	Mean	StDev

1		0.073751	0.02379
2		0.072632	0.02379
3		0.064580	0.02379
4		0.058506	0.02379
Size			
1		0.093199	0.01434
2		0.076124	0.02028
3		0.060417	0.02869
4		0.039729	0.02869
position			
1		0.026550	0.02060
2		0.044975	0.02060
3		0.130577	0.02060
Size*position			
1	1	0.039340	0.02484
1	2	0.095544	0.02484
1	3	0.144712	0.02484
2	1	0.035907	0.03513
2	2	0.030027	0.03513
2	3	0.162439	0.03513
3	1	0.007143	0.04969
3	2	0.037088	0.04969
3	3	0.137021	0.04969
4	1	0.023810	0.04969
4	2	0.017241	0.04969
4	3	0.078135	0.04969

Analysis of Variance for Mortality (**transformed data**), using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Critical value						
Line	3	0.08952	0.07496	0.02499	2.15	
3.86 n.s.						
Size	3	0.10239	0.10239	0.03413	2.94	
3.86 n.s.						
Line*Size	9	0.10430	0.10430	0.01159		
position	2	0.97660	0.81946	0.40973	16.43	0.000
Size*position	6	0.07311	0.07311	0.01218	0.49	0.815
Error	72	1.79598	1.79598	0.02494		
Total	95	3.14190				

Effects of within-gap position using the three largest size classes

Factor	Type	Levels	Values
Line	fixed	4	1 2 3 4
size	fixed	3	2 3 4
position	fixed	2	3 4

Analysis of Variance for mortality, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
critical value						
Line	3	0.008090	0.002513	0.000838	0.09	4.76
n.s.						
size	2	0.017437	0.017437	0.008719	0.99	4.76
n.s.						
Main plot error	6	0.053100	0.053100	0.008850		

position	1	0.000006	0.001651	0.001651	0.19	0.667
size*position	2	0.019054	0.019054	0.009527	1.11	0.353
Error	17	0.146378	0.146378	0.008610		
Total	31	0.244065				

Least Squares Means for mortality

Line	Mean	StDev
1	0.1813	0.03458
2	0.1576	0.03458
3	0.1719	0.03458
4	0.1609	0.03458
size		
2	0.1368	0.02320
3	0.1838	0.03281
4	0.1832	0.03281
position		
3	0.1755	0.02445
4	0.1603	0.02445
size*position		
2 3	0.1159	0.03281
2 4	0.1577	0.03281
3 3	0.1889	0.04640
3 4	0.1786	0.04640
4 3	0.2216	0.04640
4 4	0.1447	0.04640

Positions forest edge 1 and 2

Factor	Type	Levels	Values
line	fixed	4	1 2 3 4
size	fixed	4	1 2 3 4
position	fixed	2	1 2

Analysis of Variance for Mortality, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Critical value						
line	3	0.05403	0.02378	0.00793	1.91	
3.86 n.s.						
size	3	0.02708	0.02708	0.00903	2.17	
3.86 n.s.						
Main plot error	9	0.03741	0.03741	0.00416		
position	1	0.01398	0.00395	0.00395	0.36	0.554
size*position	3	0.01331	0.01331	0.00444	0.40	0.755
Error	44	0.48963	0.48963	0.01113		
Total	63	0.63545				

Least Squares Means for Mortality

1	Mean	StDev
1	0.055672	0.03092
2	0.058317	0.03092
3	0.025418	0.03092
4	0.003643	0.03092
size		
1	0.067442	0.01865
2	0.032967	0.02637
3	0.022115	0.03730
4	0.020525	0.03730
position		

1	0.026550	0.02187
2	0.044975	0.02187
size*position		
1 1	0.039340	0.02637
1 2	0.095544	0.02637
2 1	0.035907	0.03730
2 2	0.030027	0.03730
3 1	0.007143	0.05274
3 2	0.037088	0.05274
4 1	0.023810	0.05274
4 2	0.017241	0.05274

