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Classification of successional forest stages in the Brazilian Amazon basin

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Abstract

Research on secondary succession in the Amazon basin has attracted great interest in recent years. However, methods used to classify successional stages are limited. This research explores a method that can be used to differentiate regrowth stages. The vegetation inventory data were collected in Altamira, Bragantina, Pedras, and Tome-Acu of the eastern Amazon basin. A nested sampling strategy, organized by region, site, plot, and subplot, was employed for field data collection. Above-ground biomass (AGB), forest stand volume (FSV), basal area, average stand height, average stand diameter (ASD), age, ratio of tree biomass to total biomass (RTB), ratio of tree volume to total volume, and ratio of tree basal area to total basal area were calculated at the site level. Canonical discriminant analysis (CDA) was used to differentiate successional stages and to identify the best forest stand parameters to distinguish these stages. This research indicates that the CDA approach can be used to classify successional forest stages, but using RTB or a combination of two stand parameters such as AGB and ASD are more feasible and recommended in practice.

Keywords: Classification; Secondary succession; Forest stand parameters; Canonical discriminant analysis; Amazon

1. Introduction

The Amazon basin contains the largest continuous tropical forest in the world; however, it has suffered serious deforestation for the last 50 years because of road-building, logging, mining, and agricultural and cattle-raising expansion (Moran et al., 1994a; Skole et al., 1994). The large area deforestation has resulted in effects on climate change, biological diversity, hydrological cycle, soil erosion and degradation (Shukla et al., 1990; Houghton, 1991; Skole and Tucker, 1993). After deforestation, regeneration of vegetation is common and the resulting landscape often consists of patches of successional forests and agricultural lands.

Different succession stages have their own stand structures and different capability in influencing the relationships between successional forests and

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ecosystem change. Previous research has shown that successional forests plays a key role in soil restoration through the accumulation of biomass, the buildup of litter and organic matter, and other beneficial soil/plant interactions (Moran et al., 2000a). In order to better understand the roles of successional forests, intensive research focused on them is needed, requiring a more universal standard that can be used to classify different successional stages. Unfortunately, to date there are few standard methods that can satisfy the requirement of such intensive research due to the complex stand structure and species composition (Moran and Brondízio, 1998). This paper presents a method that can be used to differentiate successional stages by examining forest stand characteristics.

2. Previous analysis of secondary succession stages

Tropical forests can be grouped roughly into categories of primary forest and successional forests. Primary forest is defined here as a forest that is not greatly disturbed by natural disasters or human activities. Successional forest is defined here as a regrowth forest following a disturbance such as deforestation. Secondary succession describes the changes of plants that live in a particular community over time. Because of the importance and different capability of successional forests in restoration of degraded moist tropical environments, accurately differentiating them into different stages is valuable for better understanding their role and their relationships with ecosystem change. This knowledge will promote better management and utilization of natural resources. Much of the research focused on successional forest analyses has been conducted in recent years and has attracted great interest (Sader et al., 1989; Lucas et al., 1993; Mausel et al., 1993; Foody and Curran, 1994; Steininger, 1996; Li et al., 1994; Moran et al., 1994a; Moran et al., 1994b; Moran and Brondízio, 1998; Tucker et al., 1998; Lu, 2001; Lu et al., 2002; Lucas et al., 2002). In previous research, at least four methods have been used for differentiating successsional stages. These methods include: (1) vegetation age (Saldarriaga et al., 1988; Uhl et al., 1988); (2) average stand height and basal area (Moran and Brondízio, 1998; Moran et al., 2000a); (3) physiognomic characteristics (Tucker et al., 1998); and (4) remote-sensing methods (Mausel et al., 1993).

Vegetation age is the most straightforward method used for the identification of successional forest stages (Saldarriaga et al., 1988; Uhl et al., 1988). In general, those successional forests with vegetation ages of less than 5 years are grouped as initial successional forest (SS1), with vegetation ages between 6 and 15 years as intermediate succession (SS2), and with the vegetation ages of greater than 15 years as advanced succession (SS3). Hence, age is the easiest way to classify successional stages, but the successional forests with different vegetation ages could have similar stand structures and the same-age successional forests could also have significantly different stand structures because of the influence of soil fertility and soil structure, precipitation patterns, land-use history, original vegetation, clearing size, and other human activities (Uhl et al., 1988; Tucker et al., 1998; Moran et al., 2000a; Moran et al., 2000b). Age alone is not a suitable forest stand parameter to predict successional stages since many factors influence structural differences among sites within the same-age class (Tucker et al., 1998).

