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Carbon sequestration potential of land-cover types in the agricultural landscape of eastern Amazonia, Brazil

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ABSTRACT

After more than 100 years of agriculture, the moist tropical primary forest in the Bragantina region, eastern Amazonia, Brazil, has been almost completely replaced by a mosaic of crops and secondary forest of different ages. Primary forest is only to be found in flooded areas. The area of secondary forest declines and the traditional slash and burn system has led to a decrease in productivity and species richness. The present study explores the potential of secondary forest to sequester atmospheric carbon as an environmental service that could be an incentive for the farmers to conserve these forests. Carbon stocks of the forest stands were estimated based on the respective aboveground biomass using the average height of the highest canopy strata in 35 secondary forest stands between 2 and 20 m height. The relationship between average stand height (AHH) and total aboveground biomass (TAGB; including litter and dead trees) is represented by $\ln TAGB = 2.4143 + 0.9428 \ln AHH$ ($R^2 = 0.84$) and $\ln TTAB_{AHH} = 1.6614 + 1.1793 \ln AHH$ ($R^2 = 0.85$) for trees only (TTAB). Tree biomass was adjusted by the correction factors for height, volume, wood density and bark. Carbon stocks reach 17, 40, 64 and 90 t C ha^{-1} when the average height of the highest canopy strata is 5, 10, 15 and 20 m, respectively. The potential carbon stock in secondary forest and other land covers was calculated combining biomass and carbon stocks with spatial information derived from Ikonos images; the results were extrapolated to the municipality of Igarapé Açu and the Bragantina region. Secondary forest higher than 2 m covers 37 % in the region, initial secondary succession 8 %, grassland 21 %, oil palm plantations 1 % and semi-permanent and annual crops 9 %. These land covers store 7.9, 0.2, 0.7, 0.15 and 0.2 Mt C, respectively. The carbon stock in secondary forest represents 5 % of the carbon released by the replacement of the original forest. Secondary forest sequesters carbon more effectively than oil palm plantations only after the first decade of growth. If carbon sequestration projects consider secondary forest as a carbon sink, the expected benefit within 10 years is 10,814 US$ (41 %) in addition to the average farm income from agricultural products (26,065 US$ within 10 years) when the current price per t CO_2 within the framework of CDM projects is considered (5.63 US$) or even more than 100 % when the price reaches 13.6 US$.

Das Potential zur Kohlenstoffspeicherung verschiedener Landbedeckungssysteme in der Agrarlandschaft Ostamazoniens, Brasilien

KURZFASSUNG

Der Regenwald in der Region Bragantina, Ostamazonien, Brasilien, ist nach mehr als 100 Jahren landwirtschaftlicher Aktivitäten fast vollkommen durch ein Mosaik von Anbauflächen und Sekundärwald unterschiedlichen Alters ersetzt worden. Reste von Primärwald kommen nur noch in Überschwemmungsgebieten vor und die traditionelle Brandrodung hat zur Abnahme von Produktivität und Artenvielfalt geführt. Die vorliegende Studie untersucht das Potenzial der Sekundärwälder, atmosphärischen Kohlenstoff zu speichern. Diese Umweltserviceleistung kann als Anreiz für Bauern dienen, die Wälder zu erhalten und dadurch ein zusätzliches Einkommen zu erwirtschaften. Zur Berechnung der oberirdischen Biomasse der Bestände wurde die durchschnittliche Höhe der höchsten Kronenschicht von 35 Sekundärwaldbeständen mit Höhen von 2 bis 20 m benutzt. Die Beziehung zwischen durchschnittlicher Bestandeshöhe (AHH) und oberirdischer Biomasse (einschl. Streu und Totholz) wird dargestellt durch $\ln TAGB = 2.4143 + 0.9428 \ln AHH$ ($R^2 = 0.84$) bzw. $\ln TTAB_{AHH} = 1.6614 + 1.1793 \ln AHH$ ($R^2 = 0.85$), wenn nur Bäume berücksichtigt werden. Bei der Berechnung der Baumbiomasse wurden Korrekturfaktoren für Höhe, Volumen, Holzdichte und Baumrinde verwendet. Die Kohlenstoffvorräte betragen 17, 40, 64 bzw. 90 t C ha^{-1} für durchschnittliche Kronenschichthöhen von 5, 10, 15 bzw. 20 m. Die potenzielle Kohlenstoffspeicherung durch Sekundärwälder und andere Pflanzendecken wurde über die Kombination von Biomasse bzw. Kohlenstoffvorräte mit räumlichen Daten aus Ikonos-Satellitenbildern errechnet; die Ergebnisse wurden auf die Fläche des Verwaltungsbezirks Igarapé Açu bzw. der Region Bragantina extrapoliert. Sekundärwald höher als 2 m bedeckt 37 % der Region, junge Sekundärvegetation 8 %, Grasland 21 %, Ölpalmen 1 % und landwirtschaftliche Anbauflächen 9 %. Diese Flächen speichern 7.9, 0.2, 0.7, 0.15 bzw. 0.2 Mt C. Die Studie ergab, dass der gespeicherte Kohlenstoff im Sekundärwald 5 % des durch die Umwandlung des Primärwaldes freigesetzten Kohlenstoffs darstellt. Des weiteren zeigte sich, dass der Sekundärwald erst nach zehn Jahren eine effektivere Kohlenstoffaufnahme pro Hektar hat als Ölpalmenplantagen. Wenn Projekte zur Kohlenstoffbindung Sekundärwälder als Kohlenstoffsenke berücksichtigen, kann das in einem Zeitraum von 10 Jahren zu erwartende Durchschnittseinkommen einer Farm (26,065 US$) aus landwirtschaftlichen Produkten um 10,814 US$ (41 %) steigen wenn der aktuelle Preis pro t CO_2 in CDM-Projekten (5.63 US$) zugrunde gelegt wird. Das Einkommen kann sich verdoppeln, wenn der Preis innerhalb von 10 Jahren 13.6 US$ erreicht.

Potencial de seqüestro de carbono em diferentes tipos de cobertura vegetal na paisagem agrícola da Amazônia Oriental

RESUMO

A floresta primária tropical úmida da região Bragantina, Amazônia, Brasil com mais de 100 anos de atividade agrícola, foi substituída em sua maioria por um mosaico de culturas agrícolas e por florestas secundárias de diferentes idades. Atualmente florestas primárias são encontradas somente em áreas de várzeas. A área de floresta secundária diminuiu e o sistema tradicional de corte-e-queima conduziram a uma diminuição da produtividade e da biodiversidade de espécies. O presente estudo aborda o potencial da floresta secundária em seqüestrar o carbono atmosférico como um serviço ambiental que poderia ser um incentivo para que os agricultores conservassem estas florestas. Estoque de carbono foram estimados em 35 florestas secundárias entre 2 e 20 m de altura, através da biomassa aérea usando a altura média da camada mais alta do dossel. A correlação entre a altura média da parcela (AHH) e a biomassa total aérea TAGB; ncluindo a liteira e árvores mortas) é representado por $\ln TAGB = 2{,}4143 + 0{,}9428 \ln AHH$ ($R^2 = 0{,}84$) e $\ln TTAB_{AHH} = 1{,}6614 + 1{,}1793 \ln AHH$ ($R^2 = 0{,}85$) somente para árvores (TTAB). A biomassa da árvore foi ajustado pelos fatores de correção para altura, volume, densidade e casca da madeira. O estoque de carbono chega a 17, 40, 64 e 90 t C ha^{-1} quando a altura média da camada mais altas do dossel é 5, 10, 15 e 20 m, respectivamente. O potencial de estoque de carbono em floresta secundária e em outras coberturas vegetais foi calculado combinando a biomassa com o estoque de carbono e com a informação espacial derivada de imagens do Ikonos; os resultados foram extrapolados para o município de Igarapé-Açú e para a região Bragantina. Florestas secundárias com mais de 2 m de altura cobrem 37 % da região, a sucessão secundária inicial cerca de 8 %, capim 21 %, plantação de palma oleaginosa 1 % e culturas anuais e semi-permanentes 9 %. Estas coberturas vegetais armazenam 7,9, 0,2, 0,7, 0,15 e 0,2 Mt C, respectivamente. O estoque de carbono na floresta secundária representa 5 % do carbono liberado pela reposição da floresta original. Somente após 10 anos de crescimento, a floresta secundária seqüestra carbono da atmosfera mais eficiente do que a plantação de óleo de palma. Se os projetos de seqüestro de carbono considerarem a floresta secundária como um sumidouro de carbono, o benefício previsto dentro de 10 anos é 10.814 US$ (41 %) adicional à renda média das propriedades rurais, obtida com os produtos agriculturais (25.065 US$ dentro de 10 anos). Está se considerando o preço atual por t CO_2 dentro da estrutura dos projetos de CDM (5,63 US$) ou mais de 100 % se o preço aumentase para 13,6 US$.

Secuestro potencial de carbono por diferentes tipos de coberturas vegetales, en el paisaje agrícola de Amazonía oriental, Brasil

RESUMEN

La actividad agrícola de los últimos 100 años ha reemplazado casi en su totalidad el bosque tropical de la región Bragantina, localizada en el este de la región Amazónica en Brasil por un mosaico de cultivos y bosques secundarios de diferentes edades. Actualmente, los remanentes del bosque primario solo se encuentran en las áreas inundadas. La extensión de bosques secundario se reduce con el tiempo y el sistema agrícola tradicional de corte y quema decrece en productividad y riqueza de especies. El presente estudio explora el potencial del bosque secundario para asimilar carbono atmosférico como un servicio ambiental que puede ser usado para incentivar la conservación de las áreas con bosques por parte de los agricultores. La cantidad de carbono en los rodales de bosques secundarios fue calculada en base a la biomasa, esta última fue estimada usando el promedio de altura de los árboles del estrato más alto en el dosel de 35 bosques secundarios con alturas entre 2 a 20 m. La relación entre el promedio de altura (AHH) y la biomasa total de la parte aérea (TAGB; incluido residuos de hojarascas y árboles muertos) es expresada por $\ln TAGB = 2.4143 + 0.9428 \ln AHH$ ($R^2 = 0.84$) y $\ln TTAB_{AHH} = 1.6614 + 1.1793 \ln AHH$ ($R^2 = 0.85$) solamente para los árboles vivos (TTAB). La biomasa de los árboles fue ajustada con factores de corrección por altura, volumen, densidad de la madera y de la corteza. Cuando el promedio de altura de los árboles del dosel superior alcanza los 5, 10, 15 y 20 m la cantidad accumulada de carbono es 17, 40, 64 y 90 t C ha^{-1} respectivamente. El potencial de almacenamiento de carbono por parte de los bosques secundarios y otros tipos de cobertura vegetal fue calculado combinando información de biomasa y cantidad de carbono con información espacial generada de análisis de imágenes Ikonos. Los resultados fueron extrapolados a toda la municipalidad de Igarapé Açu y a la región Bragantina. El bosque secundario mayor a 2 m de altura se extiende en el 37 % del área de la región, sucesión secundaria inicial en el 8 %, pastos en el 21 %, plantaciones de palma aceitera en el 1 % y cultivos semipermanentes y anuales en el 9 %. Estos tipos de cobertura acumulan 7.9, 0.2, 0.7, 0.15 y 0.2 Mt C respectivamente. El carbón almacenado en el bosque secundario representa solamente el 5 % del carbono emitido por la eliminación del bosque original. El bosque secundario es más eficiente para secuestrar carbono comparado con plantaciones de palma aceitera, solamente después de primera década crecimiento. En el caso de que nuevos proyectos consideren el bosque secundario como un sumidero de carbono, los beneficios esperados en un plazo de 10 años es 10814 US$ (41 %) adicional al promedio de renta neta que los agricultores reciben por la venta de productos agrícolas (26065 US$ ha^{-1} en un plazo de 10 años), cuando es considerado el precio actual de la t CO_2 en el marco de proyectos de MDL (5.63 US$) o más del 100 % si el precio incrementase a 13.6 US$.

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ACKNOWLEDGEMENTS

LIST OF ABBREVIATIONS

AHH	Average height of the highest canopy stratum (m)
BA	Basal area (m^2 ha^{-1})
C	Carbon
CDM	Clean Development Mechanism
CO_2	Carbon dioxide
DBH	Diameter measured at breast height (1.30 m; cm)
DWC_i	Dry weight of tree components (leaves, branches, trunk; kg)
GHG	Greenhouse gas
HCF	Height correction factor
SD	Standard deviation
SDTB	Total standing dead tree biomass (t ha^{-1})
SE	Standard error
TAB	Tree aboveground biomass (kg)
TAGB	Total aboveground biomass (t ha^{-1})
TBEF	Tree biomass expansion factor
TBRF	Tree biomass reduction factor
TDWL	Total dry weight of litter (t ha^{-1})
TTAB	Total live tree aboveground biomass (t ha^{-1})
VCF	Volume correction factor
WCF	Weight correction factor
WD	Wood density (g cm^{-3})

1 INTRODUCTION

The Bragantina region is located in eastern Amazonia, Northern Brazil, covering around 9000 km^2 and with a long history of agricultural activities. For over 150 years, human activities have modified the landscape and reduced the primary forest area to less than 5 % of the original cover (Hedden-Dunkhorst et al., 2004). Land use consists mainly of livestock grazing and cultivation of annual and perennial crops mixed with spontaneous forest vegetation in the fallow areas. During the past 40 years, the population has rapidly increased and the road network expanded, which has led to increasing pressure on the land resources. As the smallholders have to produce increasing amounts of food supplies for the neighboring cities, fallow periods are shortened, and soils and fallow vegetation have become degraded. Although the Bragantina region is an old colonized region, other tropical areas along the Amazonian basin have been recently deforested and 30 % of these areas are covered by secondary forests (Fearnside and Guimarães, 1996; Houghton et al., 2000). Alternatives uses for secondary forest must be developed in order to avoid the degradation of further areas. Forest management and atmospheric carbon sequestration of secondary forest are alternatives to be explored.

The present study comprises four main chapters that aim to:

- explain the importance of tropical rain forest as a regulator of the global climate and producer of goods and services,
- describe the florisitic composition and structural characteristics of secondary forest in the Bragantina region,
- provide new equations to estimate the carbon assimilation potential of secondary forest using height as a predictive variable, and
- estimate the carbon sequestration potential on farms and in the landscape of the municipality of Igarapé Açu and the Bragantina region combining different sources of data and methodologies.

Finally, conclusions with respect to the potential carbon sequestration in the study area and the forest stand characteristics will be provided.

2 TROPICAL RAIN FOREST AND GLOBAL CLIMATE CHANGE

2.1 Global climate change

Carbon dioxide (CO_2) is one of the main gases in the atmosphere. Since the Industrial Revolution (mid 19th century), CO_2 concentration in the atmosphere has increased from 285 to 366 parts per million by volume (ppmv), which is about 28 % higher than the pre-industrial level. The main factors responsible for this increase are fuel combustion and the reduction of forest areas due to land-use changes. During the 20th century, the CO_2 concentration remained high as a result of emissions following land-use change and deforestation in the tropics and was responsible for 60 % of the carbon (C) emissions by land-use changes and management, with average fluxes of 2.2 gigatons (Gt) of carbon per year during the 1990s (Houghton, 2003). The average global temperature increased by 0.6 ºC and is expected to increase from 1.4 to 5.8 ^{o}C by the year 2100 through the increase in the concentration of atmospheric gases with a greenhouse effect (GHG). Variation in the atmospheric concentration of some GHGs has important consequences for the warming effect. Carbon dioxide is the gas with the lowest global warming potential (GWP) among the GHGs, but the increase in concentration and the long lifetime time in the atmosphere make it responsible for about 70 % of the warming. Small changes in the global atmospheric temperature are expected to modify rainfall patterns, raise the sea level and increase the frequency of extreme weather events, with subsequent economic and social impacts. A synthesis of the different indicators of global climate change and its effects during the twentieth century are summarized in Table 1.1.

With the creation of the United Nation Framework Convention on Climate Change (UNFCCC) after the 1992 Earth Summit in Rio de Janeiro, countries began to look for appropriate measures to reduce the emission of GHGs and to take action. During the Third Conference of Parties of the Convention (COP 3) in Japan in 1997, the attending countries adopted the Kyoto Protocol, where industrialized nations agreed to reduce their overall GHGs emissions by 2008-2012 by at least 5 % compared to 1990 levels (UNFCCC, 1998). The protocol entered into force on 16 February, 2005. In the protocol, several mechanisms were proposed to reduce GHG emissions and to increase GHG removals by sinks. One is the Clean Developement Mechanism (CDM)

(Article 12), by which industrialized countries can assist developing countries in achieving sustainable development, at the same time reducing their emissions and fulfill their commitments (UNFCCC, 1998). Several GHG trading systems have emerged during the past years, e.g., for certificates for emission reduction (Lecocq and Capoor, 2005).

Table 2.1 Main indicators of global changes in atmosphere, climate and biophysical system in the 20th century

Indicator	Observed Changes
Concentration indicators	
Atmospheric concentration of CO_2	280 ppmv for the period 1000–1750 to 368 ppmv in year 2000 (31±4 % increase).
Terrestrial biospheric CO_2 exchange	Cumulative source of about 30 giga tons (Gt) of C between the years 1800 and 2000; but during the 1990s, a net sink of about 14±7 Gt C.
Atmospheric concentration of CH_4	700 parts per billon (ppb) for the period 1000–1750 to 1,750 ppb in year 2000 (151±25 % increase).
Atmospheric concentration of N_2O	270 ppb for the period 1000–1750 to 316 ppb in year 2000 (17±5 % increase).
Tropospheric concentration of O_3	Increased by 35±15 % from the years 1750 to 2000, varies with region.
Stratospheric concentration of O_3	Decreased over the years 1970 to 2000, varies with altitude and latitude.
Atmospheric concentrations of HFCs, PFCs, and SF6	Increased globally over the last 50 years.
Weather indicators	
Global mean surface temperature	Increased by 0.6±0.2°C over the 20th century; land areas warmed more than the oceans (*very likely*).
Northern Hemisphere surface temperature	Increase over the 20th century greater than during any other century in the last 1000 years; 1990s warmest decade of the millennium (*likely*).
Diurnal surface temperature range	Decreased over the years 1950 to 2000 over land: nighttime minimum temperatures increased at twice the rate of daytime maximum temperatures (*likely*).
Hot days / heat index	Increased (*likely*).
Cold / frost days	Decreased for nearly all land areas during the 20th century (*very likely*).
Continental precipitation	Increased by 5–10 % over the 20th century in the Northern Hemisphere (*very likely*), although decreased in some regions (e.g., north and west Africa and parts of the Mediterranean).
Heavy precipitation events	Increased at mid- and high northern latitudes (*likely*).
Frequency and severity of drought	Increased summer drying and associated incidence of drought in a few areas (*likely*). In some regions, such as parts of Asia and Africa, the frequency and intensity of droughts have been observed to increase in recent decades.

Table 2.1 continued

Biological and physical indicators	
Global mean sea level	Increased at an average annual rate of 1 to 2 mm during the 20th century.
Duration of ice cover of rivers and lakes	Decreased by about 2 weeks over the 20th century in mid- and high latitudes of the Northern hemisphere (*very likely*).
Arctic sea-ice extent and thickness	Thinned by 40 % in recent decades in late summer to early autumn (*likely*) and decreased in extent by 10-15% since the 1950s in spring and summer.
Non polar glacier	Widespread retreat during the 20th century.
Snow cover	Decreased in area by 10 % since global observations became available from satellites in the 1960s (*very likely*).
Permafrost	Thawed, warmed, and degraded in parts of the polar, sub-polar, and mountainous regions.
El Niño events	Became more frequent, persistent, and intense during the last 20 to 30 years compared to the previous 100 years.
Growing season	Lengthened by about 1 to 4 days per decade during the last 40 years in the Northern hemisphere, especially at higher latitudes.
Plant and animal ranges	Shifted pole ward and up in elevation for plants, insects, birds, and fish.
Breeding, flowering, and migration	Earlier plant flowering, earlier bird arrival, earlier dates of breeding season, and earlier emergence of insects in the Northern Hemisphere.
Coral reef bleaching	Increased frequency, especially during El Niño events.

(Source: Watson et al., 2001)

2.1.1 The role of forest in the global climate change

The original world forest area (around 8000 years ago), before conversion by human activities, was estimated to be 6.22 x 10^9 ha, but only 54 % of this forest area has remained (Bryant et al., 1997). Around 750 Mha (million hectares) have been transformed into different agricultural uses, and since the industrial revolution, 136±55 Gt C have been emitted to the atmosphere by the transformation of forest ecosystems (Lal et al., 1998 cited by WBGU 1998; IPCC, 2000). Conversion of forest to agriculture and to other land use during the 20th century was responsible for 33 % of the 28 % increase in the atmospheric CO_2 concentration (IPCC, 2000).

Destructive activities in the forest have a direct influence on the atmospheric carbon concentration as 50 % of the dry wood material consists of carbon (Brown, 1997). Deforestation affects the soil-carbon stock, modifying any previous equilibrium in the system, and dying roots and decomposition processes release more carbon to the atmosphere. In addition, residuals of wood and leaf material on the surface decompose and release the carbon accumulated in the forest biomass to the atmosphere. Not all wood materials are burned during the first fire, i.e., the efficiency of burning (carbon released as gas) averages 39.4 % of the original material. Some parts are converted to charcoal (2.2 %) or to small amounts of graphitic particles, which are burnt again during subsequent fires releasing further carbon (Fearnside, 2000).

Pristine forest is considered to have a neutral carbon-balance system, i.e., emissions and removals of carbon are in equilibrium, although recent research shows that the net productivity of primary forest is increasing and is related to weather variation (IPCC, 2000; Phillips et al., 1998). Extraction of wood without appropriate management could convert the forest stand into a source of atmospheric carbon through the decomposition of litter material and damaged trees. Appropriate forest management reduces emissions through the accumulation of carbon in the remaining trees after selective logging leading to a positive carbon balance. On the other hand, the harvested materials store the carbon for a long period of time until they decay or are burnt. Carbon fixation can be enhanced by improving the growth rates through thinning, weeding or fertilization (Hoen and Solberg, 1994). In the context of the Kyoto Protocol, forest management in tropical countries constitutes an alternative to ensure the continuity of forests, providing a choice of income to farmers and ensuring the uptake of atmospheric carbon in highly valuable wood tree species. In the case of afforestation or reforestation (when forest develops in areas previously not covered by forest or where a new forest develops in previously forested areas), they represent net sinks, where carbon is assimilated during the photosynthesis process as a component of the cellular structure of different vegetable tissues until tree maturity when the positive rate ends and then declines.

Information about changes in forest covers and land use is essential to understand their contribution to the emission or reduction of GHGs and their effect on climate change. Precise estimations of these changes and the ability of forest and land covers to assimilate carbon would help to build good predictive models to apply strategies to mitigate and to adapt to global climate changes.

2.2 Tropical rain forest

Per definition tropical forests are forests growing between the two tropic parallels lines and those forests that extend outside these limits to areas with tropical weather influence. Tropical forest extends on rain and moist to semi-arid regions (Holdridge, 1967). Tropical rain forest with its two types, rain forest (real rainforest) and moist forest (monsoon forest and montane/cloud forest), play an important role in the global weather regulation and account for more than 50 % of all living species, hosting some of the biologically most diverse areas on the planet (Dupuy et al., 1999). The most biodiverse forests occur in west Amazonia, in Yanamono, Peru, and in the Cuyabeno Reserve, Ecuador with more than 300 trees species ha^{-1} with a diameter larger than 10 cm at breast height (Mori, 1994; Richards, 1996).

Tropical rain forest represents around 7 % of the world's total land area and stores 46 % of the living terrestrial carbon pools (Brown and Lugo, 1982). Estimations report that when tropical rain forest is burned or removed, sequestration of the released carbon in trees would require between 50 years to centuries under secondary succession (Houghton et al., 2000; Koskela et al., 2000; Lucas, et al., 1996; Saldarriaga et al., 1988). However, not all stands accumulates carbon at the same rate; the rate depends on species composition, site condition and previous land use (Brown and Lugo, 1990; Fearnside and Guimarães, 1996; Moran et al., 2000a; Moran et al., 2000b; Hondermann, 1995; Uhl et al., 1988).

The area occupied by tropical rain forest around the world amounts to $1.17x10^{9}$ ha (Groombridge and Jenkins, 2002) and is the target of extensive pressure through the demand for wood products, expansion of agricultural land and population increase.

Tropical deforestation started more than a century ago, but the process has accelerated during the last 30 years, with a forest loss of 13 Mha yr^{-1} (WBGU, 1998). The original area of tropical forests has shrank to less than half, and the tropical forests have been replaced mainly by agriculture and secondary vegetation (vegetation growing in secondary succession over a long and short periods of time), the latter currently covering more than 30 % of the tropical rain forest area (Brown and Lugo, 1990; FAO, 2000). The Amazonian primary forest used to cover an area of about 7.6 million km^2, extending over nine countries (INPA, 2005) but has been reduced in many areas. In Brazil, the National Institute for Spatial Research (INPE) estimated that more than 630,000 km^2, which is around 13 % of the Brazilian Amazon rain forest, were deforested until 2003, and the rate from 2002 to 2003 reached 24,600 km^2 $year^{-1}$ (INPE, 2005). In Amazon region the major causes of deforestation is caused by increase in the size of settlements, advance of agricultural frontiers (Nascimento, 2003), expansion of areas for cattle production (Fearnside and Guimarães, 1996) and the demand for products, infrastructure and land by the growing population.

2.3 Secondary forest

The forests generated from secondary succession are termed secondary forest and are the result of natural or human disturbance of previous natural forest areas (Dupuy et al., 1999). Due to the dynamic process of use and abandonment of land through shifting cultivation, cattle production, permanent agriculture, fuel-wood extraction, harvesting or burning (Brown and Lugo, 1990), secondary forest in tropical areas consists of a mosaic of stands with mixed-age and structure. Currently, secondary forest covers more than 350 Mha around the world, where 50 % is to be found in tropical South and Central America. In the Brazilian Amazon 30 % of the deforested area contains young secondary forest (Fearnside and Guimarães, 1996; Houghton et al., 2000).

The importance of secondary forest is due to the fact that it can provide valuable benefits when long-term growth is allowed. These new forest areas protect the soil against erosion, restore soil productivity, provide new wildlife habitats, and wood and non-wood products for farmers, and regulate water streams among others. Secondary forests show a rapid increase in biomass, accumulating atmospheric carbon in wood, leaves and roots, soil surface and underground, with a productivity of almost double that of primary forest (Smith et al., 2000; Brown and Lugo, 1990). It could save more than 90 t ha^{-1} to 120 t ha^{-1} in stands between 20 years old to 30 years old in Amazon basin (Honzák et al., 1996; Lucas et al., 1996; Steininger, 2000).

In agricultural system of cycles of slash and burn, vegetation develops during fallows. Using this practice, common in tropical areas, farmers cut and burn the secondary vegetation to cultivate the area for a short period. After yields decline, the land is abandoned for several years and the subsequent spontaneous vegetation grows again and restores soil nutrients. After slashing with the application of fire, nutrients are liberated and easily let them available for following crops. Nevertheless, most of the carbon that was assimilated in the different compartments of the growing vegetation is released to the atmosphere, and the positive contribution to carbon sequestration by assimilation during the growing period is lost.

2.4 Bragantina region

The Bragantina region is located in Pará state in the east of the Amazonian basin, Brazil, and covers an area of approximately 8700 km^2 and includes 13 municipalities (IBGE, 2005a). A long agricultural tradition and old landscape types characterize the region. Construction of the railway that connected the city of Belém with the town of Bragança began in 1883 and numerous settlements developed near the railway line. Due to the creation of the highway to Brasilia and the economic uncompetitiveness of the railway, this closed in 1966 (Denich and Kanashiro, 1993, Kemmer, 1999). Despite this, the population grew and the land was almost completely deforested (> 90 %) and replaced by agriculture and cattle farms. Salomão (1994) estimated that around 180 Mt (million tons) C were emitted to the atmosphere by the conversion of 0.95 Mha of forest to other land covers. Today the landscape consists of a complex mosaic of different farm sizes and areas assigned to production of commercial and subsistence crops (Sousa Filho et al., 1999a), mixed with patches of secondary forest. Primary forest only occurring along river banks and small creeks.

Slash and burn practices are practiced in the region because of low fertility of soil. During fallow period, fallow vegetation recover soil productivity; nevertheless, fallow periods in the region are being reduced to satisfy market demands and the growing population pressure (Denich and Kanashiro, 1995; Metzger, 2002; Metzger, 2003). Furthermore, the area of cropped land has increased in order to compensate the reduction of soil fertility. In addition, land use has been intensively mechanized and the production of crops, as in many cases, changed from subsistence production to the monoculture of cash crops (Denich and Kanashiro, 1995). The short fallow period and high fire frequency are not favorable for the recovery of nutrients lost during the land preparation and cropping phases (Hölscher, 1997; Mackensen et al., 1996). The agricultural system, which has been in operation for over 150 years, is now collapsing due to the decrease in soil productivity and vitality of the fallow vegetation. Secondary forest management or implementation of carbon sequestration projects are alternatives to the current agricultural activities, which can contribute to an increased uptake of atmospheric carbon and provide additional economic benefits to farmers. According to the study by Salomão (1994), only in the Bragantina region there is a total potential carbon uptake of 1.7 Mt yr^{-1} by secondary forest at a rate of 2 t C ha^{-1} yr^{-1}.

3 STRUCTURE AND FLORISTIC COMPOSITION OF SECONDARY FOREST

3.1 Introduction

Secondary forest includes forest formed as a consequence of human impact on forestlands (Brown and Lugo, 1990) and of natural disturbances. To date, more than 13 % of the tropical rain forest in Brazil has been deforested (INPE, 2005) and been replaced by at least on 30 % by secondary forest, mainly as a result of cattle production activities (Fearnside and Guimarães, 1996; Fearnside, 1996), but also to a great part as a result of agricultural slash-and-burn practices in the Amazon region. Secondary forest normally grows after cropping or cattle grazing during a fallow period, and the frequency of fallows is strongly related to the rotation of land use on the farms. Fallow vegetation (vegetation cover growing for a certain period in areas occupied previously by agriculture or other land use or by forest) develops into a forest fallow when the fallow period is long enough to allow the trees to grow and build up a forest stand. The benefits of fallow vegetation are the same as those provided by secondary forest (Chapter 2), but most important for the farmers is the restoration of soil productivity to ensure continuity of the different agricultural activities.

The landscape in the Bragantina region in east Amazonia, Brazil, has been modifed during the last 150 years by slash-and-burn agriculture with crop rotation in the same productive units, and fallow vegetation plays an important role in local agricultural production, alternating in space and time with crops and pastures. The increase in population in the neighboring cities is leading to an increased demand for food, in turn leading to shortened fallow periods to increase the frequency of crops and to apply unsustainable land preparation. As a result, the time for the soil to accumulate nutrients to ensure sustainability of the slash-and-burn system (Hölscher, 1997; Mackensen et al., 1996) and to maintain crop yields (Smith et al., 2000) is inadequate.

Old secondary forest stands are rare in the Bragantina region. However, high and medium-hight stands are allow to further develop, since farmers concentrate work mainly on young fallow areas where the land preparation is easier (Denich and Kato, 1995; Smith et al., 2000).

In the Bragantina region, the continuity of fallow vegetation in areas previously occupied by agriculture or other land use is threatened. Alternatives to the current cropping system should be consider to prevent degradation of soils and vegetation. Management of secondary forest can provide wood products and environmental services such as carbon sequestration. Understanding of floristic composition, arrangement in the structure and species dynamics in these forests will facilitate conservation and forest management practices.

3.1.1 Regeneration process in fallow vegetation

Fallow vegetation in Bragantina regenerates in two ways, i.e., by seeds or by vegetative resprouting. Seed production varies between species, and regeneration through seeding is possible in young secondary forest. However, Denich (1986a) found that after a short period of 6 months only few seeds germinated, showing the low capacity of plants to produce viable seeds that can survive the high rate of attack by fungus and bacteria. Futhermore, the slash-and-burn practice also contributes to the destruction of seed banks and new seedlings (Denich and Kanashiro, 1995; Smith et al., 2000; Vieira, 1996).

The high fragmentation of the landscape is threatening the existence of species that depend exclusively on animals to pollinate flowers and disperse seeds (Vieira et al., 1996). Seeds do not disperse far from the producer trees and new seeds from adjacent older vegetation are rare (Stevens and Gottberger, 1995). Vieira et al. (1996) studying differences between primary forest and fallow vegetation in the Bragantina region observed that 34.5 % of the species of the original forest could still find favorable conditions in the neighboring areas for reproducing after the land was not longer used for agricultural purposes. The regeneration strategy of fallow vegetation after the cropping period changed from seeding to resprouting after at least 3 slash-and-burn cycles. In fallow stands of more than 30 years and 4 cycles of slash and burn approximately 60 % of the plants regenerated by sprouting (Stevens and Tillery-Stevens, 1995).

The shortening of fallow periods limits plant reproduction and trees do not have enough time to reach maturity to produce viable seeds. On the other hand, mechanized agriculture reduces the ability of the root systems to survive and maintain the vitality of the fallow vegetation (Denich and Kanashiro, 1995). Permanent and semi-permanent crops like oil palm, black pepper and passion fruit are common in the Bragantina region. These crops require land preparation that usually includes stump removal, plowing and harrowing. Furthermore, they strongly modify soil structure and vegetation type, and negatively influence the regeneration of fallow vegetation during the subsequent fallow period (Pereira and Vieira, 2001). After abandonment of the these cropped lands, the fallow vegetation takes over the area again, but with important irregularity in structure and species composition (Denich and Kanashiro, 1995; Hondermann, 1995). The survival and maintenance of healthy secondary forest as fallow vegetation is guaranteed only with the manual land preparation in traditional agriculture with short cropping periods and long fallows (SHIFT-Capoeira, 2003)

3.1.2 Development stages in secondary succession

Secondary succession is defined as the sequential changes in tree species composition while forest stands grow in areas previously covered by primary forest. Clear stages are characterized by the presence of species better adapted to the new site conditions (Finegan, 1992; Peña-Claros, 2001). However, the course of the succession and the floristic variability will be controlled by the phenology stage of species at the time of land abandonment, the colonization strategy of species (seeds or sprouts), the presence of remaining trees in the area, soil fertility and the previous land-use practices (Smith et al., 1997; Finegan, 1997).

During the secondary succession, the stand changes both in species composition and structure. These changes are recognized by farmers in the Bragantina region, who define three main stages of stand development based on tree height and dimension, and vegetation type:

“juquira”	grass and shrubs
“capoeira fina”	thin and small trees
“capoeira grossa”	thick and tall trees

The time that the vegetation requires to reach each of the size categories depends on species composition, previous land-use practices and site characteristics. According to Denich and Kanashiro (1995), in lands that are not degraded, trees in stands require more than 3 to 7 years to exceed 5 m in height and more than 20 years to reach diameter larger than 10 cm (diameter at breast height 1.30 m - DBH), and heights more than 10 m (Salomão, 1994; Vieira, 1996).

3.1.3 Diversity of secondary forest

The floristic composition of secondary forest in the Bragantina region is the result of many years of human influence and changes in the forest cover. Denich (1986a) defined the vegetation community in the municipality of Igarapé Açu, Bragantina region as a product of anthropogenic substitution. This human-induced vegetation is characterized by a varied number of plant communities. In 4- and 5-year old secondary forest stands, Denich (1986b) found a total of 173 species of plants arranged in 50 families, which included trees, vines/lianas and shrubs. In another study in the same municipality, Magalhães and Gonçalves (1998) found 99 species and 46 families of trees with a DBH larger than 5 cm as well as herbs and vines in an area of 1.2 ha in a more than 13-year-old secondary forest.

Vieira et al. (1996) compared the species diversity of primary forest with that of secondary forest in the Bragantina region. They found that species richness in the primary forest was always higher than in any secondary forest stand. In the primary forest, they counted 268 species with a DBH larger than 5 cm, while in secondary forests of 5, 10, 20 and 40 years these values were 62, 84, 108 and 112, respectively. In similar research, in stands of 3, 6, 10, 20, 40 and 70 years in the municipality of São Francisco do Pará in the same region, Almeida (2000) found a total 195 species with 18, 15, 32, 53 and 54 species, respectively, when the trees had a DBH larger than 2 cm in the 3-year-old stands and larger than 5 cm in the others. The differences in species richness according to Almeida (2000) could be attributed to intensive previous use of the land and the number of agricultural cycles. In the 70-year-old stand, the species composition and richness did not correspond to that in the primary forests (Shannon-Wiener Diversity Index gave values of 3.46 and 3.93 respectively). She affirmed that in order to reach the diversity of primary forest, secondary forest stands require seed deposition from neighboring primary forest stands.

3.1.4 Structural characteristics of secondary forest

A common view of secondary forest is that its structure is simple and characterized by a high density of individuals of small diameter (Brown and Lugo, 1990). However, stands in secondary forests can differ in structures according to their origin, i.e., differences are the result of previous land use, soil type, agricultural land preparation and species composition (Baar, 1997; Hondermann, 1995). The structural characteristics of secondary forest stands change with age, while the change rate is controlled by site and weather conditions. While the forest grows, the canopy structure and floristic composition change (Vieira, 1996), stem density decreases and the individual tree diameter, stand height, stand basal area (BA = sum of tree section areas per ha) and stand volume (sum of stem volumes) increases (Brown and Lugo, 1990; Fearnside and Guimarães, 1996). As secondary forests develop and get older, they become similar to primary forests (Budowski, 1961 cited by Brown and Lugo, 1990; DeWalt et al., 2003). Nevertheless, specific structural characteristics and species composition make it possible to distinguish between old secondary forest stands and primary forest (Moran et al., 2000a; Moran et al., 2000b).

Studies focusing on secondary forest as complex strata systems are rare. Most of the studies consider stands as the organization of trees and saplings (small trees higher than 2 meters and smaller than 5 cm in diameter) in one single stratum, and forest parameters are based on the information provided by trees bigger than a minimum diameter. In most cases, the sapling component is not considered although it represents an important part of the basal area (Moran et al., 2000a; Moran et al., 2000b) and species richness of the stand. In the Amazon region, there are few studies that show the forest as a multi-strata system and describe growth phases. Moran et al. (2000a, 2000b) observed in 5 sites along the Amazon region that secondary forest was arranged in 3 main groups characterized by floristic composition, age and structure. Height and basal area were the main parameters used to differentiate classes. Watrin (1994) also used the same approach, but the age classes differed in range, while Peña-Claros (2001) studied the forest as an arrangement of trees in 3 main strata, i.e., understory, subcanopy and canopy.

3.1.5 Age estimation

The age of a secondary forest is a useful parameter to estimate the rate of growth and the recovery rate of the stand and to compare growth among stands. When floristic composition, soil and climate conditions are alike, secondary forest stands can be similar using the parameter age, but land-use history and land-preparation practices for different land uses are modifier factors that cause difficulties in the comparison process. Tucker et al. (1998) suggested the use of structural criteria rather than age to compare and aggregate data sets. Finegan (1997) came to the same conclusion and suggested that age does not characterize forest appropriately.

It is not always easy to obtain precise information on stand age of secondary forest from the farmers. Ferreira et al. (2000) stated that 50 % of the farmers that they interviewed in the municipality of Igarapé Açu had lived in the area for more than 20 years and the others for a shorter period, while some were relatively new in the area. A large proportion of the farmers was not able to give precise information on the age of the forest stands, although they had been in the area for long time. This situation was also experienced by Hondermann (1995) when he needed information on the age of secondary forests in the same municipality. Sometimes, external data such as sequential satellite images can provide the required information (Honzák et al., 1996; Lucas, et al., 1996; Metzger, 2003), but these may not always be available due to temporal, spatial, weather and cost limitations.

Some researchers explored age estimation by counting wood rings in wood samples from selected trees. This procedure provides precise values in temperate forests, where the conditions of seasonality produce visible changes in the structure of wood cells. In the case of tropical rain forest, this application is limited as the trees have a relatively constant growth rate over all the year. In tropical areas with a marked seasonality, however, rain patterns can affect the growth of many species, and age estimation by interpretation of wood rings is possible (Mattos et al., 1999; Pumijumnong, 1999; Tomazello and Cardoso, 1999).

3.2 Objectives

In this chapter, species richness, species dynamics and stand characteristics of 35 secondary forest stands in the municipality of Igarapé Açu considering horizontal and vertical structure are described.

3.3 Methodology

3.3.1 Study site

The study area covers approximately 100 km^2 in the municipality of Igarapé Açu, Bragantina region, Brazil, and is located between the coordinates -1° 8' 51.1800" south / -47° 38' 22.7040" west and -1° 13' 34.4280" south / -47° 32' 12.3719" west (Figure 3.1). In this area all development phases of secondary forest in the municipality and those forests most frequent in the Bragantina region are represented.

