CHAPTER 3 - VEGETATION STRUCTURE AS AN INDICATOR FOR LAND-COVER DYNAMICS ASSESSMENT IN THE AMAZON

'Esse mato tem palmeiras…'

3.1 - Disturbance and secondary succession in the Amazon: short review and motivation

The ecological literature on succession is extensive. Rather than making too broad a review about the topic, the focus is on some concepts related to vegetation regrowth as a background for this study in tropical forests of Rondônia. Since Cowles' observations around the shores of Lake Michigan (Cowles 1911) and Clements'(1916, 1928, 1936) numerous studies, many theoretical ideas about succession in several fields have been argued. According to Drury and Nisbet (1973), in spite of all the different approaches and competing conceptualizations, there is considerable agreement on the general trend of succession. During the 1960s, authors attempted to develop a general theory of structural and functional characteristics of a community's development (Hutchinson 1965, MacArthur et al. 1966, Levins 1968). Odum (1969) proposed a model for the process, discussing how the energy balance in the ecosystem progressively changed. Whittaker (1970) described changes in different vegetation variables through the course of succession ending up in a climax community. Most of these studies focused on temperate regions. The application of the succession concept to tropical forest ecosystems started gaining importance when Richards (1952) called attention to processes following disturbance. Since then, many studies have been carried out in different tropical sites. The paragraphs below describe some findings of works completed in the 1980s and 1990s.

Forest communities show variation due to availability of flora, biophysical differences between formations, and disturbances. Within formations, variation is related to topography, soils, seedling arrival, and success (Whitmore 1998). The fragility or susceptibility to damage from disturbance in a forest ecosystem is a consequence of its ecological characteristics. In tropical rain forests, most soils are infertile, with a low content of nutrients, making the nutrient cycling an important mechanism to maintain the ecosystem. When the process is disturbed, nutrients can be rapidly lost (Jordan 1989).

There are various sorts of forest disturbance. The greater the disturbance of a mature forest the longer it will take to recover. The extreme situation is when disturbance produces intense degradation with no chance for recovery. In this case, the process may be followed by ecosystem degradation (loss of structural and functional integrity), environmental degradation (loss of populations or critical functions), biodiversity degradation (loss of genetic diversity), and agricultural degradation (loss of productivity) (Vieira et al. 1993). Degradation may increase environmental risks such as flammability (Nepstad et al. *Flames* 1999). But when these extremes do not occur, succession starts the recovery of vegetation in a dynamic process. Abandonment brings rapid transformation to a competitive environment that induces successional change (Kellman 1980).

Secondary tropical forests originate from some source of disturbance (Corlett 1995). Succession generally refers to changes in species composition and abundance during or following disturbance of a site. The process is dependent on four main sources of recovery: regeneration of remnant individuals, germination from the soil seed bank, sprouting from cut or crushed roots and stems, and seed dispersion and migration from other areas (Tucker et al. 1998).

Sharp distinctions between successional stages are often artificial (McCook 1994), but useful to differentiate between forest or secondary formations. The most common distinction within forest species is between two contrasting ecological groups: pioneers (short- and long-lived) and climax species (Whitmore 1998). Climax species can germinate and establish seedlings below a canopy, whereas pioneer species require full light. Therefore, succession is the process where pioneer (light-demanding) species establish themselves in big canopy gaps, climax (shade-tolerant) species follow, pioneers die creating small gaps, and mature forest species grow up.

The physiognomic outcome of this continuous process of restoration is a change in vegetation structure, analyzed in this chapter for the study area in Rondônia. Brown and Lugo (1990) enumerate five main structural characteristics typifying secondary forests: high total density but low density of trees > 10 cm diameter at breast height (DBH); low basal area; short trees with small diameters; low woody volume; and high leaf area indices. These characteristics change with time giving place to different stages of vegetation toward a forest formation.

Some succession trends are typical in tropical forests: initial floristic composition influences later stand composition; leaf area index (LAI) and production peak early in succession; and streamwater nutrient losses decline rapidly as biomass accumulates (Uhl and Jordan 1984). Successional vegetation appears to be better adapted than crop plants to the diminishing nutrient availability. Another important adaptation of successful successional species is their high dissemination capability and high sprouting capability after fire, both depending on disturbance intensity and duration (Vieira et al. 1996).

Several studies have been done to understand how characteristics of disturbance influence the rate of recovery. Although no one theory can explain all factors controlling succession, some variables appear to be more important than others. In the Amazon, three main factors control succession: availability of regeneration mechanisms (e.g., sprouts, seeds buried in the soil, seeds dispersed from surrounding areas); availability of seed germination and seedling establishment microhabitats (e.g., fruit trees and slash piles); and availability of nutrients, which may be affected by previous management (Uhl 1987). Tree species diversity and biomass accumulation vary depending on time and intensity of land use before recovering. A key factor retarding succession is the slow rate at which primary forest species become established on abandoned farms (Uhl et al. 1988). Some barriers to tree establishment include low propagule availability, seed predation, seedling predation, seasonal drought, and root competition with old vegetation (Nepstad et al. 1991). Although the natural forest recovery indicates a remarkable resilience, Saldarriaga et al. (1988) estimated that 190 years would be taken by a previously cultivated site to reach mature forest basal area and biomass values. Also, the number of tree species present after 40 years of succession is less than half the number in mature forests (Vieira et al. 1996).

