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Applications of satellite images and field databases to analyze agroforestry systems in Brazil

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Abstract — *Agroforestry systems (AFS) are part of a land use strategy aimed at maintaining environmental services in Brazilian Amazonia. Retention of ecosystem carbon stocks is an important environmental service considering the changing atmospheric composition and its effects on climate. We quantified the role of AFS on aboveground biomass (AGB) and carbon storage (CS) in the municipality of Tomé-Açu, Pará, Brazil. Satellite images information and multiscale databases were used to locate and analyze agroforestry. The different agroforestry plots were divided into four classes: AFS 1, AFS 2, AFS 3 and AFS 4. The indirect method, which is based on allometric equations for different species and diametric classes, was used to calculate the AGB (average was of 106 Mg ha^{-1}) and CS (average was of 48 Mg C ha^{-1}).The biomass storages in the AFS of Tomé-Açu indicate that these production systems accumulate important C amounts in their vegetation, and may contribute to the CO_2 sequestration process, indicating possibilities for environmental, economic and social sustainability.*

Keywords*— *Geotechnology, Carbon Storage, Sustainable Agriculture.

I. INTRODUCTION

In the Amazon region of Brazil, the land conversion into agricultural systems and/or pastures provokes substantial releases of carbon dioxide [1]. Current research seeks efficient production systems to maintain carbon (C) sequestration and storage in biomass and in the soil agroforestry systems have high potential for C sequestration and for the reduction of greenhouse gases emissions [2, 3]. They also present possible of synergic interactions with sustainable adaptation and development, generating jobs and income and contributing to biodiversity and to the conservation of hydrological regimes [4].

In Brazil, especially in Amazonia, AFS have been broadly studied in the past years, with emphasis on family farms [5, 6, 7). The AFS in Amazonia have demonstrated comparative advantages in contrast to monocultures. Besides avoiding soil degradation and improving soil physical and chemical conditions through an increase in the amount of soil organic matter, they constitute an economically effective land use because the production per area unit is high. This is especially true when annual, semi-perennial, perennial, woody and non-woody species, along with livestock, are combined simultaneously in a way that is compatible with the standards of family farmers [8, 9]. That AFS with a selection of native fruit and wood trees restored abandoned or degraded areas in Amazonia, and recovered not only the land productive capacity, but several environmental services, such as C fixation by biomass, water cycling and biogeochemical regulation [10].

Agroforestry systems are diverse, and each system has different edaphoclimatic conditions and species composition. The biomass estimation in agroforestry systems is complicated by the high dispersion of the areas and to variation management systems. While some biomass studies have been carried in agroforestry systems using destructive methods, these are extremely labor intensive. For agroforestry systems with a forest structure indirect quantification of biomass using non-destructive measurements from field inventors, algometric equations and remote sensing generates valuable data for estimation of carbon storage in the AFS vegetation [4, 11, 12, 13].