Moran and Brondízio (1998) and Moran et al. (2000a) defined successional stages of Amazonian tropical forest based on the analysis of average stand height and basal area. They found that forest stand height was a significant discriminator of regrowth in SS1, SS2, and SS3 stages. In general, SS1 has average stand heights of less than 6 m and basal areas of less than 10 m^2/ha. SS2 has the stand height ranging from 7 to 15 m associated with basal area ranging from 10 to 25 m^2/ha. SS3 has similar basal area as SS2 but has higher average stand height, ranging from 13 to 17 m. However, overlap exists in basal area and average stand height between SS2 and SS3. It is difficult to classify those successional forest sites when their basal areas and average stand heights overlap.

Tucker et al. (1998) developed a complex successional stage classification system based on physiognomic characteristics from the combined Altamira and Bragantina field data. The primary structural features which uniquely identify each stage include: (1) the contribution of trees and saplings to total basal area; (2) average total height; (3) mode total height; (4) average diameter at breast height; (5) tree basal area; and (6) standard deviation of total height, which indicates the degree of structural diversity among individual plants. They found that the central discriminating factor between successional stages was the contribution of sapling and trees to the fallow's total basal area. The sapling/tree basal area relationships can help predict other structural features and effectively differentiate regrowth stages. For example, the percent tree contribution to total basal area is zero in SS1, between 14 and 49% in SS2 and between 50 and 93% in SS3. However, basal area is often affected by the vegetation density and species composition. It is not a suitable stand parameter when using it to classifying successional stages in different environmental sites (Lu, 2001).

In the Amazon basin, remote-sensing technology has been extensively used to analyze successional stages during the past 10 years (Lucas et al., 1993; Mausel et al., 1993; Foody and Curran, 1994; Li et al., 1994; Moran et al., 1994a; Moran et al., 1994b; Brondízio et al., 1994, 1996; Foody et al., 1996; Steininger, 1996; Rignot et al., 1997; Moran and Brondízio, 1998; McCracken et al., 1999; Lu, 2001; Lu et al., 2002; Lucas et al., 2002). Mausel et al. (1993) analyzed landsat thematic mapper (TM) spectral responses with different successional stages and concluded that TM data can be used successfully to identify three successional stages if supported by strong field survey data. Similar studies were conducted by Moran et al. (1994a), Li et al. (1994), and Brondízio et al. (1996). They found that extraction and classification of homogeneous objects (ECHO) was a good classifier for distinguishing different successional stages and mature forest. However, the classification accuracy greatly depends on the quality of training datasets and requires abundant and accurate field measurements from all classes of interest. One of the key steps for successful classification is to select high quality successional forest sites as training sample datasets. Confusion often occurs in identifying different successional stages or distinguishing between advanced successional forest and mature forest, since remotely sensed data primarily capture canopy information. The canopy structures between advanced successional forest and mature forest can be very similar, although they have different ages, species complexity, and biomass amounts. The smooth transition between different successional stages also causes differentiation difficulty.

Previous research has indicated that there are no ideal methods that can be used to classify different successional stages in the moist tropical region. Hence, this paper attempts to develop a new method for distinguishing successional stages in order to meet the requirement of comparative analysis. It is assumed that a good method for differentiating successional stages should have the following characteristics: (1) simple and straightforward, easy to use; (2) comprehensive factors that can describe the difference between various successional stages and can reflect the different forest stand structures and environmental influence; (3) a standard that can be used for a large area; and (4) a potential for application using remote-sensing data in a large area.

3. Methods

3.1. Description of the study area

Altamira lies along the Transamazon highway and has experienced high rates of deforestation and secondary succession with the implementation of agro-pastoral projects since colonization began in 1971 (Moran, 1976). In contrast, Marajo historically has been home to native nonindigenous (i.e. Caboclo)