In general terms, soil fertility and land-use history emerge as the critical factors influencing the rate of forest regrowth (Tucker et al. 1998). Uhl et al. (1982) found that the time of recovery depends on land use following removal. Logging, slash/burn/abandon, and slash/burn/agriculture/abandon cycles have increasing secondary succession duration. Large cleared patches, where seed sources are far away, may take hundreds of years to return to primary forest. In another study, Uhl et al. (1988)

confirmed these findings. Different regeneration patterns occurred depending on land management following deforestation. Forest regenerated vigorously on sites of previously light use (biomass accumulation of 25% after 8 years.). Tree species richness was also high. Moderately grazed pastures also developed forest, but biomass accumulation and tree species richness were lower. Abandoned pastures subjected to heavy use had the least distinct patterns of succession (eight-year-old site was dominated by grasses and forbs). Only where land has been used too intensively for long periods is reforestation uncertain. Thus, in the absence of fire, forests recover on abandoned sites, accumulating biomass and species at a rate that is inversely related to the intensity of use prior to abandonment (Nepstad et al. 1991).

From the considerations above, it becomes clear that if we want to understand the variables affecting patterns of forest succession, we need to know the disturbance history. Recently, remote sensing and GIS have improved significantly the capability to monitor processes of LULC change (B. Turner 1995, National Research Council 1998). Land-cover classifications using these tools became fundamental to understand and monitor processes of deforestation and secondary succession, particularly in the tropics (Mausel et al. 1993; Moran et al. 1994, 1996; Foody et al. 1996; Steininger 1996). The integration of these methods of analysis, field data about vegetation structure and composition, and ecological research provide new opportunities for the study of dynamic processes such as forest disturbance and recovery at ecosystems and landscapes. For regional and landscape assessments, the study of vegetation structure in tropical forests is even more effective than floristic composition because of general spectral responses to vegetation communities at resolutions such as those in Landsat TM images.

In this chapter, the results for vegetation structure in Machadinho and Anari are presented as a basis for discussing the spectral response of secondary stages when using Landsat TM images. The rationale behind this approach is to follow an itinerary from the continuous vegetation variability found in the field to specific categories of secondary succession useful for LULC classifications such as presented in the next chapter.

3.2 - Data collection

A number of techniques are available for obtaining quantitative information about the structure and composition of terrestrial plant communities (Randolph 1997). This research focused on vegetation structure rather than composition because of its effects on different spectral responses of tropical secondary forests (Brondizio 1996, Lucas et al. 1998). Since the main goal was to collect vegetation data to inform LULC classifications based on satellite images, some important decisions were necessary when planning fieldwork.

The first step was to perform preliminary satellite image classifications through unsupervised techniques (Jensen 1996, Lillesand and Kiefer 2000). The results provided a general overview about land cover and spectral variability in the area, allowing the stratification of major classes to be sampled. Archival work also indicated the importance of collecting data about different stages of vegetation regrowth, based on structure and land-use history (Uhl 1987, Brondizio 1996).

Fieldwork was carried out during the dry seasons of 1999 and 2000. Assisted by a team of three graduate students and three local workers, 32 surveys were completed encompassing land-cover classes such as forest, initial secondary succession (SS1), intermediate secondary succession (SS2), and advanced secondary succession (SS3). The goal of surveying these classes was to depict major stages of vegetation regrowth regarding their structure and spectral responses.

3.2.1 - Sampling strategy

Once in the field, preliminary image classifications and three-band color composite printouts indicated candidate areas to be surveyed. A flight over the areas provided visual insights about the size, condition, and accessibility of sites. After driving extensively throughout the settlements, field observations provided a sense about the structure of regrowth stages, mainly based on total height and ground cover of dominant species (Lemée 1978, Conant et al. 1983). Indicator species, such as *Cecropia sp*., *Vismia sp*, palms, grassy vegetation, and lianas also helped in secondary succession stage assignment. To allow integration with spectral TM data, areas smaller than 1 ha were discarded. As a preliminary baseline, maximum tree heights of 8, 10, and 12 m, and maximum ages of 5, 10, and 15 years were suggested for SS1, SS2, and SS3, respectively. These numbers were assigned by approximation to allocate the formations to be surveyed, thus not necessarily indicating the real boundaries between regrowth stages, as it will be developed and discussed later in this chapter. Also, two plot samples served as control sites. Both of them were cleared from primary forest and then allowed to recover without further interference as part of a regrowth experiment conducted by EMBRAPA. In 1999, one control site was 13 years old (SS3) and the other was 3 years old (SS1).

The procedure used for surveying vegetation was a multi-level technique adapted from CIPEC (1998). The surveys were carried out in areas with relatively homogeneous ecological conditions (i.e., topography, distance from water, and surrounding land use) and uniform physiognomic characteristics (Godron et al. 1968). After defining the area to be surveyed (plot sample), three sub-plots were randomly installed to cover the variability within the plot sample. A sub-plot is composed of three nested squares (Figure 11): one for sampling ground cover and tree or woody climber species seedlings (1 m^2); one for sampling sapling information (9 m^2); and one for sampling trees and woody species (100 m^2). The center of each sub-plot was randomly selected. Seedlings were defined as young trees or shrubs with a maximum stem diameter less than 2.5 cm. Saplings were defined as young trees with DBH between 2.5 cm and 10 cm. Trees were defined as woody plants with a DBH greater than or equal to 10 cm. Height, stem height, and DBH were measured for all trees in a 100 m^2 area. Height and DBH were measured for all saplings in a 9 m^2 area. Ground cover estimation and counting of individuals were carried out for seedlings and herbaceous vegetation in a 1 m^2 area.

Based on previous work (Jurdant et al. 1977, Duranton et al. 1982, Brondizio 1996), a survey protocol was used to describe the environment and the vegetation. The protocol encompassed qualitative observations (e.g., topography, soil texture, and land-use history) and quantitative variables (e.g., canopy closure, average canopy height, and vegetation measurements). Some variables were pre-coded in order to maximize the efficiency of data collection in the field (Appendix 1). This procedure provided an objective description about the sites, optimizing later data manipulations. A vegetation profile was also drawn for each sampled plot. Every plot was registered with a Global

Positioning System (GPS) device to allow further integration with spatial data in Geographic Information Systems (GIS) and image processing systems. Differential correction was not used because the plot size was larger than the error associated with regular GPS measurements in fieldwork. In-depth interviews with landowners were conducted at each sample location to investigate land-use history and inform classifications of satellite images from previous dates (1994 and 1988). Questions were asked to ascertain when the secondary growth was last cut, clearing and burning procedures, management techniques, types of crop or pasture grown, time since the land was abandoned, and other pertinent land-use information. In total, 32 plots, 96 sub-plots, and 288 nested squares were surveyed.