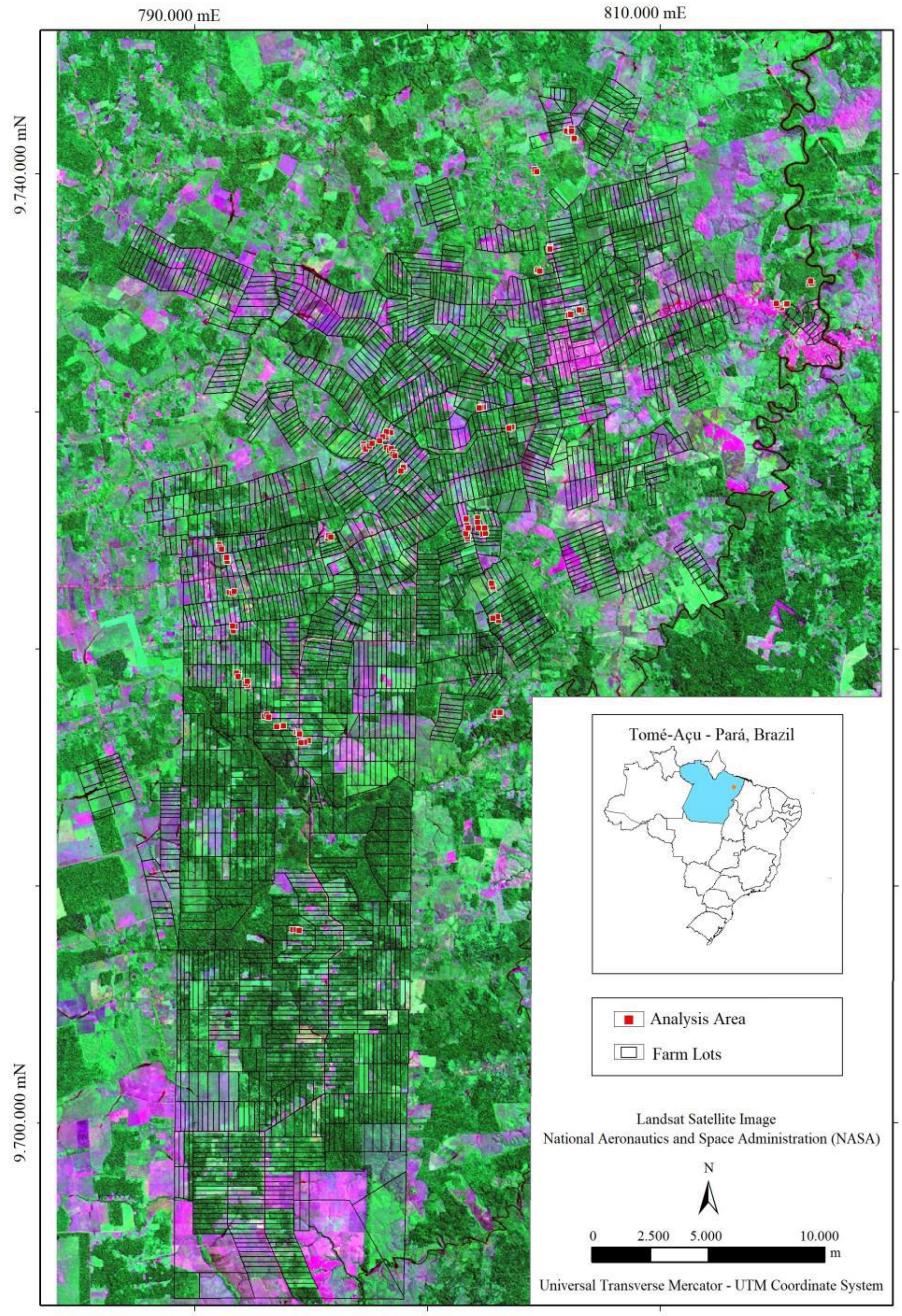

Fig. 1 Study area showing property boundaries superimposed on a false color composition Landsat 5 images in Tomé-Açu, Pará – Brazil.

II. MATERIALS AND METHODS

This study was carried out in the Quatro Bocas district in the municipality of Tomé-Açu, located in the northeastern region of Pará state, Brazil (Figure 1).

In this study, the objective is to estimate aboveground biomass and carbon storage in agroforestry systems in Amazonia using satellite images information, databases and indirect methods based on sampling in established sites in Tomé-Açu, Para State in the Brazilian Amazon.

Topography in the region is characterized by low flat plateaus, terraces, and lowlands with altitudes varying from 14 to 96 m. The soils are classified as Ferralsols, Plintosols and Fluvisols and has a humid mesothermal climate – Ami according to the Köppen classification – with high average annual temperatures (26ºC) and relative air humidity rate of about 85%. The average annual rainfall is 2,300 mm. The original vegetation is that of lowland dense ombrophilous forest, which has been intensely altered [14].

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A Landsat satellite image from the National Aeronautics and Space Administration (NASA) and database images from the Google Earth was used to identify the distribution of farm lots, where areas with potential for field surveys were selected. A total of 40 sampling plots were selected at random. In each sampling unit located using a Global Positioning System (GPS) receiver [15]. Information about land use and cover history, AFS ages, floristic arrangement, percentage of canopy cover, percentage of herbaceous plants, litter, and exposed soil were also collected.