Analysis of Variance for Mrt3M, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Critical value						
line	3	0.28877	0.21351	0.07117	3.65	
3.86 n.s.						
size	3	0.10421	0.10421	0.03474	1.78	
3.86 n.s.						
line * size	9	0.17527	0.17527	0.01947		
position	1	0.02115	0.01069	0.01069	0.43	0.517
size * position	3	0.03378	0.03378	0.01126	0.45	0.719
Error	44	1.10255	1.10255	0.02506		
Total	63	1.72572				

Gaps only

Factor	Type	Levels	Values
line	fixed	4	1 2 3 4
size	fixed	4	1 2 3 4

Analysis of Variance for Mortality, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
line	3	0.007323	0.007323	0.002441	0.40	0.752
size	3	0.024150	0.024150	0.008050	1.33	0.287
Error	25	0.151468	0.151468	0.006059		
Total	31	0.182941				

Least Squares Means for Mortality

line	Mean	StDev
1	0.1789	0.02878
2	0.1484	0.02878
3	0.1383	0.02878
4	0.1607	0.02878
size		
1	0.1182	0.01946
2	0.1380	0.02752
3	0.1899	0.03892
4	0.1804	0.03892

2. Felling gaps

Growth

Analysis of Variance for growth in the trunk zone and in the undisturbed forest understorey (Table 4.12)

Source	DF	SS	MS	F	P
Position	1	0.0144	0.0144	1.18	0.303
Error	10	0.1219	0.0122		
Total	11	0.1363			

Level	N	Mean	StDev	Individual 95% CIs For Mean Based on Pooled StDev			
Understorey	5	0.2148	0.0326	(-----*	-----)		
Trunk zone	7	0.2850	0.1400		(-----*	-----)	
Pooled StDev = 0.1104				0.160	0.240	0.320	

Tukey's pairwise comparisons

Family error rate = 0.0500
 Individual error rate = 0.0500

Critical value = 3.15

Intervals for (column level mean) - (row level mean)

1	
2	-0.2143 0.0739

Analysis of Variance for growth in the crown zone and forest understorey (Table 4.12)

Source	DF	SS	MS	F	P
Position	1	0.09789	0.09789	17.17	0.002
Error	10	0.05702	0.00570		
Total	11	0.15491			

Level	N	Mean	StDev	Individual 95% CIs For Mean Based on Pooled StDev			
Understorey	5	0.21480	0.03263	(-----*	-----)		
Crown zone	7	0.39800	0.09378		(-----*	-----)	
Pooled StDev = 0.07551				0.20	0.30	0.40	

Tukey's pairwise comparisons

Family error rate = 0.0500
 Individual error rate = 0.0500

Critical value = 3.15

Intervals for (column level mean) - (row level mean)

1	
3	-0.28172 -0.08468

Paired T for Growth in the trunk zone and in the crown zone (Table 4.12)

	N	Mean	StDev	SE Mean
Trunk zone	7	0.3980	0.0938	0.0354
Crown zone	7	0.2850	0.1400	0.0529
Difference	7	0.1130	0.1629	0.0616

95% CI for mean difference: (-0.0377, 0.2637)

T-Test of mean difference = 0 (vs not = 0): T-Value = 1.84 P-Value = 0.116

Recruitment

Analysis of Variance for recruitment in the trunk zone and in the undisturbed forest understorey (Table 4.13)

Source	DF	SS	MS	F	P
position	1	2527277	2527277	9.45	0.012
Error	10	2673273	267327		
Total	11	5200550			

Level	N	Mean	StDev	Individual 95% CIs For Mean Based on Pooled StDev			
Understorey	5	462.0	265.1	(------*-----)			
Trunk zone	7	1392.9	631.4	(-----*-----)			
Pooled StDev = 517.0				0	600	1200	1800

Tukey's pairwise comparisons

Family error rate = 0.0500
Individual error rate = 0.0500

Critical value = 3.15

Intervals for (column level mean) - (row level mean)