3.2.2 - Database implementation

A database was built to integrate all vegetation data collected during fieldwork. Its design was based on other studies with the objective of allowing comparisons through different study sites in the Amazon (CIPEC 1998). The main motivation behind this initiative was to maintain the integrity between spatial locations of every surveyed plot with vegetation characteristics as a basis for the integration with spectral data obtained from the analysis of Landsat TM images. A detailed description about image processing is included in the next chapter.

Figure 12 shows the relationships between tables in the database. The vegetation type (i.e., SS1, SS2, SS3, and forest) and spectral data were related to plot data (e.g., location and age) and its local characteristics (i.e., soil and land-use history). Plot data was also related to sub-plot data, which included vegetation structure. The latter was divided in two tables: tree/sapling data for plants with collected DBH and height; and seedling/herbaceous data for plants with collected number of individuals and ground cover.

In total, the database counted 288 records for the sub-plot data table, referring to all squares surveyed in the field. The tree/sapling table included 1075 plants with DBH greater than 2.5 cm (672 trees and 403 saplings). The seedling/herbaceous table included 249 plants.

3.3 - Data analysis

The steps carried out for data analysis are illustrated in Figure 13. The following sections describe the main procedures implemented. Special attention was given to the definition of vegetation structural variables and the analysis of spectral data in order to achieve a better knowledge about the regrowth stages present in the study area.

3.3.1 - Descriptive comparisons through photos and vegetation profiles

A first picture about the variation in vegetation structure from the early stages after abandonment up to forest is given by visual characteristics. After some training it becomes easier to decide between distinct classes mainly if a small number of possible choices is assigned (i.e., SS1, SS2, SS3, and forest). Of approximate character, the distinction of classes is not very evident in the beginning but becomes consistent after field experience. Following Daget and Godron (1982), the classification is appropriate when the observer hesitates in deciding between two and only two neighbor classes. This hesitation becomes acceptable after preliminary surveys and means that the classes are well adapted to the description of the actual heterogeneity within the plot sample.

Certainly, when making those decisions, an ecologist is intuitively using variables such as height, biovolume, ground cover, dominant and indicator species, among others. To help the analysis, an extensive photo collection was generated. Each photo received the survey number to allow further examination as a register about the ecological condition of each sampling site. On the other hand, several vegetation profiles were drawn to complete the graphic representation of vegetation structure.

3.3.2 - Variables analyzed

Some specific variables were calculated based on collected field data with the purpose of characterizing vegetation stands in a quantitative basis. As the focus was on structure rather than species composition, all variables were calculated for size classes, mainly the dominant strata (i.e., trees and saplings). Literature review about the study of secondary succession in the tropics provided insights about the variables to use. Formulas and definitions were compiled from Mueller-Dombois and Ellenberg (1974), Greig-Smith (1983), Schreuder et al. (1993), and Kent and Coker (1994). In the equations given below, the following abbreviations are used: DBH = diameter at breast height; BA = basal area; H = height; Y = biomass.

- DENSITY

The number of individuals of a size class in the stand is important to characterize vegetation. Density is determined by counting the number of individuals of each size class on each sample plot, and then estimating the average number of stems of each size class per unit area sampled.

- DIAMETER AT BREAST HEIGHT (DBH)

Diameter at breast height is the most frequently measured variable in vegetation surveys and has multiple uses. Overbark diameter measurements at breast height (1.5 m from the ground) are quick, easy, inexpensive, relatively accurate, and usually correlated with other variables, such as basal area, volume or biomass. In the field, DBH was measured with diameter tape and averaged for the classes of interest (i.e., trees and saplings). It is expressed in centimeters.

- BASAL AREA

Basal area is the horizontal (cross-sectional) area occupied by the trunk of a species or size class. It is expressed in square meters per hectare (m^2/ha) and its formula is:

$$BA = (DBH/2)^2 * \pi \ / \ \text{area sampled}$$

- TOTAL HEIGHT

Total height is a straightforward parameter used for direct measurement purposes and also for the calculation of volume or biomass. It is expressed in meters. Once in a stand, the height of some trees was measured with a hand-held clinometer. The values obtained were used as controls for height estimation of other trees and saplings using a five-meter rod as a reference. The estimation was crosschecked between two or three observers to achieve consensus.

- BIOMASS

Biomass is the equivalent weight of an individual or group of individuals (e.g., trees and saplings). The method of calculation can be destructive (actually cutting and weighing what is being measured) or an estimation, based on allometric equations. It can be measured for aboveground biomass, belowground biomass, wood biomass, leaf biomass, and fruit biomass. In this research, the analysis was restricted to aboveground biomass through the use of two allometric equations for its estimation. Due to its application to forested areas in Rondônia, the equation given by Brown et al. (1995) was used for trees with DBH greater than 10cm, where:

$$Y = 0.0326 * (DBH)^2 * H$$

For saplings (2.5 cm < DBH < 10 cm), the equation given by Honzák et al. (1996) was used, where:

$$Y = \exp[-3.068 + 0.957 \ln (D^2 * H)]$$

Caution should be taken when analyzing aboveground biomass estimations, as they are dependent on several variables such as hollowness, wood density for every species, bark, presence of palms, vines, and dead biomass (Fearnside 1992). The goal of these estimations was to have another parameter for comparison across the size classes (i.e., trees and saplings) and vegetation formations (i.e., SS1, SS2, SS3, and forest) within the study area.