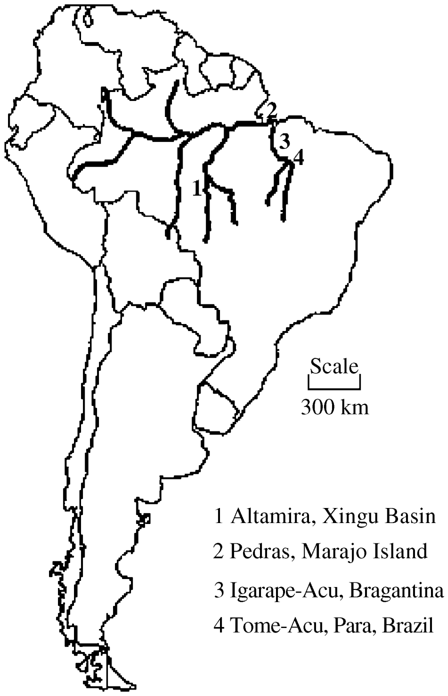
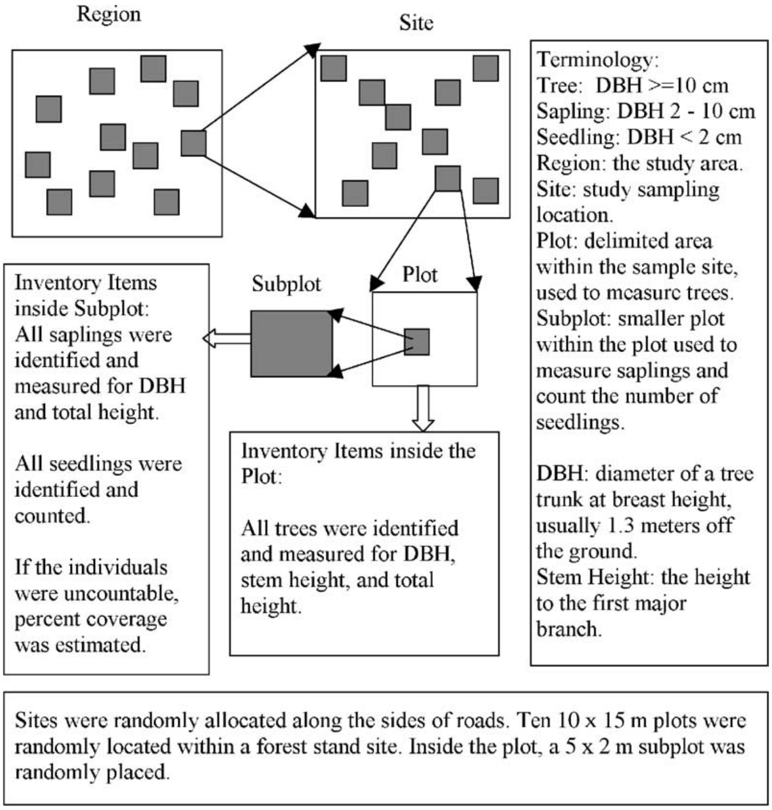


Fig. 1. Locations of the four Amazon study areas.



Inventory Items inside Subplot:
All saplings were identified and measured for DBH and total height.

All seedlings were identified and counted.

If the individuals were uncountable, percent coverage was estimated.

Inventory Items inside the Plot:

All trees were identified and measured for DBH, stem height, and total height.

Terminology:
Tree: DBH >=10 cm
Sapling: DBH 2 - 10 cm
Seedling: DBH < 2 cm
Region: the study area.
Site: study sampling location.
Plot: delimited area within the sample site, used to measure trees.
Subplot: smaller plot within the plot used to measure saplings and count the number of seedlings.

DBH: diameter of a tree trunk at breast height, usually 1.3 meters off the ground.
Stem Height: the height to the first major branch.

Sites were randomly allocated along the sides of roads. Ten 10 x 15 m plots were randomly located within a forest stand site. Inside the plot, a 5 x 2 m subplot was randomly placed.

Fig. 2. A nested sampling strategy for vegetation inventory during field work.

population engaged primarily in agroforestry activities in floodplain and swidden agricultural fields. The Bragantina region has gone through several land use phases and short-fallow swidden cultivation is now dominant. Cultivation of secondary growth areas has been common for decades, and islands of mature forest are rare. Tome-Acu has experienced the most intensive agriculture of the four sites (a black pepper monoculture until the late 1960s), and for the past two decades it has been associated with agroforestry development conducted by the Japanese colonists who have lived there since the 1930s. It is now experiencing the start of pasture formation. Fig. 1 shows the locations of the four study areas discussed above.

3.2. Field data collection

A nested sampling strategy, organized by region, site, plot, and subplot, was employed to collect vegetation inventory data (Fig. 2). The region is the highest categorical level, representing the study area that includes all sample sites. Sites in this region were selected for plot sampling. In general, 10 plots (10 m × 15 m) in each site are allocated and one randomly selected subplot (5 m × 2 m) is nested within each plot. Plots are designed to inventory trees and subplots are used to inventory saplings, seedlings, and herbaceous species. In each plot, all the individual trees (diameter at breast height or DBH = 10 cm) were identified and measured for DBH, stem height (the height of the first major branch), and total height. In the subplot, all saplings (between 2 and 10 cm DBH), seedlings (less than 2 cm DBH), and herbaceous vegetation (as a percent of ground cover) were identified and counted, and diameter and total height were recorded for all individuals with DBH between 2 and 10 cm. Table 1 summarizes the vegetation inventory data collected from selected study areas. A total of 52 sites of different successional forest stages and 12 sites of mature forests were measured during the dry season in 1992–1994.