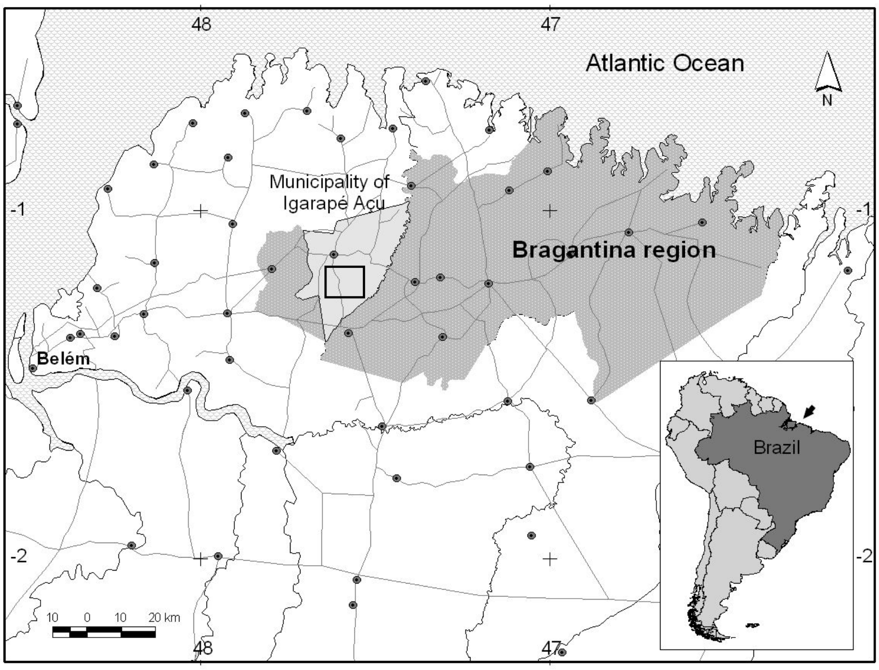


Figure 3.1 Study area (100 km^2) in the municipality of Igarapé Açu, Bragantina region, Brazil

The climate in the region is humid tropical with high relative air humidity varying between 80 and 89 % (Bastos and Pacheco, 1999; Sá, 1986); annual precipitation is between 2300 and 3000 mm (Bastos and Pacheco, 1999; Brasil_SUDAM, 1984, cited by Sá, 1986) with rain falling mainly between December and June. Annual frequency of days with precipitation varies from 180 to 240 days (Brasil SUDAM 1984, cited by Sá, 1986). In the dry season, there can be no rainfall for several days to weeks. In the dryest month, rainfall amounts to 60 mm. Depending on the data source, average maximum temperatures range between 30 and 33.8 °C and minimum temperatures between 20 and 22.6 °C (Bastos and Pacheco, 1999; Denich and Kanashiro, 1998; Sá, 1986).

Uplands and floodplains dominate the landscape of the Bragantina region. The soil is loamy to sandy (Silva and Carvalho, 1986), represented by Oxisols and Ultisols (USDA Soil Taxonomy) (Denich and Kanashiro, 1998). Under the Brazilian soil classification, the Latossolo amarelo soil type prevails in the region (IBGE/CNPS-EMBRAPA, 2001), but the traslocation of clay and organic matter particles to the topsoil by erosion processes causes the evolution of soil to a new type classified as Podzólico amarelo (Denich and Kanashiro, 1998). Soils are poor in organic matter and macronutrients and have a low effective cation exchange capacity (SHIFT-Capoeira, 2003), low pH and high aluminum content (Denich and Kanashiro, 1995; Hölscher, 1997).

The area was colonized around 150 years ago, and since then intensive land use has transformed the landscape into an agricultural land-use type typical for the region. In the municipality of Igarapé Açu the remaining primary forest is concentrated alongside rivers and small creeks and is very fragmented due to fires, wood extraction and agricultural activities. The remaining land is covered by a mosaic of agriculture and cattle grassland mixed with secondary forest in different development stages. In 1991, secondary forest covered 73 % of the area (Watrin, 1994) and has been replaced by agriculture at the rate of 3 % yr^{-1} (Metzger, 2002).

3.3.2 Fieldwork activities

Data were collected during two field surveys: the first at the end of the dry season 2003-2004 (November-January) and the second 6 months later between the next rainy season and dry season 2004-2005 (July). The activities concentrated on measurements of tree dimension, classification of tree species and stratification of the canopy.

Selection of study plots

Due to the fact that secondary forest growth is strongly influenced by previous land management and species composition (Vanclay, 1994; Hondermann, 1995), the sample plots were selected in order to include all possible variations in structure and floristic composition of secondary forest stands under traditional slash-and-burn activities while looking for the maximum potential growth of the forest stands. Thirty five plots were selected from different forest stands avoiding differences due to previous management. The plots fulfilled the following conditions:

- the study plot must be included in a secondary forest stand and should not be a small isolated plot,
- the forest stand should not show evidence of wood extraction or uncontrolled fire since abandonment,
- the forest stand should have maximum tree density indicative of maximum capacity to sustain trees,
- the forest stand should look healthy; stands with *Cecropia sp*. were not included in the study, since this species is indicator of land degradation in a very modified agricultural landscape (Denich, 1986; Rull, 1999),
- the stands cover all ranges of height in the secondary forests in the region,
- the plots are evenly distributed over the study region,
- authorization from the landowners is available.

Potential areas were first located in satellite images of Ikonos sensor from October 22, 2002 and November 27, 2003 and ground truthed. If the areas fulfilled all requirements, they were selected for installation of the plots. In the field, an initial random point was located in the forest stand from where the boundaries of the study plot were determined. Each plot was geo-located with a GPS device.

Study plot design

The variation in height and growth of secondary forest was considered using different plot sizes. Plot size was based on a previous visual estimation or by use of a clinometer to determine the average height of selected trees from the highest stratum of crowns in the canopy. In total, 7 plot sizes were defined; stands with an average height lower than 2 m were not included (Table 3.1). The size and shape of the study plots was defined following the recommendation of Alder and Synnott (1992).

Table 3.1 Size of study plots related to average height of trees in highest canopy stratum

	Plot type						
	1	**2**	**3**	**4**	**5**	**6**	**7**
Height range (m)	2 -<4	4 - <6	6 - <8	8 - <10	10 - <15	15 - <20	>20
Area (m^2)	4	25	100	100	200	400	625

On each plot, two lines with 3 equidistant points were determined from which the information on the stand was collected. The distance between lines and points varied according to the dimension of the plot (Table 3.2).

Table 3.2 Plot dimension and distance between sample lines and sample points

Plot type		**1**	**2**	**3 and 4**	**5**	**6**	**7**
Plot dimension (m)		**2x2**	**5x5**	**10x10**	**10x20**	**20x20**	**25x25**
Equidistance	**Lines**	Not applicable	2	4	4	8	10
	Points	Not applicable	1.5	2.5	5	5	6
Distance from plot corner	**Lines**	Not applicable	1.5	3	3	6	7.5
Distance from plot border	**First point**	Not applicable	1	2.5	5	5	6

In plot size type 1, no lines and points were marked, but instead, all trees in the area were sampled.

Canopy stratification

The canopy of secondary forest can be stratified in several strata. While the forest grows in height, the stand changes from a simple and single stratum to 2 to 3 strata in the canopy. In order to include these variations in the survey, trees in the plots were classified in strata according to the relative location in the canopy compared to the neighboring trees.

Measurement of trees

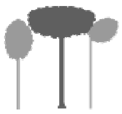
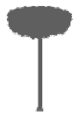
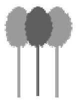
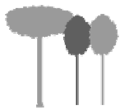
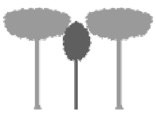
All living and dead trees with a DBH larger than 1 cm were measured with forest calipers or diameter bands (mm graduation) and classified per stratum position and tree condition. In plot types 1 and 2, measurements were taken at ground level. All dead trees were classified as belonging to the lowest stratum.

Trees in secondary forest stands do not show a substantial increase in the trunk buttress, but when there were anomalies in the trunk such as bifurcation or increase in diameter through wood wounds, the DBH was measured above the wood expansion or division, and two or more individuals were accounted for the cases where the trunk was subdivided in several stems.

Closest to each of the six sample points, representative live trees were selected in each canopy stratum. In the case of the highest stratum, the selected trees were those that reached the upper surface of the canopy (top canopy trees). However, this does not mean that the highest trees were always chosen, sometimes small trees located in depressions of the canopy that had reached the top surface of the canopy were also selected. This approach guaranteed the approximation to the average height of the highest canopy stratum using top heights (Loetsch et al., 1973) with a sampling density of more than 96 height measurements per hectare when the average height was near to 20 m. In stands with a multi-strata organization, 12 to 18 trees were chosen among all canopy strata, each tree was identified taxonomically, and the DBH again measured. In the case of plot type 1, all woody plants located in the area were measured (total plant height, trunk height and DBH) and identified.

Dawkins (1958 cited by Alder and Synnott, 1992) proposed classification of crown position and form for high trees in the forest. In the present study, this classification was adapted to the secondary forest as a function of the dominance and crown shape of trees in the highest canopy stratum. The selected trees were classified into 4 categories of crown position and 5 of crown shape (Table 3.3). This classification was not performed for plot type 1, as the trees in this plot type were mostly small and had the same type of crown position and shape.

Table 3.3 Classification of trees of highest canopy stratum of secondary forest according to relative crown position and crown shape

Tree crown position	Type	Description	Tree crown shape	Type	Description
	1	Dominant		1	Well developed and wide
	2	Co-dominant		2	Straight and small
	3	Non-dominant 1		3	Skewed to one side
				4	Skewed and small
	4	Non-dominant 2		5	One main branch, other branches dead

Most of the selected trees per canopy stratum were cut for fresh biomass determination (see Chapter 4, sections 4.4.2, 4.4.3 and 4.5.4), and total tree length and trunk length measured. Total length was used as an estimator of the total height. In some plots, trees were not cut but their height was measured by telescope pole (cm) until 15 m or by electronic clinometer when higher measurements were necessary. Trunk height was the distance between the trunk bottom to the first branch forming the top of the crown (this height is sometimes higher than the distance to the first branch) and total height the distance from the bottom of the trunk to the top of the crown. Average tree and trunk height for each canopy stratum in the plot were estimated using the corresponding measurements of 6 sample trees.

Age estimation

The seasonality of the rain in the study region suggests that some tropical trees could show changes in their wood structure. Using the cut trees from the 30 plots surveyed in the first fieldwork season, a section piece of trunk wood was extracted from the first 50 cm of the stem above the soil surface (Figure 3.2).

These pieces were used to estimate the age of each tree and using the highest average age of the tree samples by canopy strata, the age of the tree stand was calculated. Interpretation of the wood rings also was useful to discover previous disturbances in the forest stands. The pieces of wood were polished and, using a magnifying glass (10+), the wood rings were counted in four directions. Counting in sections with very highly compressed rings was avoided to reduce errors and avoid underestimation of age.

Figure 3.2 Example of trunk section of *Banara guianensis* used to count wood rings and estimate tree age

3.3.3 Analysis process

Based on the information collected from field, canopy structure, variation of tree density along the growth of secondary forest, species composition and distribution in the canopy, stand parameters and tree crown conditions were analysed. Horizontal and vertical distribution and dynamics of trees and species were analyzed based on graphs, regression equations and multivariate analyses. Stand age was estimated by counting wood rings and by regression models and the results related to farmers descriptions.

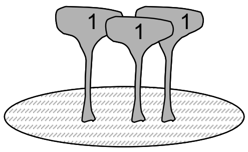
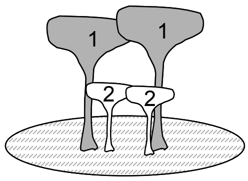
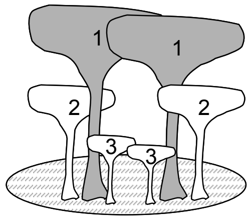
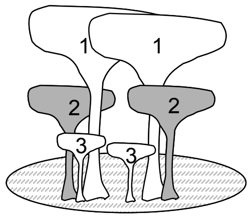
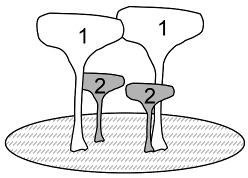
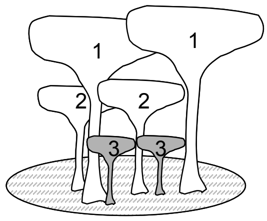
3.4 Results

3.4.1 Canopy strata

Secondary forest varies in structure while it increases in height and age. It changes from a simple stand structure characterized by a high density of individuals with small crowns, to a multi-strata arrangement, where new trees take advantage of space and resources and develop underneath the main crown layer. In the secondary forest stands in the study area, the trees were arranged up to three main strata (Figure 3.3) (Table 3.4). The highest stratum was composed mainly of dominant and codominant trees; stunted trees with crowns located in this stratum were also considered as belonging to this level. This highest stratum was found both in stands with a single simple stratum and in stands with a complex arrangement of several strata. This level can comprise trees with heights from 2 m to more than 23 m. The intermediate level was presented in stands with three main canopy strata. The trees in this layer extended on average from 8.1 m to 11.7 m height and grew under the shade of the highest stratum. The crowns in this stratum were separate from the upper and lower strata. The existence of this stratum expressed the most advanced canopy arrangement. The lowest stratum was present in stands with two or three main canopy strata and trees developed between an average minimum and maximum height of 4.2 m and 8.4 m, respectively.

Figure 3.3 Multi-stratified secondary forest stand arranged in two main strata

Table 3.4. Location of different canopy strata in the canopy of secondary forest stands in the municipality of Igarapé Açu, Bragantina region, Brazil

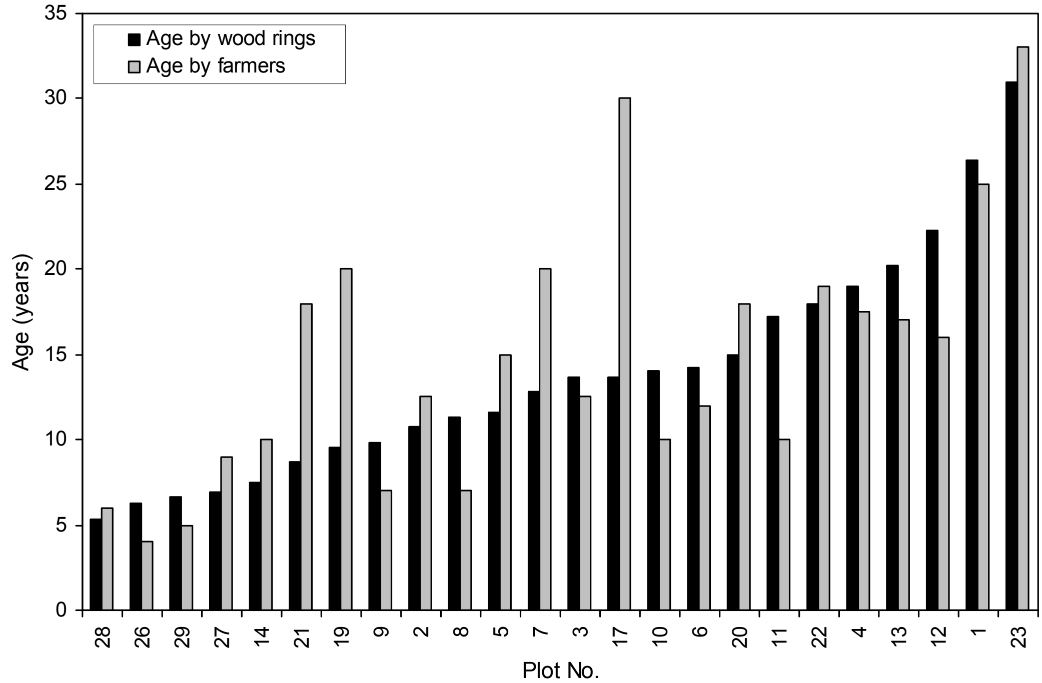
	Canopy structure		
	One canopy stratum	Two canopy strata	Three canopy strata
Highest stratum (1)			
Intermediate stratum (2)			
Lowest stratum (2) (3)			

3.4.2 Age estimation

The estimations of age for some stands are coincident or very close using the methods based on wood ring counting and the parameter age provided by the farmers; while for other stands, the age is over- or underestimated (Figure 3.4.a). The accuracy of the age given by the farmers shows considerable variation. Some farmers were not old enough or had not been living on the farm long enough to provide a precise estimation, they just approximated the age based on their knowledge of occupation time and height of the forest.

On average, farmers' estimations differed by an average of 4 years among the 24 plots compared to the corresponding calculated values using wood rings, with a maximum of 16 years (Plot 17, Figure 3.4.a). When stands were stratified according to height, i.e., lower and higher than 10 m, groups of data showed average differences of 3.8±4.3 (mean±SD) and 2.6±1.8 years, respectively. Age estimation based on both methodologies shows low correlation for the set of data from the 25 stands (Figure 3.4.b).

a)



b)

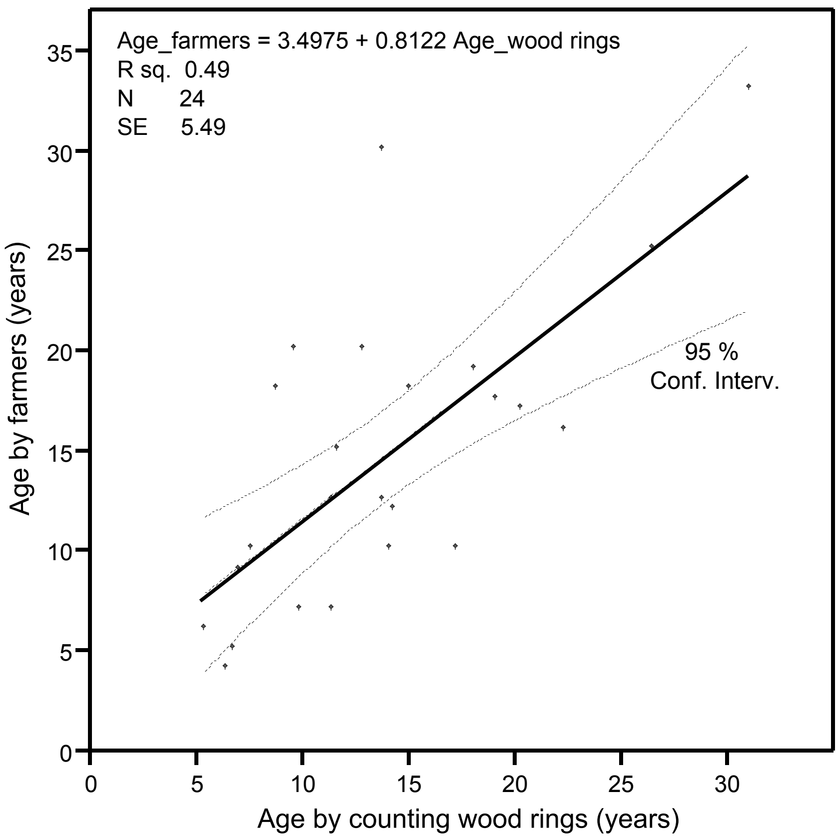


Figure 3.4 a) Stand age estimation by farmers and by counting wood rings; b) Correlation between estimation of age by farmers and age by counting wood rings in secondary forest stands in the municipality of Igarapé Açu, Bragantina region, Brazil

For some forest stands, no trunk-wood samples were taken and thus no direct estimation of the age of the highest stratum by counting wood rings was performed. Here, age was calculated using an allometric equation based on the age and the average total height of the cut trees of the uppermost canopy stratum from other stands (Figure 3.5).

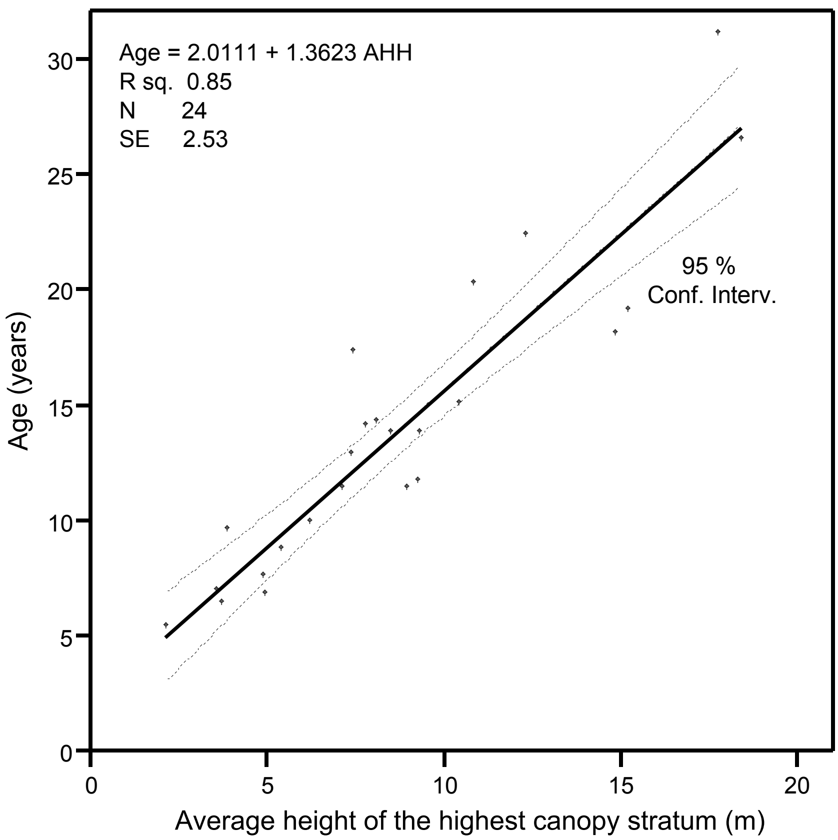


Figure 3.5 Stand age estimation based on average height of highest canopy stratum (AHH) of secondary forest stands in the of municipality of Igarapé Açu, Bragantina region, Brazil

Table 3.5 shows the stand age based on farmers' estimations, wood rings and the equation of Figure 3.5, which is based on the average height of the highest canopy stratum. The age of young stands, which should be well known by the farmers, differs from the estimations through wood ring counting; a possible explanation is that farmers take the beginning of the fallow period just after the last harvest. However, trees begin to resprout earlier, i.e., after the last weeding. These trees will have competitive advantages and will occupy the higher part of the canopy during early stages.

Table 3.5 Estimation of age of secondary forest stands in the municipality of Igarapé Açu, Bragantina region, Brazil, using counting of wood rings, farmers' estimations and regression model based on average height of highest canopy stratum (AHH)

Plot	AHH (m)	Average age based on wood rings (years)			Average age based on farmers estimation (years)
		Highest stratum	Intermediate stratum	Lowest stratum	
25	2.1	5.5			?
28	2.2	5.3			6
27	3.6	6.9			9
26	3.7	6.3			3-4
19	3.9	9.5			20
24	4.2	7.8			?
14	4.9	7.5			10
29	4.9	6.7			5
21	5.4	8.7			18
9	6.2	9.8			7
2	7.1	10.8			10-15
7	7.4	12.8			>20
11	7.4	17.2			10
10	7.8	14.0			10
6	8.1	14.2			12
17	8.5	13.7			30
8	8.9	11.3			7
5	9.2	11.6			15
3	9.3	13.7			10-15
20	10.4	15.0	12.7	7.0	18
30	10.7	*16.6			?
13	10.9	20.2		9.5	17
12	12.3	22.3		16.0	16
31	12.5	*18.9			?
32	13.9	*21.0			?
34	14.4	*21.6			16
22	14.8	18.0	12.8	7.7	18-20
4	15.2	19.0		13.5	15-20
33	15.7	*23.4			>33
16	16.4	*24.4	16.0	12.7	>30
35	16.4	*24.3			30
23	17.7	31.0	16.5	11.0	33
1	18.4	26.4		14.0	>25
18	18.6	27.2	20.7	8.3	30
15	19.1	*28.1	25.0	11.2	30

* Age (years) calculated by equation; Age = 2.0111 + 1.3625 AHH, R^2 = 0.85

In the study area only a few of the sample sites were covered by forest stands as high as 20 m; the age of these stands estimated by counting wood rings was between 20 and 30 years. In the study region, Vieira (1996) recorded 21 and 25 m for the highest trees in 40- and 20-year-old stands, respectively, while Almeida (2000) and Tucker et al. (1998) found that 20-year-old stands reached almost 20 m. On the other hand, Watrin (1994) observed an average height of only 12 m in an 18-year-old stand in Igarapé Açu. These values do not make clear how tree age can explain height as a function. Furthermore, although the stands were of the same height, ages varied by as much as factor 2 among the sites of the same region. However, in the present study, the data of age estimated by counting wood rings and stand height of 24 plots correlated significantly (p=0.0001) with time (Figure 3.6).

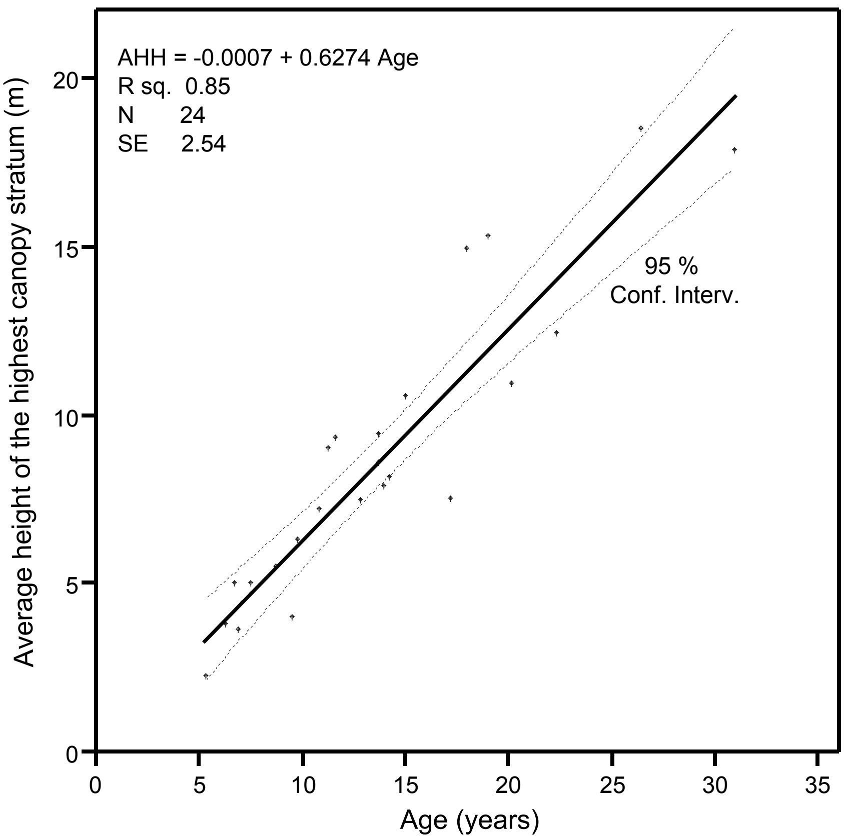


Figure 3.6 Relation of average height of highest canopy stratum (AHH) and age of secondary forest in the municipality of Igarapé Açu, Bragantina region, Brazil

In contrast, differences in ages among trees in the same stand and among plots with similar forest structures were observed. Trees such as *Tapirira guianensis* and *Croton matouriensis*, when dominant in the stands, showed marked age differences compared with neighboring trees, and always had the highest number of wood rings. This could be due to the fact that these trees can produce more than one ring during a year or that these trees had remained in the area during the previous cropping period, providing the seeds for new individuals. Consequently, the estimated age differed considerably from that of the other trees in the stand. On the other hand, under favorable conditions, new successional tree species could rapidly reach the highest stratum, generating a mixture of older and younger individuals. In this case, the real age of the stand could be underestimated.

3.4.3 Stem density

The selection process during 150 years of slash-and-burn activities in the study region only allowed the reproduction of tree and shrub species that are capable of resprouting, tolerate felling, produce viable seeds in a short growth time and survive frequent fires and land preparation. Most of the trees growing in the fallow period have several stems, they resprout from the same stump or root system and thus, several stems in fact represent an individual tree (Figure 3.7).

Figure 3.7 Example of a single tree composed of several stems sharing the same root system in a slashed-and-burned area in the agricultural landscape of the municipality of Igarapé Açu, Bragantina region, Brazil

The unit "trees per hectare" when describing secondary forest stands in the Bragantina region is not always appropriate. More adequate would be use of the unit "stems per hectare" besides other variables such as species composition, structure and biomass.

The number of stems in the highest stratum in the canopy varies with the increase in stand height. There is a tendency for stem density to decrease from more than 60,000 small stems ha^{-1} in a low stand to around 3,100 stems ha^{-1} in a medium-height stand (10 m) and to around 700 stems ha^{-1} when the stand reaches 18 m (Table 9.1 in Appendix 1). This reduction can be explained by a negative exponential model with a coefficient of determination (R^2) of 0.9 (Figure 3.8)

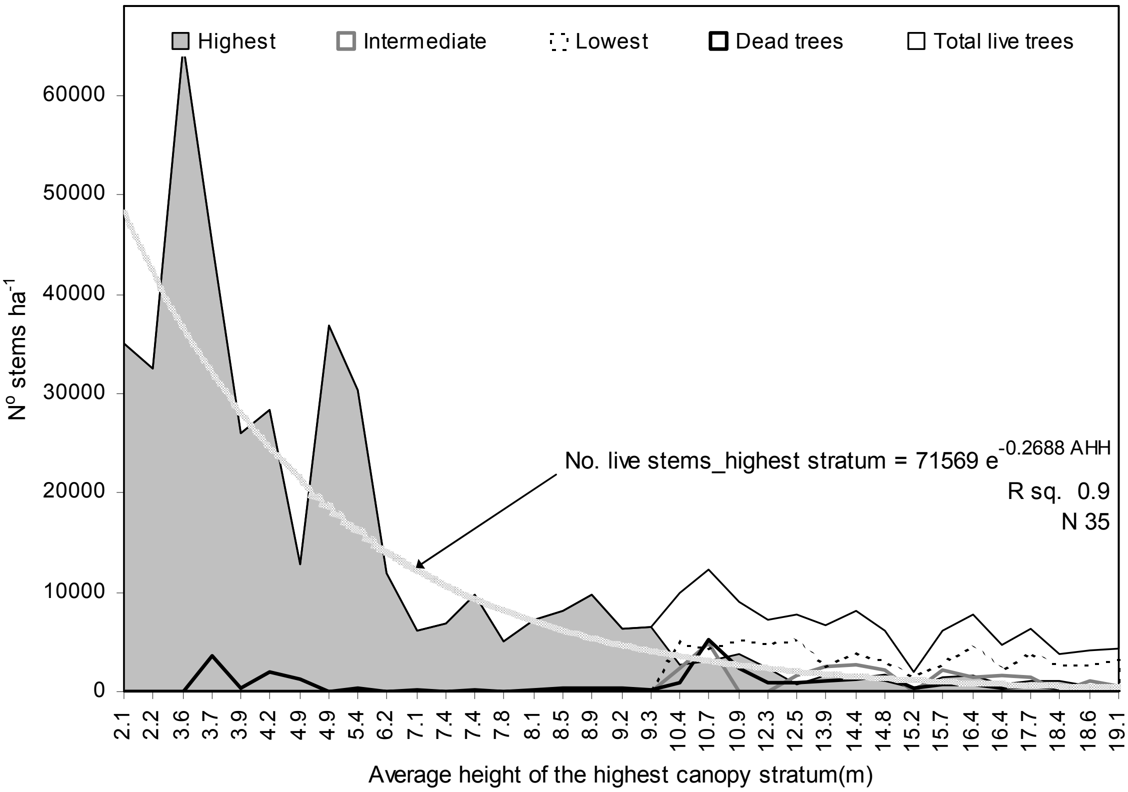


Figure 3.8 Variation of stem density along canopy strata and stand height, and relation between number of stems per ha^{-1} and the average height of the highest canopy stratum (AHH) in secondary forest in the municipality of Igarapé Açu, Bragantina region, Brazil

The intermediate and lowest canopy strata varied in stem density when the stands got older, and they start to be present in a multi-strata structure just after the uppermost canopy stratum had reached 10 m height (Figure 3.8). They were characterized by variations in stem density along growth, showing distinct peaks that sometimes reached more than 4,900 and 5,300 small stems ha^{-1} in the intermediate and in the lowest stratum respectively. During the initial growth phase, where only one stratum was observed, the stands had on average more than 20,000 stems ha^{-1}, reaching peaks of 30,000-65,000 stems ha^{-1} until 5.5 m height.

Dead trees were present in all development stages, with peaks that sometimes correlated with stem density; however, there was not clear relation between tree mortality and stand density. The maximum number of dead trees (5,150 stems ha^{-1}) was observed in stands between 10 and 11 m height, when a multi-strata began to develop. The number of dead trees declined to an average of 862 stems ha^{-1} around 15 m height. In stands of 19 m height, the mortality rate decreased by 86 % compared to the 18 m height and does not overpass the 90 stems ha^{-1}. The data reflect the importance of a high stem density for stand growth and the resulting mortality of trees with low competitiveness, allowing the development of a multi-strata structure in the canopy. In the higher stands, the number of living stems in the uppermost canopy stratum tended to stabilize, and the mortality rate slowly decreased with increasing stand height.

When stem density is expressed as a function of average age, the trend changed somewhat (Figure 3.9), i.e., the multi-strata structure appeared after the stand had reached an age of 15 years. This confirms observations by Moran et al. (2000a, 2000b) and Watrin (1994). In this study, in older stands, stem density in the highest stratum decreased to 786 stems ha^{-1} after 25 years.

Lowest stratum presented the maximum number of trees among the strata in the plots, this high density is important to ensure an adequate tree stand density for future stand growth.

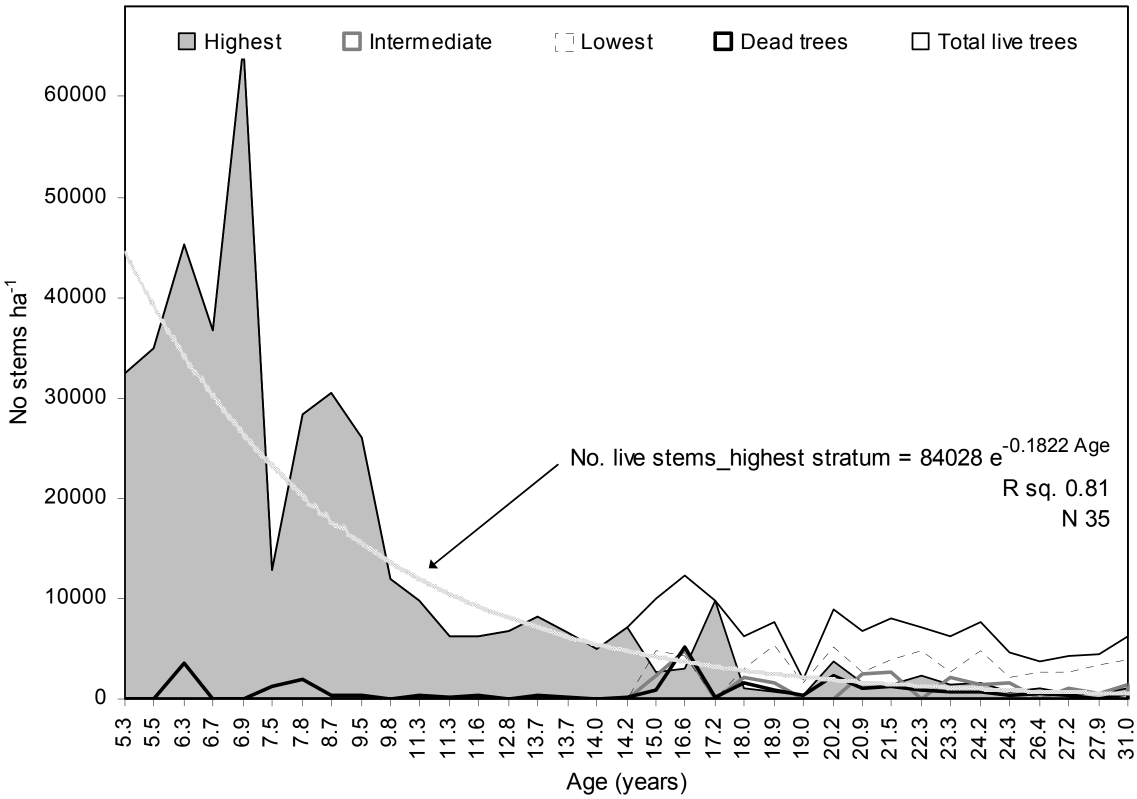


Figure 3.9 Variation of stem density along canopy strata and stand age, and relation between number of stems per ha^{-1} and age of stand in secondary forest in the municipality of Igarapé Açu, Bragantina region, Brazil

3.4.4 Floristic composition

In highly modified landscapes such as the study region, secondary succession is mainly generated by resprouting from remaining stumps and root systems of previous trees. However, during the development of stands in the study area, an interchange of species among the strata in the canopy indicates replacement and dynamic adaptation of species to new conditions. In total, 81 species from 34 families were identified in the different canopy strata in the secondary forest stands (Table 3.6). These values are not representative of the total species richness in the secondary forest in the study area, since the sampling was designed to obtain information on the structural characteristics of the different stands based on the selected trees and not on canopy species richness. In the region, Vieira (1996) found 81 species in a 20-year-old plot with an area of 250 m^2; this value is similar to the total number of species surveyed in this research for a total area of 8137 m^2.

Table 3.6 Species of selected trees in 35 plots of secondary forest in the municipality of Igarapé Açu, Bragantina region, Brazil

Species	**Family**
Abarema cochleata (Wild.) Barnaby & Grimmes	Fabaceae
Abarema jupunba (Willd.) Britton & Killip. Var. jupunba	Fabaceae
Allophylus edulis (A. St.-Hil.) Radlk. var. edulis	Sapindaceae
Ambelania acida Aubl.	Apocynaceae
Annona montana MacFad.	Annonaceae
Annona paludosa Aubl.	Annonaceae
Aspindosperma excelsum Benth. A.	Apocynaceae
Balizia elegans (Ducke) Barneby & J.W. Grimes	Fabaceae
Banara guianensis Aubl.	Flacourtiaceae
Byrsonima aerugo Sagot	Malpighiaceae
Byrsonima amazonica Griseb.	Malpighiaceae
Byrsonima densa (Poiret) A.P. De Candolle	Malpighiaceae
Casearia arborea (Rich.) Urb.	Flacourtiaceae
Casearia decandra Jacg.	Flacourtiaceae
Casearia javitensis H.B.K.	Flacourtiaceae
Chamaecrista apoucouita (Aubl.) H.S. Irwin & Barneby	Fabaceae
Connarus perrotettii (DC.) Planch (var. angustifolius Radlk)	Connaraceae
Cordia exaltata Lam.	Borraginaceae
Croton matourensis Aubl	Euphorbiaceae
Cupania diphylla Valh.	Sapindaceae
Cupania scrobiculata Rich.	Sapindaceae
Cybianthus sp. Mart.	Myrsinaceae
Derris spruceanum Benth.	Fabaceae
Emmotum fagifolium Desv.	Icacinaceae
Eschweilera coriacea (DC.) Mart. ex Berg.	Lecythidaceae
Eschweilera ovata (Cambess.) Miers	Lecythidaceae
Eschweilera sp.	Lecythidaceae
Eugenia biflora (L.) DC.	Myrtaceae
Eugenia coffeifolia DC.	Myrtaceae
Eugenia flavescens DC.	Myrtaceae
Eugenia guianensis Aubl.	Myrtaceae
Guatteria poeppigiana Mart.	Annonaceae
Guatteria schomburgkiana Mart.	Annonaceae
Heisteria densifrons Engl.	Olacaceae
Hirtella racemosa Lamarck	Chrysobalanaceae
Inga fragelliformis (Vell.) Mart.	Fabaceae
Inga heterophylla Willd.	Fabaceae
Inga thibaudiana DC.	Fabaceae
Lacistema pubescens Mart.	Lacistemataceae
Lacunaria crenata (Tulasne) A.C. Smith	Quiinaceae
Lecythis lurida (Miers) S. A. Mori	Lecythidaceae
Licania canescens Benoist	Chrysobalanaceae
Licania kunthiana Hook. f.	Chrysobalanaceae
Maprounea guianensis Aubl.	Euphorbiaceae

Table 3.6 continued

Species	Family
Margaritaria nobilis L.f.	Euphorbiaceae
Maytenus myrsinoides Reisse K. 1861	Celastraceae
Miconia guianensis(Aubl.) Cogn.	Melastomataceae
Miconia minutiflora (Bonpl.) DC.	Melastomataceae
Myrcia cuprea (O. Berg) Kiaersk.	Myrtaceae
Myrcia deflexa (Poir.) DC.	Myrtaceae
Myrcia fallax (Rich.) DC.	Myrtaceae
Myrcia sylvatica (G. Mey.) DC.	Myrtaceae
Myrciaria tenella (DC.) O. Berg	Myrtaceae
Nectandra cuspidata Nees	Laureaceae
Neea floribunda P.& E.	Nyctaginaceae
Neea oppositifolia Ruiz. & Pav.	Nyctaginaceae
Ocotea opifera Mart.	Lauraceae
Ormosia paraensis Ducke	Fabaceae
Ouratea cataneaeformis Engl.	Ochnaceae
Palicourea guianensis Aubl.	Rubiaceae
Platonia insignis Mart.	Clusiaceae
Poecilanthe effusa (Huber.) Ducke	Fabaceae
Pogonophora schomburgkiana Miers ex Benth. .	Euphorbiaceae
Pouteria macrophylla (Lam.) Eyma	Sapotaceae
Rollinia exsucca (Dun.) DC.	Annonaceae
Saccoglottis guianensis Benth.	Humiriaceae
Simaba cedron Planch.	Simaroubaceae
Siparuna amazonica (Martius) A.L. De Candolle	Monimiaceae
Siparuna guianensis Aubl.	Monimiaceae
Swartzia brachyrachis Harms	Swartzieae
Tabernaemontana angulata Mart	Apocynaceae
Tabernaemontana heterophylla (Vahl.) Muell.	Apocynaceae
Talisia carinata Raldlk.	Sapindaceae
Talisia megaphylla Sagot ex LAT Radlkofer	Sapindaceae
Talisia retusa R.S. Cowan	Sapindaceae
Tapirira guianensis Aubl.	Anacardiaceae
Tapura amazonica Poepp. & Endl.	Dichapetalaceae
Terminalia amazonica (Gmell.) Exell	Combretaceae
Thyrsodium paraense Hub.	Anacardiaceae
Virola calophylla Warb.	Myristicaceae
Vismia guianensis (Aubl.) Choisy	Clusiaceae

The similarity among species was studied by means of cluster analysis using as grouping variables the maximum height among trees of the same species, the canopy stratum that contains the maximum height for the species and in which strata the species occurs. Data were standardized to range from 0 to 1. The analysis (Figure 3.10) produced two main groups of species at level 22 of the rescaled distance and six groups at level 12.5.