The aboveground biomass estimation can be obtained by direct or indirect method [16]. The direct method is more accurate, but harder and more costly because of the need of cut and weigh all the trees in the sample area. The indirect method is quicker and has lower costs, but it is subject to measurement errors, which are not always mentioned [12]. This work used the indirect method for C and biomass estimation, with simple random sampling. Two factors were relevant for that choice: first, the wide scope of the sampling areas; and second, the impossibility of cutting the vegetable components of the studied agroforestry systems.

The aboveground biomass (AGB) equations developed in Pará State [17, 18], were used to estimate *Theobroma cacao* L., *Euterpe oleracea* Mart., *Theobroma grandiflorum* Schum. and other species in agroforestry systems (AFS). To estimate the carbon storage (CS) for the different systems classified, their AGB was multiplied by a factor of 0.45 aboveground C based [19]. The agroforestry classes (AFS 1, AFS 2, AFS 3 and AFS 4) were defined based on values for canopy cover (CC%), diameter at breast height (DBH), basal area (G), and total height (H) following [15].

III. RESULTS AND DISCUSSION

The results of satellite images information and multiscale databases analyzes show the landscape mosaic is dominated by pasture, agricultural fields, agroforestry systems, and secondary forests. Forest remnants are observed especially at the margins of streams. Tomé-Açu started its agricultural development in the 1920's, with the beginning of the Japanese immigration to the region. The immigrants implanted horticulture and, later, black pepper (*Piper nigrum* L.). They were provided with lands by the Brazilian government, which made technological development possible and turned Pará into the greatest black pepper producer in Brazil. With the decay of the black-pepper cycle from the 1970's on, caused by fusarium blight, the farmers looked for new production alternatives.

The way out of this ecological crisis for the immigrants was to diversify their activities, with emphasis in native and exotic fruit trees that initiated a new economic cycle for the region [20]. Crop diversification was associated to a new production system, the agroforestry systems, developed from countless local experiments that generated different production arrangements with various species and promoted the products into new markets.

The current agroforestry systems (1 to 35 years old) have great variety of fruit and timber tree species. That the success of the region's agricultural development results from the great experience of the Japanese-Brazilian farmers, from their innovative thinking, their holistic view of future markets and their social-minded spirit, which made possible the creation of the Cooperativa Agrícola Mista de Tomé-Açu (Camta) in 1931, whose intention was to sell vegetables and nowadays commercializes the agroforestry products (fruit, pulp, juice and oil) in various countries [21, 22].

The data obtained in the studied agroforestry inventory were 5,697 individuals ha^{-1} with DBH (Diameter at Breast Height) greater than 2.5 cm, belonging to 29 plant families and 54 distinct species, were inventoried in the studied AFS. These numbers are similar to those found observed 27 families and 61 species, and observed 26 families and 59 species, both during analyses of AFS in the municipality of Cametá, Pará State, Brazil [23, 24]. The values are somewhat lower than those found in studied the floristic composition of AFS in the Acre river valley and observed 94 species from 38 plant families [24] and greater than the 18 families and 28 species during analysis of AFS in the municipality of Igarapé-Açu, Pará State, Brazil [25].

Three species (*T. cacao* L., *E. oleracea* Mart., and *T. grandiflorum* Schum.) represent 51% of the relative frequency (F_r); 69.2% of the relative density (D_r); 51.1% of the relative dominance (Do_r), and 56.8% of the total importance value index ($IVI = F_r + D_r + Do_r$) of the 54 species observed in the AFS in Tomé-Açu. Also obtained greater IVI values for *T. grandiflorum* and *E. oleracea* in agroforestry in Pará State [23, 25].

The aboveground biomass (AGB) and carbon storage (CS) estimation per hectare were calculated individually for each sampling unit and averaged for the different AFS. The analysis of AGB and after CS estimation data shows increasing values for AFS 1 (6), AFS 2 (22), AFS 3 (42) and AFS 4 (120 Mg C ha^{-1}), which is also observed for species richness (Figure 2, 3, 4, 5 and 6). The ABG and CS values (106 Mg ha^{-1} and 48 Mg C ha^{-1}) observed for AFS with ages between 1 and 35 years are within the averages

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estimated and reported 50 Mg C ha^{-1} of average CS in Amazonian AFS [2].