Table 1
Summary of collected sites, plots, and subplots from the study areas

Region	Successional forests			Mature forest			Total sites
	Sites	Plots	Subplots	Sites	Plots	Subplots	
Altamira	18	111	219	2	20	20	20
Bragantina	14	98	187	4	28	28	18
Pedras	8	51	157	5	30	30	13
Tome-Acu	12	110	135	1	10	10	13
Total	52	370	698	12	88	88	64

3.3. Calculation of forest stand parameters

The diameter at breast height (DBH) and total tree height are two basic parameters of individual trees, which are often measured in the fieldwork. Other vegetation stand parameters such as stand volume, above-ground biomass, and basal area can be calculated based on the DBH and/or tree height of individual trees at a plot or site level. Eight vegetation stand parameters: average stand diameter, average stand height, basal area, forest stand volume, above-ground biomass, ratio of tree biomass to total biomass, ratio of tree volume to total volume, and ratio of tree basal area to total basal area, were calculated at the site level.

Individual tree volume is defined as the function of DBH, tree height, and tree form factor: $V = \mathrm{BA} \times H \times \mathrm{FF}$; where V is volume, BA basal area, H tree height and FF is tree form factor, defined as the ratio of tree diameter at middle height and tree diameter at breast height (Spurr, 1952). In practice, the diameter at middle tree height is not easily available. In this research, the volume (m^3) for an individual tree is defined as a function of basal area and total height:

$$V = \mathrm{BA} \times H \quad \text{or} \quad V = 10^{-4} \times \tfrac{1}{4}\pi \times D^2 \times H \tag{1}$$

where $\mathrm{BA} = (\pi/4) \times D^2$, D the tree DBH (cm) and H is the total tree height (m).

Two models were used to calculate above-ground biomass of individual trees. For those individual saplings and trees with DBH less than 25 cm, formula (2) (Nelson et al., 1999) was used to calculate the biomass:

$$\ln(\mathrm{DW1}) = -2.5202 + 2.1400 \times \ln D + 0.4644 \times \ln H, \tag{2}$$

where DW1 is individual tree or sapling biomass (in kg) when DBH is less than 25 cm. This model was established using 132 sample trees from successional forests with DBH between 1.2 and 28.6 cm (Nelson et al., 1999). The study area was located in the central Amazon of Brazil. Hence, this model is used in this research when the DBH falls within 1.2–28.6 cm. However, this model is not suitable to extrapolate the biomass estimation for those trees with DBHs greater than 25 cm because few sampling trees of this size were used to develop this model. Thus, for those individual trees with DBHs greater than 25 cm, formula (3) (Overman et al., 1994) was used to calculate the biomass:

$$\ln(\mathrm{DW2}) = -3.843 + 1.035 \times \ln(D^2 \times H), \tag{3}$$

where DW2 is the individual tree biomass when DBH is greater than or equal to 25 cm. This model for biomass estimation was established using 54 sample trees from mature lowland ‘‘terra firme’’ forest in the Amazon with DBH between 8 and 100 cm (Overman et al., 1994). However, this model is not suitable for estimating biomass for those trees with DBHs of less than 10 cm because only one sample tree of that size was used to establish this model.

In our research, forest stand parameters such as biomass and volume at a given site were aggregated from the individual sapling and tree parameters. The formulas listed below were defined for calculation of forest stand parameters at a site level.

1. Average stand diameter (ASD; cm):

$$\mathrm{ASD} = \sqrt{\frac{\left(\sum_{i=1}^{s}\mathrm{DS}^2\right) \times (\mathrm{PA}/\mathrm{SA}) + \sum_{j=1}^{m+n}\mathrm{DT}^2}{s+m+n}} \tag{4}$$

2. Average stand height (ASH; m):

$$\mathrm{ASH} = \frac{\left(\sum_{i=1}^{s}\mathrm{HS}\right) \times (\mathrm{PA}/\mathrm{SA}) + \sum_{j=1}^{m+n}\mathrm{HT}}{s+m+n} \tag{5}$$

3. Basal area (BA; m^2/ha):

$$\mathrm{BA} = \frac{\sum_{i=1}^{s}\mathrm{BAS}}{\mathrm{SA}} + \frac{\sum_{j=1}^{m+n}\mathrm{BAT}}{\mathrm{PA}} \tag{6}$$

4. Forest stand volume (FSV; m^3/ha):

$$\mathrm{FSV} = \frac{\sum_{i=1}^{s}\mathrm{VS}}{\mathrm{SA}} + \frac{\sum_{j=1}^{m+n}\mathrm{VT}}{\mathrm{PA}} \tag{7}$$