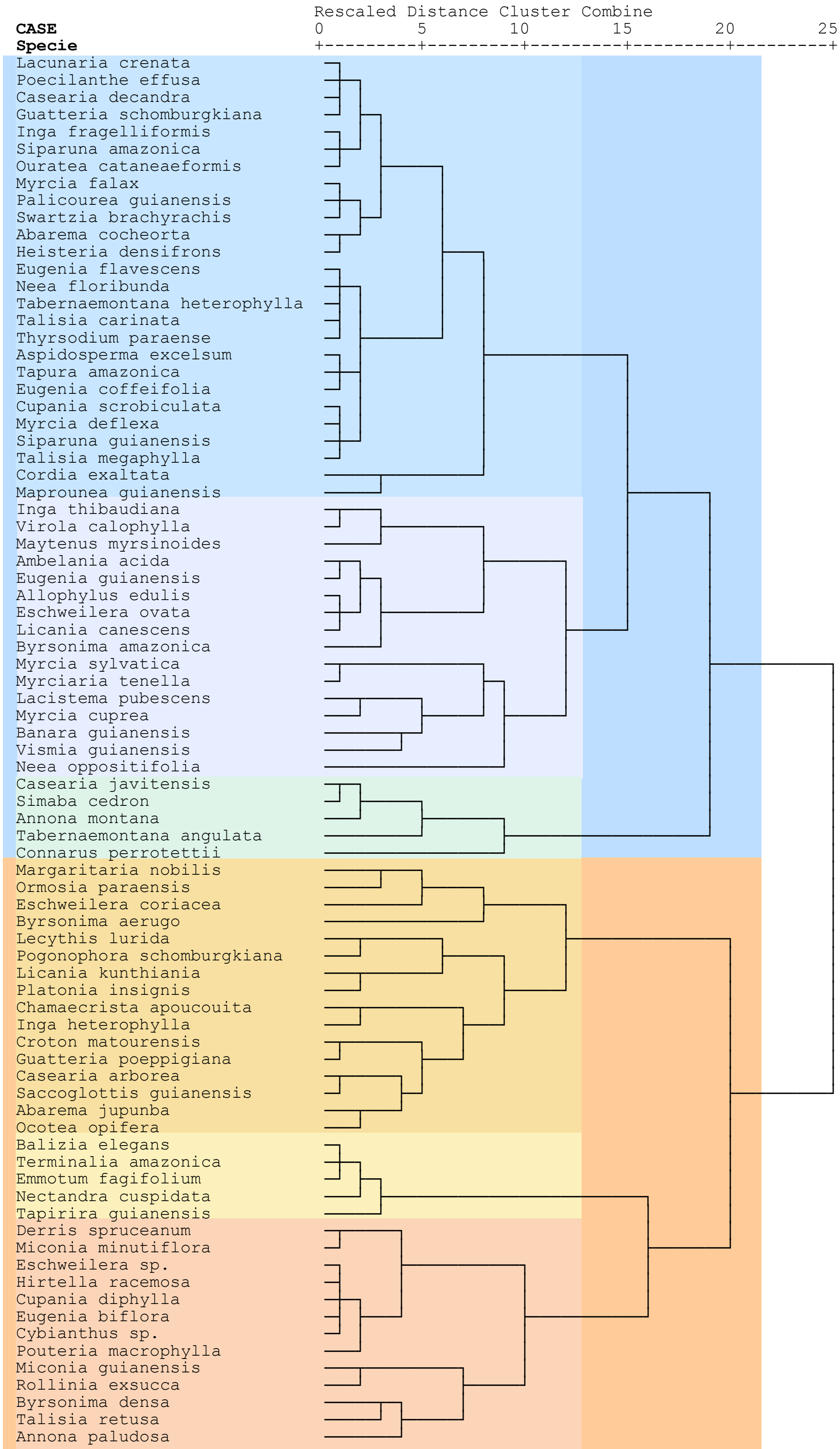


Figure 3.10 Hierarchical cluster analysis of 81 tree species from 35 plots of secondary forest in the municipality of Igarapé Açu, Bragantina region, Brazil, using average groups linkage and Euclidean distance as similarity measurement. The tested variables were maximum species height, canopy strata where the species was present and canopy stratum that contained the maximum height of the species

When species were plotted by their presence and maximum height per canopy stratum, several groups were distinguished, which reflect the arrangement of the species in the canopy (Figure 3.11). These groups are characterized as follows:

- Species always grow in the highest canopy stratum when the stand consists of a single or a multi-strata organization.
- Species are present in stands with three strata in the canopy, but they are only found in the intermediate stratum.
- Species are present in stands with two or three strata in the canopy, but they are only found in the lowest stratum.
- Species are present in the three strata of the canopy, but reach the maximum height either when they form part of the highest stratum.
- Species are present in the three strata of the canopy, but reach the maximum height when they form part of the intermediate stratum.
- Species grow only in the highest and intermediate stratum. The maximum height can be reached by trees growing in any of these strata..
- Species grow only in the highest and lowest stratum. The maximum height can be reached by trees growing in any of these strata.
- Species grow only in the intermediate and lowest stratum. The maximum height is reached by trees growing in the intermediate stratum.

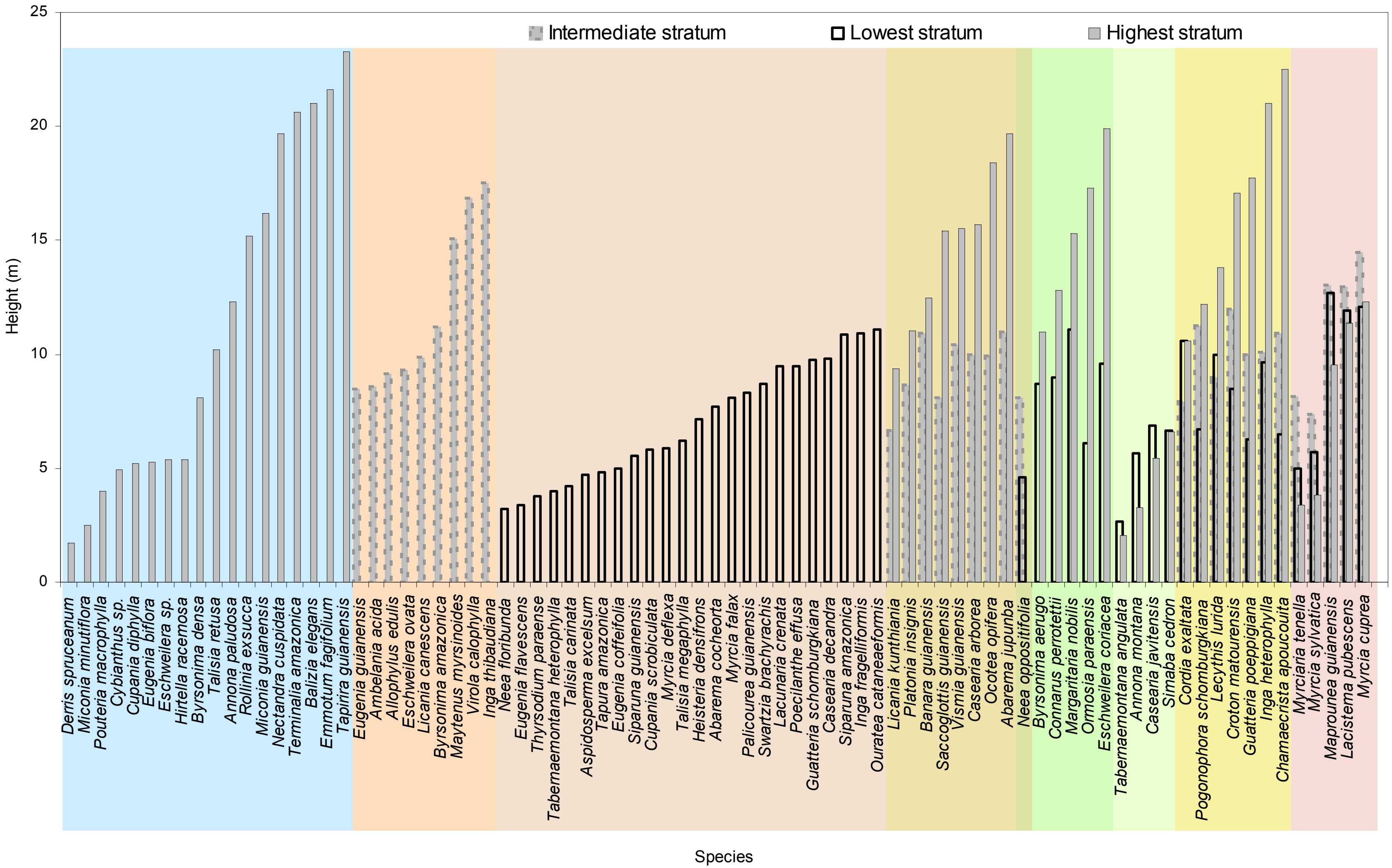


Figure 3.11 Distribution of species by height and arrangement in the canopy strata in 35 plots of secondary forest in the municipality of Igarapé Açu, Bragantina region, Brazil

The upper canopy stratum of high secondary forest stands is constitued of species of late succession, as well as by species from lower levels. Species like *Inga heterophylla*, *Ocotea opifera*, *Casearia arborea* and *Rollinia exsucca*, common in small secondary forest areas, were also present in the highest stratum of some stands, dominating the canopy at a height of 15-20 m. Other species such as *Tapirira guianensis* and *Abarema jupunba* were only present in medium to high secondary forests. Dominant species in the low fallow stands, like *Lacistema pubescens*, survived in higher secondary forest as very thin trees with small crowns in the intermediate level, receiving sunlight through very small gaps between the crowns. This species was also observed with a relative abundance of almost 10 % by Almeida (2000) in a 40-year-old secondary forest of 35 m height.

Species frequently growing higher than 10 m in the lowest stratum were *Siparuna amazonica* and *Inga fragelliformis* and those reaching higher than 15 m in the intermediate stratum were *Virola calophylla* and *Inga thibaudiana*. Only 6 species found in the highest canopy stratum were higher than 20 m, i.e., *Balizia elegans*, *Chamaescrista apoucouita, Emmotum fagifolium, Inga heterophylla, Tapirira guianensis* and *Terminalia amazonica*. Seven species in the lowest stratum (*Chamaescrista apoucouita*, *Croton matourensis*, *Eschweilera coriacea, Guatteria poeppigiana*, *Inga heterophylla, Ocotea opifera and Ormosia paraensis*) had increased in height and become dominant in forest stands higher than 15 m. Four species (*Abarema jupunba, Casearia arborea, Margaritaria nobilis and Saccoglottis guianensis*) specific of the intermediate and highest stratum became dominant in heights when they reach 15 m.

The location of these species in these groups gives an idea of their adaptability to the site conditions and their competitiviness. Unfortunately, some of these species where only found once and it is difficult to compare them with others that had high occurrence (i.e., *Lacistema pubescens*, *Inga heterophylla, Myrcia cuprea*, *Vismia guianensis, Ocotea opifera* and *Rollinia exsucca*). The 10 most frequent species accounted for 54% of identified individuals and 36 species from the total 81 species were only observed and measured once (Table 3.7). To better understand species dynamics and organization, a larger number of individuals per representative species is necessary.

Table 3.7 Frequency and percentage of occurrence of tree species in 35 sample plots of secondary forest in the municipality of Igarapé Açu, Bragantina region, Brazil

Species	Frequency per stratum			Total	%
	Highest	Inter-mediate.	Lowest	Frequency	
Lacistema pubescens	31	12	20	63	15.4
Inga heterophylla	21	3	3	27	6.6
Myrcia cuprea	12	6	6	24	5.9
Vismia guianensis	20	1		21	5.1
Ocotea opifera	16	2		18	4.4
Rollinia exsucca	18			18	4.4
Pogonophora schomburgkiana	6	4	5	15	3.7
Chamaecrista apoucouita	5	5	2	12	2.9
Myrciaria tenella	3	1	7	11	2.7
Tapirira guianensis	11			11	2.7
Croton matourensis	7	2	1	10	2.5
Abarema jupunba	6	3		9	2.2
Casearia arborea	7	2		9	2.2
Casearia javitensis	5		4	9	2.2
Guatteria poeppigiana	4	4	1	9	2.2
Myrcia sylvatica	5	1	1	7	1.7
Banara guianensis	5	1		6	1.5
Lecythis lurida	2	2	2	6	1.5
Ormosia paraensis	3		2	5	1.2
Cordia exaltata	2	1	1	4	1.0
Maprounea guianensis	1	2	1	4	1.0
Neea oppositifolia		1	3	4	1.0
Palicourea guianensis			4	4	1.0
Platonia insignis	3	1		4	1.0
Annona montana	2		1	3	0.7
Annona paludosa	3			3	0.7
Byrsonima aerugo	2		1	3	0.7
Casearia decandra			3	3	0.7
Eschweilera coriacea	1		2	3	0.7
Hirtella racemosa	3			3	0.7
Margaritaria nobilis	2		1	3	0.7
Poecilanthe effusa			3	3	0.7
Byrsonima densa	2			2	0.5
Connarus perrotettii	1		1	2	0.5
Derris spruceanum	2			2	0.5
Heisteria densifrons			2	2	0.5
Inga fragelliformis			2	2	0.5
Licania canescens		2		2	0.5
Licania kunthiania	1	1		2	0.5
Myrcia deflexa			2	2	0.5
Neea floribunda			2	2	0.5
Sacoglottis guianensis	1	1		2	0.5
Simaba cedron	1		1	2	0.5
Tabernaemontana angulata	1		1	2	0.5
Talisia retusa	2			2	0.5

Table 3.7 continued

Species	Frequency per stratum			Total	%
	Highest	Inter-mediate.	Lowest	Frequency	
Abarema cocheorta			1	1	0.2
Allophylus edulis		1		1	0.2
Ambelania acida		1		1	0.2
Aspidosperma excelsum			1	1	0.2
Balizia elegans	1			1	0.2
Byrsonima amazonica		1		1	0.2
Cupania diphylla	1			1	0.2
Cupania scrobiculata			1	1	0.2
Cybianthus sp.	1			1	0.2
Emmotum fagifolium	1			1	0.2
Eschweilera ovata		1		1	0.2
Eschweilera sp.	1			1	0.2
Eugenia biflora	1			1	0.2
Eugenia coffeifolia			1	1	0.2
Eugenia flavescens			1	1	0.2
Eugenia guianensis		1		1	0.2
Guatteria schomburgkiana			1	1	0.2
Inga thibaudiana		1		1	0.2
Lacunaria crenata			1	1	0.2
Maytenus myrsinoides		1		1	0.2
Miconia guianensis	1			1	0.2
Miconia minutiflora	1			1	0.2
Myrcia falax			1	1	0.2
Nectandra cuspidata	1			1	0.2
Ouratea cataneaeformis			1	1	0.2
Pouteria macrophylla	1			1	0.2
Siparuna amazonica			1	1	0.2
Siparuna guianensis			1	1	0.2
Swartzia brachyrachis			1	1	0.2
Tabernaemontana heterophylla			1	1	0.2
Talisia carinata			1	1	0.2
Talisia megaphylla			1	1	0.2
Tapura amazonica			1	1	0.2
Terminalia amazonica	1			1	0.2
Thyrsodium paraense			1	1	0.2
Virola calophylla		1		1	0.2
Total	228	66	102	396	100

The presence of the 10 most frequent species in all strata varies according to the development of the stands. *Lacistema pubescens, Myrciaria tenella* and *Pogonophora schomburgkiana* were present mainly in the low (2-6 m height) and medium (5-15 m height) secondary forest. *Rollinia exucca*, *Myrcia cuprea*, *Vismia guianensis* and *Ocotea opifera* occurred in medium secondary forest while *Tapirira guianensis and Chamaecrista apocouita* were observed in medium to high (> 15 m height) secondary forest. *Inga heterophylla* was found along all the development stages of secondary forest.

Species diversity in the stands was estimated using the Shannon-Wiener Diversity Index (Shannon, 1948) that combines the information of species richness and abundance. The equation of the Shannon-Wiener Diversity Index (SDI) is:

$$SDI = -\sum_{i=1}^{i=s} p_i \ln p_i$$

p_i the number of individuals of species "i" over the total number of individuals in the plot.

s total number of species in the plot.

The SDI values in the present study are lower for young fallow vegetation than those reported by Vieira (1996) and Almeida (2000) for their study sites in the Bragantina region. However, after the stands reached 15 m height, values increased and were higher than some estimations. The maximum SDI determined for the study area equals 4.33 in Plot 18; this is very close to the value obtained by Vieira (1996) in a primary forest stand and higher than the values reported by Almeida (2000). The values are in all cases lower than the range reported by Saldarriaga et al. (1988) for secondary forest stands of the same age in the north-western Amazon basin.

Figures 3.12.a and 3.12.b show the relation between the SDI and age and height of the stand respectively. The predictive quadratic equations explain the data variation with a significant relation (p=0.0001) and R^2 of 0.49 and 0.57, respectively.

a)

b)

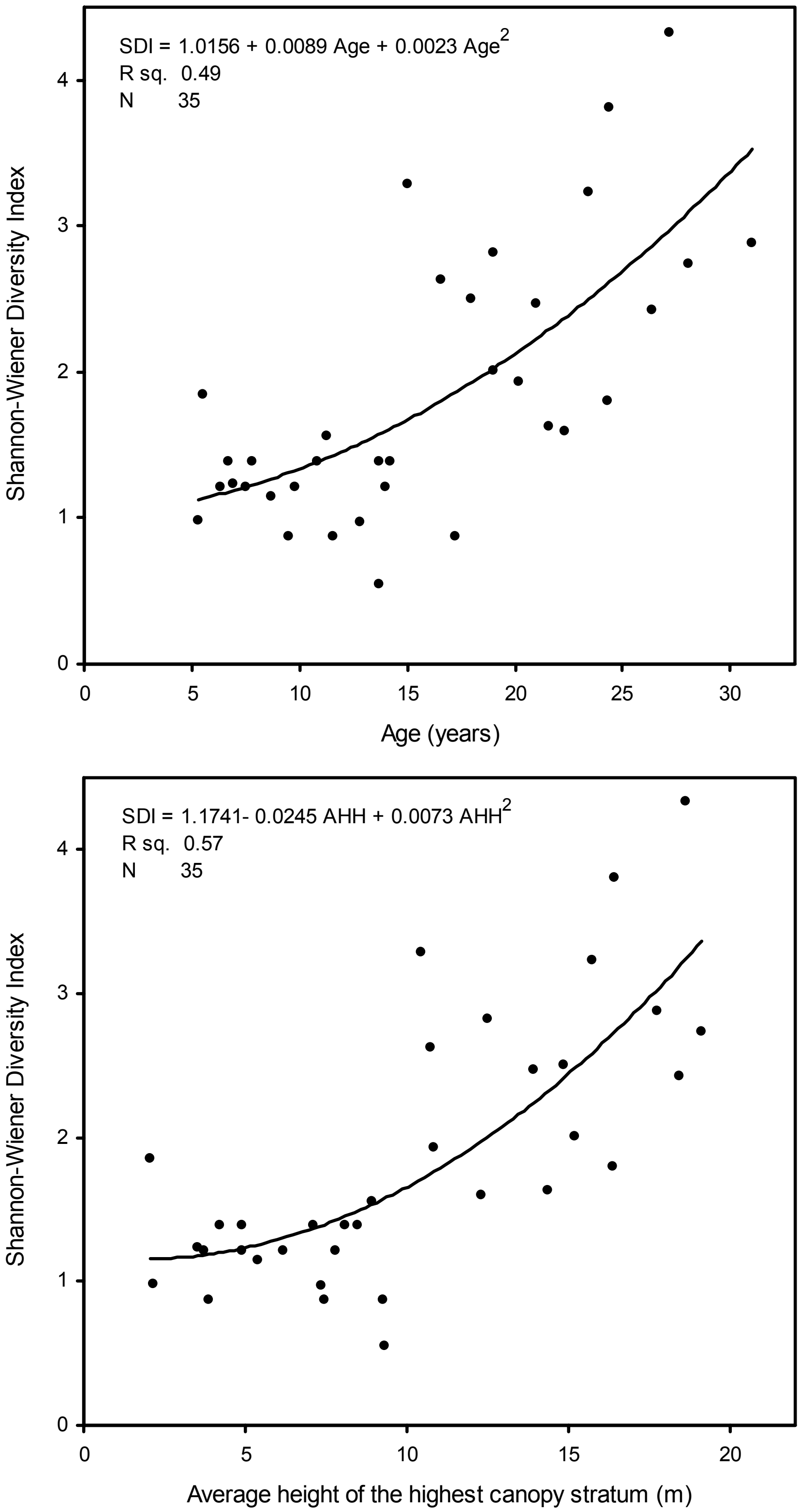


Figure 3.12 Relation between Shannon-Wiener Diversity Index (SDI) and stand age (a) and average height of the highest canopy stratum (AHH) (b) of 35 secondary forest stands in the municipality of Igarapé Açu, Bragantina region, Brazil

The distribution of the SDI values against age and height shows that diversity in young stages is irregular, depending on how well the plants are able to colonize the area by resprouting or seeds. Increased competition leads to a reduction in species richness. Competition also leads to high mortality when the stands are around 14 to 15 years old or have reached 10 m height; here niches are created, i.e., space and resources, that are filled by new species. Later, diversity increases with stand age and reaches values close to those of primary forest (Saldarriaga et al. 1988), as a consequence of the reduction of a number of pioneer trees in the canopy which are replaced by long-lived and shade tolerant pioneer species (Peña-Claros, 2001). Moran et al. (2000a, 2000b) observed that secondary forests of about 15 years old go through changes in floristic composition, which mark the transition from "intermediate" secondary succession classes to "advanced". The increase in diversity is also directly related to the number of strata in the canopy (Figure 3.13).

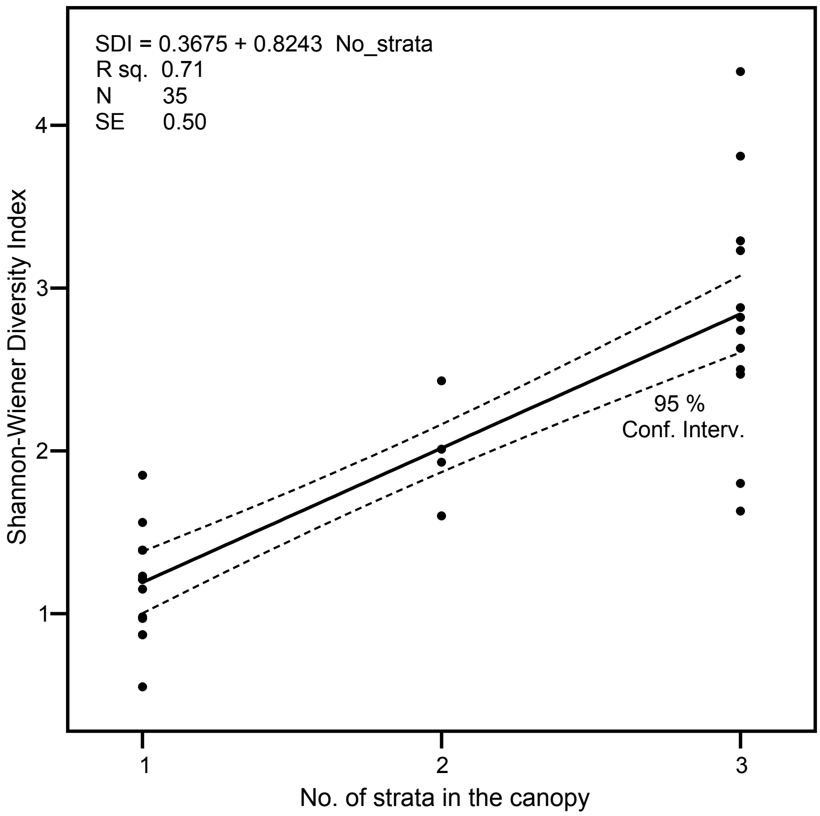


Figure 3.13 Increment of Shannon-Wiener Diversity Index (SDI) according to number of canopy strata in 35 plots of secondary forest in the municipality of Igarapé Açu, Bragantina region, Brazil

To obtain comparable values among stands with multi-strata or single-strata tree organization, the Shannon Evenness Index (Shannon, 1948) was calculated. This index expresses the grade of similarities when the maximum diversity in the samples is considered. The Shannon Evenness Index (SEI) is calculated as:

$$SEI = \frac{SDI}{SDI_{\max}}$$

SDI Shannon-Wiener Diversity Index

SDI_{max} diversity under conditions of maximal equitability

The SEI does not always increase with the number of strata in the canopy. In the study plots, single-stratified stands reached the lowest (0.30) and highest values (1.00) in SEI among all stands (Table 3.8). These extremes are associated to the variation in the number of pioneer species in early stages. This floristic variation depends on the origin and course of the succession in the stands.

3.4.5 Stand structure characteristics

Similarity among forest stands was tested using variables that describe growth, diversity and structure. The cluster analysis classified stands in three groups based on the variables total trunk volume, basal area, number of canopy strata, average height of the highest canopy stratum, Shannon-Wiener Diversity Index (Shannon, 1948) and Shannon Evenness Index (Shannon, 1948); the agglomerative method was average group linkage and the similarity measurement was Euclidean distance (Figure 3.14 and Table 3.8).

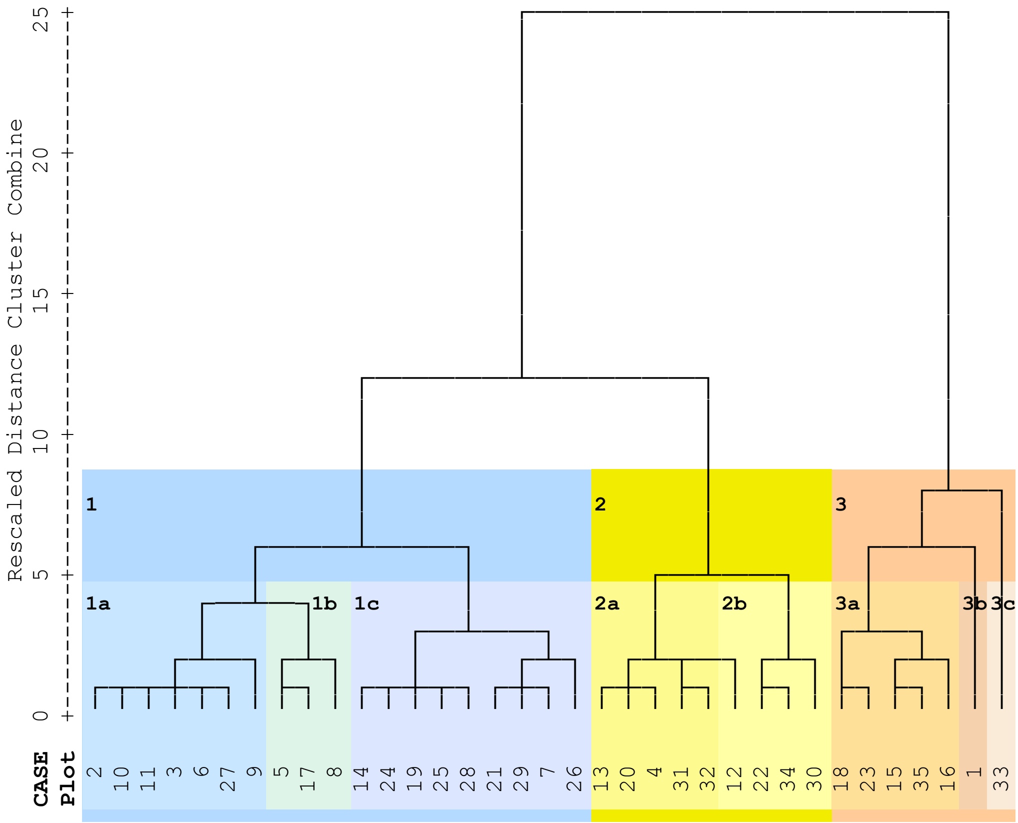


Figure 3.14 Hierarchical cluster analysis of 35 plots of secondary forest in the municipality of Igarapé Açu, Bragantina region, Brazil, using average groups linkage and Euclidean distance as similarity measurement. The selected variables were total trunk volume per ha^{-1}, basal area, number of canopy strata, average height of highest canopy stratum, Shannon-Wiener Diversity Index and Shannon Evenness Index

The cluster analysis produced three main groups of plots at level 9 of the rescaled distance and eight groups at level 5. Clusters differ in the combination of some stand characteristics. Cluster 1 comprises stands lower than 10 m with only one stratum and a trunk volume lower than 71 m^3 ha^{-1}. This cluster can be subdivided in three subgroups according to the trunk volume, first subgroup (1a) has volume higher than 38 m^3 ha^{-1} and lower than 52 m^3 ha^{-1}, subgroup "1b" ranges from 60 m^3 ha^{-1} to 71 m^3 ha^{-1} and subgroup "1c" from 10 m^3 ha^{-1} to 31 m^3 ha^{-1}. Plots in Cluster 2 extend in the average height of the highest stratum from higher than 10 m to lower 15.2 m and the trunk volume from higher than 86 m^3 ha^{-1} and lower than 121 m^3 ha^{-1}. The number of strata in the canopy varies from 2 to 3. Cluster 3 includes high values of volume and height. In this cluster, Plot 1 and 33 can be classified in two new subgroups

Table 3.8 Forest stand characteristics based on the groups identified from cluster analysis of 35 plots of secondary forest in the municipality of Igarapé Açu, Bragantina region, Brazil

Plot	Cluster group	Height highest stratum (m)	Basal area (m^2 ha^{-1})	Total trunk volume (m^3 ha^{-1})	No. strata in canopy	Shannon Diversity Index	Shannon Eveness Index	Stems highest stratum (No ha^{-1})	Stems inter-mediate stratum (No ha^{-1})	Stems lowest stratum (No ha^{-1})	Dead stems (No ha^{-1})
27	1a	3.55	15.69	44.10	1	1.23	0.79	65000	0	0	0
9	1a	6.19	12.22	38.40	1	1.21	0.78	12000	0	0	0
2	1a	7.12	10.89	46.40	1	1.39	0.89	6200	0	0	100
11	1a	7.43	13.88	47.30	1	0.87	0.56	9800	0	0	200
10	1a	7.79	13.54	46.10	1	1.21	0.78	5000	0	0	0
6	1a	8.07	17.12	49.70	1	1.39	0.89	7200	0	0	200
3	1a	9.32	12.91	51.90	1	0.55	0.36	6550	0	0	225
17	1b	8.48	14.64	70.60	1	1.39	0.89	8200	0	0	300
8	1b	8.93	15.67	60.40	1	1.56	1.00	9800	0	0	400
5	1b	9.24	15.65	67.00	1	0.87	0.56	6300	0	0	300
25	1c	2.06	7.65	11.90	1	1.85	1.19	35000	0	0	0
28	1c	2.15	6.00	9.80	1	0.98	0.54	32500	0	0	0
26	1c	3.71	12.42	23.20	1	1.21	0.31	45200	0	0	3600
19	1c	3.88	9.86	14.10	1	0.87	0.56	26000	0	0	400
24	1c	4.22	9.45	16.70	1	1.39	0.30	28400	0	0	2000
14	1c	4.90	5.29	15.60	1	1.21	0.78	12800	0	0	1200
29	1c	4.92	17.82	29.40	1	1.39	0.41	36800	0	0	0
21	1c	5.38	18.13	31.40	1	1.15	0.74	30400	0	0	400
7	1c	7.35	11.09	30.40	1	0.97	0.62	6800	0	0	0
20	2a	10.43	16.54	87.30	3	3.29	0.70	2700	2400	4800	900
13	2a	10.85	19.48	86.20	2	1.93	0.57	3750		5250	2400
31	2a	12.47	16.31	96.20	3	2.82	0.60	752	1632	5312	832
32	2a	13.92	19.47	94.50	3	2.47	0.53	1650	2500	2600	1050
4	2a	15.21	16.75	87.30	2	2.01	0.65	416		1536	288
30	2b	10.74	20.33	109.50	3	2.63	1.69	3100	4900	4350	5150
12	2b	12.32	18.96	101.80	2	1.60	0.51	2300		4850	950
34	2b	14.35	20.19	120.60	3	1.63	0.35	1400	2700	3950	1200
22	2b	14.84	18.55	119.40	3	2.50	0.53	1100	2100	3000	1550
35	3a	16.37	25.97	191.10	3	1.80	0.38	1550	1450	4725	775
16	3a	16.43	25.72	183.90	3	3.81	0.81	752	1664	2192	336
23	3a	17.74	24.88	205.30	3	2.88	0.92	1000	1425	3850	525
18	3a	18.60	26.14	204.50	3	4.33	0.93	512	1056	2672	352
15	3a	19.13	23.80	195.70	3	2.74	0.59	608	464	3328	48
1	3b	18.41	27.63	166.70	2	2.43	0.78	1024		2752	448
33	3c	15.72	31.69	234.20	3	3.23	0.69	1425	2175	2625	750

characterized also by high values of BA and SDI. The height of plots in this cluster are higher than 15.7 m. Plot 33 shows the highest basal area in the study area, exceeding 31 m^2 ha^{-1} and the second highest stand trunk volume even though the height of this plot was the lowest in Cluster 3. This extraordinary growth could be related to good site conditions. All plots in this cluster are formed by three strata with the exception of Plot 1 that had two strata. Height and basal area in Cluster 2 and 3 are higher than those proposed by Moran et al. (2000a, 2000b) for their class "advanced regrowth stage", (height 13 to 17 m; basal area 10-15 m^2 ha^{-1}).

The observed clusters well describe the organization of secondary forest stands from 2 m to almost 20 m height. Until the 10 m height, stands consisted of a single stratum in the canopy, while between 15 m and 20 m, most of the forest stands consisted of 3 main strata. The wide range classes of the secondary forest, i.e., lower (2-10 m), intermediate (10-15 m) and high (>15 m) correspond well with the structure and species composition of the stands.

Table 3.8 shows also that stands with a variable stem density have the same volume: Stands with few stems have a similar volume to very dense stands (i.e., plots 10-11, plots 4-13, plots 14-24, plots 22-34 and plots 23-18). However, with the same number of stems, the variation of basal area and stand height result in substantial differences in total volume (i.e., plots 2-5, 9-14, 16-31, and 22-23). The same average height of the highest canopy stratum is reached by both less dense and dense stands, by stands with lower density but with more strata in the canopy, and by variable stem density in the strata.

The increment in basal area tends to decline in advanced stages of the secondary succession, caused by a transitional period to mature forest (Moran et al., 2000a; Moran et al., 2000b). This situation was observed in the study plots, but the regression model that related the rate of increment in the basal area to age of the secondary forest can only explain 34 % of the data variability (R^2 = 0.34, p=0.0001; Figure 3.15).

Tucker et al. (1998) expressed that basal area is a poor indicator of successional development in stands between 7 and 20 years old. Several combinations of stem densities for well developed trunks and saplings could exhibit similar basal area. They observed that in the Bragantina region the regeneration strategy is based on a large number of saplings until the stand is around 20 years old, and these contribute most to the basal area.

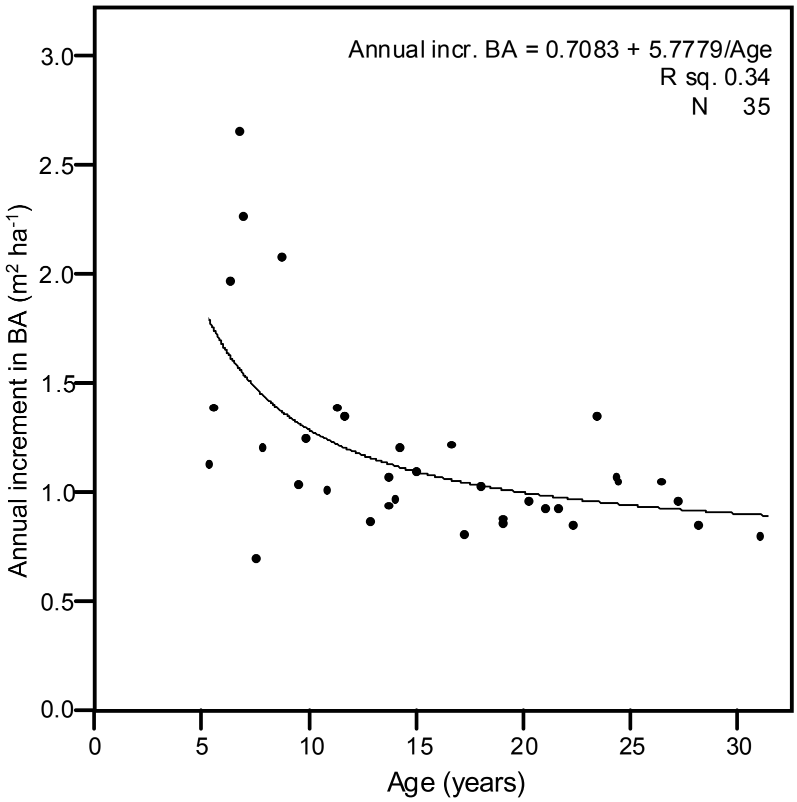


Figure 3.15 Annual increment in basal area (BA) in 35 plots of secondary forest in the municipality of Igarapé Açu, Bragantina region, Brazil

The basal area in well defined multi-strata stands in the study area reached values similar to those in some primary forests in the region (Mackensen et al., 2000; Salomão, 1994; Vieira, 1996). These estimations lie between the values found by Almeida (2000), Salomão (1994) and Vieira (1996), who worked in forest stands in the Bragantina region, and those in other studies in the Amazon region (Alves et al., 1997; Moran et al., 1996; Saldarriaga et al., 1988; Steininger, 2000; Tucker et al., 1998).

In this study, trees with a minimum diameter of 1 cm and higher than 2 m were included in the measurements. In contrast, other studies limited the measurement to trees with a minimum DBH of 5 cm (Almeida, 2000; Salomão, 1994; Vieira, 1996) or higher. Small trees are very important components in secondary forest (Moran et al., 2000a; Moran et al., 2000b; Tucker et al., 1998) and constituted up to 42 % of the basal area in the study plots. When the average height of the highest canopy stratum was around 10 m, saplings still constituted an important fraction of the stand basal area with around 30 %, this value declined to 10 % when stands reached 15 m height (Table 3.9). At this height, the basal area of plot 33 consisted of only 7 % saplings; this stand was located on a site with extraordinary good conditions that allowed significant tree growth, specially of the basal area.

Table 3.9 Percentage of saplings in total basal area in 35 plots of secondary forest in the municipality of Igarapé Açu, Bragantina region, Brazil

Plot	Saplings (No. ha^{-1})	Trees (No. ha^{-1})	Total basal area (m^2)	Saplings (%)	Trees (%)	AHH (m)
24	28400	0	9	100	0	4.22
25	35000	0	8	100	0	2.06
27	65000	0	16	100	0	3.55
28	32500	0	6	100	0	2.15
26	44800	400	12	94	6	3.71
19	25600	400	9	90	10	3.88
29	36000	800	16	90	10	4.92
14	12400	400	5	85	15	4.90
9	10800	1200	9	76	24	6.19
21	28800	1600	14	75	25	5.38
8	7600	2200	8	50	50	8.93
11	8000	1800	7	47	53	7.43
7	5600	1200	5	44	56	7.35
2	4300	1900	4	34	66	7.12
3	4350	2200	4	31	69	9.32
13	6650	2350	6	30	70	10.85
20	7750	2150	5	30	70	10.43
17	5800	2400	4	27	73	8.48
6	4000	3200	5	27	73	8.07
10	3200	1800	4	26	74	7.79
30	9750	2600	5	26	74	10.74
5	3700	2600	4	25	75	9.24
12	4750	2400	4	22	78	12.32
31	6000	1696	3	21	79	12.47
34	6200	1850	4	19	81	14.35
22	4100	2100	3	14	86	14.84
32	4300	2450	2	12	88	13.92
4	1056	896	2	10	90	15.21
15	2928	1472	2	10	90	19.13
16	2656	1952	2	9	91	16.43
35	5300	2425	2	9	91	16.37
23	4275	2000	2	8	92	17.74
33	3525	2700	2	7	93	15.72
18	2848	1392	2	7	93	18.60
1	1616	2160	2	7	93	18.41
Average				42		

During the first years of succession in the secondary forest, stems diameter was not larger than 5 cm, they gradually increasing with stand growth. When the stands exceeded 15 m height, they had on average around 2000 stems ha^{-1} with a DBH larger than 5 cm. The increase in the number of stems with a larger diameter when the stand is around 10 m is closely related to mortality and stratification. The stands reach a critical point when they are around 14 years old or 10 m high, and only because many trees die can the remaining trees continue to grow. While the trees increase in size, the number of saplings declines, but the sapling-tree ratio remains high. The declining percentage of saplings is explained by an exponential equation that adjusts to the data with a R^2 of 0.93 (p=0.0001) (Figure 3.16).