- RATIOS

Some ratios between variables were also calculated. Inspired by previous work (Tucker 1996, Tucker et al. 1998), the goal was to depict the contribution of each major group of plants (i.e., trees and saplings) in relation to values found for the entire vegetation formation or for the other group. Therefore, three ratios are presented in this chapter:

Density of saplings to density of trees

Percent tree contribution to total basal area

Percent sapling contribution to total basal area

3.3.3 - Integration of spectral data

One of the main goals of fieldwork was to collect sufficient data to carry out the multi-temporal supervised classification of satellite images. For the purpose of image analysis, each plot sample became a ‘training sample,’ that is, an area of known identity that is used during supervised classification to identify areas of unknown identity (Mausel et al.1990). Each one of these areas was selected as an ‘area of interest’ (AOI) with specific spectral characteristics. GPS collected points and color composite printouts used in the field allowed the accurate positioning of each of these areas. The mean reflectance for the training samples was extracted for each TM band as well as the value for the Normalized Difference Vegetation Index (NDVI) (Lillesand and Kiefer 2000). The values were exported to the corresponding table in the database to allow their integration with vegetation structure data.

3.3.4 - Statistical analysis

The first step to achieve a better understanding about a specific set of numeric data is to perform an exploratory data analysis (Burt and Barber 1996). There are several methods, techniques, and statistical packages to accomplish this task. The first approach focused on graphic methods of analysis. Quantitative methods were used to inform the discussion in terms of the scientific motivation for this chapter.

Graphs are tools for analysis and communication (Schmid 1983). They provide a different perception about data, summarizing observations based on some defined output. Cleveland and McGill (1985) have shown that graphical methods are successful if the decoding process is effective. Moreover, some methods are better than others in terms of graphical perception. To avoid problems during data interpretation, simple and effective graphical methods such as boxplots and scatterplots were used. A boxplot is a summary plot based on the median, quartiles, and extreme values. The box represents the interquartile range that contains 50% of the values. The whiskers are lines that extend from the box to the highest and lowest values, excluding outliers. A line across the box indicates the median. In the scatterplot, one numeric variable is plotted against another, representing graphically the distribution of both variables (Ott 1993).

After becoming familiar with data through graphic methods, a second type of analysis is done through numeric procedures. Statistics is generally defined as a methodology for collecting, presenting, and analyzing data. Multiple purposes are recognized for the use of statistics, including its capability to summarize data, validate theories, provide forecasts, evaluate trends, and select a particular sample of interest. Descriptive statistics is used to organize and summarize data. Inferential statistics combines descriptive statistics with probability theory, generalizing the results of a study of a few individuals to a larger group. The mean is the most commonly used measure of central tendency. It is the ‘center of gravity’ or the ‘balancing point’ of a set of observations. However, the mean does not account for the variability of data in the range of values. To determine how typical the measure of central tendency is in a distribution, it is necessary to analyze measures of dispersion. Standard deviation is the most commonly used measure of dispersion. Mean, standard deviation, minimum and maximum values were used for the study of structural vegetation variables.

Another numeric approach in exploratory data analysis is the study of statistical relations between two variables. Pearson’s correlation coefficient and its significance levels were used to measure the strength of association between the variables under analysis.

Finally, analysis of variance (ANOVA) was used as a statistical technique designed to determine whether or not a particular classification of the data is meaningful. Data are decomposed to structure an F-test to test the hypothesis that the between-class variation is large relative to the within-class variation, which implies that there is a significant variation in the dependent variable between classes. The theoretical background about the procedures used and statistical significance of results obtained was based on literature about the topic (among others, Ott 1993, Shaw and Wheeler 1994, Gujarati 1999).

3.4 - Vegetation structure of secondary succession and forest in Machadinho and Anari

3.4.1 - Phyto-physiognomy and general patterns of succession classes and forest

This section describes the main characteristics of each vegetation type sampled during fieldwork (i.e., SS1, SS2, SS3, and forest).

- INITIAL SECONDARY SUCCESSION (SS1)

Six sites were sampled to represent SS1. Their ages are three and five years according to information gathered from interviews with landowners. Earlier stages of abandonment (one and two years) were not sampled because of their spectral similarity with other LULC features, such as degraded pasture and perennial agriculture. The discussion about the role of pasture in Amazonian landscapes is an important issue, when related to its different functions in terms of land use or land cover. It is common to see initial stages of secondary succession used for cattle ranching as well as abandoned pastures, where land cover follows the trend of vegetation recovery. To avoid misinterpretation and to keep control over this dichotomy, it was assumed that the percentage ground cover was the variable defining the threshold between the classes 'pasture' and SS1. Thus, areas with grass cover greater than 75% were defined as cultivated pasture. Areas with grass cover between 25 and 75% and used as pasture were assigned as degraded pasture. SS1 was assigned solely to areas where the grass cover was less than 25%, which generally occurs in sites that have been abandoned for more than two years. Each of the six sites sampled has its own history of occupation and abandonment that, together with their different ages and biophysical characteristics, produces an internal variability within the class.

The profile in Figure 14 shows a phyto-physiognomic representation of a SS1 plot. Table 5 summarizes structural characteristics of these sites. Pioneer species such as light-demanding herbaceous plants, grasses, vines, seedlings, and saplings dominate SS1. These species have a short life cycle, high growth rate and high reproductive resource allocation (Gómez-Pompa and Vasquez-Yanes 1981). Some tree species become important after the second or third year of regrowth. Besides palms, species commonly associated with this period include *Vismia sp*. and *Cecropia sp*, as illustrated in Figure 14.