5. Above-ground biomass (AGB; kg/m^2):

$$\mathrm{AGB} = \frac{\sum_{i=1}^{m}\mathrm{DW1}_i + \sum_{j=1}^{n}\mathrm{DW2}_j}{\mathrm{PA}} + \frac{\sum_{k=1}^{s}\mathrm{DW1}_k}{\mathrm{SA}} \tag{8}$$

6. Ratio of tree biomass to total biomass (RTB):

$$\mathrm{RTB} = \frac{\text{tree biomass}}{\text{total biomass}} \tag{9}$$

7. Ratio of tree volume to total volume (RTV):

$$\mathrm{RTV} = \frac{\text{tree volume}}{\text{total volume}} \tag{10}$$

8. Ratio of tree basal area to total basal area (RTBA):

$$\mathrm{RTBA} = \frac{\text{tree BA}}{\text{total BA}} \tag{11}$$

In the above equations, DS, HS, BAS, and VS are sapling DBH, height, basal area, and volume, respectively; DT, HT, BAT, and VT tree DBH, height, basal area, and volume, respectively; m is the total tree number when DBH falls within 10–25 cm in a site; n the total tree number when DBH is greater than or equal to 25 cm in a site; s the total sapling number when DBH falls within 2–10 cm in a subplot area; and PA and SA are the total plot area and total subplot area (in m^2) in a site, respectively.

3.4. Data analysis

Canonical discriminant analysis (CDA) is used to classify a categorical dependent variable that has more than two categories (e.g. different successional stages here), based on a number of interval independent variables. The purpose of using CDA in this research is to investigate the differences among various successional stages and to find the best forest stand parameters that can be used to distinguish these stages. The category of dependent variable in this research is the different successional stages. In the initial classification, age was used to classify these successional stages into four categories: SS1 when age is 1–5 years, SS2 when age is 6–15 years, SS3 when age is 16–29 years, and SS4 when age is greater than 30 years. The independent variables are forest stand parameters calculated using formulas (4)–(11) at the site level: AGB, FSV, BA, ASD, ASH, RTB, RTV, and RTBA.

The implementation of CDA provides some important information for classifying sample plots and identifying important parameters (Huberty, 1994; Markin, 1996). For example, a scatterplot of the first two CDA functions provides information related to vegetation clusters. The eigenvalues show how much of the variance in the dependent variables is accounted for by each function. Relative percent of variance indicates how many functions are important. The first function maximizes the difference between the values of the dependent variable. The second function is orthogonal to it and maximizes the difference between values of the dependent variable, controlling for the first factor, and so on. Wilk's Lambda is used to test the significance of each discriminant function, specifically the significance of the eigenvalue for a given function. It measures the difference between groups of the centroid (vector) of means on the independent variable. The smaller the Wilk's Lambda, the greater the difference, and the more important the independent variable is to the discriminant function. Canonical correlation (R) measures the association between the groups formed by the dependent variable and the given discriminant function. A larger correlation R value indicates high correlation between the discriminant function and the groups (McGarigal et al., 2000).

4. Results and discussion

4.1. Classification of successional stages

The successional stages were first roughly classified according to vegetation age and CDA was used to investigate the difference between the stages. Fig. 3

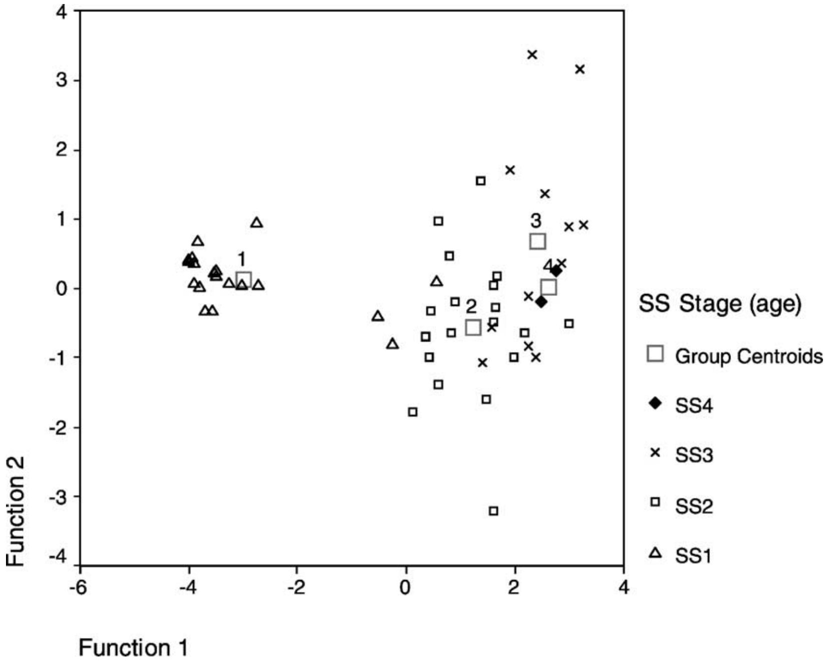


Fig. 3. Scatterplot of cases by the first two functions from canonical discriminant analysis based on the original successional stages grouped by age.