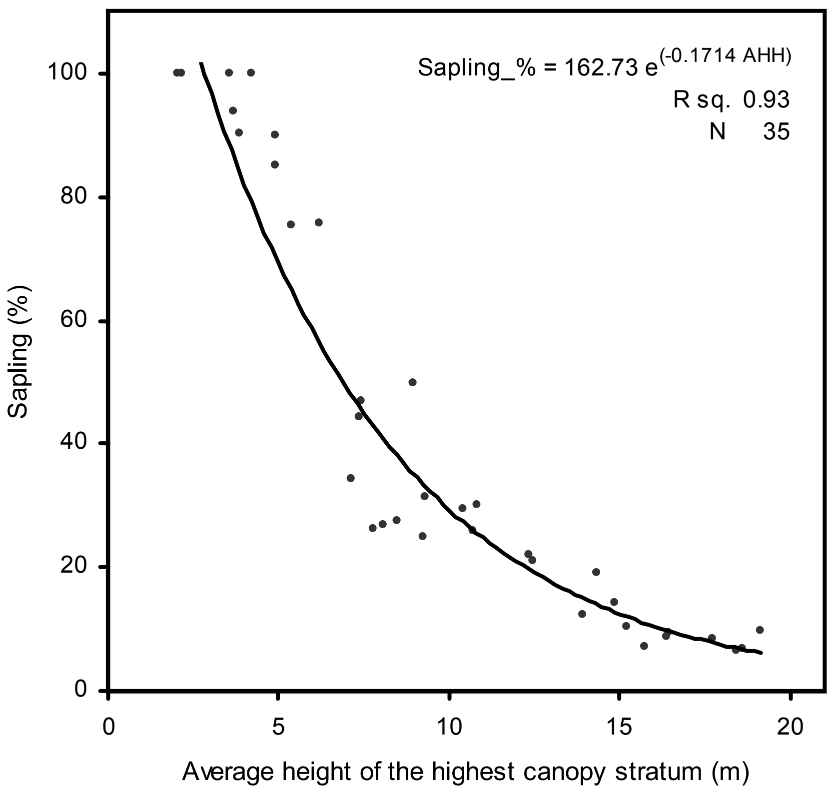


Figure 3.16 Percentage of saplings in relation to average height of highest canopy stratum (AHH) in 35 plots of secondary forest in the municipality of Igarapé Açu, Bragantina region, Brazil

From the above-described analyses it can be seen that during the development of secondary forest, species composition, tree density and structure vary. Stands develop from a single stratum of shrubs and heliophyte tree species into a secondary forest stand with a multi-strata structure, with variable stem densities per stratum and a medium level of species richness. New strata develop under the protection of and in the space underneath the crowns of higher trees and in the niches left by dead trees in the canopy. In the study sites, forest stands of similar average heights were organized as follows:

- One to two strata with few trees, large basal area per stem.
- One to two strata with many trees, small basal area per stem.
- Several strata with many trees, small diameter and small basal area per stem.
- Several strata with few trees in the upper stratum contributing most of the basal area, and many trees in the lower strata.
- In good-condition sites, several strata with many stems, large diameter and basal area per stem.

3.4.6 Crown position and shape

Trees in the highest canopy stratum compete with each other for light, nutrients and space. In the maturity process, some trees acquire a well organized crown shape making maximum use of the resources. In contrast, other trees grow where resources are limited, expressing reduced crown size and sometimes unhealthy appearance. When the information of crown position in relation to neighboring crowns and crown shape is analyzed, it can be seen that the canopy of the highest stratum consists of 50 % of codominant trees, while only 14 % of the trees are dominant and 36 % are dominated by the neighboring trees, even though all of them are able to reach the top and receive direct sunlight (Table 3.10).

Only 13.5 % of the trees that reached the highest stratum in the canopy presented well organized, open and balanced crowns; in most cases, these correspond to the dominant trees. The most frequent crown shapes among trees in the highest stratum were found on straight-upright trees with small crowns (36 %) and skewed trees with two crown shapes (crown skewed, and crown skewed and small) (46 %). Small crowns expressed the competition among the trees in the stand as a result of tree density. The skewed shape of some trees is the response to strategies for capturing more sunlight from small gaps in the canopy or to competition with other tree species. The crowns of

5 % of the trees were almost completely dead; however, at least one branch had live leaves. This amount give an idea of how much the highest canopy stratum will contribute to total tree mortality in the near future.

Table 3.10 Frequency of crown position and crown shape from selected trees in the highest stratum in the canopy of 32 plots of secondary forest (higher than 4 m) in the municipality of Igarapé Açu, Bragantina region, Brazil

Plot	AHH (m)	Crown position				Crown shape					Total Freq.
		1	2	3	4	1	2	3	4	5	
1	18.4	2		2	2	2		1	3		6
2	7.1		3	1	2	1	2	1	2		6
3	9.3		3	2	1		3	2	1		6
4	15.2	1	4	1		1	2	2	1		6
5	9.2	1	4	1		1	3	1	1		6
6	8.1		3	3			1	4	1		6
7	7.3	1	3		2	1		2	2	1	6
8	8.9		5	1			2	3	1		6
9	6.2		5		1		3	1	1	1	6
10	7.8		3	2	1	1	1	3		1	6
11	7.4		4	2		2	4				6
12	12.3	1	2	2	1	1	1	2	2		6
13	10.8	2	3	1			4	1	1		6
14	4.9	1	3		2		3	1	2		6
15	19.1		3	3			4	1	1		6
16	16.4	3	1	1	1	2	2	2			6
17	8.5		3	1	2		3	1	2		6
18	18.6	2	3		1	2	1	1	1	1	6
19	3.9	2	1	3		2	2	1	1		6
20	10.4		4		2		1	2	3		6
21	5.4		2	2	2		3	2	1		6
22	14.8	1	2	2	1	1	3	1		1	6
23	17.7		5		1		4	2			6
24	4.2		3	2	1	1	1		2	2	6
26	3.7	1	2		3		2	1	1	2	6
29	4.9	2	2	1	1	1	2	3			6
30	10.7		4	2		1	3	2			6
31	12.5	3	2	1		2	1	2	1		6
32	13.9	2	4				3	2	1		6
33	15.7	1	4	1		2	1	2	1		6
34	14.3		4	1	1		4	1	1		6
35	16.4	1	2	2	1	2		4			6
Total		27	96	40	29	26	69	54	34	9	192
%		14.1	50.0	20.8	15.1	13.5	35.9	28.1	17.7	4.7	

Tree crown position	
1	Dominant
2	Co-dominant
3	Non-dominant 1
4	Non-dominant 2

Tree crown shape	
1	Well developed and wide
2	Straight and small
3	Skewed to one side
4	Skewed and small
5	One main branch, others dead

3.4.7 Uncontrolled fire

High mortality can be observed in dense stands where debris provided by the uppermost canopy and lower strata accumulate as litter material, which increases toward the end of the dry season. Slash activities allow more air to circulate in the understory of neighboring stands and the material accumulated on the soil surface during the dry period rapidly dries. Uncontrolled fires thus find favorable conditions and burn the litter layer, small trees, bark, and the lower part of the main canopy of neighboring stands or even, in the worse case, the complete stand. In the study area, uncontrolled fires are common during the dry period and were observed in many high secondary forest stands during fieldwork activities (see also section 5.4.2). Past uncontrolled fire events could be recognized by the irregular structure of the canopy, presence of gaps and mixed-age tree composition. When trees in the upper canopy are not damaged too seriously and survive, the forest stand recovers its vitality and develops into a less dense stand with a closed canopy. A number of uncontrolled fires was discovered during the counting of wood rings in some plots, i.e., some samples showed charcoal residuals between rings, which indicated past disturbance events that affected the normal development of the stand. Sample plots 7, 18, 20, 21, and 23 contained trees with signs of previous uncontrolled fires.

3.5 Conclusions

Secondary forest as fallow vegetation in the Bragantina region is an important component in the agricultural cycle of many small farmers, and during the fallow periods after cropping, vegetation covers the area and restores soil properties. While secondary forest grows, it varies both in floristic composition and structure, i.e., from simple dense groups of small trees, the stands develop into tall and stratified forests.

Competition was present during the whole growth period, increasing in importance to an age of 15 years, when many trees died and space became available to new plants. These new trees organized in new canopy strata and under favorable conditions, they grew and reached the upper canopy in the following years. While the stand grew in height, new space was created under the strata, and new site conditions developed resulting in the establishment of new groups of tree species. Around 15 years after the fallow period started or when the forest stands were higher than 10 m, the stands were composed of 2 to 3 clearly distinguished strata, and around 30-year-old stands reached a height of 20 m.

Forest diversity was variable and affected by the growth of the trees in the stand, site conditions and previous land use. In general, diversity increased with height and age of the stand. The diversity of species in high stands approximated those found in primary forests in the region.

This study shows the importance of including all trees in the estimation of basal area and volume, i.e., trees with a DBH larger than 5 or 10 cm as well as the small trees, since more than 8.4 % of the basal area is attributed to saplings in stands higher than 15 m and more than one third in stands between 5 and 15 m.

Secondary forest stands were not characterized by a simple structure, but consisted of a varying combination of tree density, height, basal area distribution and number of canopy strata. The same stand wood volume can be reached by few well developed trees, by many small trees in dense stands or by multi-strata stands. Variation in tree density controlled the size of tree diameters, but did not much affect height.

Disturbances during the growth of the forest stands, such as uncontrolled fire can affect the age structure and the development of the stand.

Estimation of the age of forest stands based on counting wood rings was proven to be consistent and practicable for the tropical tree species in the region. Information provided by the farmers on the age of secondary forest stands should be viewed with caution, since considerable errors can be expected.

4 SECONDARY FOREST BIOMASS

4.1 Introduction

Thirteen percent of the Brazilian Amazon region is deforested (INPE, 2005) and more than 30 % is covered by secondary forest (forest growing in a secondary succession as a consequence of natural or human impacts on forest land) originating after 1970 (Fearnside and Guimarães, 1996). Many of these forest stands are incorporated in the agricultural production system, which is based on slash-and-burn practices. The conservation and management of the secondary forest ensures, among others, continued goods supply, maintains and recovers soil fertility, avoids deforestation pressure on nearby primary forest and forms a carbon sink. Not all secondary forests produce the same amount of woody biomass, which is defined as the quantity of dry vegetal material per unit of area (Brown, 1997). Inter- and intra-regional differences in growth rate can be associated with different impacts through land-use history and their effect on forest recovery (Moran et al., 2000a; Moran et al., 2000b).

During the secondary succession the vegetation system evolves with time from an association of shrubs, herbs and grasses to a well formed forest with a structure and species richness similar to that of primary forest. In the process, the amount of wood material in the stand increases rapidly a with rate sometimes similar to that in primary forest (Brown and Lugo, 1990).

Understanding the increment in wood and organic matter in the stand provides information for management practices and for assessing the contribution of secondary forest to the assimilation and emission of carbon dioxide during growth or deforestation processes, since half of the dry material consists of carbon (Brown, 1997), and its emission through decay and fire or its uptake by regrowth will have a direct effect on the global carbon balance.

Forest biomass can be assessed by different methods, but precise and practical procedures for estimating biomass will ensure the availability of carbon data along secondary forest growth. Allometric equations based on height as the predictive variable can provide representative values. Average stand height is controlled by soil fertility and is the parameter that best indicates differences in stand structure (Moran et al., 2000a; Moran et al., 2000b).

In this chapter, the biomass of secondary forest stands in the municipality of Igarapé Açu, Bragantina region, eastern Amazonia, will be assessed and the accumulation of biomass along the growth in height will be modeled.

4.2 Forest biomass

The forest biomass can be organized in several pools,, i.e., living biomass, dead biomass and soil. The living biomass consists of aboveground and belowground biomass and the dead biomass of dead wood and litter (small fragments of dead material on the ground surface). Living aboveground biomass includes live standing trees and undergrowth components, and the belowground biomass the live roots. Dead wood comprises standing and lying dead trees or any woody debris on the ground larger than 10 cm in diameter (IPCC, 2003; Araújo et al., 1999).

4.2.1 Methods for predicting forest biomass

Forest biomass can be predicted by direct or indirect methods. With direct methods, all trees over a defined area are cut down, and by determining the total dry weight of the material, the biomass per unit area can be calculated. A simple option is to cut down representative trees of each diametric class or select trees by a stratification method, convert all components of the trees to dry weight and then determine the biomass of the remaining trees based on the values of the selected trees. The total live tree aboveground biomass (TTAB) will be the sum of all estimations per category. Indirect methods involve the use of mathematic models generated by previous destructive or non-destructive methods that relate variables such as diameter, basal area (BA - sum of tree sections and expressed as m^2 ha^{-1}), tree height and wood density to the aboveground biomass or dry weight (Araújo et al., 1999). Indirect methods have the advantage of reducing the time for obtaining a good approximation of the real biomass of the forest and avoiding destruction or modification of the stand. These predictive equations can be extrapolated to other regions with similar climatic conditions, stand structures and floristic composition, thus avoiding repetitive work. Numerous methods exist, but the predictions suggest that no method is optimal, as they all depend on the selected function relationship and the type of independent variable (Alves et al., 1997; Chave et al., 2004; Honzák et al., 1996; Overman et al., 1994).

Predictions also vary with the representativity of the data set (trees) used to develop the models (Araujo et al., 1999; Chave et al., 2004; Nelson et al., 1999); sometimes data used to generate the models come from different forest inventories and regions and do not match with the site-specific conditions. Local-specific models for predicting biomass have been shown to be more precise with respect to the specific plant community and site conditions (Chambers et al., 2001; Nelson et al., 1999). Equations for predicting biomass should not be applied in other areas without previous comparative analysis of the site conditions. In most cases, a high variability exists among the forest regions, and the use of an inappropriate model could lead to inaccurate biomass values. There are no equations that cover all types of forests due to the variability in the site quality and representativity of the forest types, i.e., high secondary forests are not always represented in predictive equations.

Honzák et al. (1996) suggested that allometric equations should be generated and applied to stands with similar characteristics and similar species composition rather than using information from large data sets, which themselves show large variations. Chave et al. (2004) recommend the use of models based on at least 100 weighted trees to avoid errors associated with the representativity of the data. They also suggested that models based on regional and pantropical data compilation should be preferred, since this reduces the heterogeneity among sites. On the other hand, Brown et al. (1989) pointed out that prediction of biomass considering growth stages and site quality will improve estimation of the potential carbon sequestration by forests.

The productivity in biomass of forests varies according to spatial distribution of forest stands (Baker et al., 2004; Houghton et al., 2001; Moran et al., 2000a; Moran et al., 2000b), site quality, type and structure of the forest, degree of disturbance by previous land-use practices (Fearnside and Guimarães, 1996; Hondermann, 1995) and climate conditions. Trees with a given diameter are taller and more productive in tropical moist zones than in tropical wet zones due to the favorable water balance and declines when the moisture either increases or decreases (Brown and Lugo, 1982; Brown et al, 1989). Biomass also varies when the size of the sample area changes (Chave et al., 2004; Saldarriaga et al., 1988); an adequately representative plot size should therefore be chosen.

Diameter, height and basal area are variables directly affected by the site quality (Baker, 1950 cited by Brown et al., 1989; Moran et al., 2000a). Prediction of biomass improves when models combine information of diameter (at breast height - DBH) with tree height to reduce the variability of data (Brown et al., 1989; Overman et al., 1994) or with height and wood density (Brown et al., 1989; Chave et al., 2004; Nelson et al., 1999; Saldarriaga et al., 1988; Uhl et al., 1988). Age is another common variable, which, when used alone, can give good correlation (Alves et al., 1997; Fearnside and Guimarães, 1996; Hondermann, 1995).

The type of variables selected to predict biomass can be a source of error. Brown et al. (1989) and Overman et al. (1994) observed that the variance of tree biomass is higher when the diameter of the trunks increases. To solve this problem and to reduce the data variability, they suggested the use of logarithmic transformation in the biomass prediction models. On the other hand, when the variable "age" is used, the land-use history is usually known and biomass can be easily predicted. However, especially in very old secondary forest stands, the precise age of the stands based on the information provided by the local people is not easy to determine (Hondermann, 1995; chapter 3, section 3.4.2). Even when the stand age is well known, predictions on the productivity of the trees can be strongly influenced by type and extent of previous land-use practices (Brown et al., 1989; Moran et al., 1996; Steininger, 2000).

Biomass equations that use height as a predictor of biomass are not frequently used due to time-intensive data collection, especially when there is a closed canopy condition as in tropical rain forest. Another reason is the lack of information on tree height compared to other variables such as trunk diameter or volume in many forest inventories (Brown, 2002).

The average height of a forest stand is a parameter that provides information on the conditions and potentialities of the site to maintain a specific tree species composition. Forest site productivity can be based on a site index, which expresses the productivity using the average height of the dominant and co-dominant trees for a specified age (Vanclay, 1994). Site index productivity is strongly influenced by soil type and local climatic conditions. After the stand reaches a maximum height, the trees continue to increase in diameter and crown size (Brown et al., 1989) and the competition for nutrients and energy continues, concentrating the biomass in some few developed high trees. Taking into consideration the previous remarks, the average height of the dominant and co-dominant trees will represent the conditions and productivity of an even-aged forest stand for a specific site (Alder and Synnott, 1992; Vanclay, 1994). The growth of secondary forest will be conditioned by site quality, which includes factors such as soil type, species composition, previous land-use practices and nutrient availability.

Research carried out in the Amazonian region shows that the best prediction of biomass for secondary forest was obtained when the total height instead of basal area or age was used as a predictive variable (Moran and Randolph, 1998; Santos et al., 2004; Schmitt, 1997; Tippman, 2000). Height is directly related with site productivity and under conditions of low nutrient availability or high modification of soil structure, the same vegetation type will grow slowly and reduce the average height of the stand for the same period compared with areas with only few changes. The average height of secondary vegetation is also a common indicator used by farmers in the Bragantina region, Pará state, Brazil, as a way to estimate the recovery of soil productivity (Smith et al., 2000).

4.2.2 Forest biomass prediction

The use of appropriate models for predicting biomass and a better understanding of the distribution pattern of forest biomass will help to obtain better estimations of its influence within the global carbon cycle (Baker et al, 2004; Chave et al., 2004; Houghton et al., 2001). Considering the extent of the Amazonian forest and the species diversity, differences in biomass values are to be expected. Some research has been performed to obtain regional predictions of forest biomass (Brown et al., 1989; Houghton et al., 2001) and the potential contribution of tropical rain forest to the emission and uptake of atmospheric carbon dioxide (Brown and Lugo, 1982; Fearnside and Guimarães, 1996; Fearnside, 1996). Not all research includes the contribution of each forest stand component such as dead trees, litter and small-diameter trees (saplings) to the total biomass value, and a comparison of different studies is thus difficult. Uncertainties regarding the predicted values of the total aboveground biomass can be observed in many publications (Araújo et al., 1999;

Brown et al., 1995; Keller et al., 2001; Honzák et al., 1996). The main reasons are the incomplete measurements of all trees in a single plot, lack of specification about the inclusion or not of dead biomass, selection of wood density values, and the inclusion of root biomass and biomass of non-tree vegetation in the estimation (Houghton et al., 2001; Brown et al., 1995).

Small trees constitute a small fraction of biomass, but when forest stands have a biomass lower than 50 t ha^{-1}, small trees with a DBH smaller than 10 cm can represent about 75 % of the aboveground biomass. Ignoring these trees would underestimate considerably the stand biomass (Brown, 2002).

The proportion of biomass in the various components of the forest differs. In two primary forests studied by Mackensen et al. (2000) in eastern Amazonia by the destructive weighing approach, they found that trees larger than 10 cm DBH represented 64.5 % - 70 % of the total live tree aboveground biomass. The rest consists of vines/lianas (6.2 %-13.8 %), epiphytes (0.3%), undergrowth (7 %-7.4 %), organic litter (4.5 %) and dead wood (10.3 %-17.7 %).

Primary forest in the Brazilian Amazon averages 463 t ha^{-1} total biomass (aboveground + belowground biomass) and 354 t ha^{-1} aboveground biomass according to an estimation performed over 2954 ha of forest distributed throughout the region (Fearnside, 2000).

4.2.3 Biomass prediction by remote sensing

Remote sensing data can be used as an alternative to obtain predictions of biomass, as it is a very cost-efficient method for covering large areas of forest and facilitates the application of repetitive analysis over the same area. For many remote areas, satellite images are the only choice to obtain forest data or to monitor areas with rapid changes in land use (Lucas et al., 1996). The repetition of images ensures the assessment of changes in biomass and carbon stock by growing forest or land-cover changes.

New technologies such as high resolution satellites, hyper-spectral sensors and laser scanners have created new methods for analyzing remote sensing data and obtaining detailed information of heterogeneous landscapes. High resolution satellites provide images of less than 1 m pixel resolution, which facilitates the discrimination and analysis of individual trees, selective logging and the distinction of small crops in tropical regions. Laser scanners (Lidar) are capable of registering the height of trees and allow prediction of forest biomass (Brown, 2002; Drake et al., 2002a; Drake et al., 2002b; Drake et al., 2003; Houghton et al., 2001; Nelson et al., 1988). The difference between the first and last pulse in the scanned forest area can be interpreted as the total height of the tree and can be used as a predictive variable of biomass. Application of laser scanning sensors is a potential technology for estimating biomass and carbon sstocks in different land covers in tropical ecosystems.

4.2.4 Biomass of secondary forest

The accumulation of biomass can differ in even-age secondary forests within the same region. Almeida (2000) and Salomão (1994), who worked in the Bragantina region and used the same predictive model, estimated biomass with marked differences. The dissimilarity seem to be related to previous land use and the heterogeneity of the tree composition in the stands.

Salomão (1994) observed that the range of variation among plots of the same age differed by the factors 3 to 9 between stands of secondary forest with the lowest biomass and those with the highest biomass. Productivity of secondary forest is strongly affected by previous land-use practices (Brown and Lugo, 1990; Alegre et al, 2001; Hondermann, 1995), i.e. stands growing in areas of previous shifting cultivation show much faster growth than those used for ranching (Fearnside and Guimarães, 1996). Table 4.1 provides some examples of different biomass values obtained by different studies in secondary forest in the Bragantina region.

There are only few biomass estimations for old secondary forest stands in the Bragantina region (Salomão, 1994; Almeida, 2000; Johnson et al.; 2001). In the Amazon region, Lucas et al. (1996) and Steininger (2000) determined between 175 t ha^{-1} and 200 t ha^{-1} total live tree aboveground biomass for 20- and 30-year-old regrowth respectively, near to Manaus. In contrast, Honzák et al. (1996) obtained 257 t ha^{-1} for a secondary forest of the same age and in the same region. In Bolivian Amazon, 170 t ha^{-1} were estimated for a 25-year-old secondary forest (Steininger, 2000). Outside of the Amazonian basin on the Pacific coast of Ecuador, a secondary forest was able to accumulate to 223 t ha^{-1} in the live tree aboveground biomass during the first 30 years after land abandonment (López et al., 2002).

Table 4.1 Estimated aboveground biomass of live trees (TTAB) and litter for secondary forest stands in the Bragantina region, Pará State, Brazil

Authors	Place	Age (yr)	TTAB (t ha^{-1})	Litter (t ha^{-1})	Comments
Denich (1986a)	Igarapé Açu	4	20±9	7.8	
Denich et al. (1998)	Igarapé Açu	4 – 5	16 – 32		
		7	36 – 66		
		10 - 12	68 – 82		
Mackensen et al. (1996)	East of Belém, Pará	7	31.2		
Kato et al. (1999)	Igarapé Açu	4	20	4	
		10	52	7	
Teixeira and Oliveira (1999)	Bragantina region	14	67.02	3.3	1 previous agricultural cycle
			66.22	3.8	
Salomão (1994)	Peixe Boi	5	13.1±3.1		DBH ≥ 5 cm
		10	43.9±4.4		DBH ≥ 5 cm
		20	80.5±8.6		DBH ≥ 5 cm
Almeida (2000)	São Francisco do Pará	3	2.1		DBH ≥ 5 cm
		6	10.2		DBH ≥ 5 cm
		10	5.8		DBH ≥ 5 cm
		20	51.9		DBH ≥ 5 cm
		40	112.1		DBH ≥ 5 cm
		70	141.4		DBH ≥ 5 cm
Johnson et al. (2001)	Peixe Boi and Nova	10	54.9		DBH ≥ 5 cm
	Timboteua, Bragantina	20	65.5		DBH ≥ 5 cm
	region	40	128.8		DBH ≥ 5 cm
Hondermann (1995)	Igarapé Açu and São	1	6.9	2.1	
	Francisco do Pará	4	19.9	7.7	
		7	37.7	8.8	
		10	77.4	12.9	

The allocation of the biomass in the structural parts of secondary forest stands was studied by Kato et al. (1999), Mackensen et al. (1996), Hondermann (1995) and Teixeira and Oliveira (1999) in the Bragantina region. They observed that the biomass in the different structural components (leaves, branches, trunk and litter) varies according to the age of the forest stand (Table 4.2). These values show that in young secondary forest an important part of the biomass is made up by the leaf component, and as the stand develops, woody material such as trunks and branches become more important.

Table 4.2 Biomass allocation by different tree components as a percentage of total aboveground biomass in secondary forest in the Bragantina region, Pará State, Brazil

Authors	Age (yr)	Leaves (%)	Woody material (%)	Litter (%)
Kato et al. (1999)	4	21	63	16
	10	14	74	12
Mackensen et al. (1996)	7	11		
Hondermann (1995)	1	55.2	44.8	
	4	23.1	76.9	
	7	17.4	82.6	
	10	11.7	88.3	
Teixeira and Oliveira (1999)	14	9	91	
	14	16	84	

The biomass of non-trees such as vines/lianas (cipos) also is high in small secondary forest but declines with time (Denich, 1986a; Restom 1996; Gehring et al., 2004; Gehring et al., 2005). After the first crop cycle under slash-and-burn agriculture, the biomass of these plants in 2- to 3-year-old stands represents 5 % of the stand biomass and reduces to 1.9 % in old regrowths in central Amazonia (Gehring et al., 2005). In the same study, regrowth following long-term land use had higher proportions of vines/lianas biomass. However, the values did not exceed 6 %.

The belowground biomass in secondary forest in slash-and-burn systems is proportionally much higher than the aboveground and is similar that of primary forest (Denich et al., 1998). The reasons are that secondary forest sometimes uses the root system of original trees to resprout; this root system continues to expand during the following growth cycles, while the aboveground biomass is merely made up of the accumulation during the last fallow period. The productivity of secondary forest is related to the extent of the root system left after clearing (Wiesenmüller et al., 2002). The ratio of belowground to aboveground biomass decreases with the time since the abandom. Hondermann (1995) observed that the root fraction in relation to the total aboveground biomass, including litter and dead trees, reduces from 57 %, 38 %, 24 % to 19 % in 1-, 4-, 7- and 10-year-old secondary forest respectively. On the other hand, the relation of root biomass to total live tree aboveground biomass in 5- and 80-year-old secondary forests was 0.2 and 0.42, respectively (Fearnside and Guimarães, 1996).

The recovery of biomass in secondary forest to the levels of former primary forests varies according to different researchers. Lucas et al. (1996) estimated 50 years, while 75, 90 and at least 190 years were estimated by Houghton et al. (2000), Salomão (1994) and Saldarriaga et al. (1988), respectively. Koskela et al. (2000) was of the opinion that secondary forests would require more than 100 years or even centuries to reach the biomass and carbon stock level of primary forest.

4.2.5 Litter biomass

Litter consists of dead material such as leaves, twigs and small branches (less than 10 cm diameter), fruits, flowers and bark lying on the soil (IPCC, 2003). During forest regrowth, the litter layer accumulates rapidly. Its amount is related to the magnitude of structural development and destruction that occurs in the stand during the first 20 years, and it constitutes an important fraction of the aboveground biomass (Brown and Lugo, 1990). Litter accumulation is affected by the season; litter fall is maximum in the dry season and more marked in secondary forest than in primary forest (Dantas, 1991).

Litter is an important component of the stand biomass in low secondary forest, sometimes reaching 12 to 13 t ha^{-1} (Diekmann, 1997; Brown and Lugo, 1990; Hedden-Dunkhorst et al., 2003; Hondermann, 1995) and constitutes the higher fraction of net primary productivity for stands less than 20 years old (Brown and Lugo, 1990).

4.2.6 Wood density

Wood density, also termed wood specific gravity, is defined as the oven-dry weight divided by the fresh volume of a wood sample (Brown, 1997; Muller-Landau, 2004). The wood density value per tree species is required for calculation of tree stem biomass. Wood density is based on 0 % moisture or other specified moisture content values and applied as a factor to the wood volume to obtain its dry weight or biomass.

Wood density varies among trees species, among trees of the same species, tree parts, among the forest stands, geographic location and successional stage (Brown and Lugo, 1990; Baker et al., 2004; Fearnside, 1997; Johnson et al., 2001; Woodcock and Shier, 2003). Furthermore, wood density varies inversely with soil fertility and is independent of rainfall seasonality and temperature (Muller-Landau, 2004). Variation in wood density among individuals of the same species may be due to variation in structural matter generated under different circumstances (Fearnside, 1997). A reduction in wood density can also be observed in trees in small to high diameter classes (Chave et al., 2004).

Average wood density values for tropical rain forest are a source of controversy among researchers (Fearnside, 1997; Baker et al., 2004) due to high diversity of tree species in tropical rain forest, low frequency of individuals per species and unknown specific wood density values per species.

The average wood density of the tree species in primary tropical rain forest in Amazonia ranged from 0.60-0.73 g cm^{-3} according to different references (Baker et al., 2004; Brown et al., 1995; Brown, 1997; Brown and Lugo, 1992; Fearnside, 1997; Houghton et al., 2001; Reyes et al., 1992; Salomão, 1994; Uhl et al., 1988). Fearnside (1997) analyzed the different publications and wood density databases available for the Amazonian forest and expressed concern about the bias occurring through the data collection of mainly tree species with medium wood density, which had been selected to satisfy commercial interests. These trees later served as input of databases used by other researchers for calculation of average wood density.

Young vegetation in secondary succession grows fast during the initial period and while it has maximum availability of sunlight. Wood should thus be lighter than in primary forest or in very old successional stands (Denslow, 1980; Rueda and Williamson, 1992 cited by Fearnside, 1997). This assumption contradicts the observation of Chave et al. (2004) who observed a reduction in wood density when diameter increases.

As in primary forest, wood density values for secondary forest species are rare, and those studies that make use of published wood density values sometimes only apply to well developed trees of primary forest, and any estimation using these values could overestimate tree biomass of secondary forest.

Specific wood density values for secondary forest vary by location and species included in the sample. Alves et al. (1997) estimated around 0.53 g cm^{-3} for a stand in Rondônia, Brazil; Nelson et al. (1999) calculated 0.52 g cm^{-3} in a stand near Manaus. In Pará state, eastern Amazon the average wood density is close to and also overpasses 0.7 g cm^{-3} (Baker et al., 2004; Uhl et al., 1988). Withelm (unpublished data) studied 125 woody species in a secondary forest in Igarapé Açu, northeastern Pará and found density values ranging from 0.24 g cm^{-3} to 0.99 g cm^{-3}, with an average of 0.69 g cm^{-3} (standard deviation 0.18).

4.3 Objectives

The analyses in this chapter will test the premise that the biomass of secondary forest stands with a regular canopy should be similar to that of other stands of similar total height, independently of the stand structure. The potential biomass along the growth of secondary forest in the municipality of Igarapé Açu, Pará State will be estimated with the aim to:

- establish a sampling method to stratify and obtain information of the stand based on the height of secondary forest,
- generate a new method to predict biomass based on the height of the highest stratum in the canopy of secondary forest,
- determine parameters to estimate the biomass of trees in secondary forest based on total tree height or trunk height, and
- determine new stand parameters of secondary forest.

4.4 Methodology

4.4.1 Study site

The study was carried out in an area of approximately 100 km^2 in the municipality of Igarapé Açu, Bragantina region, Brazil, localized between the coordinates - 1° 8' 51.1800" south / -47° 38' 22.7040" west and -1° 13' 34.4280" south / -47° 32' 12.3719" west (Figure 4.1). This area covers 12.6 % of the municipality and all development phases of secondary forest in the municipality and those forests most frequent in the Bragantina region are represented.

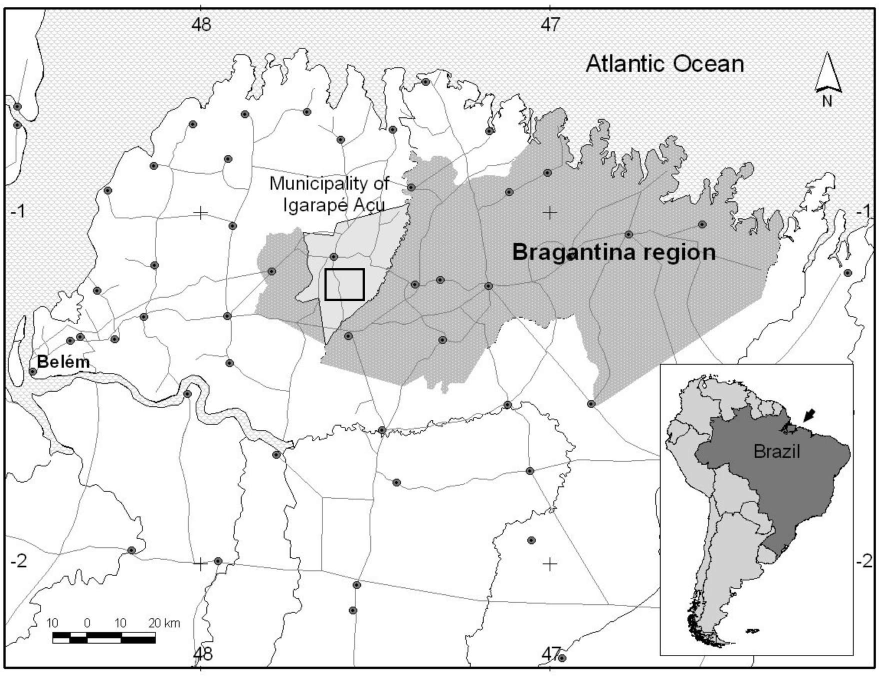


Figure 4.1 Study area (100 km^2) in the municipality of Igarapé Açu, Bragantina region, Brazil

The climate in the region is humid tropical with high relative air humidity varying between 80 and 89 % (Bastos and Pacheco, 1999; Sá, 1986); annual precipitation is between 2300 and 3000 mm (Bastos and Pacheco, 1999; Brasil_SUDAM, 1984, cited by Sá, 1986) with rain falling mainly between December and June. Annual frequency of days with precipitation varies from 180 to 240 days (Brasil SUDAM 1984, cited by Sá, 1986). In the dry season, there can be no rainfall for several days to weeks. In the dryest month, rainfall amounts to 60 mm. Depending on the data source, average maximum temperatures range between 30 and 33.8 °C and minimum temperatures between 20 and 22.6 °C (Bastos and Pacheco, 1999; Denich and Kanashiro, 1998; Sá, 1986).

Uplands and floodplains dominate the landscape of the Bragantina region. The soil is loamy to sandy (Silva and Carvalho, 1986), represented by Oxisols and Ultisols (USDA Soil Taxonomy) (Denich and Kanashiro, 1998). Under the Brazilian soil classification, the Latossolo amarelo soil type prevails in the region (IBGE/CNPS-EMBRAPA, 2001), but the traslocation of clay and organic matter particles to the topsoil by erosion processes causes the evolution of soil to a new type classified as Podzólico amarelo (Denich and Kanashiro, 1998). Soils are poor in organic matter and macronutrients and have a low effective cation exchange capacity (SHIFT-Capoeira, 2003), low pH and high aluminum content (Denich and Kanashiro, 1995; Hölscher, 1997).

The area was colonized around 150 years ago, and since then intensive land use has transformed the landscape into an agricultural land-use type typical for the region. In the municipality of Igarapé Açu the remaining primary forest is concentrated alongside rivers and small creeks and is very fragmented due to fires, wood extraction and agricultural activities. The remaining land is covered by a mosaic of agriculture and cattle grassland mixed with secondary forest in different development stages. In 1991, secondary forest covered 73 % of the area (Watrin, 1994) and has been replaced by agriculture at the rate of 3 % yr^{-1} (Metzger, 2002).

4.4.2 Fieldwork activities

Data were collected during two field surveys: the first at the end of the dry season 2003-2004 (November-January) and the second 6 months later in between the next rainy season and dry season 2004-2005 (July). The same data were collected in both surveys. Activities concentrated on measurements of tree dimension (trunk diameter, trunk height and total height), collection of litter biomass data, identification of tree species, and the fresh and dry weight of representative trees. In the second survey, the latter activity was not performed.

Selection of study plots

As secondary forest growth is strongly influenced by previous land management and species composition (Vanclay, 1994; Hondermann, 1995), the sample plots were selected such that all possible variations in structure and floristic composition of secondary forest stands under traditional slash and burn activities were included while looking for the maximum potential growth of the forest stands. Thirty-five plots were selected from different forest stands avoiding differences due to previous management. The plots fulfilled the following conditions:

- the study plot must be included in a secondary forest stand and should not be a small isolated plot,
- the forest stand should not show evidence of wood extraction or uncontrolled fire since abandonment,
- the forest stand should have maximum tree density indicative of maximum capacity to sustain trees,
- the forest stand should look healthy; stands with *Cecropia sp*. were not included in the study, since they are indicator of land degradation in a very modified agricultural landscape (Denich, 1986a; Rull, 1999),
- the stands cover all ranges of height in the secondary forests in the region,
- the plots are evenly distributed over the study region,
- authorization from the landowners is available.

Potential areas were first located in satellite images of Ikonos sensor from the dates 22/10/2002 and 27/11/2003 and ground truthed. If the areas fulfilled all requirements, they were selected for installation of the plots. In the field, an initial random point was located in the forest stand from where the boundaries of the study plot were determined. Each plot was located with a GPS device.

Study plot design

The variation in height and growth of secondary forest was considered using different plot sizes. Plot size was based on a previous visual estimation or by use of a clinometer to determine the average height of selected trees from the highest stratum of crowns in the canopy. In total, 7 plot sizes were defined; stands with an average height lower than 2 m were not included (Table 4.3). The size and shape of the study plots was defined following the recommendation of Alder and Synnott (1992).

Table 4.3 Size of study plots related to average height of trees in highest canopy stratum

	Plot type						
	1	**2**	**3**	**4**	**5**	**6**	**7**
Height range (m)	2 -<4	4 - <6	6 - <8	8 - <10	10 - <15	15 - <20	>20
Area (m^2)	4	25	100	100	200	400	625

On each plot, two lines with 3 equidistant points were determined from which the information on the stand was collected. The distance between lines and points varied according to the dimension of the plot (Table 4.4).

Table 4.4 Relation between plot dimension and distance between sample lines and sample points

Plot type		**1**	**2**	**3 and 4**	**5**	**6**	**7**
Plot dimension (m)		**2x2**	**5x5**	**10x10**	**10x20**	**20x20**	**25x25**
Equidistance	**Lines**	Not applicable	2	4	4	8	10
	Points	Not applicable	1.5	2.5	5	5	6
Distance from plot corner	**Lines**	Not applicable	1.5	3	3	6	7.5
Distance from plot border	**First point**	Not applicable	1	2.5	5	5	6

In plot size type 1, no lines and points were marked, but instead, all trees in the area were sampled.

Litter sample collection

After demarcation of the plots, litter material was collected in those places where the six points were located. The material on the soil surface was enclosed by a metal frame (1 m^2), collected, sieved to remove sand particles (mesh 1 mm^2) and weighed (IPCC, 2003). In the case of plot type 1, only one sample from 1 m^2 was collected in each plot. In the case of plot type 2, the frame square measured 0.25 m^2. The material was fresh weighed (mechanical precision scales OHaus^{TM}, of maximum tare 2610 g and precision 0.1g) and later a small subsample was collected from each sample, deposited in a paper bag and also fresh weighed. In total, six subsamples were collected from each plot. All material longer than 1 mm and smaller than 10 cm in diameter was included in the samples and subsamples.

A group of subsamples was used to estimate remaining sand or clay particles in the litter samples after sieving. The material was sieved in the field and then after oven-drying (105 °C) in order to calculate the weight in percentage of these particles. This value was then subtracted from the estimated litter value in all samples and subsamples.

Canopy stratification

As explained in Chapter 3, in the canopy of secondary forest, several strata can develop while the stand grows, and the structure of the canopy changes from a simple and dense main stratum to a multi-strata structure when the stand exceeds 10 m height. In order to include these variations in the survey, the trees in the plots were classified in strata according to their relative location in the canopy in comparison with the neighboring trees.

Tree measurement

All living trees and standing dead trees larger than 1 cm DBH were measured with forest calipers or diameter bands (mm graduation). In plot types 1 and 2, tree diameters were measured at ground level. All standing dead trees were classified as belonging to the lowest stratum in the plot.

Trees in secondary forest stands do not show a substantial increase in the trunk buttress, but when there were anomalies in the trunk such as bifurcation or increase in diameter through wood wounds, the DBH was measured above the wood expansion or division, and two or more individuals were counted in the cases where the trunk was subdivided in several stems.

Close to each of the six sample points, representative live trees were selected in each canopy stratum. In the case of the highest stratum, the selected trees were those that reached the upper surface of the canopy (top canopy trees). However, this does not mean that the highest trees were always chosen; sometimes small trees located in depressions of the canopy that had reached the top surface of the canopy were also selected. This approach guarranteed the approximation to the average height of the highest canopy stratum using top heights (Loetsch et al., 1973) with a sampling density of more than 96 height measurements per hectare when high stands were near to 20 m. In stands with a multi-strata organization, 12 to 18 trees were chosen among all canopy strata, each tree was identified taxonomically and the DBH again measured. In the case of plot type 1, all woody plants located in the area were measured (total plant height, trunk height and DBH) and identified.

Most of the selected trees per canopy stratum were cut for fresh biomass determination, and total tree length and trunk length measured. Total length was used as an estimator of the total height. In some plots, trees were not cut and their height was measured by telescope pole (cm) until 15 m or by electronic clinometer when higher measurements were necessary. Trunk height was the distance between the trunk bottom to the first branch forming the top of the crown in the tree (this height is sometimes higher to than the first branch) and total height as the distance from the bottom of the trunk to the top of the crown. Average tree and trunk height for each canopy stratum in the plot were estimated using the corresponding measurements of 6 sample trees.

Fresh weight of tree components and litter

The cut trees were divided into the main tree parts or aboveground components, i.e., leaves, branches and trunk. The material was placed on a canvas and immediately weighed in order to minimize the loss of moisture through evaporation (Zerbini, 1992). The material was weighed using a mechanical precision scales for small samples (OHaus^{TM} maximum tare 2610 g and precision 0.1g) and two balances for heavier samples (mechanical balance, maximum tare 300 kg, precision 100 g, and a nails clock balance, 200 g precision).

