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}.