1	
2	-1605 -256

Analysis of Variance for recruitment in the crown zone and in the undisturbed forest understorey (Table 4.13)

Source	DF	SS	MS	F	P
Position	1	2299920	2299920	10.67	0.008
Error	10	2156130	215613		
Total	11	4456050			

Level	N	Mean	StDev	Individual 95% CIs For Mean Based on Pooled StDev			
Understorey	5	462.0	265.1	(------*-----)			
Crown zone	7	1350.0	559.0	(-----*-----)			
Pooled StDev = 464.3				0	500	1000	1500

Tukey's pairwise comparisons

Family error rate = 0.0500
 Individual error rate = 0.0500

Critical value = 3.15

Intervals for (column level mean) - (row level mean)

```

          1
    3      -1494
          -282
    
```

Paired T for recruitment in the crown and trunk zones two years after gap creation (Table 4.13)

	N	Mean	StDev	SE Mean
Recruitment-trunk	7	1393	631	239
Recruitment-crown	7	1350	559	211
Difference	7	43	1071	405

95% CI for mean difference: (-948, 1033)

T-Test of mean difference = 0 (vs not = 0): T-Value = 0.11 P-Value = 0.919

Mortality

Analysis of Variance for mortality in the trunk zone and undisturbed forest understorey, one year after gap creation in the felling gaps in the Pedro Peixoto Colonisation Project (Table 4.14)

Analysis of Variance for C17

Source	DF	SS	MS	F	P
pst3	1	0.6368	0.6368	19.27	0.001
Error	10	0.3305	0.0330		
Total	11	0.9673			

Level	N	Mean	StDev	Individual 95% CIs For Mean Based on Pooled StDev		
1	5	0.6420	0.1172	(-----*-----)		
3	7	0.1748	0.2143	(------*-----)		
Pooled StDev = 0.1818				0.25	0.50	0.75

Tukey's pairwise comparisons

Family error rate = 0.0500
 Individual error rate = 0.0500

Critical value = 3.15

Intervals for (column level mean) - (row level mean)

```

          1
    3      0.2301
    
```

0.7044

Analysis of Variance for mortality in the trunk zone and undisturbed forest understorey, from the first to the second year after gap creation in the felling gaps in the Pedro Peixoto Colonisation Project (Table 4.14)

Source	DF	SS	MS	F	P
position	1	0.00001	0.00001	0.01	0.942
Error	10	0.01177	0.00118		
Total	11	0.01178			

Level	N	Mean	StDev	Individual 95% CIs For Mean Based on Pooled StDev		
Understorey	5	0.03492	0.00953	(------*-----)		
Trunk zone	7	0.03341	0.04360	(------*-----)		

--

	Pooled StDev =	0.03431	0.020	0.040	0.060
--	----------------	---------	-------	-------	-------

Tukey's pairwise comparisons

Family error rate = 0.0500
 Individual error rate = 0.0500

Critical value = 3.15

Intervals for (column level mean) - (row level mean)

1	
2	-0.04326 0.04626

Analysis of Variance for mortality in the crown zone and undisturbed forest understorey, from the first to the second year after gap creation in the felling gaps in the Pedro Peixoto Colonisation Project (Table 4.14)

Source	DF	SS	MS	F	P
position	1	0.01913	0.01913	3.65	0.085
Error	10	0.05234	0.00523		
Total	11	0.07147			

Level	N	Mean	StDev	Individual 95% CIs For Mean Based on Pooled StDev		
Understorey	5	0.03492	0.00953	(------*-----)		
Crown zone	7	0.11590	0.09307	(------*-----)		

--

	Pooled StDev =	0.07234	0.000	0.060	0.120
--	----------------	---------	-------	-------	-------

Tukey's pairwise comparisons

Family error rate = 0.0500
 Individual error rate = 0.0500

Critical value = 3.15

Intervals for (column level mean) - (row level mean)

```

          1
    3     -0.17537
         0.01340
  