Since vines/lianas and herbaceous plants can constitute an important part of the biomass of young secondary vegetation, in plot size type 1 all trees, vines/lianas and non-woody plants were also cut and weighed. The vines/lianas were differentiated in leaves and stems.

A representative subsample was collected from each tree component (trunk, branches and leaves) of each cut tree and fresh weighed. A total of 6 subsamples was collected from each tree section for each canopy stratum in the study plots.

Subsamples (litter, leaves, branches and trunks) were oven-dried at 105 °C until constant weight. The dry subsamples were weighed using the electronic precision scale KERN EW1500–2m (precision 0.01 g and maximum tare 1500 g). During weighing, the weights increased, as the samples rapidly absorbed moisture from the air. In order to minimize errors in the estimation of dry weight, the weights were adjusted by subtracting a quantity equalivalent to the average percentage of weight increase obtained from a group of subsamples for each tree component. During each weighing session, 10 or more subsamples per tree component and litter were separated randomly and weighed immediately after being taken out of the oven and after two hours; this time was long enough for the material to cool down to ambient temperature. The remaining samples were measured also after two hours. In total, 72 subsamples for trunks, 73 for leaves and branches and 115 for litter material were collected to estimate the weight increment. These numbers exceed the minimum required for each tree component and litter, allowing an error of 0.5-0.6 g with a confidence interval of 99 %. Table 4.5 shows the weight increment in percentage of each subsample type, the minimum calculated sample size and total collected samples.

Table 4.5 Percentage of average weight increment in oven dried subsamples after 2 hours outside the oven, minimum subsample size, and total number of weighed subsamples

	Leaves	Litter	Branches	Trunk
Average weight variation (%)	4.24	2.91	1.13	0.70
Minimum sample size	71	92	16	71
Total subsamples weighed	73	115	73	72

4.4.3 Tree aboveground biomass

The estimation of individual tree aboveground biomass requires knowing the biomass of each tree component (leaves, branches and trunk). The calculation of biomass can be estimated in two ways: by summing up the dry weight of each tree component or by multiplying stand parameters with biomass correction/expansion factors. These two approaches were applied for estimation of tree aboveground biomass.

The dry weight of each tree component was calculated using the product of total fresh weight of the tree component per ratio of dry weight over fresh weight determined from the subsamples. The tree aboveground biomass is the sum of the dry weight of each component:

$$DWC_c = \frac{DW_{si}}{FW_{si}} * FWC_c$$

DWC_c total dry weight of the component c
DW_{si} dry weight of the subsample i
FW_{si} fresh weight of the subsample i
FWC_c fresh weight of the component c
c trunk, branches or leaves component

$$TAB = \sum DWC_c$$

DWC_c total dry weight of the component c
TAB tree aboveground biomass
c trunk, branches or leaves component

On the other hand, the estimation of aboveground biomass using the parameters trunk volume and wood density required adjustment by several correction factors. These factors approximate the calculations to the real value of the tree aboveground biomass and facilitate estimations by different approaches (source of data). The correction factors and equations are provided in Table 4.6.

Table 4.6 Correction factors used to calculate tree aboveground biomass

Correction factor	Calculation	Variable	Description
Wood density	$\frac{DWC_t}{WD_p} \leq Vol_t$	• DWC_t: dry weight of trunk • WD_p: published wood density for species i • Vol_t: trunk volume calculated by DBH and trunk height	When the first part of this ratio is bigger, the wood density of the specific tree was higher than the published value, and the wood density for this tree was corrected and approximated to the relation between the dry weight (calculated from field data) over the volume of a cylinder (calculated by DBH and trunk height).
Bark	$BCF = 0.9861$	• BCF: bark correction factor	Bark density is around 80 % of that of wood density (Fearnside, 1997). The average percentage of bark of the total aboveground biomass taken from reference studies is 6.95 % (Jordan and Uhl, 1978; Mackensen et al., 2000). The BCF was applied to the DWC_t to correct the estimation of biomass caused by bark density.
Height	$HCF = \frac{H_t}{H}$	• HCF: height correction factor • H_t: trunk height • H: total height	This factor when is applied to the total height adjusts the height of the tree to the length of the trunk until the first branch that reaches the top of the crown.
Volume	$VCF = \frac{\frac{DWC_t}{WD}}{\pi * H_t * \frac{DBH^2}{4}}$	• VCF: volume correction factor • DWC_t: dry weight of trunk • WD: wood density • π: the number Pi (3.14159) • H_t: trunk height • DBH: diameter at breast height or in some plots diameter at ground level	Also called form factor (López et al., 2002), this is the relation of the real volume of the trunk to the volume of a hypothetic cylinder of a diameter equal to the DBH and height equal to H_t. Real volume is calculated as the relation of DWC_t over WD. This factor adjusts the volume from a cylinder to the real volume of the trunk.

Table 4.6 continued

Correction factor	Calculation	Variable	Description
Weight	$WCF = \frac{DWC_t}{TAB}$	• WCF: weight correction factor • DWC_t: dry weight of trunk • TAB: total dry weight of the tree (aboveground biomass	This factor relates the tree trunk dry weight to the total dry weight of the aerial part of the tree (including branches and leaves). The weight correction factor adjusts the biomass of the trunk to the total aboveground biomass.
Tree biomass reduction factor	$TBRF = HCF*VCF*WCF$	• TBRF: tree biomass reduction factor • HCF: height correction factor • VCF: volume correction factor • WCF: weight correction factor	This factor transforms the biomass of a hypothetic cylinder of diameter equal to the DBH and height equal to the total tree height to the approximated biomass of the tree, which has a specific trunk length with a volume smaller than the cylinder, where total weight includes branches, leaves and trunk.
Tree biomass expansion factor	$TBEF = VCF * WCF$	• TBEF: tree biomass expansion factor • VCF: volume correction factor • WCF: weight correction factor	When only the trunk height is known, the application of this factor to the biomass of a cylinder of equal to the DBH and height to the trunk height gives the total dry weight of the whole tree.
Weight correction factor of dead trees	$WCF_d = \frac{DWC_t}{DWC_{t+b}}$	• WCF_d: weight correction factor of dead trees • DWC_t: dry weight of trunk • DWC_{t+b}:dry weight of trunk and branches	This correction factor adjusts the biomass to the dry weight of the trunk and branches. Values were approximated using data from trees in the lowest canopy layer.

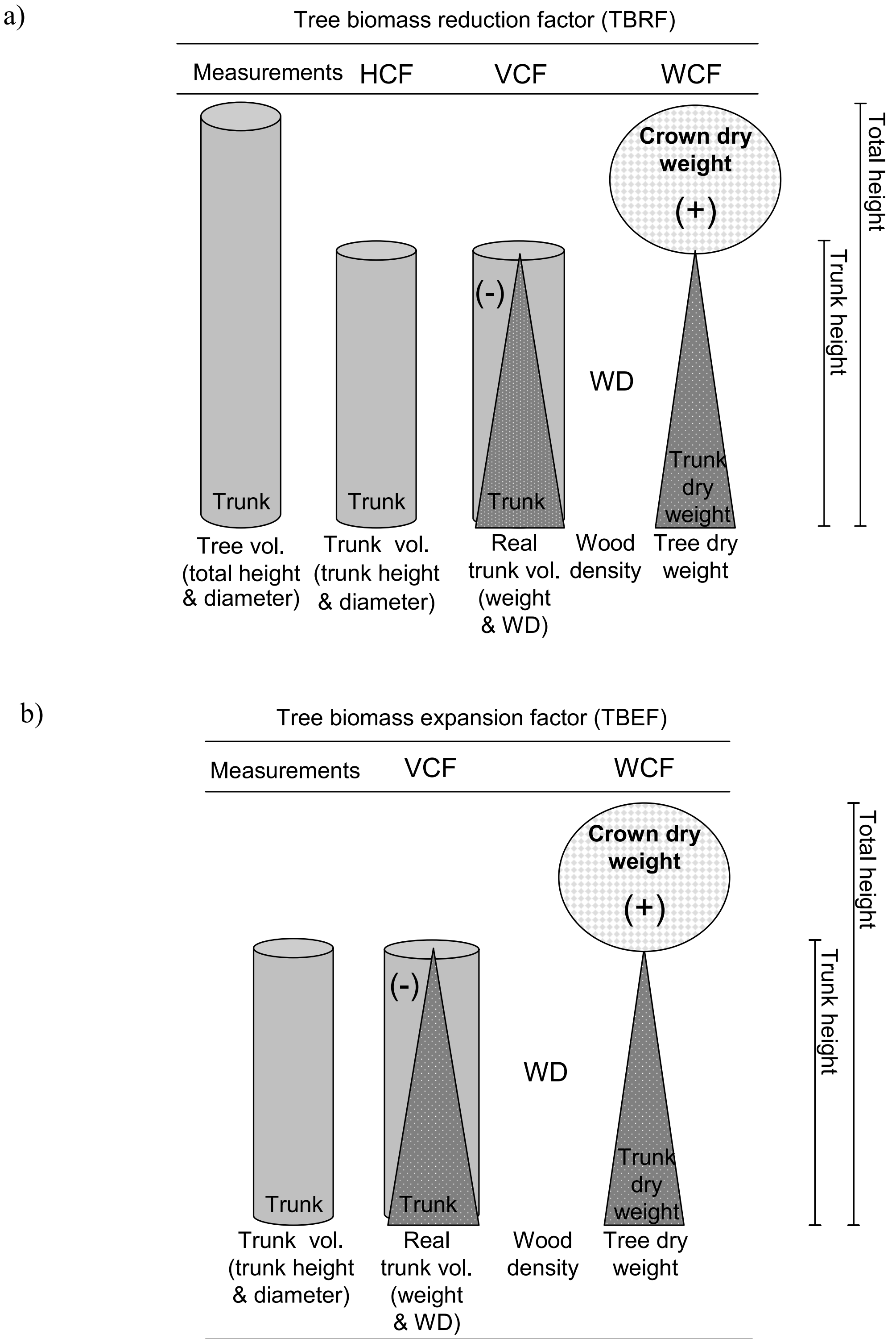
Reference wood density values per species were obtained from research performed in the same or in nearby study areas (Block, 2004; Salomão, 1994; Withelm, 1993), from similar studies in the Amazonian region (Steege and Hammond, 2001; Hoheisel, 1988) and from other studies (Brown, 1997; Chudnoff, 1980; Fearnside, 1997; IPCC, 2003; Reyes et al, 1992; Simpson, 1996). Wood densities with a 12 % moisture content were transformed to 0 % using the equation published by Reyes et al. (1992). Wood density for the respective genus or the approximation between the total trunk dry weight over trunk volume was used when no data from publications or databases for specific tree species were available. Unusual approximated wood density values higher than 1.25 g cm^{-3} were eliminated from the analysis to avoid possible errors in the measurement procedure. Only 4 species showed a higher value: *Pogonophora schomburgkiana* (2 individuals), *Eschweilera coriacea* (1 individual) and *Maprounea guianensis* (1 individual).

Correction factors for volumes and weight of those trees remaining in the stand (plots 15, 16, 18, 23, 30-35) were calculated using the average values calculated for the other trees of the same species and stratum type from the other plots, or the average of values of trees of the same species and different stratum type from the other plots when only one tree of the specific species and strata was uncut, or the averages of the other trees in the same canopy stratum in the plot when different tree species were concerned.

The averages of the height, volume and weight correction factors, as well as of the wood density and biomass reduction factor were calculated per canopy stratum and per plot site. These averages were used to predict the total aboveground biomass in each plot.

Tree biomass reduction and biomass expansion factors can be used to correct biomass according to the approach selected for collecting data in the field. When only the total height is known, the reduction factor should be applied, and when only the trunk height is known, the expansion factor should be applied. Figure 4.2 illustrates the use of these factors.

Athough hollow in trees in primary moist tropical forest can reduce the biomass by 9.2 % (Fearnside, 1997), this anomaly was not present in any of the cut trees in the study stands.



HCF	height correction factor
VCF	volume correction factor
WCF	weight correction factor
WD	wood density

Figure 4.2 Two approaches for estimating tree aboveground biomass, using tree biomass reduction (a) and biomass expansion factors (b)

4.4.4 Total live tree aboveground biomass

The total live tree aboveground biomass of the stands was calculated as the sum of the tree biomass in each canopy stratum. Each tree was associated with a basal area (m^2 ha^{-1}) and canopy stratum. Trees were grouped by canopy strata, and the sum of the basal area of the trees in each stratum was multiplied by the corresponding average height of 6 selected trees, average wood density and average tree biomass reduction factor.

$$TTAB = \sum_{i=1}^{i=n} \left(BA_{Si} * AH_{Si} * AWD_{Si} * ATBRF_{Si} \right)$$

$TTAB$	total live tree aboveground biomass
BA_{Si}	basal area of canopy stratum i
AH_{Si}	average height of 6 trees in canopy stratum i
AWD_{Si}	average wood density of 6 trees in canopy stratum i
$ATBRF_{Si}$	average tree biomass reduction factor of 6 trees in canopy stratum i
n	number of canopy stratum

4.4.5 Biomass of standing dead trees

It is assumed that dead trees in secondary forest are normally small dead trees located in the lowest part of the canopy when the stand is compound of 2 or 3 layers (lowest canopy stratum, see Chapter 3, section 3.4.1), as well as confined dead trees that used to be located in the lowest stratum, and broken-dead stems. The biomass of standing dead trees was calculated according to the following equation:

$$SDTB = BA_d * AH_{SL} * AWD_{SL} * AHCF_{SL} * AVCF_{SL} * AWCF_{dSL}$$

$SDTB$	total standing dead tree biomass
BA_d	total basal area of dead trees
AH_{SL}	average height of trees in lowest canopy stratum
AWD_{SL}	average wood density of trees in lowest canopy stratum

$AHCF_{SL}$	average height correction factor of trees in lowest canopy stratum
$AVCF_{SL}$	average volume correction factor of trees in lowest canopy stratum
$AWCF_{dSL}$	average weight correction factor of dead trees in lowest canopy stratum

4.4.6 Litter biomass

Litter biomass was calculated applying the ratio dry weight/fresh weight from subsample material to the total dead material collected aboveground in the sample, adding up all litter biomass samples and expressing the result in tons per hectare:

$$DWL_i = \frac{DWL_{si}}{FWL_{si}} * FWL_i$$

$$TLB = \sum_{i=1}^{i=n} DWL_i \times \frac{10000}{area}$$

TLB	total litter biomass
DWL_i	dry weight of litter in sample i
DWL_{si}	dry weight of litter in subsample i
FWL_{si}	fresh weight of litter in subsample i
FWL_i	fresh weight of the litter in sample i
$area$	total area of samples in the plot in hectares unit

4.4.7 Total stand aboveground biomass

Total aboveground biomass is the sum of the three main components, TTAB, SDTB and TDWL and expressed in tons per hectare for each stand:

$$TAGB = \sum (TTAB + SDTB + TLB)$$

$TAGB$	total aboveground biomass
$TTAB$	total live tree aboveground biomass
$SDTB$	total standing dead tree biomass
TLB	total litter biomass

4.4.8 Forest growth models

The variation in biomass of secondary forest during height growth was modeled with cohort allometric equations based on the average height of 6 trees in the highest canopy stratum. The sum of the dry weight values of trees in the plot was used as a reference of the total live tree aboveground biomass of the stand. The statistical differences between both approaches were assessed by a T test of the means. Data were also compared with other predictive models proposed by Brown (1997), Nelson et al. (1999), Overman et al. (1994) and Uhl et al. (1988).

4.5 Results

4.5.1 Average wood density

In total, 359 wood density values, corresponding to 81 species of 34 families were analyzed for 35 stands of secondary forest. The average wood density was 0.7 g cm^{-3} with a standard error of 0.015 (Table 4.7). This value is similar to those estimated by Baker et al. (2004), Fearnside (1997), Uhl et al. (1988) and Withelm (unpublished data) in Pará State (0.69 to 0.72 g cm^{-3}), but higher that the average proposed by Brown (1997), Chudnoff (1980) and Reyes et al. (1992) for tropical moist forest. The value is in agreement with the suggestion of Fearnside (1997), who stated that the average wood density for tropical rain forest in Amazonia could be higher than 0.69 g cm^{-3} if better botanical identification is perform. According to Muller-Landau (2004), variation of wood densities is mainly inversely related to soil richness; in the Bragantina region, soils are poor and degraded, which could be a reason for the high value in this study compared with other regions in Amazonia and other tropical rain forest stands.

The calculated average wood density value was higher than the 0.65 g cm^{-3} for low young secondary forest estimated by Block (2004) in the same region. In contrast, in this research, stands of different tree sizes and ages up to more than 30 years old were studied.

The differences between wood density corrected by the wood density factor and the wood density from reference publications could be attributed to the variation of wood density due to specific site conditions and intra-species and intra-wood variations (Fearnside, 1997; Woodcock and Shier, 2003).

Table 4.7 Trunk wood density (WD) values classified by canopy stratum of 82 species of secondary forest in the municipality of Igarapé Açu, Bragantina region, Brazil

Tree species	**WD canopy stratum (g cm^{-3})**					**WD per species**
	Highest			**Inter-mediate**	**Lowest**	
	<10 m	**>10 m**	**Mean**			**(g cm^{-3})**
Abarema cochleata					0.566	0.566
Abarema jupunba		0.629	0.629	0.629		0.629
Allophylus edulis				0.421		0.421
Ambelania acida				0.540		0.540
Annona montana	0.441		0.441		0.518	0.479
Annona paludosa	0.579	0.496	0.552			0.552
Aspidosperma excelsum					0.749	0.749
Balizia elegans		0.701	0.701			0.701
Banara guianensis	0.686	0.600	0.669	0.600		0.635
Byrsonima aerugo	0.593	0.593	0.593		0.593	0.593
Byrsonima amazonica				0.610		0.610
Byrsonima densa	0.618		0.618			0.618
Casearia arborea	0.760	0.760	0.760	0.760		0.760
Casearia decandra					0.780	0.780
Casearia javitensis	0.742		0.742		0.616	0.679
Chamaecrista apoucouita	0.893	0.893	0.893	0.893	0.893	0.893
Connarus perrotettii		0.830	0.830		0.830	0.830
Cordia exaltata		0.580	0.580	0.580	0.580	0.580
Croton matourensis		0.490	0.490	0.469	0.469	0.476
Cupania diphylla	0.791		0.791			0.791
Cupania scrobiculata					0.779	0.779
Cybianthus sp.	0.851		0.851			0.851
Derris spruceanum	0.667		0.667			0.667
Emmotum fagifolium		0.830	0.830			0.830
Eschweilera coriacea		0.724	0.724	0.724	1.247	0.898
Eschweilera ovata				0.623		0.623
Eschweilera sp.	0.710		0.710			0.710
Eugenia biflora	0.820		0.820			0.820
Eugenia coffeifolia					0.787	0.787
Eugenia flavescens					0.829	0.829
Eugenia guianensis				0.749		0.749
Guatteria poeppigiana	0.854	0.562	0.708	0.479	0.479	0.555
Guatteria schomburgkiana				0.496		0.496
Heisteria densifrons					0.679	0.679
Hirtella racemosa	0.791		0.791			0.791
Inga fragelliformis					0.722	0.722
Inga heterophylla	0.800	0.800	0.800	0.800	0.800	0.800
Inga thibaudiana				0.816		0.816
Lacistema pubescens	0.620	0.610	0.620	0.638	0.610	0.623
Lacunaria crenata					0.621	0.621
Lecythis lurida	0.880	0.880	0.880	0.880	0.880	0.880
Licania canescens				0.880		0.880
Licania kunthiana		0.749	0.749	0.749		0.749

Table 4.7 continued

Tree species	WD canopy stratum (g cm^{-3})					WD per species
	Highest			Inter-mediate	Lowest	
	<10 m	>10 m	Mean			(g cm^{-3})
Maprounea guianensis	0.670		0.670	0.670		0.670
Margaritaria nobilis	0.571	0.571	0.571	0.571		0.571
Maytenus myrsinoides				0.760		0.760
Miconia guianensis		0.606	0.606			0.606
Miconia minutiflora	0.740		0.740			0.740
Myrcia cuprea	0.843	0.820	0.840	0.807	0.826	0.824
Myrcia deflexa					0.793	0.793
Myrcia fallax					0.850	0.850
Myrcia sylvatica	0.880		0.880	0.880	0.880	0.880
Myrciaria tenella				0.950	0.950	0.950
Nectandra cuspidata		0.526	0.526			0.526
Neea floribunda					0.560	0.560
Neea oppositifolia				0.466	0.517	0.491
Ocotea opifera	0.572	0.560	0.564	0.560		0.562
Ormosia paraensis		0.670	0.670		0.670	0.670
Ouratea cataneaeformis				0.694		0.694
Palicourea guianensis					0.576	0.576
Platonia insignis		0.679	0.679	0.679		0.679
Poecilanthe effusa					0.940	0.940
Pogonophora schomburgkiana	1.051	0.970	1.019	0.970	0.970	0.986
Pouteria macrophylla	0.680		0.680			0.680
Rollinia exsucca	0.590	0.590	0.590			0.590
Simaba cedron	0.502		0.502		0.820	0.661
Siparuna amazonica					0.677	0.677
Siparuna guianensis					0.733	0.733
Swartzia brachyrachis					0.730	0.730
Tabernaemontana angulata					0.358	0.358
Tabernaemontana heterophylla					0.478	0.478
Talisia carinata					0.862	0.862
Talisia megaphylla					0.840	0.840
Talisia retusa	0.742	0.779	0.760			0.760
Tapirira guianensis	0.612	0.612	0.612			0.612
Tapura amazonica					0.749	0.749
Terminalia amazonica		0.750	0.750			0.750
Thyrsodium paraense					0.623	0.623
Virola calophylla				0.640		0.640
Vismia guianensis	0.754	0.720	0.745	0.720		0.733
Saccoglottis guianensis		0.870	0.870	0.870		0.870
Average trunk WD among species (g cm^{-3})	0.719	0.692	0.705	0.693	0.724	0.700
Standard error (SE)	0.024	0.023	0.019	0.026	0.026	0.015
Number of species	31	31	45	34	42	81

Steininger (2000) observed that wood density varied along tree development. To test this hypothesis, the wood density data of each species was divided into the observable canopy strata; the differences among means between strata with the T test were not statistically significative (p=0.001), neither in high nor in low- to medium-vegetation (vegetation height based on when canopy structure showed stratification, lower or higher than 10 m; see Chapter 3, section 3.4.1).

4.5.2 Litter biomass

The total litter biomass values per plot are almost 3 to 4 times higher than those stated in numerous studies for the Bragantina region. The highest average of total litter biomass was 22.9 t ha^{-1} (plot 20; Table 4.8). This value was close to that observed by Martius et al. (2004) in an 8-year-old plot of secondary forest in central Amazonia (24.7±3.03 t ha^{-1}). In another study, Hondermann (1995) estimated 19 t ha^{-1} after 10 years of fallow in a neighboring municipality in the Bragantina region.

Variation among biomass samples was observed in the plots. This was also experienced by Martius et al. (2004), who related the disparity to changes in micro-sites (Table 4.8). Litter also expresses changes in the dynamics of species in the forest stand (Martius et al., 2004). In this study, no clear relationship between age, height, stand dead trees, tree density, diversity (Shannon-Wiener Diversity Index) and litter biomass was observed. Among all samples of all plots, average litter biomass was 12.4 t ha^{-1} and standard error 0.7. This average was also quite high when compared with other studies (Denich, 1986a; Luizão and Luizão, 1991; Texeira and Oliveira, 1999), but similar to the biomass accumulated in forest stands in 10 years according to Hedden-Dunkhorst et al. (2003). They also showed that litter in stands between 5 and 10 years old could reach a stock of 14 t ha^{-1}. All their values were registered in the middle of the dry season.

The selection of stands based on high tree density, canopy closure and not visible perturbation, among others criteria, can contribute significantly to high biomass values in the litter layer. High tree density implies early closure of the canopy, competition for resources, higher number of dead trees, thus higher accumulation of material in the litter layer. Litter biomass represented up to 49 % of the stand biomass of young secondary forest and dropped to 4 % in the highest forest stand (Table 4.8).

Table 4.8 Average and standard deviation (SD) of total litter biomass (TLB), and percentage of litter biomass of total aboveground biomass (TAGB) in relation to season, average height of the highest canopy stratum (AHH) and age in 35 secondary forest stands in the municipality of Igarapé Açu, Bragantina region, Brazil

Plot	AHH (m)	Age (years)	Average TLB (t ha^{-1})	SD TLB (t ha^{-1})	% of TAGB	Season
1	18.41	26.40	14.1	1.43	7.8	End of dry season (November 2003-January 2004)
2	7.12	11.33	13.7	2.47	18.5	
3	9.32	13.67	22.9	3.16	26.6	
4	15.21	19.00	13.0	5.65	12.4	
5	9.24	11.60	13.1	5.34	16.0	
6	8.07	14.20	12.6	2.02	12.9	
7	7.35	12.83	9.0	1.42	17.7	
8	8.93	11.25	11.8	1.83	14.0	
9	6.19	9.83	12.6	1.57	18.6	
10	7.79	14.00	9.3	2.42	10.4	
11	7.43	17.17	9.8	1.46	10.6	
12	12.32	22.33	9.5	1.29	10.2	
13	10.85	20.17	10.7	3.88	10.8	
14	4.90	7.50	11.7	2.75	36.2	
15	19.13	27.87	9.5	1.92	4.2	
16	16.43	27.16	7.8	1.36	4.1	
17	8.48	13.67	10.9	2.05	17.4	
18	18.60	24.00	13.2	4.25	7.8	
19	3.88	9.50	10.3	3.48	39.8	
20	10.43	15.00	22.7	3.29	21.8	
21	5.38	8.67	2.6	0.44	5.2	
22	14.84	18.00	17.0	3.01	13.9	
23	17.74	31.00	20.3	4.92	10.9	
24	4.22	7.83	11.0	3.43	38.6	
25	2.06	5.50	13.5		43.0	
26	3.71	6.33	20.6	2.87	41.3	
27	3.55	6.90	12.9		29.2	
28	2.15	5.33	15.1		48.6	
29	4.92	6.67	10.5	4.11	20.7	
30	10.73	16.61	13.0	2.06	8.6	End of rainy season (July 2004)
31	12.47	18.93	10.7	2.36	10.0	
32	13.92	20.87	7.9	1.65	8.4	
33	15.72	23.29	11.8	4.26	5.4	
34	14.35	21.45	11.6	1.75	7.4	
35	16.37	24.16	8.0	2.81	3.6	
Mean among plots			12.4		17.5	
Standard error (SE) among plots			0.7			

The influence of the dry season in the first survey was very strong, as many trees were without leaves and litter accumulation was very high. This situation was also observed by Dantas, (1991), Luizão and Luizão (1991) and Martius et al. (2004). On the other hand, Silva and Lobo, (1982) observed that short dry periods have no significant effect on litter accumulation. Litter is known to decompose more rapidly in conditions of high humidity and temperatures than in drier conditions, and thus the accumulated amount of litter should be different according to season. This hypothesis was tested using the average values of litter samples obtained at the end of dry season 2003-2004 (29 plots) and the estimation of litter from 6 plots following the next rainy season. Comparison of the means of both groups with the T test did not show a significative difference (p=0.001) (Table 4.9).

Table 4.9 Statistical differences between average values of total litter biomass calculated for two different seasons in secondary forest stands in the municipality of Igarapé Açu, Bragantina region, Brazil

Season	No. of plots	Mean	SE of mean
End of dry season	29	12.81	0.82
End of rain season	6	10.50	0.86

T test for equality of means (equal variances assumed)						
T	df	Sig. (2-tailed)	Mean Diff.	SE of Diff.	95 % Conf. Int. of Diff.	
					Lower	Upper
1.23	33	0.22	2.32	1.87	-1.36	6.13

SE Standard error

It was calculated that after sieving, on average, the samples still contain around 5 % of adhered sand particles. In the samples from the plot with clay soil (plot 32), clay represented 25 % of the dry weight.

4.5.3 Total standing dead tree biomass

The methodology applied here to estimate the biomass of standing dead trees combines the guidelines provided by IPCC (2003) with some simplifications. The assumption that dead trees belong to the lowest stratum is due to the fact that most of the dead trees are found in the lower level, where mortality is high due to lack of incoming light and the high tree density. The few bigger dead trees in the study plots were considered to have the same height as the lower stratum of the canopy. This assumption underestimates the biomass of this component. On the other hand, the assumption that the wood condition of the dead trees is the same as that of live trees greatly overestimates the biomass. Under the circumstances that not more information was collected from the field, for the purpose of this research it was assumed that over- and under-estimation would be balanced.

No clear relationship was found between total standing dead tree biomass and average height of the highest canopy stratum. However, total standing dead tree biomass increased when the stand was around 10-m high, becoming variable in the following height classes (Figure 4.3). This increase in mortality can also be associated with the competition originating from the high tree density and the beginning of multi-strata organization in the canopy (Chapter 3, section 3.4.3).

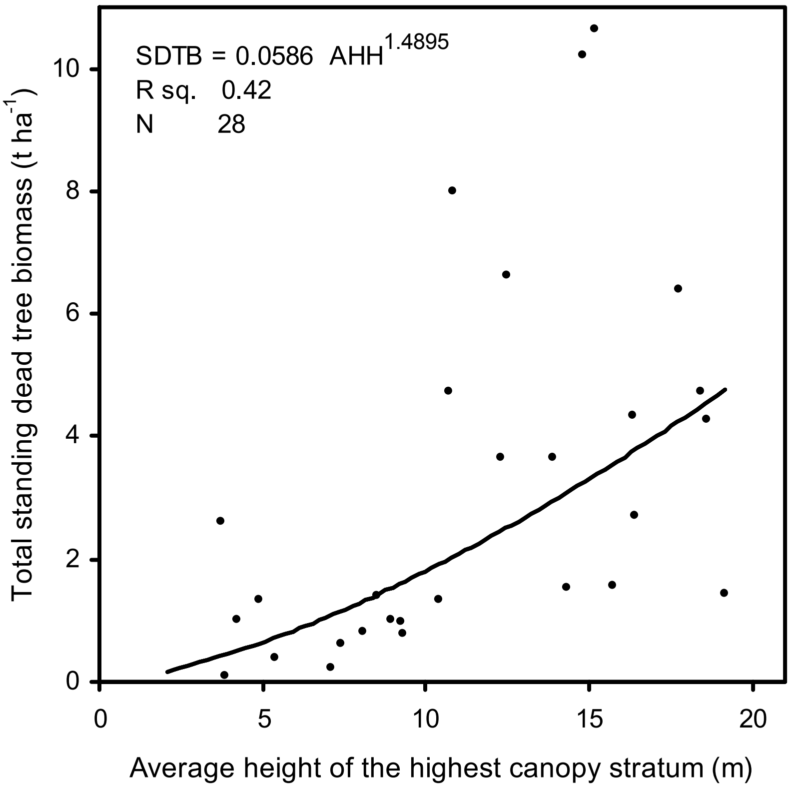


Figure 4.3 Total standing dead tree biomass (SDTB) estimated as function of average height of highest canopy stratum (AHH) in 28 secondary forest stands in the municipality of Igarapé Açu, Bragantina region, Brazil

Total standing dead tree biomass depends on the number and volume of dead trees and the wood density of the lower stratum. The combination of these variables leads to high variation in the estimations. Maximum values were observed when the stands were around 15-16 m high or 22-23 years after abandonment according to the age model (Chapter 3, section 3.4.2, Figure 3.5).

In 28 plots dead trees were found. Total standing dead tree biomass averaged 3.1±0.6 t ha^{-1} and represented on average 2.9±0.5 % of the total aboveground biomass, but could reach to 10.2 % (Table 4.10).

Table 4.10 Total standing dead tree biomass (STDB) and relation to the measured total aboveground biomass (TAGB) in 28 secondary forest stands in the municipality of Igarapé Açu, Bragantina region, Brazil

Plot	TAGB (t ha^{-1})	SDTB (t ha^{-1})	% SDTB in TAGB
19	25.8	0.1	0.4
24	28.5	1.0	3.5
14	32.4	1.3	4.2
21	49.8	0.4	0.8
26	50.0	2.6	5.2
17	62.9	1.4	2.2
2	73.8	0.2	0.3
5	81.6	1.0	1.2
8	83.7	1.0	1.2
3	85.9	0.8	0.9
11	92.1	0.6	0.7
12	93.3	3.7	3.9
32	93.9	3.6	3.9
6	97.2	0.8	0.8
13	98.3	8.0	8.2
20	104.0	1.3	1.3
4	104.3	10.6	10.2
31	107.3	6.6	6.2
22	122.7	10.2	8.3
30	150.9	4.7	3.1
34	155.6	1.5	1.0
18	169.2	4.3	2.5
1	180.9	4.7	2.6
23	186.9	6.4	3.4
16	190.1	2.7	1.4
33	219.2	1.6	0.7
35	225.4	4.3	1.9
15	225.6	1.4	0.6
Mean		3.1	2.9
SE		0.6	0.5

4.5.4 Stand biomass

The biomass of secondary forest depends on the combination of several stand variables such as basal area, stand height and average wood density. The final predictive equation of total aboveground biomass was generated by data from 35 plots using the average height of 6 selected trees from the highest canopy stratum as the independent variable. In this study, all sites are considered as having the same site conditions except for plot 32, which has a high proportion of clay soil.

Data of total aboveground biomass of the secondary forest stands increased in variability when the height of the stand increases. Stand biomass of plot 33, 35, 4 and 30 behaved as extreme values in the data distribution. To reduce this effect a logarithmic transformation was applied to both set of data, the average height of the highest canopy stratum and the total aboveground biomass.

The accumulated biomass of all living trees, dead trees and litter components responded to growth in height according to the linear equation 4.5.4.a. Figure 4.4 illustrates the data distribution and the fitting model.

$$\ln TAGB = 2.4143 + 0.9428 \ln AHH \quad (4.5.4.a)$$

R^2 0.84

TAGB total aboveground biomass (t ha^{-1}), including litter and dead trees

AHH average height of the highest canopy stratum (m)

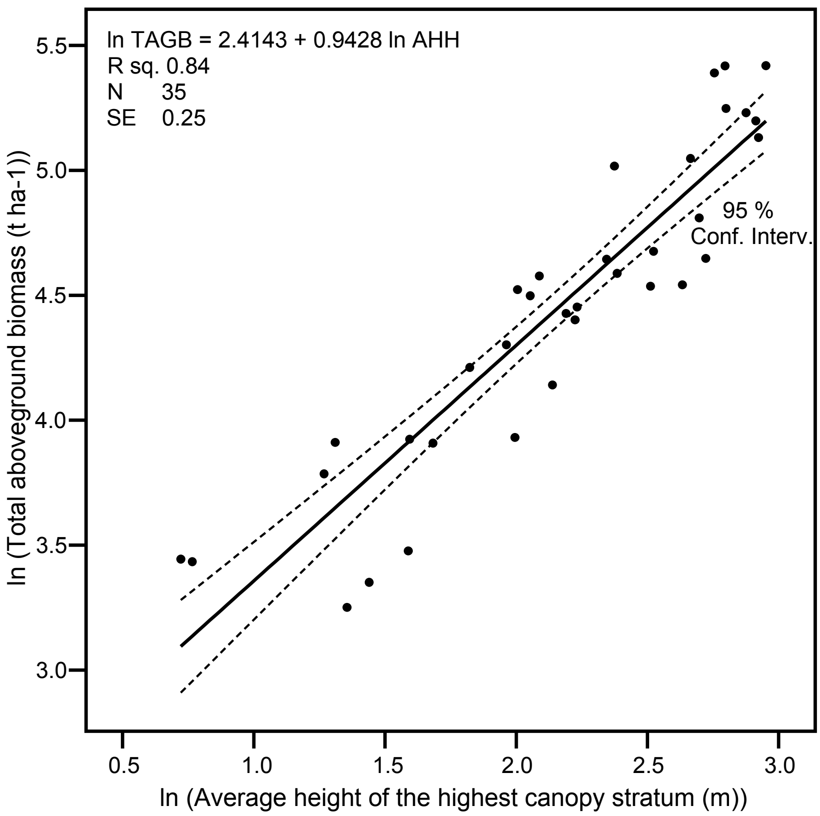


Figure 4.4 Relation of natural logarithm of total aboveground biomass (ln TAGB - includes litter and dead trees) to natural logarithm of average height of the highest canopy stratum (ln AHH) in 35 secondary forest stands in the municipality of Igarapé Açu, Bragantina region, Brazil

The total live tree aboveground biomass accounted on average for 79.5±2.2 % (mean±SE) of the total aboveground biomass in the selected plots and accumulation also responded to the linear model represented by equation 4.5.4.b (Figure 4.5).

$$\ln TTAB_{AHH} = 1.6614 + 1.1793 \ln AHH \qquad (4.5.4.b)$$

R^2	0.85
$TTAB_{AHH}$	total live tree aboveground biomass (t ha^{-1})
AHH	average height of the highest canopy stratum (m)

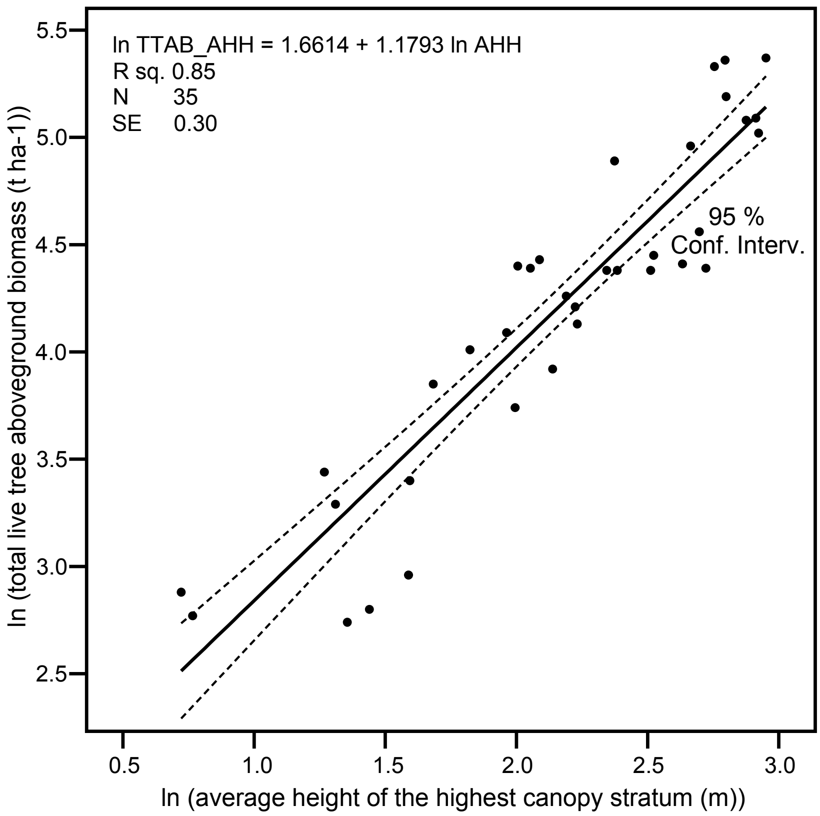


Figure 4.5 Relation of natural logarithm of total live tree aboveground biomass (ln $TTAB_{AHH}$) to natural logarithm of average height of the highest canopy stratum (ln AHH) in 35 secondary forest stands in the municipality of Igarapé Açu, Bragantina region, Brazil

The prediction of stand biomass obtained from live trees in each plot and based on the average height of the highest canopy layer (equation based on height) was cross-checked with the prediction based on the sum of the dry weight of the trees as a function of the tree diameter (equation based on diameter).

The aboveground dry weight (tree aboveground biomass) increases in variability when trunk diameter increases (Figure 4.6.a). As it was explained before, this dispersion also was reduced applying a logarithmic transformation to the square diameter and to the aboveground biomass of each tree (Brown et al., 1989; Nelson et al., 1999; Overman et al., 1994). A lineal regression model was fitted with 359 measurements of tree diameter and weight (Figure 4.6.b).

The total biomass of the stand was calculated as the sum of tree aboveground biomass per plot expressed in tons per hectare (Eq. 4.5.4.c and Eq. 4.5.4.d).