illustrates the scatterplot that is derived from the first two CDA functions and Table 2 provides the CDA classification results based on the original successional stages grouped by age. An overall classification accuracy of 73.1% was obtained. The main confusions were from SS2 and SS3 and from SS3 and SS4. The SS4 classification accuracy was especially low because SS4 had similar forest stand structures as SS3 although SS4 were older than SS3. Also SS2 and SS3 classification accuracies were not satisfactory. These classification results imply that vegetation age is not a good forest stand parameter to distinguish successional stages because vegetation ages are not linearly related to the forest stand parameters and many factors affect the relationships between age and forest stand features (Moran and Brondizio, 1998; Moran et al. (2000a,b)).

Table 2
Classification results using canonical discriminant analysis of original successional stages grouped by age

Class	SS1	SS2	SS3	SS4	Total
Count					
SS1	16	3	0	0	19
SS2	0	13	2	4	19
SS3	0	4	7	1	12
SS4	0	0	0	2	2
Percent					
SS1	84.2	15.8	0	0	100.0
SS2	0	68.4	10.5	21.1	100.0
SS3	0	33.3	58.3	8.3	100.0
SS4	0	0	0	100.0	100.0

Note: 73.1% of original, grouped cases were correctly classified.

The CDA approach can identify misclassified cases and provide their predicted categories for those misclassified cases. Therefore, these misclassified cases can be adjusted to a suitable category based on the predicted one from the CDA results. This process can be repeated and misclassified cases can be adjusted until all cases are almost 100% correctly classified into suitable categories. The following analysis focuses on the results from the adjusted successional stages. Fig. 4 illustrates the result after repeatedly implementing CDA. Thus all cases are successfully classified into SS1, SS2, SS3, and SS4 with almost 100% accuracy. The first CDA function can almost classify all cases into suitable successional stages. The second CDA function is suitable for differentiating SS1 from SS2

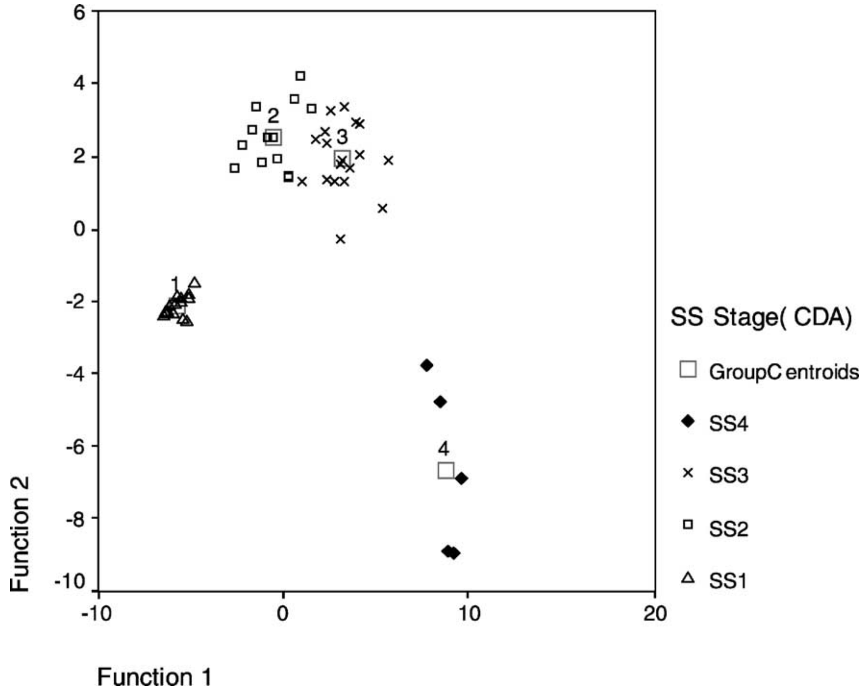


Fig. 4. Scatterplot of cases by the first two functions from canonical discriminant analysis based on the adjusted successional stages.

and SS4 from SS3, but cannot distinguish SS2 from SS3.