```

Paired T for mortality in the crown zone and trunk zone, from the first to the second year after gap creation in the felling gaps in the Pedro Peixoto Colonisation Project (Table 4.14)

Paired T for mortality in the trunk zone and crown zone one year after gap creation

	N	Mean	StDev	SE Mean
Trunk zone	7	0.0334	0.0436	0.0165
Crown zone	7	0.1159	0.0931	0.0352
Difference	7	-0.0825	0.1209	0.0457

95% CI for mean difference: (-0.1943, 0.0293)

T-Test of mean difference = 0 (vs not = 0): T-Value = -1.81 P-Value = 0.121

Analysis of Variance for mortality in the crown zone and undisturbed forest understorey, in the first two years after gap creation in the felling gaps in the Pedro Peixoto Colonisation Project (Table 4.14)

Source	DF	SS	MS	F	P
pst3	1	0.4639	0.4639	26.54	0.000
Error	10	0.1748	0.0175		
Total	11	0.6386			

Level	N	Mean	StDev	Individual 95% CIs For Mean Based on Pooled StDev		
+-				-----+-----+-----+-----		
1	5	0.0443	0.0154	(------*-----)		
3	7	0.4431	0.1702		(-----*-----)	
+-				-----+-----+-----+-----		
Pooled StDev =		0.1322		0.00	0.20	0.40
0.60						

Tukey's pairwise comparisons

Family error rate = 0.0500
Individual error rate = 0.0500

Critical value = 3.15

Intervals for (column level mean) - (row level mean)

```

          1
    3     -0.5713
         -0.2263
  
```

Appendix 6

Anova tables generated by the data analysis in Chapter 5

Analysis of Variance for relative growth rate according to species group (Table 5.2)

Source	DF	SS	MS	F	P
Group	5	0.0030058	0.0006012	7.52	0.000
Error	48	0.0038382	0.0000800		
Total	53	0.0068440			

Level	N	Mean	StDev	Individual 95% CIs For Mean Based on Pooled StDev		
Short pioneer.	9	0.034444	0.014196	(-----		
*-----)						
Big pioneer.	9	0.030333	0.012010	(-----*-----		
--)						
Pioneers	9	0.033222	0.010580	(-----		
*-----)						
Canopy	9	0.019222	0.003383	(-----*-----)		
Understorey	9	0.017111	0.002315	(-----*-----)		
Shade tolerant.	9	0.017667	0.002291	(-----*-----)		
				-----+-----+-----+-----+-----		

Pooled StDev =	0.008942		0.0160	0.0240	0.0320	

Tukey's pairwise comparisons

Family error rate = 0.0500
 Individual error rate = 0.00464

Critical value = 4.20

Intervals for (column level mean) - (row level mean)

	1	2	3	4	5
2	-0.008408 0.016630				
3	-0.011297 0.013741	-0.015408 0.009630			
4	0.002703 0.027741	-0.001408 0.023630	0.001481 0.026519		
5	0.004814 0.029852	0.000703 0.025741	0.003592 0.028630	-0.010408 0.014630	
6	0.004259 0.029297	0.000148 0.025186	0.003036 0.028075	-0.010964 0.014075	-0.013075 0.011964

Analysis of Variance for relative growth rate (transformed value) according to species group (Table 5.2)

Source	DF	SS	MS	F	P
Group	5	848.5	169.7	9.85	0.000
Error	48	826.8	17.2		

Level	N	Mean	StDev	Individual 95% CIs For Mean Based on Pooled StDev		
Total	53	1675.3				
1	9	15.768	5.084	(-----*-----)		
2	9	17.464	6.136	(-----*-----)		
3	9	15.503	3.781	(-----*-----)		
4	9	22.907	3.515		(-----*-----)	
5	9	24.852	2.622		(-----*-----)	
6	9	24.219	2.514		(-----*-----)	
Pooled StDev = 4.150				15.0	20.0	25.0