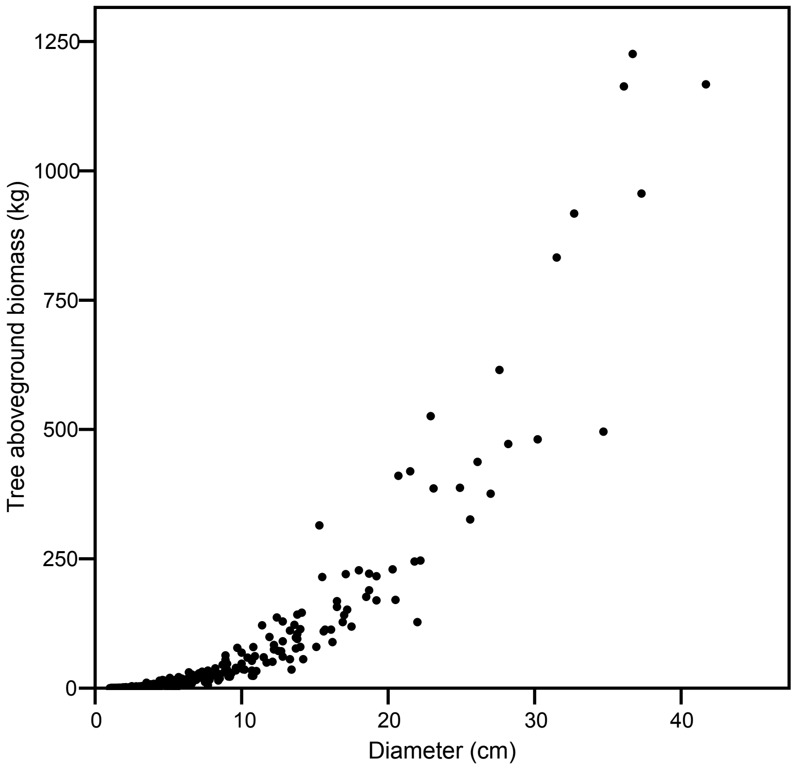
$$TAB = e^{\left(-1.9457 + 1.2341 \ln DBH^{2}\right)} \qquad (4.5.4.c)$$

TAB	tree aboveground biomass (kg)
DBH	diameter at breast height (cm)

$$TTAB_{DBH} = \left(\sum_{i=1}^{i=n} TAB_i\right) \times \frac{10000}{area\_plot} \times \frac{1}{1000} \qquad (4.5.4.d)$$

$TTAB_{DBH}$	total live tree aboveground biomass (t ha^{-1}) based on diameter
TAB_i	aboveground biomass of tree i (kg)
area_plot	area of study plot (m^2)
n	number of trees in plot

a)



b)

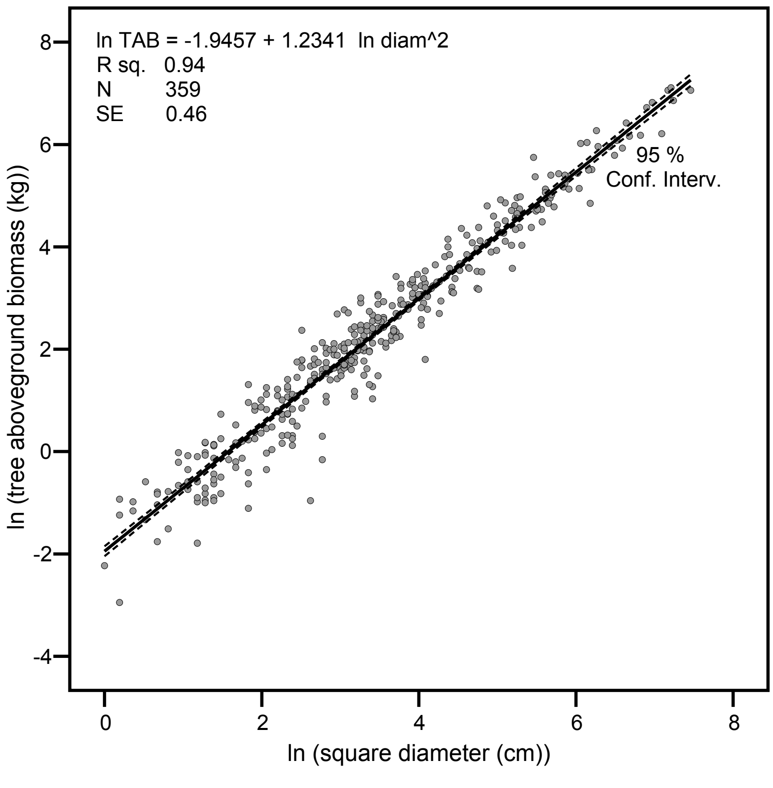


Figure 4.6 a) Scatterplot of the increment of variability of tree aboveground biomass with tree diameter
b) Logarithmic transformation of tree aboveground biomass (ln TAB) and square diameter (ln diam^2) of 359 trees of secondary forest stands in the municipality of Igarapé Açu, Bragantina region, Brazil

The predictions of total live tree aboveground biomass obtained with the two calculations (Eq. 4.5.4.b and 4.5.4.d) were compared to the values provided by the equations of Brown (1997), Nelson et al. (1999), Overman et al. (1994) and Uhl et al. (1988). The equation proposed by Brown (1997) applies to moist tropical forests with DBH ranging from 5 to 135 cm. Overman et al. (1994) built an equation for trees in moist tropical forest based on their study in primary forest in Colombia for trees with a DBH from 8 cm to more than 100 cm. As aforementioned in this study (section 4.2.6), wood density values differ according to the region. In secondary forest in the south of Pará State, Uhl et al. (1988) used a similar wood density (0.71 g cm^{-3}) to the one calculated for the trees in this study area (section 3.6.1), while Nelson et al. (1999) in a secondary forest near Manaus worked with a wood density about 23 % lower (0.54 g cm^{-3}). In order to approximate the stand data in this study to the conditions of the latter site, the predictions of biomass provided by the equations derived from height and diameter were reduced by 23 %. Furthermore, the prediction based on the average height of the trees in the highest canopy stratum was also reduced by a correction factor (height factor) that relates the average height of all trees in the highest canopy stratum, calculated from the equation between diameter and height of 392 trees (Eq. 4.5.4.e; Figure 4.7), to the average height of the 6 selected trees in the highest canopy stratum.

$$H = 0.2265 + 5.3253 \ \ln DBH \qquad (4.5.4.e)$$

R^2	0.85
H	total tree height (m)
DBH	diameter at breast height (cm)

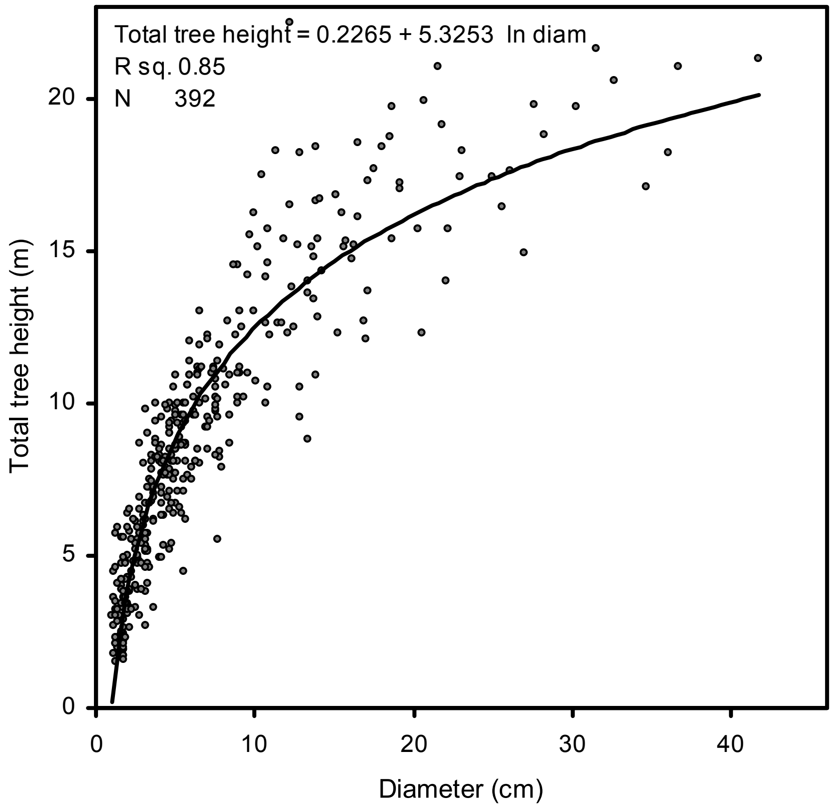


Figure 4.7 Logarithmic relationship between tree diameter (DBH in most cases) and total height of trees in secondary forest stands in the municipality of Igarapé Açu, Bragantina region, Brazil

Comparing the values generated by all the above equations, 5 pairs of equations show significant differences; these include differences between the tested equations (using diameter and height) and the predictions generated with Uhl et al. (1988) and Nelson et al. (1999) equations. Only the equation based on diameter also differs from the Brown (1997) model (Table 4.11).

Table 4.11 Statistical differences among means of total live tree aboveground biomass predicted by different equations in 35 secondary forest stands in the municipality of Igarapé Açu, Bragantina region, Brazil

Pair No.	Method	Paired differences				t	df	Sig (2-tailed)
		Mean of diff.	SE of Mean	95% Conf. Int. of Diff. Lower	95% Conf. Int. of Diff. Upper			
Pair 1	Biomass based on diameter Biomass based on AHH	3.950	3.657	-3.481	11.381	1.080	34	0.288
Pair 2	Biomass based on diameter Biomass based on AHH with reduction by height factor	4.571	4.183	-3.930	13.071	1.093	34	0.282
Pair 3	Biomass based on diameter with reduction of 23 % of biomass Biomass based on AHH with reduction of 23 % of biomass	-3.048	2.821	-8.780	2.685	-1.080	34	0.288
Pair 4	Biomass based on diameter Biomass by Brown (1997) equation	3.745	0.303	3.130	4.361	12.370	34	0.000
Pair 5	Biomass based on diameter Biomass by Overman et al. (1994) equation	0.991	0.337	0.307	1.676	2.942	34	0.006
Pair 6	Biomass based on diameter Biomass by Uhl et al. (1988) equation	18.733	3.469	11.684	25.782	5.401	34	0.000
Pair 7	Biomass based on diameter with reduction of 23 % of biomass Biomass by Nelson et al. (1999) equation	-8.878	0.728	-10.356	-7.399	-12.202	34	0.000
Pair 8	Biomass based on AHH Biomass based on AHH with reduction by height factor	0.621	1.918	-3.276	4.518	0.324	34	0.748
Pair 9	Biomass based on AHH Biomass by Brown (1997) equation	-0.204	3.595	-7.511	7.102	-0.057	34	0.955
Pair 10	Biomass based on AHH Biomass by Overman et al. (1994) equation	-2.958	3.681	-10.439	4.523	-0.804	34	0.427
Pair 11	Biomass based on AHH Biomass by Uhl et al. (1988) equation	14.783	4.291	6.063	23.503	3.445	34	0.002
Pair 12	Biomass based on AHH with reduction of 23 % of biomass Biomass by Nelson et al. (1999) equation	-11.925	3.193	-18.415	-5.436	-3.735	34	0.001

Mean values of biomass calculated from predictions by equations using either diameter or average height of trees in the highest stratum both show values that are statistically similar. Furthermore, the equations show no statistical differences to the results given by Overman et al. (1994), although the equations were generated with different sets of tree data from opposite ends of the Amazonian forest and from different growth conditions (secondary and primary forest). Even so, especially when the diameter approach is used, the approximations in the results are very close in all stands (Table 4.12).

The stand biomass calculated by the average height of six trees in the uppermost canopy stratum is not statistically different to the biomass predicted from the average height of all trees of the same canopy stratum.

The prediction of total live tree aboveground biomass along the growth varies according to the applied equation, i.e., the Brown (1997) model underestimates compared to the estimation based on diameter; the predictions performed with Nelson et al. (1999) equation were higher than the estimations corrected due to lower wood density, while the equation of Uhl et al. (1988) always gave lowest values, except when stands were lower than 5 m (Figure 4.8). Since the different models were developed with different representative groups of trees from different places with diverse species composition, stand structure, tree density and different land-use history, the differences in values are feasible and can be related to the combination of all these variables. The equation of total live tree aboveground biomass using height of the highest canopy stratum predicts on average, lower values along the height range of 2 to 20 m height in secondary forest stands in comparison to predictions based on diameter.

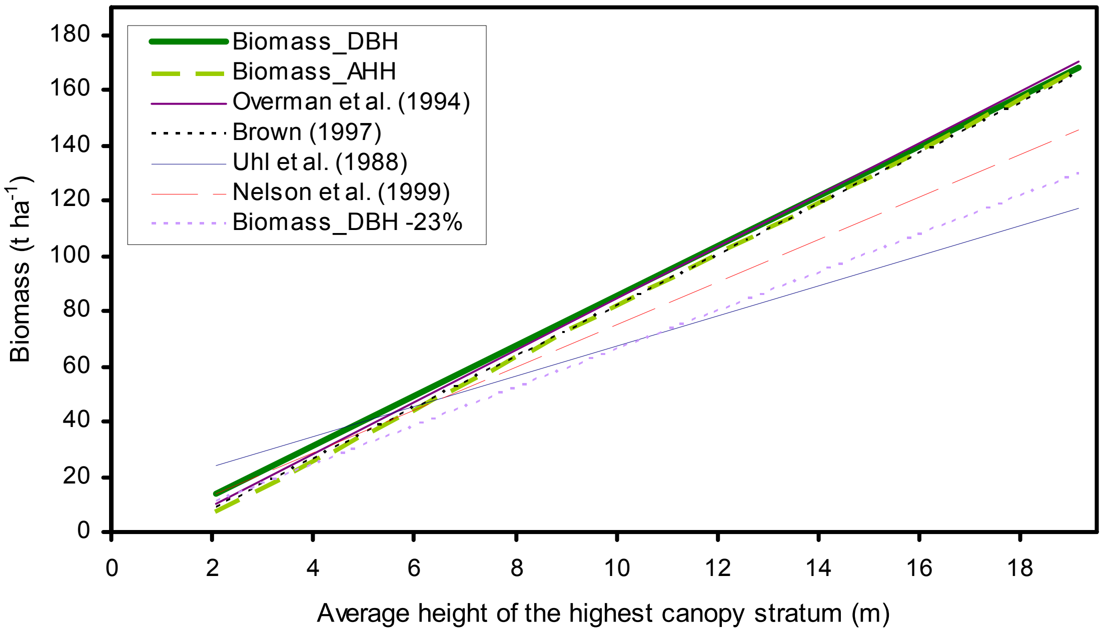


Figure 4.8 Comparison of behaviour of different biomass equations based on lineal regression of the predicted values in 35 secondary forest stands in the municipality of Igarapé Açu, Bragantina region, Brazil. Predictions of total live tree aboveground biomass provided by equations Biomass_DBH, Overman et al. (1994), Brown (1997), Uhl et al. (1988), Nelson et al. (1999) and Biomass_DBH-23% are obtained as the sum of individual tree biomass predicted using trunk diameter at the breast height (DBH). The predictions of Biomass_AHH are based on average height of the highest canopy stratum (AHH)

When the estimation of stand biomass using the diameter of trees is taken as the nearest approximation to the real biomass value, it can be assumed that forest stands in the municipality of Igarapé Açu, with heights of 2 m, 5 m, 10 m, 15 m and 19 m, can accumulate in the total live tree aboveground biomass around 35 t ha^{-1}, 58 t ha^{-1}, 85 t ha^{-1}, 125 t ha^{-1} and 178 t ha^{-1}, respectively. In contrast, for the same height ranges, 12 t ha^{-1}, 35 t ha^{-1}, 80 t ha^{-1}, 128 t ha^{-1} and 170 t ha^{-1} are predicted using the equation derived from the average height of the highest canopy stratum, respectively (Table 4.12).

Table 4.12 Prediction of total live tree aboveground biomass (TTAB) based on equations of tree diameter (DBH), average height of the highest canopy stratum (AHH) and Overman et al. (1994) and estimation of variation (CV - coefficient of variation) among 35 secondary forest stands in the municipality of Igarapé Açu, Bragantina region, Brazil

Plot	AHH (m)	Predicted $TTAB_{DBH}$ (t ha^{-1})	Predicted $TTAB_{AHH}$ (t ha^{-1})	Predicted TTAB based on Overman et al. (1994) eq. (t ha^{-1})	CV among the predictions
25	2.06	42.99	12.34	39.52	0.53
28	2.15	27.00	12.99	24.65	0.35
27	3.55	65.60	23.49	61.12	0.46
26	3.71	34.37	24.69	32.00	0.17
19	3.88	28.79	26.03	26.92	0.05
24	4.22	27.39	28.76	25.60	0.06
14	4.90	15.37	34.29	14.36	0.53
29	4.92	55.08	34.49	51.77	0.23
21	5.38	60.56	38.31	57.37	0.23
9	6.19	42.70	45.19	40.57	0.05
2	7.12	46.20	53.29	44.76	0.09
7	7.35	47.78	55.37	46.40	0.10
11	7.43	55.62	56.02	53.58	0.02
10	7.79	64.91	59.31	63.63	0.05
6	8.07	75.05	61.77	72.87	0.10
17	8.48	65.44	65.54	63.73	0.02
8	8.93	62.95	69.67	60.64	0.07
5	9.24	78.43	72.53	77.41	0.04
3	9.32	55.69	73.21	54.02	0.17
20	10.43	75.04	83.59	73.19	0.07
30	10.73	95.29	86.43	93.27	0.05
13	10.85	91.54	87.65	89.59	0.02
12	12.32	99.25	101.80	98.34	0.02
31	12.47	87.19	103.22	86.50	0.10
32	13.92	103.23	117.52	102.14	0.08
34	14.35	108.18	121.85	107.20	0.07
22	14.84	103.31	126.75	102.84	0.12
4	15.21	75.80	130.52	77.33	0.33
33	15.72	196.94	135.65	197.80	0.20
35	16.37	153.36	142.29	153.32	0.04
16	16.43	180.69	142.97	184.19	0.14
23	17.74	151.83	156.47	152.22	0.02
1	18.41	192.59	163.44	195.93	0.10
18	18.60	194.32	165.45	198.75	0.10
15	19.13	161.71	171.06	163.96	0.03
Average		86.35	82.40	85.36	0.14
CV		0.60	0.59	0.62	

The average differences in the biomass predictions for all stands are subestimated by 4.6 % when the method derived from height is compared to the diameter method. The mean of the coefficient of variation among the stands using height or diameter is similar to that obtained using the Overman et al. (1994) equation. Among the predicted values for each plots with the different equations, the coefficient of variation was on average not higher than 14 %. Maximal variation concentrates mainly in stands lower than 5 m high.

In case it should be necessary to relate total aboveground biomass based on average height of highest canopy stratum to that based on diameter, Eq. 4.5.4.f (Figure 4.9) can be applied.

$$TTAB_{DBH} = 6.2894 + 0.9716\ TTAB_{AHH} \tag{4.5.4.f}$$

R^2	0.82
$TTAB_{DBH}$	total live tree aboveground biomass (t ha^{-1}) using diameter
$TTAB_{AHH}$	total live tree aboveground biomass (t ha^{-1}) using average height of trees in highest canopy stratum (AHH)

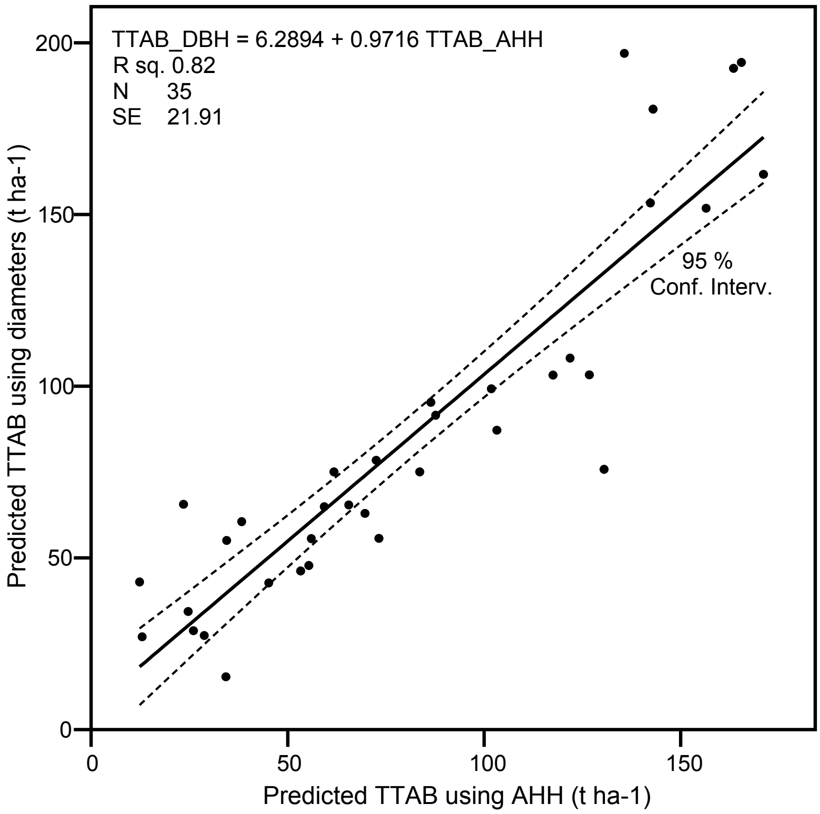


Figure 4.9 Relation of total live tree aboveground biomass between equations using diameter of trees (TTAB_DBH) and equation using average height of the highest canopy stratum (TTAB_AHH) based on 35 secondary forest stands in the municipality of Igarapé Açu, Bragantina region, Brazil

The prediction of total live tree aboveground biomass corresponds to the values published by different researchers for tropical moist forest, even when the average height of trees in the highest canopy stratum is applied. For stands lower than 12-m height, the calculated values are congruent with those obtained by destructive measurements by Tippmann (2000) in Igarapé Açu. Biomass of medium-aged stands was in the range of values observed by Saldarriaga et al. (1989) for secondary forest stands in northwest Amazonia. However, for older stands, their estimations are far lower than those calculated using the equations derived from diameter and height, even when the predictions are reduced by 16 % due to differences in wood densities (0.59 g cm^{-3}). Similar results were achieved by López et al. (2002) when they compared their own measurements with the results of the allometric equations of Saldarriaga et al. (1988) and Nelson et al. (1999).

The total live tree aboveground biomass of high stands are in the range of the biomass estimated by Honzák et al. (1996), López et al. (2002), Lucas et al. (1996) and Steiniger (2000) There is not enough information on high and old secondary forest exists in the Bragantina region for comparison with the values of total live tree aboveground biomass calculated in this study. Almeida (2000), Johnson et al. (2001), Salomão (1994) and Vieira et al. (2003) studied the biomass of young to old stands in the Bragantina; their predictions are lower than those calculated with the two equations used in this study when the same basal area in the stand is taken as reference. These authors used the equation developed by Uhl et al. (1988) to predict tree biomass. This equation also gave the lowest predictions when applied to all diameters in the stands. The equation was developed for secondary forest of the municipality of Paragomina, where the weather conditions are drier than in Igarapé Açu.

The equation based on average height of the highest canopy stratum predicts that an old stand with an average height of around 19 m could accumulate a biomass of 170 t ha^{-1}, this value is 64 % of the biomass predicted by Salomão (1994) for primary forest stands in the municipality of Peixe Boi (266 t ha^{-1}) or 67 % when the prediction based on diameter is used.

4.5.5 Tree height

The total height of individual trees can be approximated using the trunk height and applying the inverse of the height correction factor (HCF^{-1}) (section 4.5.4, Table 4.6). Trees in the upper canopy stratum have an average HCF^{-1} of 0.66. The means of the heights of 32 plots calculated with this factor show no significant differences when compared with the mean of measured height (Table 4.13). These values can be used to approximate to the average height of the highest canopy stratum and to predict the total live tree aboveground biomass in the stand using Eq. 4.5.4.b or the total aboveground biomass using Eq. 4.5.4.a.

Table 4.13 Statistical differences among the mean values of tree height calculated using the inverse of the height correction factor (HCF^{-1}) and height measurements of trees in 32 plots of secondary forest in the municipality of Igarapé Açu, Bragantina region, Brazil

Method	No. of plots	Mean	SE of mean
Measured height	32	10.6	0.875
Calculated height by HCF^{-1}	32	10.7	0.851

T test for paired samples							
Paired Sample	Method	Mean	No. of plots	SE of mean	T	df	Sig. (2-tailed)
Pair 1	Measured height Calculated height by HCF^{-1}	-0.143	32	0.259	-0.551	31	0.585

SE Standard error

4.5.6 Tree aboveground biomass

Based on the available information, three main alternatives are proposed to estimate the individual tree aboveground biomass. As explained in section 4.4.3 and Figure 4.2, biomass can be estimated using the “tree biomass reduction factor” calculated from the selected trees per stratum. This factor is on average 0.73 for trees in the highest canopy stratum, 0.72 for trees in the intermediate level and 0.77 for those in lowest. Furthermore, tree aboveground biomass can be estimated applying the “tree biomass expansion factor” to the trunk height, which is on average 1.21 for the highest, 1.01 for the intermediate and 1.09 for the lowest canopy stratum (Table 4.14). The third alternative is using the Eq. 4.5.4.c derived from diameter.

Table 4.14 Alternatives for estimating aboveground biomass of individual trees of the different canopy layers based on total height or trunk height and tree biomass reduction factor (BRF) or tree biomass expansion factor (BEF) in secondary forest in the municipality of Igarapé Açu, Bragantina region, Brazil

	Total height	Trunk height
Stratum	**TBRF**	**TBEF**
Highest	0.73	1.21
Intermediate	0.72	1.01
Lowest	0.77	1.09

4.6 Conclusions

Two main equations were proposed in this chapter to predict biomass in secondary forest stands. The first is based on the sum of individual tree biomass calculated from the tree diameters, and the second on the average height of the highest canopy stratum.

The methodology developed in this research to calculate aboveground biomass based on height is simple and quick and can be applied with the information on the total height of only six trees selected from the highest canopy stratum. The methodology allows assessment of the stand aboveground biomass using two different options. When the condition of the canopy closure is such that it is almost impossible to estimate the top canopy height, these values can be estimated based on trunk height multiplied by the inverse of the height correction factor. The average height of the 6 trees in the highest canopy stratum can be used to predict the total aboveground biomass. This flexibility can help to develop own surveys and to obtain the required information independent of the canopy closure condition. The methodology for tree selection applied in this study also takes into account possible irregularities of the surface of the highest canopy stratum independent of the arrangement of trees in the stand.

It must be borne in mind that the prediction of live aboveground biomass using average height of the highest canopy stratum can result in an average subestimation of 4.6 % along the growth compared with the prediction based on the diameter of individual trees.

In ideal conditions, the variation in average height of dominant and codominant trees will represent the productivity of the stand at several growth stages; however, this assumption is skewed when the site has been changed by land preparation, thus reducing the growth potential of trees. Under these conditions, even-aged stands in the same region could give different biomass values, and removing the predictive variable “age” from the biomass prediction is recommended. Although height is also affected by previous land-use practices, a reduction in total height would give the stand a structure and accumulated biomass amount similar to younger stands, so two stands with different ages but similar average height can have similar biomass values.

The combination of site quality and anthropogenic management results in forest stands with particular species composition and structure development. New “height-biomass” relationships must be found for other sites. The model proposed in this study can be applied to the secondary forest in the municipality of Igarapé Açu, to sites in the Bragantina region with similar soil, vegetation type and height range (2-20 m) or to other stands of moist tropical secondary forest which have similar stand structure and average wood density placed in regions with comparable weather and soil conditions to those in the present study.

Although signs of reduced site productivity were observed in the municipality of Igarapé Açu, the accumulation of biomass in secondary forest under the old traditional slash-and-burn system is still similar to that in other areas in the Amazon region due to the high wood density values of the trees.

High values of litter accumulation was observed. The amount was enhanced by tree stand density and not affectedof seasonality.

Although competition among trees and tree mortality are high in secondary forest, the average standing dead trees biomass represents in average only the 3 % of the total aboveground biomass.

5 CARBON STOCK IN DIFFERENT LAND COVERS IN THE AGRICULTURAL LANDSCAPE OF EASTERN AMAZONIA

5.1 Introduction

Deforestation in the tropics, e.g., through the conversion of forest to grassland and agriculture land, contributes to the emission of greenhouse gases. In the 1980’s, this was responsible for 90 % of the net released carbon dioxide (CO_2) by the replacement of forests to agriculture (IPCC, 2000).

As a result of the abandonment or fallowing of productive lands, 30 % of the tropical forest worldwide (Brown and Lugo, 1990) and 13 % in Brazilian Amazon region (INPE, 2005) is currently covered by secondary forest (spontaneous forest growing in a secondary succession as a consequence of natural or human impacts on forest lands). Over a long period, this forest has a high potential for uptake of the carbon (C) emitted by the previous deforestation. Secondary forest can absorb carbon with a rate of 1 to 4.5 t ha^{-1} yr^{-1}, accumulating more than 100 t C ha^{-1} during the first 15 years (Brown and Lugo, 1990). In the Bragantina region, Pará state, Brazil, nearly 1 million ha of tropical moist forest have beeen slashed and converted to agriculture land, releasing more than 180 Mt (million tons) C (Salomão, 1994). The traditional agriculture activities rotate in time and space with secondary forest, but intense land use has led to reduced fallow periods of only 3 to 7 years (Denich and Kanashiro, 1995; Metzger, 2002; Metzger, 2003), and intensive modification by mechanization of land preparation impairs the sustainability of the agricultural systems (Hölscher, 1997; Hölscher et al., 1997). To stop this trend, management practices such as enrichment of fallows with fast growing leguminous trees and mulching technology have been tested to increase biomass and nutrients in short period for future crops (Brienza Jr., 1999; Hedden-Dunkhorst et al., 2004; SHIFT-Capoeira, 2003). On the other hand, alternative as mechanisms that support the commmercialzation of carbon rights for secondary forest will increase the incomes of the local farmers and at the same time incentive forest conservation and obatin important ecological benefits.

In this chapter, the carbon stock of secondary vegetation (vegetation growing in secondary succession over a long and short periods of time) and representative land covers in three study areas will be assessed, i.e., in a study area of 100 km^2, in the municipality of Igarapé Açu and in the Bragantina region. These areas share similar land-cover types, land-use practices, history and weather and site conditions. In addition, using a map of farm properties, the contribution of each land-cover type to the carbon stock at the farm level will be estimated.

5.1.1 Carbon stock in different land covers

Carbon is considered as a fraction of the biomass, and its potential assimilation is determined by the type of cover, and its area and permanence in time. In the Bragantina region, several land-covers types of both natural and agriculture origin extend over the area, and their importance has been studied by several researchers (Almeida, 2000; IBGE, 2005b; Lu et al., 2002; Metzger, 2002; Salomão, 1994; Vieira et al., 2003; Watrin, 1994); among them, only Salomão (1994) estimated the carbon stock of secondary forest, while the other studies focused mainly on land-cover area distribution.

For the Amazonian basin and tropical regions around the world, some studies exist that estimated the carbon stock of different agricultural land covers or provide data on the carbon factor of the respective biomass. Alegre et al. (2001) assessed the carbon content of several land-cover types in Peruvian Amazon in areas with Ultisol soils with low fertility and high aluminum saturation. Denich et al. (2000) estimated that passion fruit (*Passiflora edulis*) and cassava (*Manihot esculenta*) in Igarapé Açu sequestered 2.6 t C ha^{-1} in 1-year-old plantations and black pepper (*Piper nigrum*) 5.3 t ha^{-1} in 2.5-year-old plantations. Rodrigues et al. (2000) estimated 41.8 t ha^{-1} of biomass for a 12-year-old oil palm (*Elais guineensis*) plantation in west Amazonia, while Viegas (1993) obtained similar values in a plantation of around 7 years old in east Amazonia. Table 5.1 shows the carbon and biomass stock of some typical agricultural land covers in Amazonia and tropical regions.

Table 5.1 Estimation of carbon storage and aboveground biomass of different agricultural land-cover types in some tropical regions

Land-use type	Site	Carbon (t ha^{-1}) Biomass (t ha^{-1})	Comments	Reference
Rice (*Oryza sativa)*	Yurimaguas, Peru	16.8 (carbon)	carbon factor 0.45	Alegre et al. (2001)
Corn (*Zea mays*)	NE Pará, Brazil	2.1 (carbon)	4 to 5 months old	Denich et al. (2000)
Cassava (*Manihot esculenta*)	Pucallpa, Peru	3.4 (carbon)	carbon factor 0.45	Alegre et al. (2001)
Cassava (*Manihot esculenta*)*	Igarapé Açu, Brazil	2.6 (carbon)	after 1 yr	Denich et al. (1998) Denich et al. (2000)
Cowpea (*Vigna unguiculata*)	NE Pará, Brazil	1.6 (carbon)	3 to 4 months old	Denich et al. (2000)
Passion fruit (*Passiflora edulis*)*	Igarapé Açu, Brazil	2.6 (carbon)	after 1 yr	Denich et al. (2000)
Black pepper (*Piper nigrum*)*	Igarapé Açu, Brazil	5.3 (carbon)	after 2 ½ years	Denich et al. (2000)
Hevea braziliensis plantation	Pucallpa, Peru	74 (carbon)	carbon factor 0.45	Alegre et al. (2001)
Mix agro-forestry system	Yurimaguas, Peru	58.6 (carbon)	carbon factor 0.45	Alegre et al. (2001)
Degraded grass by annual fire	Yurimaguas, Peru	1.8 (carbon)	carbon factor 0.45	Alegre et al. (2001)
Degraded grass*	Pucallpa, Peru	3.1 (carbon)	carbon factor 0.45	Alegre et al. (2001)
Improved grass (*Brachiaria decumbes*)*	Yurimaguas, Peru	4.8 (carbon)	carbon factor 0.45	Alegre et al. (2001)
Oil palm (*Elais guineensis*) plantation*	NE Pará, Brazil	2.30 (biomass)	after 2 years, included fruits	Viégas (1993)
Oil palm (*Elais guineensis*) plantation*	NE Pará, Brazil	5.30 (biomass)	after 3 years, included fruits	Viégas (1993)
Oil palm (*Elais guineensis*) plantation*	NE Pará, Brazil	12.70 (biomass)	after 4 years, included fruits	Viégas (1993)
Oil palm (*Elais guineensis*) plantation*	NE Pará, Brazil	19.90 (biomass)	after 5 years, included fruits	Viégas (1993)
Oil palm (*Elais guineensis*) plantation*	NE Pará, Brazil	32.10 (biomass)	after 6 years, included fruits	Viégas (1993)
Oil palm (*Elais guineensis*) plantation*	NE Pará, Brazil	43.60 (biomass)	after 7 years, included fruits	Viégas (1993)
Oil palm (*Elais guineensis*) plantation*	NE Pará, Brazil	56.70 (biomass)	after 8 years, included fruits	Viégas (1993)
Oil palm (*Elais guineensis*) plantation	Pucallpa, Peru	41.4 (carbon)	~20 years; carbon factor 0.45	Alegre et al. (2001)
Oil palm (*Elais guineensis*) plantation*	Western Amazonia	41.8 (biomass)	after 12 years, carbon factor 0.43	Rodrigues et al. (2000)
Oil palm (*Elais guineensis*) plantation*	Malasyia	85 (biomass)	after 23 years	Khalid et al. (1999)
Oil palm (*Elais guineensis*) plantation*	Malasyia	86 (biomass)	after 25 years	Nordin (2002)
Oil palm (*Elais guineensis*) plantation	Benin	14.75-14.94 (carbon)	1-5 years; West African savannas	Thenkabail et al. (2002)

* Information used for calculation in section 4.3.3

In the Bragantina region, those studies that focused on the biomass and carbon stock of natural land covers were mainly carried out in secondary forests (Almeida, 2000; Denich et al., 2000; Salamão, 1994; Hondermann, 1995). According to estimations for the eastern Amazonia region, secondary forest assimilates atmospheric carbon in the aboveground biomass at a rate of 2 t C $ha^{-1}yr^{-1}$ (Salomão, 1994; Teixeira and Oliveira, 1999; Vieira et al., 1996), however carbon values differ due to different site conditions and applied methodologies or models. Denich et al. (2000) collected the results of many studies in the region and summarized that secondary vegetation growing in fallow periods can accumulate after:

- 1 year — between 3 and 5 t C ha^{-1}
- 4 years — between 8 and 16 t C ha^{-1}
- 7 years — between 18 and 33 t C ha^{-1}
- 10 years — between 34 and 41 t C ha^{-1}

In Chapter 4 of this research, it was shown that the best estimation of biomass and consequently for carbon is obtained when the estimation does not consider age. The variation in site conditions caused by previous land use and land preparation modify the predictions among sites (Hondermann, 1995). As an alternative, stand height can be used to compare and express the biomass and carbon stock in forest stands (Chapter 4, section 4.5.4). Secondary forest of around 5, 10, 15, and 20 m height can store 17, 40, 64 and 90 t C ha^{-1} respectively, in the avobeground biomass of live trees.

5.1.2 Municipality of Igarapé Açu

Igarapé Açu is one of the 13 municipalities in the Bragantina region, and covers 786 km^2. The municipality is located at 1° 07’ 33” south latitude and 47° 37’ 27” west longitude, around 100 km east of the city of Belém. According to the population census, in 2000 the municipality had 32,400 inhabitants, with 60 % concentrated in the urban areas and 40 % living in the rural areas; while average population density was 40.7 inhabitants per km^2 (IBGE, 2001). In the year 2004, the population increased to 44.7 inhabitants per km^2 (IBGE, 2005a). The main productive activity in the municipality is agriculture.

The history of the municipality goes back 110 years ago, when the settlement Jambu Açu was established in 1895. In 1901, the area was crossed by the railway Belém-Bragança from west to east (Kemmer, 1999; Silva et al., 1998), which helped to strengthen the agricultural activities in the region. Since then, the traditional slash-and-burn system and new mechanized land preparation have deforested and transformed more than 95 % of the area (Watrin, 1994).

Farm characterization

The rural area of Igarapé Açu presents a mixed pattern of farm types. A few farmers cultivate mainly oil palm and practice cattle farming. On the other hand, a large group of farmers works on small farms producing basic food for their own consumption and for commercial purposes; their income is low and they generally do not use high technology to work the land (Ferreira et al., 2000; Hedden-Dunkhorst et al., 2004).

The average farm size is the result of different grades of aggregation based on the original property distribution (25 ha) (Ferreira et al., 2000). This aggregation is identified by Smith et al. (2000) as a consequence of the so-called “fallow crisis”. Here, the farmers sell their farms when soil productivity declines due to degradation of the land, and in many cases, neighboring farmers or outsider producers buy the land, creating large homogeneous and productive pasture areas (Metzger, 2003) or land for permanent and semipermanent crops (i.e., black pepper, oil palm, coconut palm). In contrast, Sousa Filho et al. (1999b) assessed that 59 % of the farmers held properties smaller than 25 ha (original size), and Hedden-Dunkhorst et al. (2003, 2004) found holdings as small as 21 ha. Mendoza-Escalante (2005) observed that from the 82 surveyed farms smaller than 100 ha, 26 % housed more than one family. The average area per family was 13.8 ha, representing 2.5 households per farm. In another survey, Ferreira et al. (2000) observed that only 47 % of the farmers possessed a land ownership title and another 47 % just occupied the land; of the people with title, 56 % had bought and 44 % inherited the land.

Productive system

Originally, rubber, rice and cotton production played and important role in the local economy (Sousa Filho et al., 2000). However, agricultural activities in the municipality today mainly consist of cattle ranching and production of annual, semi-permanent and permanent crops (Ferreira et al., 2000).

The main agricultural products of the municipality are: black pepper, passion fruit, beans and cassava (Guimarães, 2002). Cultivation is based on the slash-and-burn system, where farmers apply land rotation, allowing land productivity to recover during a fallow period. In the cropping phase, farmers obtain up to 2 or 3 crops in 1 to 1.5 years. The main annual crops are rice, corn, cassava and beans, and the most frequent semi-permanent and permanent crops are oil palm, black pepper and passion fruit. The main processed product is toasted cassava meal (farinha). Black pepper and passion fruit plantations and pastures have been established by 43, 35, and 37 %, respectively, of the farmers (Hedden-Dunkhorst et al., 2003). According to some surveys among farms, permanent and semi-permanent crops covered 15 %-16 % of properties area in 1997 and 1998 respectively (Ferreira et al., 2000; Silva et al., 1998; Smith et al., 2000).

The main income among the small farmers is obtained from annual crops, cassava toast meal (fahrina), muruci fruits (*Byrsonima crassifolia* (L) Kunth), beans and firewood, and to a small part from corn, black pepper, coconut and charcoal (Ferreira et al., 2000).

Although the utilization of forest products is not a priority of the farmers in the municipality (Ferreira et al., 2000), these can contribute up to 21 % of the total income (Ferreira et al., 2000; Smith et al., 2000), however, 70 % of the income produced from wood and non-wood products is consumed by the farmers themselves (Ferreira et al., 2000).

Sousa Filho et al. (1999b) identified 15 types of productive units in the municipality of Igarapé Açu, concentrated in 4 size levels (micro, small, medium and large) and 6 productive systems (agriculture, agro-silviculture, agro-extractive, cattle farming, agro-cattle farming). According to farm size, farmers are specialized in different activities; 59 % of the farms are smaller than 26 ha and activities here are mainly subsistence agriculture. Other farms are 25 to 100 ha in size and cover 37.4 %

of the municipality; here the farmers practice subsistence agriculture, agro-extractive, agro-silviculture, agro-cattle farming, cattle farming. Most of the commercial crops can be found in these units. The remaining farms are bigger than 100 ha (3.6 %) and specialized in mechanized agriculture, agro-cattle farming, agro-silviculture and cattle farming.

Secondary vegetation

Secondary vegetation has developed alternating with cropping period since the beginning of settlement in the area. the current species composition of secondary vegetation is the result of human-induced selection over a long period (Denich, 1986a), where only those tolerant to frequent disturbances of the environment and capable of revegetating during the fallow periods survived.

Farmers allow secondary vegetation to grow in order to recover soil productivity. The length of the fallow period varies among farmers depending on land use, farm size and external market demands. Fallow periods have been reduced to 3-7 years (Denich and Kanashiro, 1995; Metzger, 2000; Metzger, 2003) or increased in area in order to compensate the declining of productivity (Denich and Kanashiro, 1995). Secondary vegetation, mainly consists of young forest fallows, which are cyclically slashed and burned. The selection of secondary forest for clearing depends on several factors, like proximity of roads, houses, and size of the trees (Denich and Kato, 1995). According to Watrin (1994), most of the old secondary forests are localized in areas with difficult access, far from main roads and with low population density. Even though old forest stands can provide wood products from big trees, farmers avoid cutting these during clearing activities as this (the cutting of the big trees) is very labor intensive. In contrast, lower and younger fallows are in areas where intensive agriculture is practiced.

The permanence of secondary forest in the rural area is influenced by the number of inhabitants and is threatened when population density exceeds 40 inhabitants/km^2 and the demand for food and wood products is high (Smith et al., 2000). In the Bragantina region, the municipalities of Bragança and Igarapé Açu have densities higher or close to this value; however, there has been considerable out migration to larger urban areas, with the result that permanent secondary vegetation in the rural areas is possible.