The biomass accumulation in a forest or agroforestry stand is affected both by environmental factors and by factors inherent to the species [26]. Besides the environmental factors, floristic factors influence the accumulated values of biomass and C. For example, the lower CS averages in comparison to AFS averages obtained in the present work at the Cametá region, Pará State, may be related to the high IVI of the *T. cacao* L, *E. oleracea* Mart., and *T. grandiflorum* Schum. trees, which corresponds to 167% of the total IVI value of the 19 species observed in AFS 3, and to 99% of the total IVI value of the 40 species observed in AFS 4.

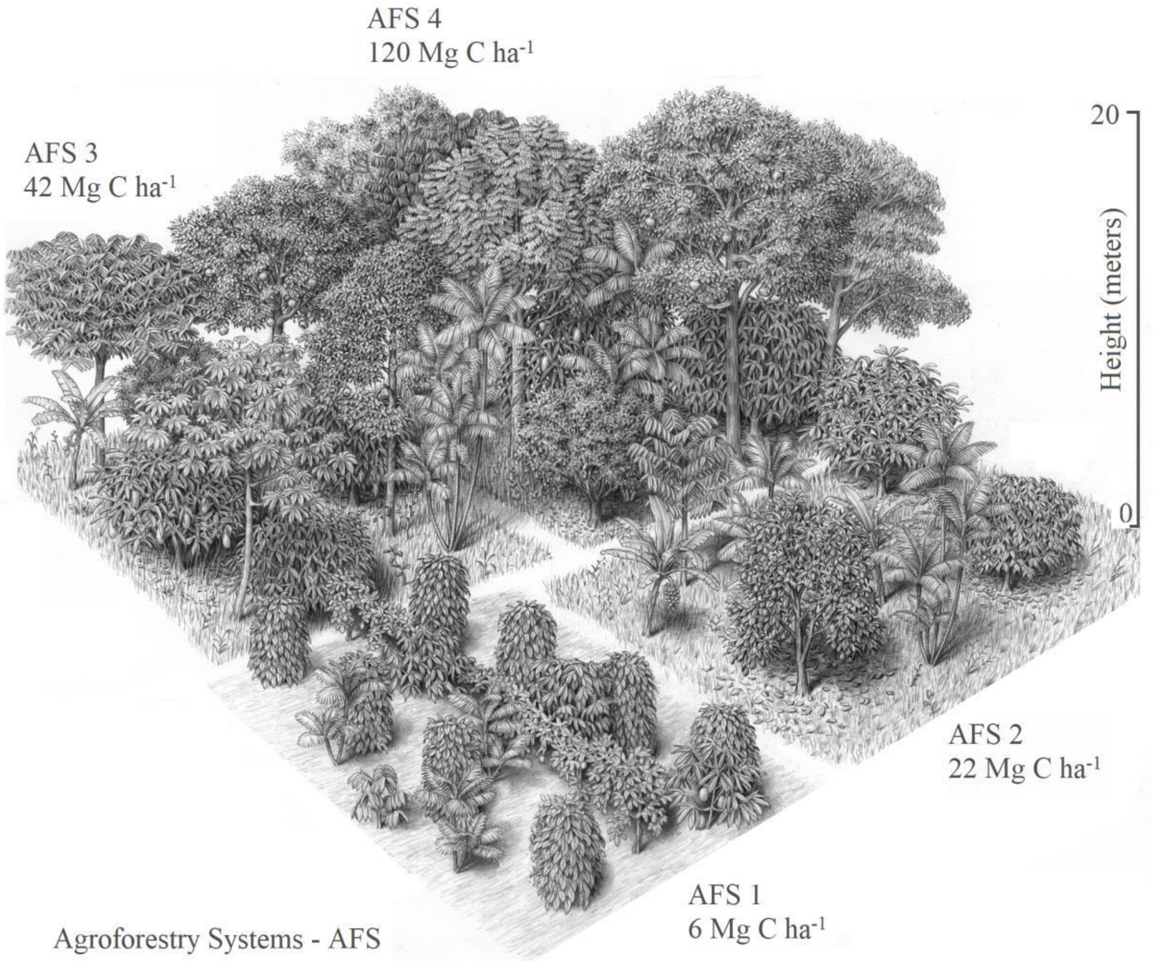

Fig. 2 Carbon storage average in different agroforestry systems (AFS 1, 2, 3 and 4) in Tomé-Açu, Pará – Brazil.