Tukey's pairwise comparisons

Family error rate = 0.0500
Individual error rate = 0.00464

Critical value = 4.20

Intervals for (column level mean) - (row level mean)

	1	2	3	4	5
2	-7.507 4.114				
3	-5.545 6.075	-3.849 7.772			
4	-12.950 -1.329	-11.253 0.368	-13.214 -1.594		
5	-14.895 -3.274	-13.198 -1.578	-15.160 -3.539	-7.756 3.865	
6	-14.262 -2.641	-12.565 -0.945	-14.527 -2.906	-7.123 4.498	-5.177 6.443

General linear model using growth as a factor and crown illumination and diameter classes as model (Table 5.3)

Factor	Type	Levels	Values
Diameter classes (D. class)	fixed	7	1 2 3 4 5 6 7
Crown exposure (crown)	fixed	3	1 2 3

Analysis of Variance for Growth, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
D. class	6	0.50110	0.20865	0.03478	1.18	0.323
Crown	2	0.92146	0.92146	0.46073	15.57	0.000
Error	136	4.02345	4.02345	0.02958		
Total	144	5.44601				

Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Growth
All Pairwise Comparisons among Levels of Dclass

D. class = 1 subtracted from:

D. class	Lower	Center	Upper	-----+-----+-----+--
2	-0.0518	0.10166	0.2551	(-----*-----
3	-0.1392	0.01425	0.1677	(-----*-----)
4	-0.0796	0.07388	0.2273	(-----*-----
5	-0.1213	0.04348	0.2083	(-----*-----
6	-0.0802	0.10230	0.2848	(-----*-----
7	-0.1932	0.03888	0.2710	(-----*-----
				-----+-----+-----+--
				-0.16 0.00 0.16

D. class = 2 subtracted from:

D. class	Lower	Center	Upper	-----+-----+-----+--
3	-0.2274	-0.08741	0.05261	(-----*-----)
4	-0.1678	-0.02778	0.11224	(-----*-----)
5	-0.2090	-0.05818	0.09268	(-----*-----)
6	-0.1673	0.00065	0.16856	(-----*-----)
7	-0.2796	-0.06277	0.15410	(-----*-----)
				-----+-----+-----+--
				-0.16 0.00 0.16

D. class = 3 subtracted from:

D. class	Lower	Center	Upper	-----+-----+-----+--
4	-0.0804	0.05963	0.1996	(-----*-----)
5	-0.1216	0.02923	0.1801	(-----*-----)
6	-0.0799	0.08806	0.2560	(-----*-----
7	-0.1922	0.02464	0.2415	(-----*-----
				-----+-----+-----+--
				-0.16 0.00 0.16

D. class = 4 subtracted from:

D. class	Lower	Center	Upper	-----+-----+-----+--
5	-0.1813	-0.03040	0.1205	(-----*-----)
6	-0.1395	0.02843	0.1963	(-----*-----)
7	-0.2519	-0.03499	0.1819	(-----*-----)
				-----+-----+-----+--
				-0.16 0.00 0.16

D. class = 5 subtracted from:

D. class	Lower	Center	Upper	
6	-0.1160	0.058827	0.2337	(-----*-----)
7	-0.2256	-0.004593	0.2164	(-----*-----)

-----+-----+-----+--

-0.16 0.00 0.16

D. class = 6 subtracted from:

D. class	Lower	Center	Upper	
7	-0.2920	-0.06342	0.1651	(-----*-----)

-----+-----+-----+--

-0.16 0.00 0.16

Tukey Simultaneous Tests
Response Variable Growth
All Pairwise Comparisons among Levels of Dclass

D. class = 1 subtracted from:

Level	Difference	SE of	T-Value	Adjusted
D. class	of Means	Difference		P-Value
2	0.10166	0.05130	1.9816	0.4311
3	0.01425	0.05130	0.2777	1.0000
4	0.07388	0.05130	1.4401	0.7790
5	0.04348	0.05510	0.7890	0.9857
6	0.10230	0.06102	1.6764	0.6329
7	0.03888	0.07760	0.5011	0.9988