In general, the structural variables show low standard deviation compared to the means, except for density of trees and the ratio between densities of saplings and trees. An important characteristic of this stage is the much higher density of saplings (7460.3 individuals/ha) compared to the density of trees (266.7 individuals/ha). High sapling competition in SS1 is also expressed by its twofold basal area compared to trees. The average DBH for trees is just 1.4 cm above the minimum sampling size (10 cm), indicating the early stage of vegetation recovery. The mean tree height of 7.8 m is relatively high compared to other sites in the Amazon (Tucker et al. 1998). This is due mainly to *Cecropia* trees competing for light and emerging to form the canopy (Figure 14). Despite the high density of saplings, trees are responsible for the greatest part of total stand biomass, which is 29.2 t/ha (metric tons per hectare) (Table 5).

- INTERMEDIATE SECONDARY SUCCESSION (SS2)

The sample for SS2 included ten sites with ages of six, eight, nine, and ten years. Figure 15 shows a profile of this vegetation. Table 6 summarizes the calculated structural variables. The physiognomic difference of this stage in relation to SS1 is evident. Saplings are still important for the stand as a whole (density of 4,814.8 individuals/ha), but the density of trees is three times greater than in SS1 (density of 763.3 individuals/ha). DBH for trees increased to an average of 13.8 cm. Total basal area is 11.5 m^2/ha. The sapling contribution of 55.6% to total basal area indicates that saplings are still very important at this stage of regrowth. However, the mean height of trees (10.1 m) is now two times greater than for saplings. Biomass increased twofold in relation to SS1 due to the increase in DBH and height of trees.

In sum, during SS2, young trees are already present but saplings still have a higher density. A closer canopy alters the microclimate, improving conditions for shade-tolerant tree species and creating an unsuitable environment for pioneer species. This profound change sets the path to a more advanced stage of vegetation regrowth.

- ADVANCED SECONDARY SUCCESSION (SS3)

Eight sites with ages of twelve and thirteen years represented SS3. It is useful to remember that the study area started to be colonized between 1981 and 1984, the satellite image was acquired in 1998, and fieldwork was done in 1999. This makes it difficult to find older stages of regrowth, with the main source being only records kept by landowners. Figure 16 illustrates a SS3 stand. The structural variables for this class are described in Table 7.

There are clear differences in vegetation structure. Although large *Cecropia* are still present, most pioneer species gave way to slow-growing, shade-tolerant forest species. Trees dominate the stand as also pointed out by previous studies (Li et al. 1994, Tucker 1996). Tree density increased to 920.8 individuals/ha while density of saplings decreased to 3,750.0 individuals/ha. Average DBH for trees is 17.1 cm and basal area results are now slightly greater for trees than for saplings (6.86 and 6.73 m^2/ha, respectively). Total basal area increased to 13.6 m^2/ha with a tree contribution of 51.1%. The mean height for trees is 3 m greater than in SS2 stands. Increases in DBH and height doubled the aboveground biomass in relation to SS2. The general appearance of this vegetation type in terms of canopy layers is similar to a forest. However, trees are still not as high or thick, as explained below.

- TROPICAL OPEN FOREST

Seven sites represented the sample for open tropical forest. As illustrated in Figure 17, a clear understory and larger trees characterize these areas. The vegetation formation comprises relatively widely spaced tree individuals, sometimes including palms, bamboo, and lianas, as described by Barros-Silva et al. (1978). These authors also reported a shorter Amazonian forest for eastern Rondônia, with height varying around twenty meters.

The structure of the tropical open forest is quite different from secondary succession stages. Results shown in Table 8 illustrate these findings. The average height is even lower than reported in the literature for other studies: 15.2 m (Barros-Silva et al. 1978, Salomão and Lisboa 1988, Alves et al. 1997). The density of saplings is the lowest of all vegetation classes sampled (2.407,4 individuals/ha). The density of trees (772.1 individuals/ha) is lower than in SS3, certainly because large *Cecropia* individuals and other pioneer species died off during the transition to forest. The mean DBH of trees (22.8 cm) is five times greater than the mean DBH for saplings (4.5 cm) indicating the dominance of trees in these sites. This characteristic is also depicted from values of basal area. Basal area for trees (12.5 m^2/ha) represents 69.4% of total basal area. An ultimate indication about the developed structure of the sampled forests in relation to the secondary succession stands is given by their total biomass of 269.2 t/ha. The importance of trees is also noticed here, as their biomass is 268.1 t/ha. Saplings contribute with just 1.1 t/ha.

A complementary way to understand differences and similarities between secondary succession stages and forests in the study area is to analyze structural variables in a comparative fashion. The next section is dedicated to this comparison.

3.4.2 - What makes a secondary succession stage?

Overall, the comparative analysis of different succession stages and the tropical open forest indicates a significant separation between the classes sampled in the field. Although the process of vegetation recovery happens on a continuous basis, the decision to choose three categories of regrowth was appropriate to characterize distinct structural phases during the process. The analysis of selected structural variables explaining this distinction is presented below.

- DBH

Figure 18 illustrates the variability in DBH for trees in all classes sampled. It is obvious the trend in increasing DBH from SS1 up to forest. As also expected, there are small overlaps between the extreme values of all classes. The range for DBH of trees in forest sites is the greatest (19.4 to 28.5 cm, Table 8), as well as its distance between the quartiles. The former is explained by the occurrence of emergent individuals competing for light, and the latter indicates the heterogeneity in the average diameter of trees during the first years of recovery. The difference between DBH for all classes is statistically significant at $p<0.001$ (Table 9).

This difference is less significant for DBH of saplings ($p<0.09$). Although it increases from SS1 to SS3, the upper quartile of a previous class is always overlapping with the lower quartile of the next class (Figure 19). It is important to notice the decrease in DBH of saplings in forest sites. This is due to the effect of shading after SS3, when a closer canopy creates an unsuitable environment for sapling development.