Land-use/land-cover distribution

Currently, more than 90 % of the original vegetation of the Bragantina region, eastern Amazonia, Brazil, has been replaced. After 4 to 6 cropping rotations following the first settlers (Hölscher 1997; Hölscher et al., 1997), the region was converted to a landscape of mixed-age secondary forest and initial secondary succession interchanged with different agricultural land covers (Figure 5.1). The original forest remains as highly exploited patches and along riverbanks and in flooded areas (Denich and Kanashiro, 1995; Watrin, 1994).

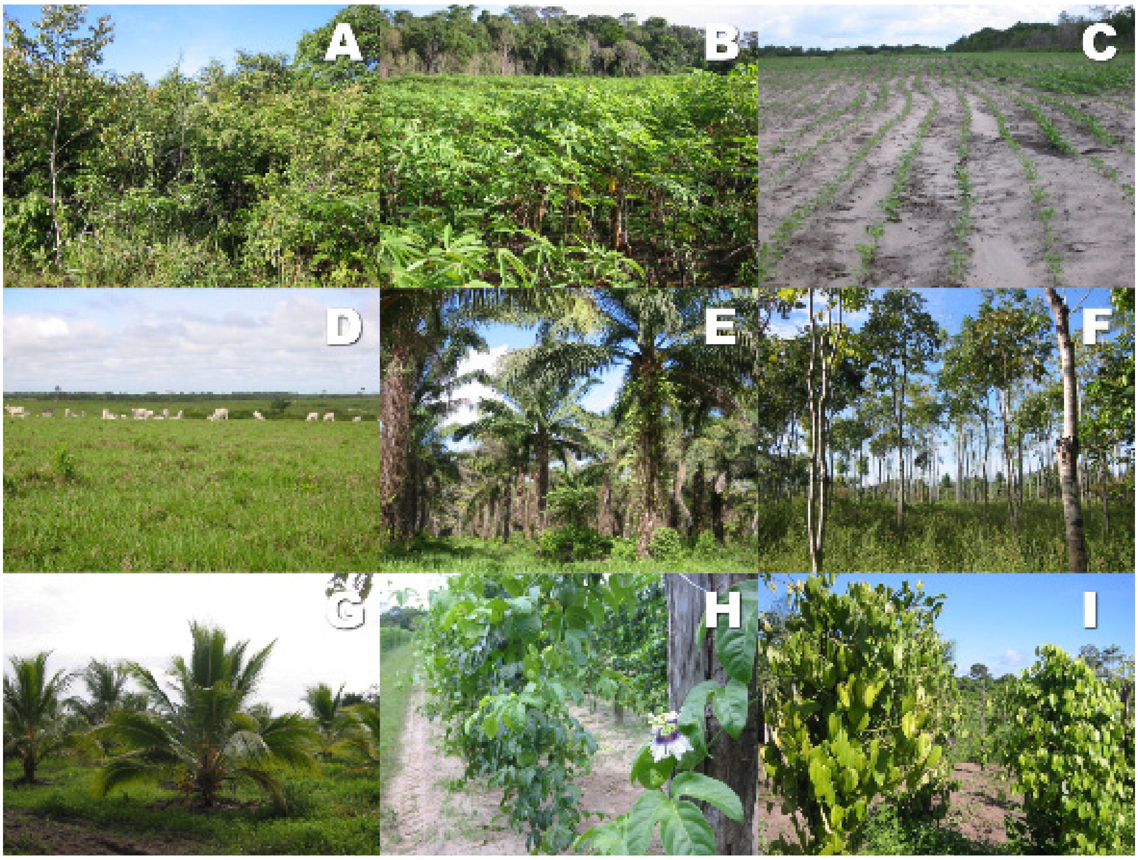


Figure 5.1 Frequent land cover types in the Bragantina region: a) secondary forest, b) cassava, c) beans, d) grassland, e) oil palm plantation, f) forest plantation, g) coconut palm plantation , h) passion fruit, i) plack pepper

The municipality of Igarapé Açu suffered the same deforestation and land occupation process as the whole Bragantina region. Using remote sensing data, it was estimated that in 1991 secondary vegetation covered 73.2 % of the municipality (Watrin, 1994). In the same study, land covers in the municipality was classified as follows:

- Young secondary vegetation 23.9 %
- Intermediate secondary vegetation 31.5 %
- Old secondary vegetation 17.8 %
- Remaining primary forest (igapó) 5.3 %
- Other land covers 21.5 %.

Of the 21.5 % of the area not covered by forest or secondary vegetation, 10.9 % was occupied by clean grass, 63.6 % by weed- and shrub-infested grass, 6.4 % by bare soils, 15.4 % by annual and semipermanent crops (passion fruit and black pepper) and 3.8 % by permanent crops (oil palm) (Watrin, 1994).

According to Metzger (2002), the secondary vegetation areas decrease at a rate of 3 % yr^{-1} due to advancing agriculture.

Grassland for cattle farming has increased and in 1985 covered over 13 % of the municipality area (IBGE, 1985 cited by Denich and Kanashiro, 1995), while in 1991 this area increased to 16 % (Watrin, 1994) and in 1997 reached 21.6 % (IBGE, 1997).

5.2 Objectives

In this chapter, the carbon sequestration potential of different land covers in the landscape of a study area of 100 km^2, in the municipality of Igarapé Açu, in the Bragantina region and at the farm scale is estimated, as well as the economic contribution to the farm income by the sequestration of carbon in secondary vegetation.

5.3 Methodology

5.3.1 Study sites

The study was performed in the Bragantina region, the municipality of Igarapé Açu and a study area of approximately 100 km^2. The latter is located between the coordinates -1° 8' 51.1800" south / -47° 38' 22.7040" west and -1° 13' 34.4280" south / -47º 32' 12.3719" west (Figure 5.2). This area represents 12.7 % of the municipality and includes all land covers in the municipality and in most of the Bragantina region. The three study areas share similar characteristics in soil, climate, land use, land cover, history and type of productive units. The Bragantina region covers 8710 km^2 and the municipality 786 km^2.

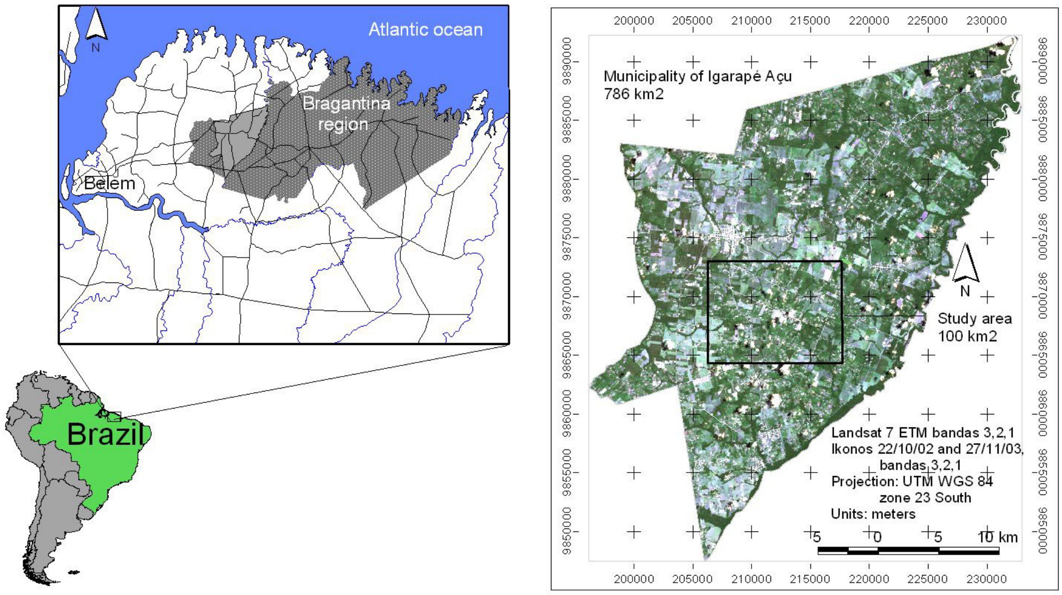


Figure 5.2 Location of study areas in eastern Amazonia, Brazil: study area of 100 km^2, municipality of Igarapé Açu and Bragantina region

The climate in the region is humid tropical with high relative air humidity varying between 80 and 89 % (Bastos and Pacheco, 1999; Sá, 1986); annual precipitation is between 2300 and 3000 mm (Bastos and Pacheco, 1999; Brasil_SUDAM, 1984, cited by Sá, 1986) with rain falling mainly between December and June. Annual frequency of days with precipitation varies from 180 to 240 days (Brasil SUDAM 1984, cited by Sá, 1986). In the dry season, there can be no rainfall for several days to weeks. In the dryest month, rainfall amounts to 60 mm. Depending on the data source, average maximum temperatures range between 30 and 33.8 $^{\circ}$C and minimum temperatures between 20 and 22.6 $^{\circ}$C (Bastos and Pacheco, 1999; Denich and Kanashiro, 1998; Sá, 1986).

Uplands and floodplains dominate the landscape of the Bragantina region. The soil is loamy to sandy (Silva and Carvalho, 1986), represented by Oxisols and Ultisols (USDA Soil Taxonomy) (Denich and Kanashiro, 1998). Under the Brazilian soil classification, the Latossolo amarelo soil type prevails in the region (IBGE/CNPS-EMBRAPA, 2001), but the traslocation of clay and organic matter particles to the topsoil by erosion processes causes the evolution of soil to a new type classified as Podzólico amarelo (Denich and Kanashiro, 1998). Soils are poor in organic matter and macronutrients and have a low effective cation exchange capacity (SHIFT-Capoeira, 2003), low pH and high aluminum content (Denich and Kanashiro, 1995; Hölscher, 1997).

According to the vegetation map of Brazil, in the Bragantina region the predominant vegetation type is secondary vegetation (IBGE-MMA, 2004). In contrast, the potential vegetation type in the region is evergreen moist tropical forest (Holdrige, 1967).

5.3.2 Remote sensing

Remote sensing processes were used to generate two main products, i.e., the classification of land covers and the interpretation of farm units based on the digitizing of farmlands in the study area of 100 km^2. Three satellite images were used, i.e., two Ikonos images approximately one year apart (October 22, 2002 and November 27, 2003) and one Landsat 7 ETM+ image (path 223, Row 061) of September 7, 2002. The first two images were used to classify land covers and delineate farm borders and the third to complete the extraction of land-cover classes to combine with the Ikonos images classification. All images are from the dry season and free of clouds, except the Ikonos image from 2003 that shows almost 20 % of cloud cover.

Image preprocessing

Ikonos images were radiometrically corrected, first by sun position, since they had differences in sun elevation angles between both dates (69º in image 2002 and 63.8º in image 2003) using the ratio between the digital pixel values and the sine of sun elevation angle (Littesand and Kiefer, 2000; Subedi, 2002) and later by atmospheric distortion. In the second case, bands in the Ikonos image 2002 were standardized to the bands of the 2003 image by subtracting the most frequent value (mode) of each histogram in the 2003 image from the histograms of the 2002 image. The mode was the only comparable parameter in both images that represented the atmospheric effect in the response of the land-cover types. After rectification, the final histograms presented a similar distribution and the same mode value. Other correction methods did not work well due to the highly variable conditions of surface reflectance and stability between both dates. Land-cover types in the area were the same in both images, but most of them showed changes with respect to vegetation growth and space arrangement.

The atmospheric effect in the Landsat image of 2002 was reduced using the correction method based on dark pixel subtraction, where the reflectance value of the darkest pixel in clean deep water for each band was subtracted from each pixel in the image bands (Hadjimitsis et al., 2004). No large and clean water bodies were present in the 100 km^2 study area, so that the correction was performed in a larger area with the presence of larger water bodies, and a final subset of the image was then cut according to the boundaries of this study area.

The geometric correction was performed in the Ikonos image 2003 and Landsat image 2002 using the Ikonos image 2002 as reference data. The latter showed the smallest and most regular displacement compared to the location of the GPS points (GPS device Garmin Venture™), without differential correction. The average displacement error for the Ikonos image 2003 was 2.525 m (RMS 0.631, RMSx 0.477, RMSy 0.412) with seven ground control points (GCP) and a polynomial transformation of order 1; as the area is mainly flat, no correction by terrain relief was performed. The geocorrection of the Landsat image showed an overall error of 1.877 pixels (RMSx 1.093 and RMSy 1.529) using eight ground control points and a polynomial transformation of order 1. All images were geolocated using the reference system UTM WGS 84, Zone 23, south and the space unit was meter.

After the images were coincident in location, a common area covering almost 100 km^2 (9903.5 ha), .i.e., the product of the intersection of the Ikonos images 2002 and 2003, was defined as the study area, and all Ikonos and Landsat images were cut using the boundaries of this new area.

Land-cover classification

The Ikonos image 2003 was acquired during the first fieldwork activities, but unfortunately it showed a cloud cover of around 20 % and a similar area with cloud shadows. In order to obtain information from under the clouds and cloud shadows, a mask of clouds and their shadows was segmented with the eCognition professional 4.0 package and reclassified by visual edition with Arcview 3.2 software. The mask was increased by a buffer area of 50 m to avoid the effect of cloud edges or light cloud shadows. This mask was applied to the Ikonos image 2003 to obtain an image without data for the area under the clouds and shadow and then inversed to the Ikonos image 2002 to extract data from those areas. The final image resulted from the combination of both images and contained information of data outside the cloud shadows provided by the Ikonos image 2003 and data from underneath the clouds and shadows by the Ikonos image 2002.

The compound image was segmented in three hierarchy levels using eCognition. The intermediate segmentation level was chosen as the one to contain the final classification classes. The classes in Level 3 were simply classified by the nearest neighboring classification; misclassified polygons were assigned manually using the support information from fieldwork experience and GPS points from different land covers. The classes included all possible land covers, and forest. The secondary vegetation was represented by three classes only. Using membership functions and class-related features for Level 1, the secondary vegetation classes were classified in 20 new classes and the grass covers in 4 additional classes. Ranges in the Normalized Difference Vegetation Index (NDVI) of bands 3 and 4 using membership functions were the main classification parameters in Level 2; this level synthesized the secondary vegetation in 7 classes and recognized 22 more land-covers types in the study area (Table 5.2).

Table 5.2 Segmentation and classification parameters of the compound Ikonos images of years 2002/2003 using eCognition 4.0

	Level 3	**Level 2**	**Level 1**
Scale parameter	20	10	10
Shape factor	0.2	0	0
Compactness	0.9	0	0
Smoothness	0.1	0	0
No classes	40	29	27
Classification type	Nearest neighbor	Membership functions of “class-related features”	Membership functions of “object- and class-related features”

It was not possible to separate the class corresponding to “riparian forest”, i.e., vegetation confined to the sides of streams, using the same methodology that was used for classifying the other classes. It is important to differentiate, this vegetation type, since in most of the cases it represents the remaining areas of primary forest and it provides numerous ecological benefits. According to Watrin (1994), this class is highly irregular in structure, the height of the trees differs considerably and it can develop over small patches. Species composition differs from that of forest stands growing in soil without flood influence. The area covered by riparian forest in the Landsat image was classified with a nearest neighbor algorithm and the result vectorized; the errors were corrected by manual editing in Arcview 3.2, and the resulting vector was added to the land-cover classification generated with eCognition. In this research, the "riparian forest" class included forest as well as secondary succession stands growing in flooded areas along streams or rivers.

The final classification resulted in 30 classes, which included riparian forest class, 7 secondary vegetation classes, 2 grass classes, 9 classes of forest plantations and permanent and semi-permanent crops, 1 annual crop class, 4 impacted cover classes, 2 aquatic ecosystem classes, 1 residential-industrial class, 1 miscellaneous class and 2 classes with no data (Table 5.3). Six of the secondary vegetation classes are grouped in three main classes with two subdivisions each class. They represent differences in growth stages and average stand height of the highest canopy stratum (see Chapter 3, section 3.4.5).

5.3.3 Biomass and carbon stock in land covers

Land-cover classification was associated with the dry aboveground biomass and carbon content values. Carbon was calculated as a ratio 0.5 of the biomass (Brown, 1997) or according to other values specified in Table 5.1. The land covers listed in this table and marked with "*", the prediction of total live tree aboveground biomass of secondary forest categories calculated using Equation 4.5.4.b in Chapter 4 for the average height values of the height classes of secondary forest (Table 5.3), and the estimation of 3 t C ha^{-1} after the first year of fallow for the initial secondary succession class (Denich et al., 2000) were used to create a database of dry aboveground biomass and carbon content of the most representative covers. The carbon stock per each oil palm class (low, medium and high) was approximated by a S-curve model based on the data of biomass reported by Viegas (1993), Khalid et al. (1999) and Nordin (2002), and the carbon fraction of 0.43 calculated from data of Rodrigues et al. (2000) and Syahrinundin (2005) to the average height value of each height class. Growth in height was based on the increment of 0.7 m yr^{-1} described by van Gelder (2004).

Table 5.3 Land-cover classes from Ikonos and Landsat images classification in the study area (100 km^2), municipality of Igarapé Açu, Bragantina region, Brazil

Class name	**Class No.**	**Description**
Riparian forest	1	Primary, intervened and secondary forest of variable height located beside streams in soils flooded most of the time or during rainy season
High secondary forest >20 m	2	Secondary forest higher than 20 m
High secondary forest 15-20 m	3	Secondary forest between 15 m and 20 m height
Medium secondary forest 10-15 m	4	Secondary forest between 10 m and 15 m height
Medium secondary forest 6-10 m	5	Secondary forest between 6 m and 10 m height
Low secondary forest 4-6 m	6	Fallow and degraded secondary forest between 4 m and 6 m height
Low secondary forest 2-4 m	7	Fallow and degraded secondary forest between 2 m and 4 m height
Initial secondary succession	8	Vegetation that grows spontaneously in areas previously cleared or under some land use. This class includes vegetation lower than 2 m height mixed with grass or dead residual material.
Burned forest	9	Forest burned by uncontrolled fires
Grass irregular	10	Natural or planted grass with irregular structure, sometimes infested by undesired plants
Grass regular	11	Natural or planted grass with regular structure and homogeneous
Forest plantation	12	Tree forest plantations for different purposes
High oil palm plantation	13	Oil palm (*Elais guineensis*) plantation between 7 m and 12 m height (average 9.5 m)
Medium oil palm plantation	14	Oil palm (*Elais guineensis*) plantation between 4 m and 7 m height (midpoint height class 5.5 m)
Low oil palm plantation	15	Oil palm (*Elais guineensis*) plantation between 1 m and 4 m height (average 2 m)
Coconut palm	16	Coconut palm (*Cocos nucifera*) plantation
Pupunha plantation	17	Palm (*Bactris gasipaes*) plantation
Citrus plantation	18	Citrus (*Citrus sp.*) plantation
Black pepper plantation	19	Black pepper (*Pipper nigrum*) plantation
Passion fruit plantation	20	Passion fruit (*Passiflora edulis*) plantation
Annual crop	21	Areas with annual crops: cassava (*Manihot sculenta*), maize (*Zea mays*), rice (*Oryza sativa*), beans (*Vigna unguiculata*)
Miscellaneous	22	Combination of soil, trees, constructions and homegarden; these areas are mainly located near to the farmhouses.
Land preparation	23	New cleared area where trees still remain on the soil surface drying (no burning)
Burned area	24	Area recently burned in grassland areas or in previously slashed fallows
Bare soil	25	Area exposed without vegetation cover; this class includes roads, land preparation, mine areas and bare soil near to houses
Large shed	26	Large building, e.g, shed or important house, which can be easily discriminated from miscellaneous and bare soil classes
Swamp cover	27	Swamp area or water pool covered by aquatic vegetation
Water body	28	Free water lakes, pools and streams
Shadow	29	Cloud shadow
Cloud	30	Cloud

5.3.4 Biomass and carbon stock in farms

Biomass and carbon stock per farm was estimated based on the combination of size and distribution of farms and the biomass and carbon stock in different land covers.

Information about the farm size was obtained from a scanned product of the land properties map of the settlement São Luis provided by the Instituto de Terra do Pará (ITERPA), scale 1:50,000, year 1979 (ITERPA, 1979), which was georeferenced and vectorized. This product was overlapped with the composition RGB 1 m resolution of the Ikonos images, and the property boundaries were adjusted to the distribution of cropped areas and the demarcations of new farms discernable in the image. Digitizing was performed with the ARCVIEW 3.2 package using an image-display scale of 1:5000. The final product is a map that adjusts to limits used by farmers to divide the productive units (farm areas used by farmers for agriculture activities and for maintaining secondary forest) in the years 2002/2003. These limits do not indicate legal farm property boundaries. In several cases, farms were not coincident to and as regular as the borders of the properties marked in the ITERPA map. A common situation observed among properties was that during clearing and agricultural activities, farmers use to use their neighbors' land or adjusted farm borders to natural elements, like riparian vegetation, or to new roads or joined several plots to form a bigger productive farm (Figure 9.1 in Appendix 2). Tippmann (2000) also observed irregularities in land property demarcation in Igarapé Açu, where many farmers had joined land according to arrangements instead of legal borders. As the study area of 100 km^2 does not include the entire settlement, some farms were completely excluded or partitioned. Only those farms that are completely inside the demarcation of the study area were used for the analyses. Farms were classified by size, with only one original plot (~1000 mx250 m, 1000 mx200 m or others) or more than one.

Farmers specialize in diverse productive activities with different land-use intensities based on farm size and economic facilities, thus influencing the distribution of the different land-cover types and the proportion of secondary forest or primary forest remaining on the farms. The land-cover classification with the associated values of biomass and carbon content was overlaid with the layer of the farm units using the ARCVIEW 3.2 package in order to estimate and characterize the potential of farms to sequester atmospheric carbon.

5.3.5 Carbon sequestration project

In the present study, an economic calculation was performed regarding to the success of carbon sequestration projects in the study area if secondary vegetation resulting from revegetation and cropland management activities is assumed as a sink under the CDM framework.

During the Seventh Conference of Parties (COP 7) to the United Nations Framework Convention on Climate Change (UNFCCC), the Marrakesh Accord was signed. Here, activities such afforestation, reforestation, deforestation, revegetation, forest management, crop management and grazing land management were identified under the land-use, land-use change and forestry sector as mechanisms for the removal of greenhouse gases (GHG). In the first commitment period agreed in the Kyoto Protocol (UNFCCC, 1998), activities other than afforestation and reforestation do not classify as removals units for sinking GHG under the Clean Development Mechanism (CDM). The inclusion of the rest of activities in future commitment periods shall be decided as part of the negotiations on the second commitment period (UNFCCC, 2001).

According to the Decision 19/CP.9 of the COP to the UNFCCC (UNFCCC, 2004), two kinds of certificates of certified emission reduction (CER) in afforestation and reforestation projects under the CDM are possible: temporary CERs (tCERs), and long-term CERs (lCERs). The first will be issued to projects with a maximum crediting period of 20 years, which may only be renewed twice. The second corresponds to a single period of up to 30 years. In both cases, the emission of certificates will be in 5-year intervals until the end of the crediting period. The tCER corresponds to the net antropogenic greenhouse gasses removed by the sinks in the project since the start of the project, while a lCER refers to the increase in the carbon stocks between two consecutive certification periods.

The economic calculation compared the current annual income per farm from agricultural product with the amount to be received through the sale of carbon credits as lCERs. The analysis was performed in 2 main scenarios based on different carbon credit prices and on the following assumptions:

- the proportion in area assigned to the project corresponds to the average extension of secondary vegetation stands in the average farm area,
- the farm area used in agricultural production is the area no covered with secondary vegetation,
- carbon uptake rates were calculated based on information provided by Denich et al. (2000) and the average of annual carbon uptakes rates. The latter were calculated from the differences in predicted carbon stock values per hectare per year. These predictions were obtained from the application of equation 4.5.4.b from section 4.5.4, and ages were calculated using the equation Age = 2.0111 + 1.3623 AHH (section 3.4.2, Figure 3.5),
- the project costs is assumed to be equal to 0 US$, the interest rate equals to Prime (May 31, 2005) and the issuance of carbon credit every 5 years.

In both scenarios, the economic benefit through certification of CO_2 uptake was tested at 10, 20 and 30 years after the project started compared to the opportunity costs that farmers will have if the land is used in the traditional agriculture system.

In addition to the previous assumptions, it is important to be aware that the economic analyses of both scenarios are not conform to the calculation procedures necessary for presentation of an afforestation/reforestation CDM project activity and that investor companies/entities need to be found that are willing to pay the high prices for the carbon credits.

5.4 Results

5.4.1 Land-cover classification

The 30 land-cover classes identified in the images of the 100 km^2 study area varied from some few hectares to more than 1700 ha. Secondary vegetation covered 51.4 % of the study area, showing all stages of secondary succession. This value is almost coincident to the prediction of the fallow-cover reduction by 3 % yr^{-1} by Metzger (2002), and to the area of secondary vegetation estimated by Watrin (1994) for the year 1991 and by Sampaio et al. (1998) for the year 1995 using of satellite images. In the studa area, "Low secondary forest from 2-4 m" represented 34 % of the secondary vegetation area, pastures covered 19.4 %, permanent and semi-permanent crops 8.2 %, annual crops 5.3 % and bare soil in burned and land preparation areas 6.5 %. The 5 largest land-cover classes were "Low secondary forest 2-4 m" (17.5 %), "Grass irregular" (13.0 %), "Low secondary forest 4-6 m" (9.7 %), "Initial secondary succession" (9.2 %) and "Medium secondary forest 6-10 m" (7.5 %) (Table 5.4). High, medium and low secondary forest higher than 2 m covered 42 % of the study area.

Table 5.4 Land-cover types, area and representativeness in study area (100 km^2), municipality of Igarapé Açu, Bragantina region, Brazil

Class No	Class name	Area (ha)	Area (%)
1	Remaining riparian forest	720.2	7.3
2	High secondary forest >20 m	38.5	0.4
3	High secondary forest 15-20 m	108.7	1.1
4	Medium secondary forest 10-15 m	594.2	6.0
5	Medium secondary forest 6-10 m	742.1	7.5
6	Low secondary forest 4-6 m	962.8	9.7
7	Low secondary forest 2-4 m	1731.0	17.5
8	Initial secondary succession	915.2	9.2
9	Burned forest	83.3	0.8
10	Grass irregular	1290.1	13.0
11	Grass regular	631.5	6.4
12	Forest plantation	24.9	0.3
13	High oil palm plantation	72.1	0.7
14	Medium oil palm plantation	250.2	2.5
15	Low oil palm plantation	183.3	1.9
16	Coconut palm plantation	23.8	0.2
17	Pupunha plantation	11.0	0.1
18	Citrus plantation	23.9	0.2
19	Black pepper plantation	221.2	2.2
20	Passion fruit plantation	25.3	0.3
21	Annual crop	525.1	5.3
22	Miscellaneous	41.2	0.4
23	Land preparation	140.7	1.4
24	Burned area	194.8	2.0
25	Bare soil	309.1	3.1
26	Large shed	1.2	0.0
27	Swamp cover	6.6	0.1
28	Water body	1.5	0.0
29	Shadow	11.4	0.1
30	Cloud	18.8	0.2
Total		9903.5	100.0

Riparian forest covered 7.3 %. This value is coincident with the estimation did by Sampaio et al. (1998) in an area larger than that of the present study; however, it is higher than the estimation of Watrin (1994) for the entire municipality, and lower than the value (13 %) calculated by Wickel (2004) for an area larger than the present study area, the main differences being size and location of the study areas. The proportion of riparian forest decreases to 7.1 % when the area studied by Wickel (2004) is adjusted to the present study area. Watrin (1994) and Wickel (2004) used Landsat images with 30 m resolution and both produced results with misclassification; the classification of Watrin (1994) did not include small forest stands along small creeks as riparian forest, while in Wickel's classification secondary forest and riparian forest were confused.

The agricultural area (including pasture, permanent, semipermanent and annual crops, and areas with land preparation or burned) covered 36.6 % of the study area. This estimation is coincident with IBGE (2005b) statistics and close to that of Wickel (2004) for his classification performed with a Landsat image year 2001, when the 3 % yr^{-1} increase in agriculture area (Metzger, 2002) is added. On the other hand, the area is 35 % larger than that calculated by Watrin (1994) in the assessment for 1991, even when reducing the estimation by 3 % yr^{-1}. Among the agricultural covers, pasture covers almost 53.1 % of the agricultural area followed by annual crops with 14.5 %, oil palm plantations with 14 %, black pepper with 6.1 %, passion fruit 0.7 %, citrus 0.7 %, coconut palm 0.7 % and pupunha 0.3 %. Wickel (2004) did not distinguished annual crops, and it seems they were included in one of the pasture classes; when both classes are summed, the estimation corresponds to the area occupied by the pasture and crop classes identified in the present research.

Semipermanent and permanent crops according to Hedden-Dunkhorst et al. (2003) and Watrin (1994) have increased in area during the last years. In this research, oil palm plantations covered 5.1 %, while semipermanent crops of passion fruit and black pepper, and associated plantations-crops with coconut palm, citrus and pupunha cover 3.1 % of the study area of 100 km^2. The percentage of annual and semipermanent crops sampled in this study covers an area 5 % larger than the estimation by Watrin (1994), and initial secondary succession is 14.7 % lower than in his assessment. Two possible answers to these differences can be found in the increase of area under agriculture in areas previously occupied by initial secondary vegetation or in a misclassification of annual crops such as cassava or corn, mistaking these for initial secondary succession when the satellite image of 1991 was used.

Figure 9.2 in Appendix 2 contains the land-cover map generated with eCognition 4.0 and Arcview 3.2. The classification accuracy was tested by means of a mask of land covers generated from GPS points. The overall accuracy as well as the Kappa value (Congalton et al., 1983) were higher than 0.91; this value shows the consistence of the classification in the study area. The main confusions were among the secondary vegetation classes. “Low secondary forest 4-6 m” (Class 6) showed the lowest precision per class (0.62) and “Medium secondary forest 10-15 m” (Class 4) the highest (0.91). “Remaining riparian forest” and “High secondary forest >20 m” were excluded from the precision analysis due to the use of different recognition methods and the lack of GPS points from fieldwork, respectively (Table 5.5).

5.4.2 Land covers on farms

The settlement Jambú Açu was originally demarked in lots of 25 ha; many of the farm divisions had changed with time due to the creation of new roads, boundaries or the merging of neighboring lots to form large farms.

The average size of the 241 selected farms (those that are fully included in the study area was 35.8±32.8 ha (mean±SD). The main changes observed in farm sizes are due to the combination of lots to create larger productive units; almost 20 % of the farms are made up of such aggregated lots and covered 45.2 % of the total area cover by farms full included in the 100 km^2 study area (86.2 km^2), the largest farm covering 253.4 ha, averaging 82.9±51.4 ha. The largest farms were dedicated mainly to cattle farming and oil palm plantations. Farms with a single lot covered 54.8 % of the study area with an averaged size of 24.3±5.9 ha. This is on average 3 ha smaller than the size estimated by Ferreira et al. (2000) for smallholders in the municipality of Igarapé Açu. On the other hand, Hedden-Dunkhorst et al. (2003 and 2004) indicated that smallholders reduced the farm size by continued splitting of land among different descendants. This situation was also observed by Mendoza-Escalante (2005) but it was not possible to detect this in the present research, since the new families mainly share the land with relatives, and there were not clear divisions that could be identified in the satellite images.

Table 5.5 Classification accuracy for 28 land-cover classes using a combination of Ikonos images (22/10/2002 - 27/11/2003) and a mask of GPS points of different land covers in a study area of 100 km^2 in the municipality of Igarapé Açu, Bragantina region, Brazil

User\Reference Class No.	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	Sum
3	57	6																											63
4	24	322																									34		380
5		22	231	8																									261
6			72	170	31																								273
7			7	76	344																								427
8				10	25	116		4																		1			156
9						3	84																						87
10						20		219	71															1					311
11									193																				193
12										130																			130
13											415																		415
14												258																	258
15													230																230
16														93															93
17															60														60
18																91													91
19																	134												134
20																		126											126
21																			249										249
22																				104									104
23																					93								93
24																						130							130
25																							72						72
26																								15					15
27																									24				24
28																										18			18
29																											411		411
30																												142	142
Unclassified	81	350	310	264	400	139	84	223	264	130	415	258	230	93	60	91	134	126	249	104	93	130	72	16	24	19	445	142	
Producer accuracy	0.70	0.92	0.75	0.64	0.86	0.83	1	0.98	0.73	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0.94	1	0.95	0.92	1	
User accuracy	0.90	0.85	0.89	0.62	0.81	0.74	0.97	0.70	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
KHAT per class	0.70	0.91	0.73	0.62	0.85	0.83	1	0.98	0.72	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0.94	1	0.95	0.92	1	
Overall accuracy	0.91																												
KHAT (Kappa analysis)	0.91																												

In the study area, 42.32 %, 52.7 % and 4.98 % of the farms were smaller than 25 ha, between 25 and 100 ha and bigger than 100 ha, respectively. These values differ from the estimation of Sousa Filho et al. (1999b), who estimated 59 % in the first size category, 37.4 % for intermediate farm sizes and 3.6 % for the largest farms. The differences express the increase in aggregation of lots on the farms.

Not all land covers are present on all farms, some gaining importance in a specific farm size. The extension of patches of different land covers also varies from farm to farm and according to the productive system of the farm.

Secondary vegetation higher than 2 m covered in average 47 % of the farm areas and 52.2 % when initial-secondary-succession vegetation was included. The latter value is 6 % lower than the estimation obtained by Hedden-Dunkhorst et al. (2004) in three municipalities in the Bragantina region, and 12 % less than that calculated for Igarapé Açu based on interviews. Agriculture cover extended to 32.9 % of the farm area, unprotected soil areas (bared soil, land preparation and burned areas) covered 5.9 % and uncontrolled burned forest as much as 0.9 % of the farm area. The values change when the presence or not of lot aggregation in the organization of the farm is considered. While agricultural area reduced to 25 %, secondary vegetation, bare soil area and uncontrolled burned forest increased to 60.8 %, 7.1 % and 1 %, respectively, on farms with unaggregated lots. On the other hand, on farms with aggregated lots, these land covers covered 42 %, 41.7 %, 4.5 % and 0.8 % of the farm area, respectively (Table 5.6).

Table 5.6 Variation of percentage of land covers according to size of productive units in the study area of 100 km^2 in the municipality of Igarapé Açu, Bragantina region, Brazil

Land cover	All farms	Farms with unaggregated lots	Farms with aggregated lots
Secondary forest + initial secondary succession	52.2	60.8	41.7
Agriculture	32.9	25.0	42.6
Bare soil	5.9	7.1	4.5
Uncontrolled burned forest	0.9	1.0	0.8
Other land covers	8.1	6.2	10.4

The areas with long fallow periods that corresponded to secondary forest stands higher than 10 m increased from 1.9±2.8 ha on farms with unaggregated lots to 6.3±11.1 ha on farms with aggregated lots. Among farms with long fallows of the three higher secondary forest classes (high secondary forest >20 m, high secondary forest 15-20 m and medium secondary forest 10-15 m), were found in 42.6 %, 57.4 % and 95.7 %, respectively, of the aggregated farms. In contrast, 20.1 %, 45.4 % and 90.2 %, respectively, were calculated for farms with unaggregated lots. These values indicate that long fallow periods and very high stands are more frequent on large farms as already observed by Metzger (2003), nevertheless patches represent in proportion the same area of the farm area, i.e., 7.6 % and 7.7 % for aggregated and unaggregated farms, respectively. On the other hand, the vegetation type of "Initial secondary succession" varied with farm size, being 9.2 %, 9.5 % and 8.9 % for all farm sizes, farms with aggregated lots and unaggregated lots, respectively. These values indicate that this vegetation type is intensively slashed, burned and cropped on small farms, where thus more of the secondary vegetation as low secondary forest is concentrated, while on aggregated farms, after several years of intense use the land becomes degraded. The area is then abandoned and secondary vegetation invades the land (Hohnwald et al., 2000).

5.4.3 Carbon sequestration potential

Landscape level

In the study area of 100 km^2, 5092 ha (51 %) were covered by secondary forest higher than 2 m and initial secondary succession, which accumulated a dry aboveground biomass of 203,228 t and had a carbon stock of 101,614 t. Land covers such as grass, oil palm and semipermanent and annual crops accumulated 7030, 7183 and 2603 t C, respectively. In total, for the dates 2002/2003 these land covers assimilated 118,431 t C.

The estimation of carbon sequestration in the municipality gaves a carbon stock of 765,086 t for secondary vegetation and 808,818 t C together with some agricultural land covers (grass, black pepper, passion fruit, annual crops and oil palm). Total sequestration in the region amounted to 8.17 Mt C for secondary vegetation and more than 9.3 Mt C for all land covers (Table 5.7).

Table 5.7 Biomass and carbon stock in the aboveground biomass of the most common land covers in three study areas: 100 km^2 area, the municipality of Igarapé Açu and the Bragantina region, Brazil, for the years 2002/2003

Study area	Land cover	Area (ha)	% of area	Biomass (t)	Carbon (t)
Study area (100 km^2)	Secondary vegetation	5092	50.9	203228	101614
	High secondary forest	147	1.5	23680	11840
	Medium secondary forest	1336	13.4	106916	53458
	Low secondary forest	2694	26.9	67141	33571
	Initial secondary succession	915	9.2	5491	2746
	Grass	1922	19.2	15623	7030
	Oil palm	506	5.1	14366	7183
	High oil palm	72	0.7	4169	2084
	Medium oil palm	250	2.5	9182	4591
	Low oil palm	183	1.8	1016	508
	Semipermanent and annual crops	772	7.7	5510	2603
	Black pepper	221	2.2	2344	1172
	Passion fruit	25	0.3	132	66
	Annual crops	525	5.3	3034	1365
	Total	8292	82.9	238727	118431
Igarapé Açu (786 km^2)	Secondary vegetation	37761	48.0	1530171	765086
	High secondary forest	978	1.2	155719	77859
	Medium secondary forest	8879	11.3	748516	374258
	Low secondary forest	21822	27.8	589449	294724
	Initial secondary succession	6081	7.7	36488	18244
	Grass	16961	21.6	22230	10004
	Oil palm	1400	1.8	39779	19889
	High oil palm	200	0.3	11543	5772
	Medium oil palm	693	0.9	25423	12712
	Low oil palm	508	0.6	2812	1406
	Semipermanent and annual crops	5320	6.8	30718	13839
	Black pepper	3	0.0	32	16
	Passion fruit	54	0.1	282	141
	Annual crops	5262	6.7	30404	13682
	Total	61441	78.2	1622899	808818
Bragantina (8710.7 km^2)	Secondary vegetation	388503	44.6	16351396	8175698
	High secondary forest	11231	1.3	1787773	893887
	Medium secondary forest	101941	11.7	8593548	4296774
	Low secondary forest	205512	23.6	5551162	2775581
	Initial secondary succession	69819	8.0	418913	209456
	Grass	185257	21.3	1730250	778613
	Oil palm	10808	1.2	307109	153555
	High oil palm	1540	0.2	89118	44559
	Medium oil palm	5348	0.6	196279	98140
	Low oil palm	3919	0.4	21712	10856
	Semipermanent and annual crops	77149	8.9	445946	200959
	Black pepper	138	0.0	1462	731
	Passion fruit	808	0.1	4201	2101
	Annual crops	76203	8.7	440283	198127
	Total	661717	76.0	18834701	9308824

The amount of carbon accumulated by aboveground biomass of secondary vegetation in the Bragantina region is equivalent to only 5.6 % of the total carbon liberated by substitution of the original primary forest (Salomão, 1994).

Secondary vegetation cover increased from 45 % to 50 % when the size of the study area decreased. Nevertheless, base on the current extension and proportion of secondary forests and initial secondary succession, the storage of carbon per unit in the aboveground biomass of the stands in the landscape of the three studies areas was similar, with values between 9.3 and 10.1 t C ha^{-1}.

Farm level

The capacity of farms to serve as sinks of atmospheric carbon depends on the types and areas of land cover present on the farms and the life cycle of the covers. Among farms that had covers of secondary forest, initial secondary succession, pasture, oil palm, semi-permanent crops of pepper or passion fruit or annual crops, the average size of patches of the land-cover classes varied from more than 0.6 ha for "High secondary forest >20 m" to almost 14.7 ha for "Medium oil palm" (Table 5.8). Secondary forests lower than 4 m showed the highest value after oil palm in area per farm followed by grass. These values express the dominance of low secondary forest in productive units (Metzger 2003); however as was previously observed for aggregated farms, the increase in agricultural activities is based mainly on cattle farming and oil palm plantations (section 5.4.2), which require large areas of farm land.

The estimation of patch sizes for secondary forest are higher than those calculated by Metzger (2003) in the same region using Landsat TM images for young and old fallow (younger and older than 6-years old, respectively): as much as 4-fold when stands are lower than 4 m and 2- fold in stands > 4m. Height ranges were calculated based on height provided by the equation AHH = -0.0007 + 0.6274 Age (Chapter 3, section 3.4.2, Figure 3.6).