D. class = 2 subtracted from:

Level	Difference	SE of	T-Value	Adjusted
D. class	of Means	Difference		P-Value
3	-0.08741	0.04681	-1.867	0.5056
4	-0.02778	0.04681	-0.593	0.9969
5	-0.05818	0.05044	-1.153	0.9100
6	0.00065	0.05614	0.012	1.0000
7	-0.06277	0.07251	-0.866	0.9770

D. class = 3 subtracted from:

Level	Difference	SE of	T-Value	Adjusted
D. class	of Means	Difference		P-Value
4	0.05963	0.04681	1.2738	0.8627
5	0.02923	0.05044	0.5795	0.9973
6	0.08806	0.05614	1.5686	0.7024
7	0.02464	0.07251	0.3398	0.9999

D. class = 4 subtracted from:

Level	Difference	SE of	T-Value	Adjusted
-------	------------	-------	---------	----------

D. class	of Means	Difference	T-Value	P-Value
5	-0.03040	0.05044	-0.6027	0.9966
6	0.02843	0.05614	0.5064	0.9987
7	-0.03499	0.07251	-0.4826	0.9990

D class = 5 subtracted from:

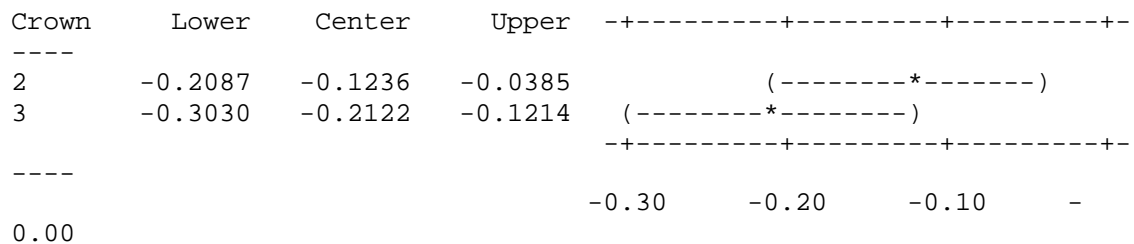
Level	Difference	SE of	Adjusted
D. class	of Means	Difference	P-Value
6	0.058827	0.05846	1.00633
7	-0.004593	0.07389	-0.06216

D. class = 6 subtracted from:

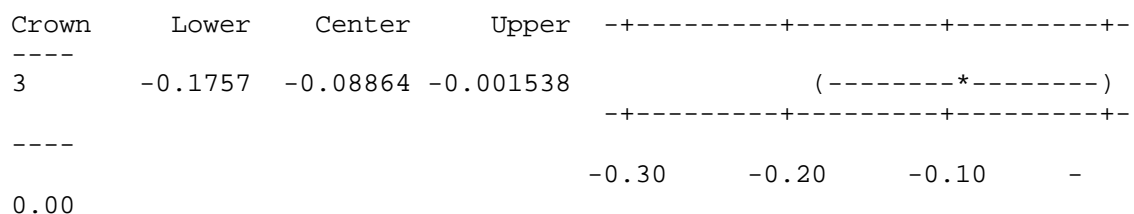
Level	Difference	SE of	Adjusted
D. class	of Means	Difference	P-Value
7	-0.06342	0.07641	-0.8300

Tukey 95.0% Simultaneous Confidence Intervals
 Response Variable Growth
 All Pairwise Comparisons among Levels of Crown

Crown = 1 subtracted from:



Crown = 2 subtracted from:



Tukey Simultaneous Tests
 Response Variable Growth
 All Pairwise Comparisons among Levels of Crown

Crown = 1 subtracted from:

Level	Difference	SE of	Adjusted
Crown	of Means	Difference	P-Value
2	-0.1236	0.03593	-3.439
3	-0.2122	0.03834	-5.536

Crown = 2 subtracted from:

Level	Difference	SE of	Adjusted
Crown	of Means	Difference	P-Value
3	-0.08864	0.03677	-2.411


```

-----+-----+-----+
0.050          -0.050    0.000

```

D. class = 4 subtracted from:

```

D. class  Lower    Center    Upper  -----+-----+-----+
-----
5          -0.02345  0.021328  0.06610      (-----*-----
-)
6          -0.04694  0.002890  0.05272      (-----*-----)
7          -0.05358  0.010781  0.07515      (-----*-----
---)
-----+-----+-----+
-----
0.050          -0.050    0.000

```

D. class = 5 subtracted from:

```

D. class  Lower    Center    Upper  -----+-----+-----+
-----
6          -0.07033  -0.01844  0.03345      (-----*-----)
7          -0.07614  -0.01055  0.05505      (-----*-----)
-----+-----+-----+
-----
0.050          -0.050    0.000

```

D. class = 6 subtracted from:

```

D. class  Lower    Center    Upper  -----+-----+-----+
-----
7          -0.05994  0.007891  0.07572      (-----*-----
---)
-----+-----+-----+
-----
0.050          -0.050    0.000

```

Tukey Simultaneous Tests
Response Variable C9
All Pairwise Comparisons among Levels of Dclass

D. class = 1 subtracted from:

Level	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	-0.03724	0.01523	-2.446	0.1880
3	-0.02261	0.01523	-1.485	0.7533
4	-0.04066	0.01523	-2.670	0.1139
5	-0.01933	0.01635	-1.182	0.8999
6	-0.03777	0.01811	-2.085	0.3673
7	-0.02988	0.02303	-1.297	0.8522

D class = 2 subtracted from:

Level	Difference	SE of	Adjusted
-------	------------	-------	----------

D. class	of Means	Difference	T-Value	P-Value
3	0.014630	0.01389	1.0530	0.9404
4	-0.003419	0.01389	-0.2461	1.0000
5	0.017910	0.01497	1.1964	0.8945
6	-0.000529	0.01666	-0.0317	1.0000
7	0.007362	0.02152	0.3421	0.9999

D. class = 3 subtracted from:

Level	Difference	SE of	Adjusted
D. class	of Means	Difference	P-Value
4	-0.01805	0.01389	0.8513
5	0.00328	0.01497	1.0000
6	-0.01516	0.01666	0.9705
7	-0.00727	0.02152	0.9999

D. class = 4 subtracted from:

Level	Difference	SE of	Adjusted
D. class	of Means	Difference	P-Value
5	0.021328	0.01497	0.7876
6	0.002890	0.01666	1.0000
7	0.010781	0.02152	0.9988

D. class = 5 subtracted from:

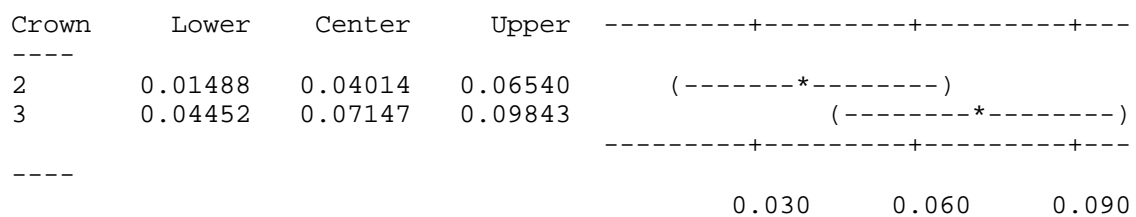
Level	Difference	SE of	Adjusted
D. class	of Means	Difference	P-Value
6	-0.01844	0.01735	0.9378
7	-0.01055	0.02193	0.9991