- BASAL AREA

Similar trends are found for basal area of trees and saplings, as its calculation is affected by DBH values. Figures 20 and 21 illustrate basal area distributions for these groups of individuals. For saplings, the classification of regrowth stages is not meaningful ($p<0.305$) indicating closer values of basal area from SS1 to forest and mainly at the succession stages (Table 9). Results for total basal area follow the increasing pattern from early secondary stages up to forest (Figure 22). This is explained by tree contribution to total basal area (Figure 23). However, the range and variance for all classes of total basal area are greater than basal area for trees because of sapling heterogeneity for this parameter (Figure 24).

- HEIGHT

Total height of individuals is an important parameter indicating the stage of recovery. Figures 25 and 26 illustrate the observed values for total height of trees and saplings, respectively. The former increases significantly from SS1 to forest ($p<0.001$). Although the height of saplings also increases, overlaps between classes occur more often ($p<0.005$) (Table 9).

Ecologically, these trends are explained by the competition for light within the vegetation community. Trees tend to grow continuously in search of higher canopy layers. As this process occurs, saplings have to deal with the variable availability of light at the understory, which increases their height variance.

- DENSITY

The density of trees increases from SS1 to SS3, but decreases at forest sites (Figure 27). Two factors determine this pattern. First, dominant species at SS3 (e.g., *Cecropia sp.*) die off during the transition to forest. Second, at the forest community level, trees continue to grow in DBH and height but the number of individuals decrease. The trend for density of saplings is the opposite. It constantly decreases from initial stages of regrowth up to forest indicating the importance of trees in more advanced recovery stages (Figure 28). The difference between classes is less significant for trees ($p<0.006$) than for saplings ($p<0.001$) (Table 9).

The relationship of density of saplings and density of trees is depicted by the ratio between these variables. During SS1, this ratio is expressed by a huge variance (Figure 29). Within this stage, the effect of previous land use is more direct, producing different outcomes for vegetation establishment. After SS2, the relationship tends to stabilize as a response to the clear pattern of density change described above.

- BIOMASS

As a function of DBH and height, the trends of aboveground biomass from SS1 to forest are affected by those variables. Biomass for trees increases constantly, achieving its highest values in forest formations (Figure 30). The higher variability for forest biomass is related to the larger range in DBH and total height in this class than in stages of regrowth (Tables 5, 6, 7, and 8). Biomass for saplings shows similar trends to that of DBH for saplings (Figures 31 and 19, respectively). It increases from SS1 to SS3, but decreases for forest, due to the lower importance of saplings in open tropical forest environments. Total biomass values behave similarly to tree biomass (Figure 32).

3.4.3 - The spectral response to vegetation structure

While structural vegetation variables seem to be good indicators of secondary successional stages, the question remains about how spectral Landsat TM bands respond to their variation. Figure 33 illustrates the spectral curves for all areas where vegetation classes were sampled. SS1 and SS2 curves have a higher variability for the mean reflectance in bands 4 and 5 than SS3 and forest. These latter classes have a smaller and well-defined range for reflectance in the near infrared (band 4) and mid-infrared (band 5).

The consequences of these spectral responses in terms of distinguishing different regrowth stages and forest are discussed below.

Figure 34 illustrates mean reflectance values for vegetation classes in band 3 (visible). Figure 35 shows these values for band 4 (near infrared), Figure 36 for band 5 (mid-infrared), and Figure 37 for the Normalized Difference Vegetation Index (NDVI). The significance of the vegetation classification in terms of separability by TM bands is given in Table 10. It is clear how band 5 differentiates regrowth stages better, although all TM bands have $p<0.001$. Band 3 shows poor distinctions in reflectance between SS1 and SS2, while SS3 overlaps with these classes of regrowth and with forest. Band 4 does not distinguish SS1 and SS2. NDVI does not separate any of the vegetation classes ($p<0.502$).

When using graphs to relate structural vegetation variables with reflectance values, other relationships are found. As described above, average total height of trees is a good indicator of succession stages, as it has distinct ranges for all vegetation classes defined (Figure 25). This parameter was used to build scatterplots with visible, near infrared, and mid-infrared TM bands. Band 3 (visible red) does not distinguish vegetation classes properly in terms of the average total height of trees (Figure 38). Infrared bands (4 and 5) show a better response for this structural parameter (Figures 39 and 40, respectively). However, only forest and SS3 are well separated. SS1 and SS2 overlap.

Several other variables reveal similar trends in relation to spectral responses in the infrared. Figures 41, 42, 43, and 44 show these responses for DBH of trees, total basal area, density of trees, and total biomass, respectively. Tridimensional graphs of DBH and total height of trees with reflectance in bands 4 and 5 also suggest that SS1 and SS2 are not well separated spectrally by TM bands (Figures 45 and 46, respectively).

The integration of spectral data with the analysis of field vegetation structure supported the decision-making process when defining classes of land cover used in the next chapters.

3.5 - The role of vegetation structure and remote sensing for the study of secondary succession dynamics in colonization areas of Amazônia

The study of vegetation structure presented in this chapter confirmed expected trends about secondary succession of tropical forests in Rondônia, which include: increase in density of trees with decrease in density of saplings; increase in DBH of trees and total basal area; increase in total height of trees; and, consequently, increase in total aboveground biomass. In addition, the results obtained for selected vegetation structure variables were depicted by spectral responses in Landsat TM bands, particularly the ones within the infrared portion of the spectrum. This last assertion has already been discussed in the literature and is due to chlorophyll absorption in the visible TM bands (1-3); mesophyll reflectance in the near infrared (band 4); and for both plant and soil water absorption in the mid-infrared bands (5 and 7) (Moran et al. 1994). The balance within and between these three groups of bands permits the differentiation of stages of succession, tropical forest, and other land-cover classes.