4.2. Identification of forest stand parameters

Eigenvalue for each CDA function is an important factor indicating its power in distinguishing between different categories. Table 3 shows that the first two functions are the most powerful differentiating dimensions because they accounts for 69.6 and 28.2% of the total variance, respectively. The third and higher CDA functions can be ignored due to their low eigenvalues. A very strong relationship between the first CDA function and the dependent variable ($R = 0.979$) implies that the first CDA function can be used to distinguish different successional stages. The second CDA function also has a strong relationship with the dependent variable, but it is relatively weak compared to the first CDA function. Comparison of Table 3 and Fig. 4 indicates that the first CDA function has the capability to differentiate successional stages because it is a comprehensive factor derived from several stand parameters (e.g. RTB, ASD). However, in practice, using CDA functions to classify successional stages is not convenient because of the time-consuming. Hence, directly using one or two suitable stand parameters are ideal to differentiate successional stages.

The Wilk's Lambda for each independent variable and structure matrix are extremely useful for identification of appropriate stand parameters for classification of successional stages. Table 4 indicates that ASD, RTB, AGB, and FSV are the most important stand parameters that contribute to the discriminant function because they have small Wilk's Lambda values (less than 0.087). The structure matrix shows the correlations of each variable with each discriminant function, indicating how closely

Table 3
Eigenvalues and canonical correlation coefficients based on adjusted successional stages using canonical discriminant analysis

Function	Eigenvalue	Percent of variance	Cumulative percent	Canonical correlation
1	22.940	69.6	69.6	0.979
2	9.293	28.2	97.8	0.950
3	0.742	2.2	100.0	0.653

Table 4
Wilk's Lambda for each independent variable and the structure matrix between CDA functions and independent variables based on adjusted successional stages

Variables	Function 1	Function 2	Function 3	Lambda
ASD	0.696	0.121	0.371	0.081
RTB	0.691	0.042	−0.346	0.083
RTV	0.656	0.098	−0.315	0.091
AGB	0.634	−0.436	0.154	0.083
FSV	0.603	−0.475	0.234	0.087
RTBA	0.600	0.014	−0.248	0.108
ASH	0.536	0.045	0.118	0.131
BA	0.302	−0.101	0.094	0.313

Note: AGB: above-ground biomass; ASD: average stand diameter; ASH: average stand height; BA: basal area; FSV: forest stand volume; RTB: ratio of tree biomass to total biomass; RTBA: ratio of tree basal area to total basal area; RTV: ratio of tree volume to total volume.

a variable is related to each CDA function. ASD and RTB are the best stand parameters because they are most strongly related to the first CDA function (the coefficients are 0.69). AGB and FSV are also good stand parameters because they are best related to the second CDA function. The results in Table 4 imply that ASD, RTB, AGB, and FSV may be good indicators when they are used for classifying different successional stages because they have small Wilk's Lambda values and strong relationships with CDA functions. In practice, one or two stand parameters are suitable because some stand parameters have strong correlations to each other. For example, AGB and FSV, RTB and RTV are very strongly related to each other—their correlation coefficients are close to 1.0 (Table 5). Therefore, according to the Wilk's Lambda values and structure matrix (Table 4) and the correlation between selected stand parameters (Table 5), it can be concluded that RTB, ASD, and AGB or FSV are the best stand parameters.

The sample cases used for classification of successional stages using CDA can be reordered and grouped according to the classification results of SS1, SS2, SS3, and SS4. Therefore, the ranges of forest stand parameters for each successional stage can be identified based on these sample sites (Table 6). The results listed in Table 6 indicate that RTB and AGB or FSV appear the best stand parameters. RTB is the only forest stand parameter that can differentiate successional forests into SS1, SS2, SS3, and SS4. AGB (or FSV) is suitable for distinction between SS2, SS3, and SS4 and ASD and ASH is suitable for distinction between SS1 and SS2, but they cannot distinguish other successional stages. Other parameters such as RTV, RTBA, BA, and age are not suitable for the classification of successional stages.

5. Discussion and conclusion

Different successional stages have their own specific stand structures. Fig. 5 illustrates the average forest stand parameters for each stage. In order to analyze the stand structures of advanced successional stage, mature forest is also included in this figure and Table 6. The slopes of these curves in Fig. 5 indicate that the tree

Table 5
Correlation coefficients between forest stand parameters

	AGE	AGB	RTB	FSV	RTV	BA	RTBA	ASD	ASH
AGE	1.000	0.431	0.641	0.393	0.653	0.371	0.629	0.603	0.664
AGB	0.431	1.000	0.840	0.993	0.817	0.884	0.845	0.847	0.801
RTB	0.641	0.840	1.000	0.811	0.995	0.752	0.996	0.942	0.922
FSV	0.393	0.993	0.811	1.000	0.782	0.897	0.815	0.826	0.765
RTV	0.653	0.817	0.995	0.782	1.000	0.733	0.994	0.942	0.920
BA	0.371	0.884	0.752	0.897	0.733	1.000	0.741	0.829	0.663
RTBA	0.629	0.845	0.996	0.815	0.994	0.741	1.000	0.936	0.915
ASD	0.603	0.847	0.942	0.826	0.942	0.829	0.936	1.000	0.890
ASH	0.664	0.801	0.922	0.765	0.920	0.663	0.915	0.890	1.000

Note: AGB: above-ground biomass; AGE: vegetation age; ASD: average stand diameter; ASH: average stand height; BA: basal area; FSV: forest stand volume; RTB: ratio of tree biomass to total biomass; RTBA: ratio of tree basal area to total basal area; RTV: ratio of tree volume to total volume.