Table 5.8 Estimated biomass and carbon storage of different land covers in the average area of patches on farms in a study area of 100 km^2, municipality of Igarapé Açu, Bragantina region, Brazil

Land cover	Average area (ha)	SD	Potential C uptake (t ha^{-1})	Aboveground biomass per average patch size (t)	Aboveground carbon per average patch size (t)
High secondary forest >20 m	0.6	1.3	90.1	110.4	55.2
High secondary forest 15-20 m	0.8	1.8	77.0	126.0	63.0
Medium secondary forest 10-15 m	2.4	4.2	51.8	249.3	124.7
Medium secondary forest 6-10 m	2.8	3.7	30.6	171.1	85.6
Low secondary forest 4-6 m	3.5	4.5	17.6	124.1	62.0
Low secondary forest 2-4 m	6.4	6.0	9.6	123.4	61.7
Initial secondary succession	3.3	4.7	3.0	19.8	9.9
Grass irregular	4.8	11.6	3.1	33.1	14.9
Grass regular	3.0	8.0	4.8	32.3	14.5
High oil palm plantation	5.9	10.8	28.9	340.4	170.2
Medium oil palm plantation	14.7	22.9	18.3	537.2	268.6
Low oil palm plantation	7.3	17.5	2.8	40.6	20.3
Black pepper plantation	2.7	6.2	5.3	28.1	14.1
Passion fruit plantation	0.8	1.1	2.6	4.1	2.1
Annual crops	2.5	3.2	2.6	14.4	6.5

Table 4.8 also shows the contribution to the carbon sequestration by each land cover using their average extension in the farms: “Medium secondary forest 10-15 m” can accumulate the highest amount of carbon (124.7 t C) among secondary forest classes on the farms. “Medium oil palm” shows the maximum carbon accumulation (268.6 t C), however in an area 6.1 times larger, followed by “High oil palm” (170.2 t C), “Medium secondary forest 10-15 m” (124.7 t C), and “Medium secondary forest 6-10 m” (85.6 t C). For the same unit area, the “High secondary forest >20 m” can accumulate 9.4 times more carbon than the “Low secondary forest 2-4 m” and 1.2, 3.1, and 34.7 times more than “High secondary forest 15-20 m”, “High oil palm” and “Annual crop”, respectively.

A hypothetic farm of average size (35.8 ha) and land-cover distribution equals to the proportions and types found for all farms can assimilate 433.8 t C among most of the most common land covers and 374 t C in the biomass of secondary vegetation (Table 5.9).

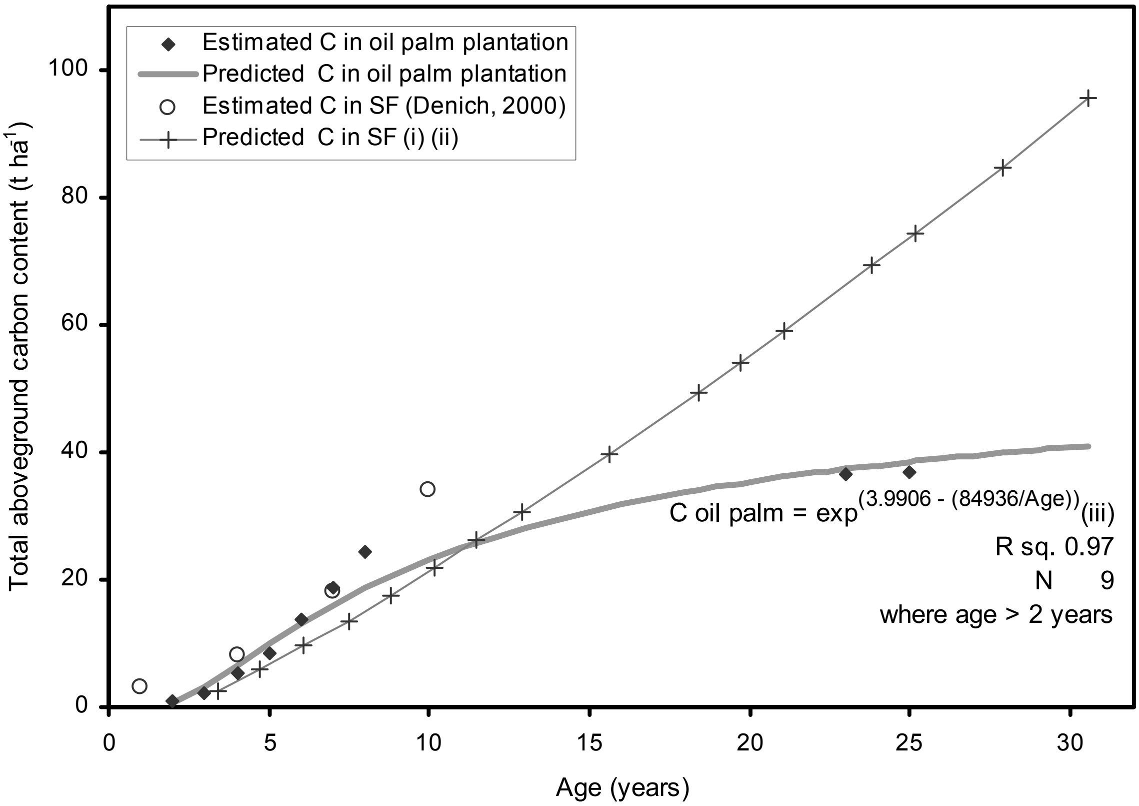
Table 5.9 Estimated carbon (C) storage in different land covers in a hypothetic farm of average size from a study area of 100 km^2, municipality of Igarapé Açu, Bragantina region, Brazil

Land cover	% of farm area	Area (ha)	Potential C uptake (t ha^{-1})	Total C uptaked (t)
High secondary forest >20 m	0.4	0.2	90.1	13.5
High secondary forest 15-20 m	1.1	0.4	77.0	30.1
Medium secondary forest 10-15 m	6.1	2.2	51.8	113.9
Medium secondary forest 6-10 m	7.6	2.7	30.6	83.5
Low secondary forest 4-6 m	9.8	3.5	17.6	61.6
Low secondary forest 2-4 m	17.9	6.4	9.6	61.8
Initial secondary succession	9.2	3.3	3.0	9.9
Grass irregular	13.1	4.7	3.1	14.5
Grass regular	5.7	2.1	4.8	9.8
High oil palm plantation	0.8	0.3	28.9	7.8
Medium oil palm plantation	2.4	0.9	18.3	15.6
Low oil palm plantation	2.0	0.7	2.8	1.9
Black pepper plantation	2.4	0.9	5.3	4.6
Passion fruit plantation	0.2	0.1	2.6	0.2
Annual crop	5.6	2.0	2.6	5.2
Others	15.7	5.6		
Total	100	35.8		432.1

Secondary vegetation on average extends over 52.2 % of the average farm area which represents about 18.6 ha and the farm can potentially accumulate 10.5 t C ha^{-1} in secondary forest only. This value is higher than the value calculated by Tippmann (2000) (7 t C ha^{-1}) for secondary vegetation on a farm of 56 ha in the municipality of Igarapé Açu.

Among land-cover types, the major potential to store carbon on the average-sized farm is secondary vegetation followed by oil palm plantations. On the average farm, the latter accumulate more than 25.3 t C. Oil palm plantations showed a higher rate of carbon accumulation during at least the first decade after plantation compared to secondary forest when prediction models for age and biomass of secondary forest are used; nevertheless, the values reported by Denich (2000) for carbon stock in secondary forest arranged close and higher than predictions in oil palm (Figure 5.3).

Using the predictive equation of carbon sequestration in oil palm plantations developed for Indonesia sites (Syahrinundin, 2005), the calculations suggest that secondary forest will requires up to 15 years to reach the carbon uptake of oil palm stands. However, after 11 years, carbon sequestration by secondary forest exceeded that of oil palm, as the life-time of this land cover is longer, leading to assimilation of a larger amount of carbon over time.



(i) Carbon uptake of secondary forest calculated as a fraction of 0.5 of total live tree aboveground biomass predicted with Equation 4.5.4.b from Chapter 4, section 4.5.4.
(ii) Age of secondary forest predicted with equation Age = 2.0111 + 1.3623 AHH from Chapter 3, section 3.4.2, Figure 3.5.
(iii) Growth model of oil palm plantations based on data from Khalid et al. (1999), Nordin (2002), Rodrigues et al. (2000), Syahrinundin (2005) and Viegas (1993).

Figure 5.3 Relation of carbon (C) stock in the aboveground biomass of oil palm plantation and secondary forest along the time in northeast Pará state, Brazil

5.4.4 Economic benefits from the sequestration of carbon

The results of the economic analysis from the sequestration of carbon show that when 52 % of the farm area (current percentage of area in the average farm covered by secondary vegetation) is allocated to a CDM project, this can provide the same income as that the obtained from agricultural products by 48 % of the farm area (~ US$ 163 ha^{-1} yr^{-1}) in the municipality of Igarapé Açu (Mendoza-Escalante, 2005); income excludes the contribution of fallow products. This can be achieved only when the price per ton CO_2 within the framework of CDM projects for reforestation and afforestation project is higher than US$ 13.6 for the three study periods (Table 9.2a in Appendix 2). In the second scenario, the price per ton CO_2 was US$ 5.63. This price corresponds to that of the first quarter of 2005 for CDM projects (Lecocq and Capoor, 2005). The benefits of the project at 10, 20 and 30 years can represent up to 41 %, 42 % and 42 %, respectively, of the farm income from agricultural products (Table 9.2b in Appendix 2).

Even though these exercices show that the economic benefits by fixation of CO_2 can add important surplus to current annual income on the average farm, the situation in reality is different, the prices for lCER are expected to be lower than the prices of CER of other CDM activities as the carbon in afforestation/reforestation projects is not permanentally stored (Subak, 2003) and carbon credits have to be replace after they expire. The project has operative costs, which were not included in the analysis. Furthermore, many of the assumptions may not remain the same over time. On the other hand, the success of the returns through revegetation/cropland management projects will also depend on the capacities of farmers to leave the vegetation untouched during each certification period.

5.5 Conclusions

The land partitioning designed 100 years ago was not longer valid on the dates of the applied satellite images, and the farm borders had adjusted to new roads, water sources and new productive units. On average, farm size had increased by 10 ha as a consequence of the merging of plots.

In the study area of 100 km^2 vegetation from secondary succession covered more than 50 %, but only 42 % was covered by secondary forest higher than 2 m. Most of the agricultural land was occupied by pasture. Secondary vegetation reduced with increasing study area size. This indicate that the intensification of land use based on extensive farming practices such as cattle grazing are more common in the Bragantina region than in the study area of 100 km^2. Although secondary vegetation covered a considerable part of the agricultural landscape, the current distribution of secondary vegetation can only accumulate a small fraction of the carbon emitted by deforestation of the original forest. Its contribution to sequestration of atmospheric carbon is low, due to the large proportion of low secondary forest and initial secondary succession on areas that are intensely slashed and burned.

Conservation and enhancement of areas with medium and old secondary forest will substantially increase the accumulation of carbon in the vegetation.

Under the assumption that half of the average farm area is assigned to a project of carbon sequestration by secondary vegetation for at least a period of 10 years, a farmer could expect additional income per farm similar to that achieved by agricultural activities (crops, cattle). However, the price per ton CO_2 within the framework of CDM projects needs to remain on the current level or increase in order to provide an incentive to farmers to preserve secondary forest. The protection of secondary vegetation for at least two certification periods will replenish the nutrients in soil and vegetation and at the same time provide benefits through CO_2 sequestration. On the other hand, diversification of farm products and avoidance of intensive agriculture will reduce pressure on land and guarantee farm income while achieving additional benefits resulting from the conservation of secondary forest areas.

Among the land covers, oil palm plantations showed the highest efficiency in the accumulation of carbon during at least the first 11 years after plantation establishment compared to secondary forest. The advantage of secondary forest as an atmospheric carbon sink can only be achieved under longer fallow periods.

6 FINAL CONCLUSIONS

Secondary vegetation in the municipality of Igarapé Açu as well as in other areas in the Bragantina region, state of Pará, Brazil, is decreasing in area due to continued intensification of land use. The shorter fallow periods have been shown to be insufficient to recover losses in productivity caused by slash-and-burn and agricultural activities. Improved management of secondary vegetation to gain the benefits associated with carbon sequestration is, therefore, called for.

Only a small fraction of carbon released by substitution of the primary forest cover was stored in the aboveground biomass of the different land covers of the region. Carbon sequestration can be enhanced in the landscape and on the farms if the proportion of long fallows increases.

Projects that include secondary vegetation as a sink of greenhause gases are a promising alternative for farmers to increase their farm income, ensure conservation of soil and plant communities, and carbon sequestration. However, activities which manage revegetation and cropland in old agriculture systems, as the one in the Bragantina region, should be included in the next commitment period after 2012 within the framework of CDM projects to allow secondary vegetation to count as removal units for sinking carbon. To ensure successful carbon sequestration, future projects should also provide incentives to farmers to diversify farm income through the introduction of new production activities that avoid removal of secondary vegetation.

Permanent cash crops such as oil palm can accumulate the same and even higher carbon amounts per unit area than secondary forest in the first 11 years, but after this secondary forest has a comparative advantage as sequestration becomes more efficient.

Since the average wood density of the tree species in the region is higher than the average value for many other areas in the Amazon region, the prediction of biomass using models generated with information on the average wood density of moist tropical forest without any differentiation of variation of wood density by regions will, without doubt, underestimate the biomass and carbon sequestration potential of secondary forest stands in Eastern Amazonia.

In the present study, 30 years after land abandonment the secondary forest had developed a multi-strata structure of around 20 m total average height and accumulated 94 t ha^{-1} of carbon in the dry biomass in live and standing dead trees and litter layer.

Secondary forest is not just organized as a group of fast growing trees of small diameter and small individual volume, but is a complex system that includes a wide spectrum of tree arrangements, where big and small trees compete for space and resources and where an important species replacement dynamics is present along forest growth.

The methodology used in the present research shows that the biomass and the carbon stock of the entire stand could be estimated by the average height of selected trees in the highest canopy stratum. Repetitive measurements of tree height over time should be useful to determine differences in height and thus to estimate the increment in biomass and carbon of secondary forest.

Considering the diversity of the study areas and stands of secondary forest surveyed in the region in previous studies, the estimation of biomass by average height of the highest canopy stratum showed values close to those determined in many studies. Nevertheless, an average subestimation of 4.6 % compared with the method based on the diameter of trees could be observed.

Many municipalities in the Bragantina region have similar climatic conditions, soil properties, trees species, land-use history and practices to those of the municipality of Igarapé Açu. Other regions in moist tropical forest should verify site conditions, average wood density and history of land-use practices to apply the equations proposed in Chapters 3 and 4. The equations should be applied within the range of the heights, diameters and ages studied here.

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8 GLOSSARY

Biomass	Total amount of aboveground living organic matter of trees and undergrowth expressed as oven-dry tons per unit area (Brown, 1997)
Canopy	Group of crowns of a forest stand organized as a single stratum or multiple strata
Dead wood	Includes all dead woody biomass not contained in the litter, either standing or lying on the soil surface, dead roots and stumps larger than or equal to 10 cm in diameter or any other predefined diameter (IPCC 2003)
Fallow period	Rest period on land without agricultural activities
Fallow vegetation	Spontaneous vegetation that grows in areas during the fallow period
Litter	Includes all dead biomass with a diameter less than a predefined minimum diameter lying on the ground in various states of decomposition above the mineral or organic soil level expressed as weight per unit area (IPCC, 2003)
Live tree aboveground biomass	Dry biomass provided by the aerial part of live trees and expressed as weight per unit area
Plot	Corresponds to the area where a forest stand develops and where samples and measurements are collected
Sapling	Small trees higher than 2 m and with a diameter smaller than 5 cm in at breast height (1.30 m)
Secondary forest	Forest generated in secondary succession after changes caused by natural events or human activities in areas originally covered by primary forest
Secondary succession	Sequential changes in the tree species composition during growth of vegetation after colonization of a perturbed area previously covered by primary forest

Secondary vegetation	Vegetation types growing in secondary succession over long or short periods of time
Top height	Total height of those trees in the uppermost stratum in the canopy. These trees have crowns totally or partially exposed to sunlight
Total aboveground biomass	Dry biomass comprising aerial part of live and dead trees, undergrowth, and litter expressed weight per unit area

9 APPENDICES

Appendix 1:

Table 9.1 Forest stand characteristics based on the average height of selected trees in the different strata (AH), basal area per strata (BA), number of stems per strata and frequency of species per strata in 35 plots of secondary forest in the municipality of Igarapé Açu, Bragantina region, Brazil

Plot	Canopy stratum	AH (m)	BA (m^2)	Stems (No. ha^{-1})	Species and frequency
15	Highest	19.13	17.37	608	*Eschweilera coriacea (1), Inga heterophylla (2), Tapirira guianensis (2), Terminalia amazonica (1)*
15	Intermediate	11.88	2.37	464	*Maprounea guianensis (2), Myrcia cuprea (4)*
15	Lowest	7.55	4.06	3328	*Byearsonima aerugo (1), Myrcia cuprea (1), Palicourea guianensis (3), Swartzia brachyrachis (1)*
15	Dead trees		0.37	48	
18	Highest	18.60	19.38	512	*Abarema jupunba (2), Emmotum fagifolium (1), Miconia guianensis (1), Nectandra cuspidata (1), Tapirira guianensis (1)*
18	Intermediate	13.80	5.15	1056	*Inga thibaudiana (1), Lacistema pubescens (2), Maytenus myearsinoides (1), Pogonophora schomburgkiana (1), Virola calophylla (1)*
18	Lowest	6.80	1.62	2672	*Aspidosperma excelsum (1), Guatteria poeppigiana (1), Lacunaria crenata (1), Neea oppositifolia (1), Siparuna amazonica (1), Siparuna guianensis (1)*
18	Dead trees		1.29	352	
1	Highest	18.41	21.18	1024	*Abarema jupunba (1), Chamaecrista apoucouita (1), Inga heterophylla (2), Tapirira guianensis (2)*
1	Intermediate	8.85	6.46	2752	*Cordia exaltata (1), Lacistema pubescens (2), Lecythis lurida (2), Palicourea guianensis (1)*
1	Dead trees		1.48	448	
23	Highest	17.74	18.18	1000	*Guatteria poeppigiana (1), Ocotea opifera (4), Ormosia paraensis (1)*
23	Intermediate	9.22	5.09	1425	*Eugenia guianensis (1), Guatteria poeppigiana (2), Lecythis lurida (1), Myrciaria tenella (1), Pogonophora schomburgkiana (1)*
23	Lowest	4.61	1.61	3850	*Casearia javitensis (1), Eugenia coffeifolia (1), Eugenia flavescens (1), Myrciaria tenella (3)*
23	Dead trees		1.78	525	
16	Highest	16.43	14.95	752	*Balizia elegans (1), Byearsonima aerugo (1), Inga heterophylla (1), Myrcia cuprea (1), Tapirira guianensis (2)*
16	Intermediate	11.06	8.79	1664	*Eschweilera coriacea (1), Guatteria schomburgkiana (1), Maprounea guianensis (1), Margaritaria nobilis (1), Myrcia cuprea (1), Ouratea cataneaeformis (1)*
16	Lowest	7.66	1.97	2192	*Annona montana (1), Heisteria densifrons (1), Inga fragelliformis (1), Myrcia cuprea (2), Myrcia falax (1)*
16	Dead trees		0.70	336	

Table 9.1 continued

Plot	Canopy stratum	AH (m)	BA (m^2)	Stems (No. ha^{-1})	Species and frequency
35	Highest	16.37	20.72	1550	*Abarema jupunba (1), Chamaecrista apoucouita (3), Lecythis lurida (1), Margaritaria nobilis (1)*
35	Intermediate	9.57	3.57	1450	*Chamaecrista apoucouita (5), Cordia exaltata (1)*
35	Lowest	4.42	1.69	4725	*Abarema cocheorta (1), Chamaecrista apoucouita (2), Myrciaria tenella (1), Neea floribunda (1), Neea oppositifolia (1)*
35	Dead trees		1.44	775	
33	Highest	15.72	24.71	1425	*Casearia arborea (1), Ocotea opifera (2), Ormosia paraensis (2), Saccoglottis guianensis (1)*
33	Intermediate	9.50	5.74	2175	*Ambelania acida (1), Byearsonima amazonica (1), Lacistema pubescens (1), Licania canescens (1), Ocotea opifera (1), Saccoglottis guianensis (1)*
33	Lowest	4.17	1.24	2625	*Casearia javitensis (1), Lacistema pubescens (1), Ormosia paraensis (2), Tabernaemontana angulata (1), Thyearsodium paraense (1)*
33	Dead trees		0.97	750	
4	Highest	15.21	12.38	416	*Banara guianensis (1), Croton matourensis (4), Vismia guianensis (1)*
4	Intermediate	7.27	4.36	1536	*Eschweilera coriacea (1), Inga fragelliformis (1), Poecilanthe effusa (3), Talisia megaphylla (1)*
4	Dead trees		2.02	288	
22	Highest	14.84	12.43	1100	*Abarema jupunba (2), Casearia arborea (1), Ocotea opifera (3)*
22	Intermediate	9.96	4.84	2100	*Abarema jupunba (3), Allophylus edulis (1), Casearia arborea (1), Myrcia cuprea (1)*
22	Lowest	4.79	1.27	3000	*Casearia javitensis (1), Myrcia cuprea (2), Myrcia deflexa (2), Tapura amazonica (1)*
22	Dead trees		3.54	1550	
34	Highest	14.35	15.08	1400	*Annona paludosa (1), Inga heterophylla (4), Vismia guianensis (1)*
34	Intermediate	9.03	3.85	2700	*Guatteria poeppigiana (1), Inga heterophylla (2), Lacistema pubescens (3)*
34	Lowest	4.69	1.26	3950	*Casearia javitensis (1), Inga heterophylla (1), Lacistema pubescens (3), Tabernaemontana heterophylla (1)*
34	Dead trees		0.70	1200	
32	Highest	13.92	14.71	1650	*Rollinia exsucca (6)*
32	Intermediate	8.33	4.09	2500	*Casearia arborea (1), Lacistema pubescens (2), Lecythis lurida (1), Myrcia sylvatica (1), Pogonophora schomburgkiana (1)*
32	Lowest	4.33	0.67	2600	*Neea floribunda (1), Neea oppositifolia (1), Pogonophora schomburgkiana (3), Talisia carinata (1)*
32	Dead trees		1.23	1050	
31	Highest	12.47	9.01	752	*Cordia exaltata (1), Croton matourensis (3), Tapirira guianensis (2)*
31	Intermediate	9.72	4.25	1632	*Banara guianensis (1), Croton matourensis (2), Inga heterophylla (1), Lacistema pubescens (1), Ocotea opifera (1)*
31	Lowest	5.22	3.06	5312	*Casearia decandra (2), Croton matourensis (1), Lacistema pubescens (1), Myrciaria tenella (1), Pogonophora schomburgkiana (1)*
31	Dead trees		2.05	832	

Table 9.1 continued

Plot	Canopy stratum	AH (m)	BA (m^2)	Stems (No. ha^{-1})	Species and frequency
12	Highest	12.32	13.65	2300	*Lacistema pubescens (1), Pogonophora schomburgkiana (2), Rollinia exsucca (1), Tapirira guianensis (1), Vismia guianensis (1)*
12	Intermediate	9.03	5.31	4850	*Casearia decandra (1), Lacistema pubescens (5)*
12	Dead trees		1.11	950	
13	Highest	10.85	14.66	3750	*Connarus perrotettii (1), Inga heterophylla (2), Rollinia exsucca (3), Talisia retusa (1)*
13	Intermediate	7.95	4.82	5250	*Connarus perrotettii (1), Inga heterophylla (2), Lacistema pubescens (2), Simaba cedron (1)*
13	Dead trees		1.89	2400	
30	Highest	10.74	15.49	3100	*Inga heterophylla (2), Platonia insignis (3), Vismia guianensis (1)*
30	Intermediate	8.74	3.82	4900	*Eschweilera ovata (1), Lacistema pubescens (1), Licania canescens (1), Neea oppositifolia (1), Platonia insignis (1), Vismia guianensis (1)*
30	Lowest	4.82	1.02	4350	*Lacistema pubescens (4), Myrcia sylvatica (1), Pogonophora schomburgkiana (1)*
30	Dead trees		2.23	5150	
20	Highest	10.43	11.37	2700	*Casearia arborea (1), Cordia exaltata (1), Guatteria poeppigiana (1), Licania kunthiana (1), Myrcia cuprea (1), Ocotea opifera (1)*
20	Intermediate	7.50	3.23	2400	*Guatteria poeppigiana (1), Lacistema pubescens (2), Licania kunthiana (1), Myrcia cuprea (1), Pogonophora schomburgkiana (1)*
20	Lowest	4.96	1.95	4800	*Cupania scrobiculata (1), Heisteria densifrons (1), Lacistema pubescens (2), Myrciaria tenella (2)*
20	Dead trees		0.66	900	
3	Highest	9.32	12.91	6550	*Inga heterophylla (5), Tapirira guianensis (1)*
3	Dead trees		0.19	225	
5	Highest	9.24	15.65	6300	*Guatteria poeppigiana (1), Lacistema pubescens (4), Ocotea opifera (1)*
5	Dead trees		0.24	300	
8	Highest	8.93	15.67	9800	*Annona paludosa (1), Casearia arborea (1), Chamaecrista apoucouita (1), Lacistema pubescens (1), Pogonophora schomburgkiana (1), Vismia guianensis (1)*
8	Dead trees		0.24	400	
17	Highest	8.48	14.64	8200	*Byearsonima aerugo (1), Byearsonima densa (2), Guatteria poeppigiana (1), Maprounea guianensis (1), Margaritaria nobilis (1)*
17	Dead trees		0.34	300	
6	Highest	8.07	17.12	7200	*Casearia arborea (1), Lacistema pubescens (1), Myrcia cuprea (2), Rollinia exsucca (1), Vismia guianensis (1)*
6	Dead trees		0.18	200	
10	Highest	7.79	13.54	5000	*Lacistema pubescens (1), Myrcia cuprea (2), Simaba cedron (1), Vismia guianensis (2)*
11	Highest	7.43	13.88	9800	*Banara guianensis (1), Myrcia cuprea (4), Rollinia exsucca (1)*
11	Dead trees		0.11	200	
7	Highest	7.35	11.09	6800	*Lacistema pubescens (2), Lecythis lurida (1), Vismia guianensis (3)*

Table 9.1 continued

Plot	Canopy stratum	AH (m)	BA (m^2)	Stems (No. ha^{-1})	Species and frequency
2	Highest	7.12	10.89	6200	*Annona paludosa (1), Casearia javitensis (1), Ocotea opifera (1), Pogonophora schomburgkiana (2), Vismia guianensis (1)*
2	Dead trees		0.05	100	
9	Highest	6.19	12.22	12000	*Casearia arborea (1), Cybianthus sp. (1), Myrcia cuprea (2), Vismia guianensis (2)*
21	Highest	5.38	18.13	30400	*Eugenia biflora (1), Hirtella racemosa (3), Talisia retusa (1), Vismia guianensis (1)*
21	Dead trees		0.17	400	
29	Highest	4.92	17.82	36800	*Cupania diphylla (1), Inga heterophylla (2), Lacistema pubescens (1), Rollinia exsucca (1), Vismia guianensis (1)*
14	Highest	4.90	5.29	12800	*Banara guianensis (1), Lacistema pubescens (2), Pogonophora schomburgkiana (1), Vismia guianensis (2)*
14	Dead trees		0.39	1200	
24	Highest	4.22	9.45	28400	*Casearia javitensis (1), Eschweilera sp. (1), Inga heterophylla (1), Lacistema pubescens (2), Pouteria macrophylla (1)*
24	Dead trees		0.64	2000	
19	Highest	3.88	9.86	26000	*Myrcia sylvatica (1), Ocotea opifera (4), Rollinia exsucca (1)*
19	Dead trees		0.07	400	
26	Highest	3.71	13.64	45200	*Annona montana (1), Banara guianensis (2), Casearia arborea (1), Lacistema pubescens (2)*
26	Dead trees		1.56	3600	
27	Highest	3.55	15.69	65000	*Myrciaria tenella (3), Lacistema pubescens (2), Vismia guianensis (1), Annona montana (1)*
28	Highest	2.15	6.00	32500	*Myrcia sylvatica (4), Lacistema pubescens (7), Casearia javitensis (1), Miconia minutiflora (1)*
25	Highest	2.06	7.65	35000	*Lacistema pubescens (5), Vismia guianensis (1), Rollinia exsucca (4), Casearia javitensis (2), Derris spruceanum (2), Tabernaemontana angulata (1)*

Appendix 2:

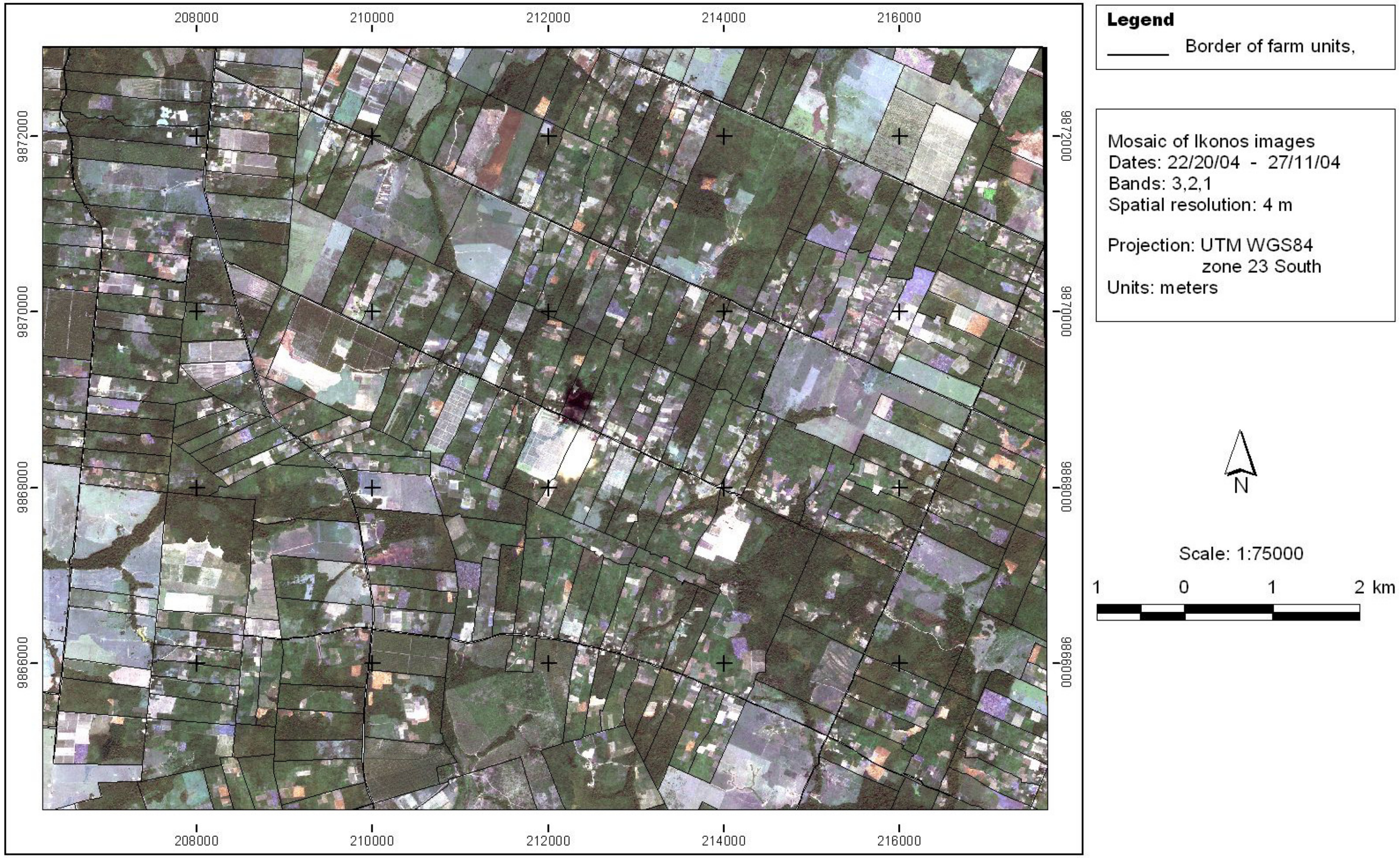

Figure 9.1 Delineation of farm areas in 100 km^2 study area in the municipality of Igarapé Açu, Bragantina region, Brazil, based on map of properties units and interpretation of mosaic of images Ikonos images of years 2002 and 2003

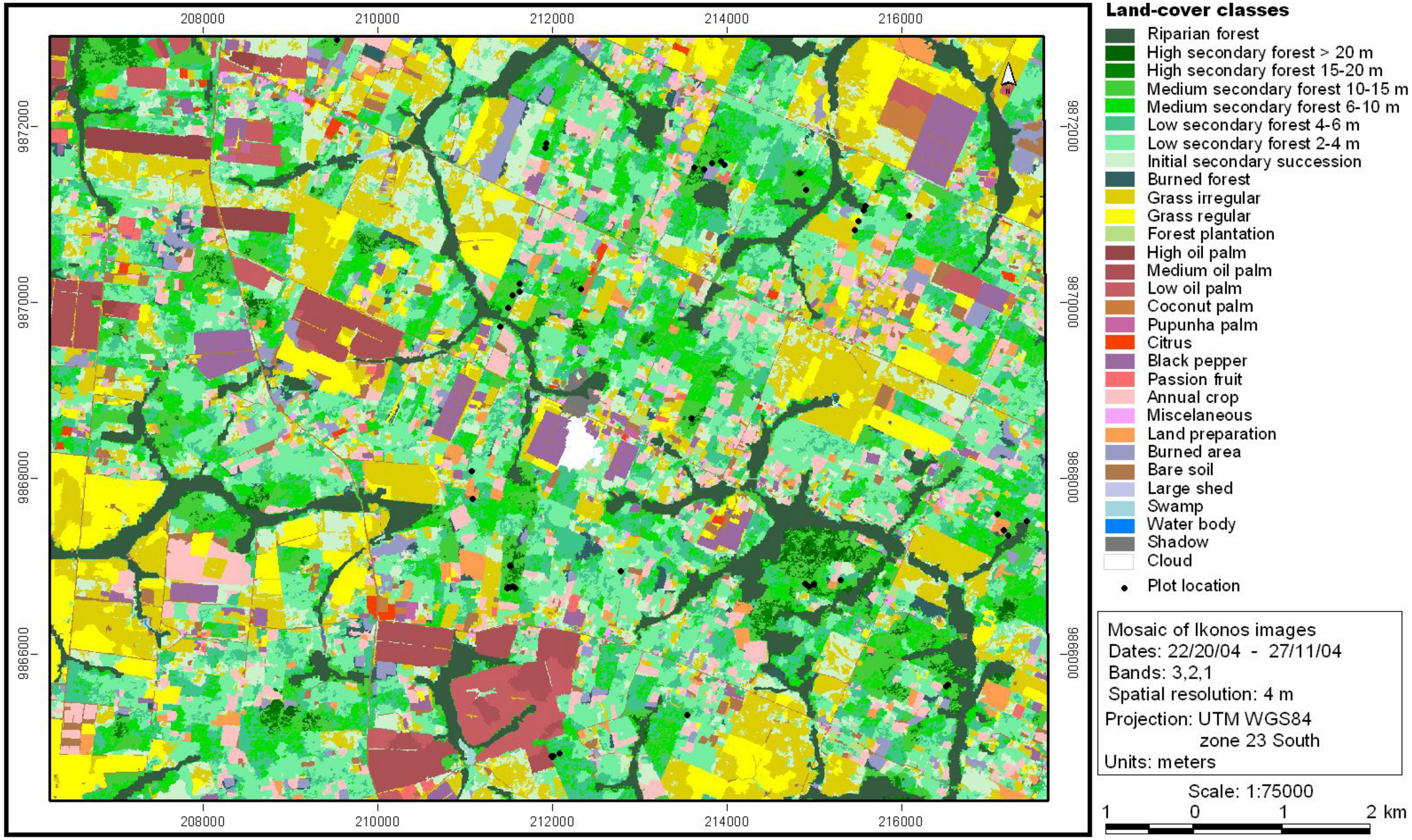

Figure 9.2 Classification of land covers in 100 km^2 study area in the municipality of Igarapé Açu, Bragantina region, Brazil, using a mosaic of Ikonos images of years 2002 and 2003

Table 9.2 Evaluation of economic viability of two scenarios of carbon sequestration project managing secondary vegetation in the average farm area in the municipality of Igarapé Açu, Bragantina region, Brazil. Scenarios a) 52 % of farm allocated to the project during 10, 20 and 30 years, carbon credit price US$ 13.6 and b) 52 % of farm allocated to the project during 10, 20 and 30 years, carbon credit price US$ 5.63

a)

Assumptions	
Farm area (ha)	35.8
% farm area use for agricultural production	48
% farm area allocated in the project	52
Uptake rate (t C ha^{-1})	
until 6 years	3
after 7 years	3.4
Project costs (US$)	0
Interest rate (Prime 31/05/05 - %)	3.5
Issuance of carbon credit (years)	5
Carbon credit price (US$ t CO_2)	13.6
Farm income (US$ ha^{-1})	163

Decisions	
at 30 years project time	
NPV_benefit / NPV_Cost	1.02
Do project?	yes
at 20 years project time	
NPV_benefit / NPV_Cost	1.02
Do project?	yes
at 10 years project time	
NPV_benefit / NPV_Cost	1.00
Do project?	yes

		With project scenario				**Without project scenario**	
		Benefits				Opportunity Costs	
Year	Carbon stock (t ha^{-1})	Uptake (t CO_2 yr^{-1})	Issuance of carbon credits	Net Revenue (US$)	NPV (US$)	Net revenue with farm products (US$)	NPV (US$)
0	0.0	204.8				2802.7	2802.7
1	3.0	204.8				2802.7	2706.9
2	3.0	204.8				2802.7	2614.3
3	3.0	232.1				2802.7	2525.0
4	4.2	232.1				2802.7	2438.6
5	6.0	232.1	1	17823.7	14978.1	2802.7	2355.3
6	9.6	232.1				2802.7	2274.7
7	11.5	232.1				2802.7	2197.0
8	13.5	232.1				2802.7	2121.8
9	15.5	232.1				2802.7	2049.3
10	17.6	232.1	2	15781.4	11144.6	2802.7	1979.2
11	21.8	232.1				2802.7	1911.6
12	23.9	232.1				2802.7	1846.2
13	26.1	232.1				2802.7	1783.1
14	30.6	232.1				2802.7	1722.1
15	35.1	232.1	3	15781.4	9365.33	2802.7	1663.2
16	37.5	232.1				2802.7	1606.4
17	39.8	232.1				2802.7	1551.5
18	44.5	232.1				2802.7	1498.4
19	49.3	232.1				2802.7	1447.2
20	51.8	232.1	4	15781.4	7870.14	2802.7	1397.7
21	54.2	232.1				2802.7	1349.9
22	59.2	232.1				2802.7	1303.8
23	64.2	232.1				2802.7	1259.2
24	66.7	232.1	5			2802.7	1216.1
25	69.3	232.1		15781.4	6613.66	2802.7	1174.6
26	74.4	232.1				2802.7	1134.4
27	79.6	232.1				2802.7	1095.6
28	84.8	232.1				2802.7	1058.2
29	90.1	232.1				2802.7	1022.0
30	92.8	232.1	6	15781.4	5557.77	2802.7	987.0
Sum at 30 years				96730.7	55529.6		54092.9
Sum at 20 years				65167.9	43358.2		42492.2
Sum at 10 years				33605.1	26122.7		26064.8

NPV Net present value

Table 9.2 continued

b)

Assumptions	
Farm area (ha)	35.8
% farm area use for agricultural production	48
% farm area allocated in the project	52
Uptake rate (t C ha^{-1})	
until 6 years	3
after 7 years	3.7
Project costs (US$)	0
Interest rate (Prime 31/05/05 - %)	3.5
Issuance of carbon credit (years)	5
Carbon credit price (US$ t CO_2)	5.63
Farm income (US$ ha^{-1})	163

Decisions	
at 30 years project time	
NPV_benefit / NPV_Cost	0.42
Do project?	no
at 20 years project time	
NPV_benefit / NPV_Cost	0.40
Do project?	no
at 10 years project time	
NPV_benefit / NPV_Cost	0.41
Do project?	no

		With project scenario				**Without project scenario**	
		Benefits				Opportunity Costs	
Year	Carbon stock (t ha^{-1})	Uptake (t CO_2 yr^{-1})	Issuance of carbon credits	Net Revenue (US$)	NPV (US$)	Net revenue with farm products (US$)	NPV (US$)
0	0.0	204.8				2802.7	2802.7
1	3.0	204.8				2802.7	2706.9
2	3.0	204.8				2802.7	2614.3
3	3.0	232.1				2802.7	2525.0
4	4.2	232.1				2802.7	2438.6
5	6.0	232.1	1	7378.5	6200.5	2802.7	2355.3
6	9.6	232.1				2802.7	2274.7
7	11.5	232.1				2802.7	2197.0
8	13.5	232.1				2802.7	2121.8
9	15.5	232.1				2802.7	2049.3
10	17.6	232.1	2	6533.0	4613.5	2802.7	1979.2
11	21.8	232.1				2802.7	1911.6
12	23.9	232.1				2802.7	1846.2
13	26.1	232.1				2802.7	1783.1
14	30.6	232.1				2802.7	1722.1
15	35.1	232.1	3	6533.0	3877.0	2802.7	1663.2
16	37.5	232.1				2802.7	1606.4
17	39.8	232.1				2802.7	1551.5
18	44.5	232.1				2802.7	1498.4
19	49.3	232.1				2802.7	1447.2
20	51.8	232.1	4	6533.0	3258.0	2802.7	1397.7
21	54.2	232.1				2802.7	1349.9
22	59.2	232.1				2802.7	1303.8
23	64.2	232.1				2802.7	1259.2
24	66.7	232.1	5			2802.7	1216.1
25	69.3	232.1		6533.0	2737.9	2802.7	1174.6
26	74.4	232.1				2802.7	1134.4
27	79.6	232.1				2802.7	1095.6
28	84.8	232.1				2802.7	1058.2
29	90.1	232.1				2802.7	1022.0
30	92.8	232.1	6	6533.0	2300.8	2802.7	987.0
Sum at 30 years				40043.7	22987.6		54092.9
Sum at 20 years				26977.6	17949.0		42492.2
Sum at 10 years				13911.5	10814.0		26064.8

NPV Net present value

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