The applicability of these findings surpasses the understanding of vegetation recovery processes at local scales. It allows the spatial-temporal monitoring of Amazonian landscapes regarding their land-cover dynamics. Being able to differentiate distinct stages of vegetation regrowth in a landscape makes it possible to draw a better picture about LULC trajectories. The use of remote-sensing techniques has improved this capability by ensuring the investigation of secondary succession in larger areas on a multi-temporal basis. However, such an enterprise is not an easy task, mainly because it artificially reduces the continuous process of vegetation recovery to a selected number of categories.

The dichotomy between natural heterogeneity and the scientific need for generalizations is a major challenge in ecological research. As the knowledge about a phenomenon being studied increases and becomes available for the scientific community, interpolations and extrapolations are readily made. The scales of space, time, and complexity are then reduced to relatively few discrete explanatory categories (Wilson 1998). It is common to see broad generalizations based on local factors and/or grouping of local heterogeneity based on generalizations.

O'Neill et al. (1986), willing to justify such attitude, recognized that some degree of abstraction is required in order to study ecological systems. The rationale behind this statement is that ecology cannot set up a single spatial-temporal scale that will be adequate for all investigations. Space-time dynamics is now understood as a central issue related to ecosystem studies (Kareiva 1994). The scale factor, widely discussed in a variety of studies, has induced the development of a hierarchical view of ecosystems (Allen and Star 1982, Bian 1997). Instead of descriptive and qualitative attempts to analyze natural heterogeneity and dynamics, quantitative approaches have shown the development of complex ecological systems toward new levels of organization (Sklar and Costanza 1991).

These processes range from local to global scales, and the argument is valid for vegetation ecological studies. This chapter focuses on tropical forests in Rondônia and their stages of succession after disturbance. If there is a common sense about what forest is, it relates to a 'vegetation community dominated by trees.' However, even within specific biomes, they may differ in structure, composition, and physiognomy. From the ecologist's standpoint, forests consist of a mosaic of gap-phase, building-phase, and mature-phase formations (Whitmore 1998).

The tentative nature of defining secondary succession classes in Rondônia based on vegetation structure data and remote sensing complies with the need to monitor land cover in the Amazon. But how many final classes need to be defined and how do they correspond with the classes used during field sampling? Do TM spectral bands depict all classes identified by the original sample? If not, which variables can be used to control the process of categorization?

One way to address these questions is to follow the regrowth trajectory in selected sites and assign stages based on age (Uhl 1987, Guariguata et al. 1997, Nelson et al. 1999). This method generally maintains control over site variability but does not allow generalization to other areas within the region due to the small number of samples. In addition, the vegetation classes are difficult to depict in TM images at this level of separation. Another way to address the heterogeneity of vegetation classes of regrowth in the Amazon is to define a range of classes based on vegetation structure (Brondizio 1996, Tucker 1996) or age (Uhl et al. 1988, Steininger 1996). This method may also be affected by the sampling strategy. For instance, if age is considered as an initial parameter to define regrowth classes, gaps between ages sampled may produce additional lack of information in order to identify the final classes. However, using stratified random sample techniques minimizes the potential pitfalls of such strategy by ensuring a broader representation of the natural variability in the study area.

For the research in Rondônia, the sample did not include ages 1, 2, 4, 7, 11, and greater than 14 years. The decision of undersampling the first and second years of succession was discussed above. In this case, the confusion with pasture in terms of land use, vegetation structure (similar to degraded pasture), and spectral responses, indicated that the accuracy of assigning SS1 increases if stands more than 2 years old are considered. The decision was supported by previous studies showing that most class errors were associated with youngest age classes (< 2 years) and with different successional pathways and vegetation composition (Foody et al. 1996). To avoid the problem, Steininger (1996) also assigned classes of regrowth starting at two years old, and included a class called ‘pasture with trees’ between ‘farmland’ (agriculture and pasture) and secondary succession.

The confusion between SS1 and degraded pasture is mostly due to a common practice among local landowners. After slashing and burning, they often seed grass for pasture. If not, they plant annual crops, then seed grass. Or they plant annual and perennial crops (mostly coffee), and, if anything goes wrong, planting grass is again seen as an alternative land use. With the use of fire, grasses tend to overcome other pioneer species, playing an important role in initial stages of succession and consequently affecting spectral classifications. After the second year, recovery by saplings and small trees diminish the importance of grasses regarding ground cover. Then, the physiognomy (structure) of a fallow is better characterized.

On the other hand, not including first- and second-year SS1 increased the averages for some key structural variables being analyzed. For example, total height and DBH of trees for SS1 in the study area were greater than reported by other comparable studies (Alves et al. 1997). Besides this initial period of regrowth and a few years of not being present in the sample, other ages were well represented (3, 5, 6, 8, 9, 10, 12 and 13 years old). Secondary succession stands older than 14 years were not sampled due to the settlements' age. Since they were established between 1980 and 1984, and fieldwork was done in 1999, the uncertainty of sampling 15-year-old or older stands would be too high. Moreover, no landowner reported a fallow that old.

The sample variability allowed the comparison of vegetation structure and spectral responses within and across classes. In general, height and DBH of trees, density of saplings, total basal area, and total biomass were good indicators of vegetation regrowth stages. All of them were significantly separated among SS1, SS2, SS3, and forest classes (Table 9). It is important to mention that many of these variables are significantly correlated, indicating that less sampling effort would be needed to depict different classes of succession in broader studies at the regional scale (Table 11). For example, DBH, basal area, height, and biomass of trees are highly correlated. As other studies have shown, height or DBH of trees could be chosen in this case to represent the stage of regrowth (Moran et al. 2000). The advantage of choosing these variables instead of basal area or biomass is the relative simplicity of directly measuring them during fieldwork and perhaps in the future using Light Detection and Ranging (LIDAR) to estimate canopy height for large regional areas.