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Fig. 3 Farm with agroforestry systems (AFS 2) in Tomé-Açu, Pará – Brazil.

Fig. 5 Farm with agroforestry systems (AFS 3) in Tomé-Açu, Pará – Brazil.

Fig. 4 Farm with agroforestry systems (AFS 2) in Tomé-Açu, Pará – Brazil.

Fig. 6 Farm with agroforestry systems (AFS 5) in Tomé-Açu, Pará – Brazil.

The occurrence of large-size trees in a small sample plot can lead to a bias to overestimate biomass [27]. This can be perceived by comparing AFS 4, which showed the greatest DBH and H averages and the greatest carbon storage estimation (120 Mg C ha^{-1}) with 1,457 individuals ha^{-1}, with AFS 3, which showed smaller CS estimation (42 Mg C ha^{-1}) even with greater abundance (1,723 individuals ha^{-1}).

The analysis of the carbon storage estimated for the agroforestry systems in Tomé-Açu shows that it represents 36% of the value reported for anthropic systems (228 Mg C ha^{-1}) [28], including the amount retained in the soil. In the potential analysis for C sequestration by these AFS, the greatest carbon storage value found for AFS 4 stands out (120 Mg C ha^{-1}).

It represents 80% of the average C stored in the analyzed upland forests (152 Mg C ha^{-1}), and 33 and 121% more than the average of the C stocked in the lowland forests (91 Mg C ha^{-1}) and in the secondary forests (55 Mg C ha^{-1}), respectively. In comparison to the work [28], the CS from AFS 4 represents 53% of the C observed for anthropic systems, including the amount retained in the soil, and thus constitutes an important alternative for C accumulation and fixation, along with the enriched secondary forests, the lowland forests or the upland forests in Brazilian Amazonia.

Together with reforestation and management of secondary forests, the AFS are viable alternatives from the environmental and economic perspectives, since they contribute to the absorption of CO_2 and to the reduction of the greenhouse effect [29]. Among the various land uses, the AFS are the ones that accumulate the greatest biomass [30]. The adoption of AFS by family farmers is a viable and relevant strategy for increasing the CS in their production systems [31].

Moreover, the biomass observed in the agroforestry systems of Tomé-Açu can easily be related to the food and fiber production capacity provided by these systems. Was already pointed out that the agroforestry systems in Tomé-Açu are a possible sustainable answer to the growing process of forest conversion into pasture in Amazonia; besides increasing the employment in the region, the income obtained by the Japanese-Brazilian farmers in their lands, whose areas range from 10 to 20 ha, is comparable to the income obtained by farmers who use 400 to 1,200 ha of land as pasture [32].

IV. FINAL CONSIDERATIONS

Satellite images information and multiscale databases expand the possibilities of agroforestry systems mapping and monitoring. Thus, spatial analyzes of agroforestry systems is strategic role in farm planning and to the benefit of more sustainable rural development.

Canopy cover, diameter at breast height, number of individuals per hectare, total height, and age are useful parameters to define the classification intervals for agroforestry systems AFS 1, AFS 2, AFS 3, and AFS 4 in Tomé-Açu. Data obtained by the structural and floristic analyses indicate, by means of the IVI, that the main species are cocoa (*Theobroma cacao* L.), açaí (*Euterpe oleracea* Mart.) and cupuaçu (*Theobroma grandiflorum* Schum.).

The agroforestry systems in Tomé-Açu indicate a viable and relevant strategy for increasing the carbon storage in Amazonian production systems, contributing significantly to the CO_2 sequestration process, pointing at possibilities for providing many economical, ecological and social benefits via its diversified products.

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