D. class = 6 subtracted from:

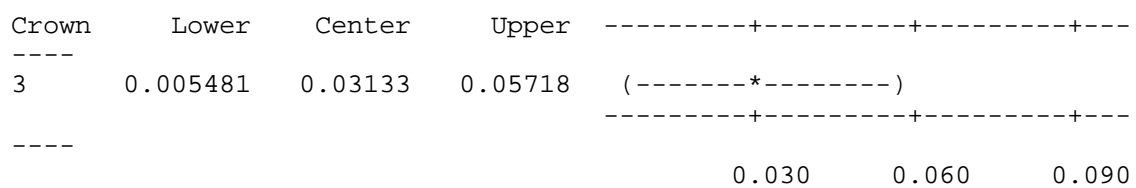
Level	Difference	SE of	Adjusted
D. class	of Means	Difference	P-Value
7	0.007891	0.02268	0.9999

Tukey 95.0% Simultaneous Confidence Intervals
 Response Variable C9
 All Pairwise Comparisons among Levels of Crown

Crown = 1 subtracted from:



Crown = 2 subtracted from:



Tukey Simultaneous Tests
 Response Variable C9
 All Pairwise Comparisons among Levels of Crown

Crown = 1 subtracted from:

Level Crown	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	0.04014	0.01066	3.764	0.0007
3	0.07147	0.01138	6.282	0.0000

Crown = 2 subtracted from:

Level Crown	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
3	0.03133	0.01091	2.871	0.0131

Anova: Single Factor for growth between trees 0 to 5 m far from the gap border and trees from 5 to 10 m far from the gap border (Figure 5.6)

SUMMARY

Groups	Count	Sum	Average	Variance
0-5 m trees	32	14	0.436	0.021
5-10 m trees	32	10.9	0.34	0.023

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.149	1	0.149	6.936	0.011	
Within Groups	1.335	62	0.022			
Total	1.484	63				

T -test of the mean for growth of the trees around the gap border from 0 to 5 m and from 5 to 10 m from the gap edge and the mean growth of the trees in the two permanent sample plots in the undisturbed forest in the same period (Figure 5.6)

Test of mu = 0.2600 vs mu not = 0.2600

Variable	N	Mean	StDev	SE Mean	T	P
5m	32	0.4364	0.1432	0.0253	6.97	0.0000
10m	32	0.3398	0.1502	0.0266	3.01	0.0052

Analysis of Variance for growth of trees 5 m around the gap border according to gap size (Figure 5.7)

Source	DF	SS	MS	F	P
Gap size	3	0.0293	0.0098	0.45	0.719
Error	28	0.6062	0.0217		
Total	31	0.6355			

Individual 95% CIs For Mean

Based on Pooled StDev

Level	N	Mean	StDev
1	16	0.4347	0.1660
2	8	0.4790	0.1567
3	4	0.4148	0.0430
4	4	0.3798	0.0718

Pooled StDev = 0.1471 0.30 0.40 0.50

Tukey's pairwise comparisons

Family error rate = 0.0500
Individual error rate = 0.0108

Critical value = 3.86

Intervals for (column level mean) - (row level mean)

	1	2	3
2	-0.2183 0.1296		
3	-0.2046 0.2444	-0.1817 0.3102	
4	-0.1696 0.2794	-0.1467 0.3452	-0.2490 0.3190

Analysis of Variance for growth of trees from 5 to 10 m far from the gap border according to gap size (Figure 5.7)

Source	DF	SS	MS	F	P
Gap size	3	0.0346	0.0115	0.49	0.694
Error	28	0.6646	0.0237		
Total	31	0.6993			

Individual 95% CIs For Mean
Based on Pooled StDev

Level	N	Mean	StDev
1	16	0.3381	0.1414
2	8	0.3809	0.2092
3	4	0.2673	0.0270
4	4	0.3367	0.1369

Pooled StDev = 0.1541 0.12 0.24 0.36 0.48

Tukey's pairwise comparisons

Family error rate = 0.0500
Individual error rate = 0.0108

Critical value = 3.86

Intervals for (column level mean) - (row level mean)

	1	2	3
2	-0.2249 0.1393		
3	-0.1642 0.3059	-0.1439 0.3712	
4	-0.2337 0.2365	-0.2133 0.3017	-0.3668 0.2279