Despite the clear separation among classes of succession and forest, when graphed against mean reflectance in infrared TM bands (Figures 39 to 46), only three clusters of samples were well differentiated (SS1 and SS2 mixed together, SS3, and forest). These results supported the decision of grouping SS1 and SS2 into a single class of regrowth. In doing that, the accuracy increases in relation to the classification system. Also, the confusion between SS1 and pasture or SS2 and perennial agriculture tends to be minimized. In addition, two classes of succession are still maintained, allowing studies of land-cover dynamics through multi-temporal analyses. In sum, the decision of going from three to two classes of vegetation regrowth was necessary to improve the performance of further analyses of land-cover dynamics.

All these findings confirm the importance of land-use history besides age in defining stages of secondary succession. However, in more recent settlements such as Machadinho and Anari, age also may be significant because there was not enough time to produce the same impact as in older settlements. This is indicated by the significant correlation between age and vegetation structure variables or spectral data mentioned above (table 11). As pointed out by Uhl et al. (1988), site age is a good predictor of aboveground biomass accumulation on light- and moderate-use sites, but not on heavy-use sites. In this chapter, age and physiognomy were used as indicators for field sampling, but, after data collection, age also can become a variable to be analyzed together with vegetation structure variables and spectral responses in TM bands.

Although some studies have attempted to assign age to secondary succession stages based on total stand biomass (Nelson et al. 1999) or canopy geometry (Steininger 1996), what has been measured is the outcome of different trajectories of land use over distinct biophysical features. The stage of regrowth in terms of vegetation structure (and species composition), and not its age, is more useful in possible applications of mapping and monitoring succession classes. However, age may be appropriate as an organizing principle of regrowth stages when sampling vegetation and interviewing local people and landowners or to be used in studying the impact of land-use history on different sites (Moran et al. 2000). In this sense, knowledge of culture and context helps to achieve a better understanding of regeneration processes in the Amazon. Moreover, the study of vegetation structure variables such as total height of trees together with the investigation on biophysical features such as soil fertility and land-use history are better indicators regarding the degree of development of a regrowth stand. The assessment of these variables at local and regional scales and the interpretation of spectral data to depict such variability provide more accurate information about the trajectory of recovery occurring at distinct colonization stages in rural settlements in the Amazon.

3.6 - Trends in research of tropical forest secondary succession

The findings and topics exposed in this chapter illustrate the importance of studying secondary succession in tropical environments. The research also identified many research initiatives regarding the integration of vegetation structure data and the use of satellite images in monitoring land-cover dynamics in the Amazon.

The rapid and aggressive regrowth of secondary vegetation in tropical areas has already been discussed by a number of researchers. The Amazon colonization produces widespread deforestation but also a mosaic of secondary successional vegetation stages. Different regeneration patterns occur depending on land management following deforestation. Although it is clear that secondary vegetation will not preserve the total biodiversity of mature forests, it is also clear that it plays an important role in the Amazonian landscape structure and function (Smith et al. 1997).

Perhaps one important question not covered by this chapter is the role of species composition within the different stages of regrowth. Studies have shown that disturbance from slash-and-burn agriculture affects species composition much more than stand structure and biomass (Uhl 1987). Vieira et al. (1996) have also pointed out that even after 40 years of recovery, richness is less than half of a primary forest. Although such an issue is of central relevance to the maintenance of local and regional biodiversity, we are far from being able to differentiate distinct tropical forest communities based on species composition when using satellite data. Current applications can only recognize different structural patterns and processes.

Research regarding these latter applications includes many new approaches. In terms of the availability of new sensors and data, optical and microwave data provide complementary information about land use and forest fragmentation. Besides overcoming the problem of cloud cover, the use of low frequency radar systems and its integration with other spatial and spectral data is promising for land-cover mapping in the Amazon (Rignot et al. 1997, Saatchi et al. 1997, Yanasse et al. 1997).

A second way of improving the extraction of earth surface feature information for LULC classifications in the Amazon is the use of state-of-the-art techniques for image processing and classification. Among others, spectral mixture analysis (Schweik 1995, Adams et al. 1995), spatial-spectral classifiers (Foody et al. 1996), spectral indices of canopy brightness (Steininger 1996) and GIS-informed classifications (Hinton 1996, Batistella 2000) are among the main trends to improve monitoring of secondary succession.

Recent questions have arisen about the importance of successional land covers to carbon sequestration (Fearnside and Guimarães 1996). Other studies have addressed the process of degradation of Amazonian forests (Nepstad et al. *Flames* 1999, Vieira et al. 1993). Activities such as selective logging have been responsible for the impoverishment of forests. Logging and fire increase forest vulnerability to future burning, ‘potentially doubling net carbon emissions from regional land use during severe El Niño episodes’ (Nepstad et al. *Large-scale* 1999).

The ecological functions of secondary forests at local and regional scales have just recently been investigated. Besides maintaining one-third of the native species, their role in carbon sequestration seems to be even more important (Vieira et al. 1996). Furthermore, successional vegetation re-evaporates an important part of the rainfall input in spite of the marked seasonal distribution of rainfall (Holscher et al. 1997). Possible regional climatic changes due to deforestation may be less severe in areas where woody secondary vegetation plays an important role in land cover.

At the local scale, the stages of secondary succession are directly associated with cycles of production and abandonment. Slash and burn clearing, cropping, and fallowing correspond to different phases within these cycles and depend on decision-making processes among the landowners. In this sense, monitoring the outcomes in terms of vegetation structure and LULC may also provide information about actions being taken by farmers. The study of LULC dynamics, and its fundamental importance to the understanding of general patterns of landscape transformation, is the goal of the next chapter.