Table 6
Characteristics of selected forest stand parameters for each successional stage and mature forest

Variables	SS1	SS2	SS3	SS4	MF
RTB	0	0.15–0.45	0.48–0.89	0.91–0.99	0.89–1.00
RTV	0	0.18–0.54	0.51–0.94	0.92–1.00	0.92–1.00
RTBA	0	0.13–0.43	0.42–0.89	0.89–1.00	0.82–1.00
AGB (kg/m^2)	0–4.62	3.41–7.03	7.28–13.55	20.34–29.30	17.45–39.45
FSV (m^3/ha)	0–49.10	34.09–84.07	89.57–185.44	303.66–517.40	273.03–658.45
BA (m^2/ha)	0–13.33	9.94–19.21	15.45–32.24	26.13–36.78	27.38–56.13
ASD (cm)	0–4.61	10.84–15.42	12.85–22.14	19.82–29.25	23.11–39.27
ASH (m)	0–6.03	6.40–11.24	8.73–14.45	11.51–20.27	15.20–20.09
Age (year)	1–5	3–15	7–29	15–25	Unknown

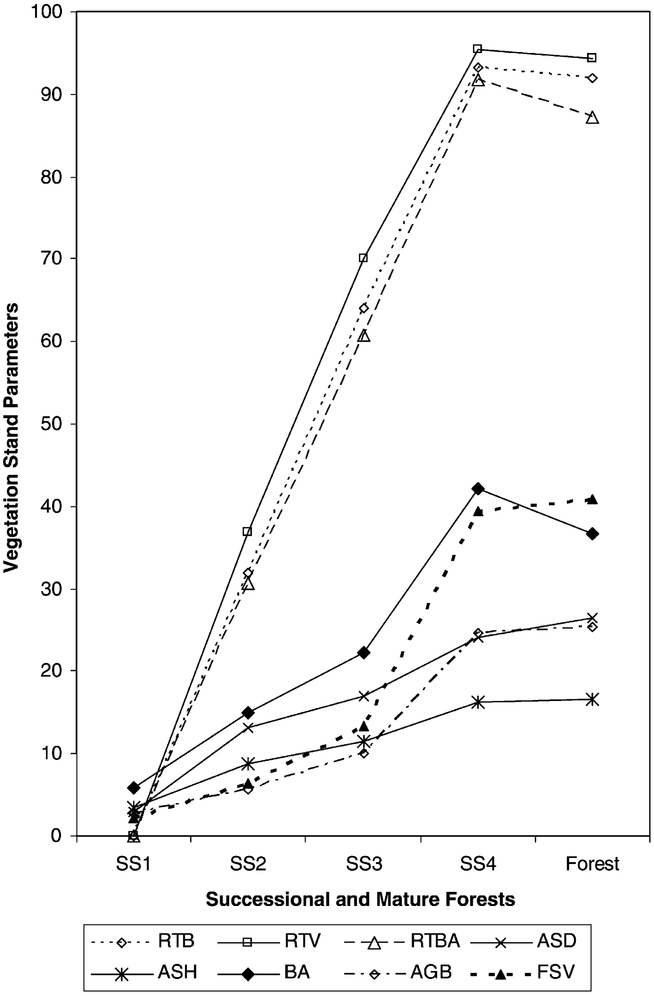


Fig. 5. Characteristics of different successional stages and mature forest. *Note*: AGB: above-ground biomass (kg/m^2); ASD: average stand diameter (cm); ASH: average stand height (m); BA: basal area (m^2/ha); FSV: forest stand volume (10 m^3/ha); RTB (RTV, RTBA): ratio of tree biomass (volume, basal area) to total biomass (volume, basal area) (percent).

contribution to total above-ground biomass (or volume, basal area) is almost linearly increased from initial to advanced successional stages (from SS1 to SS4). This implies that sapling or seedling vegetations are rapidly decreased as vegetation grows. The increase rates of above-ground biomass, forest stand volume, and basal area increase slowly at the initial stages (SS1 and SS2), then they rapidly increase in advanced stages (SS3 and SS4). In contrast, average stand diameter and height increased relatively fast in initial stages, then increase slowly in advanced stages.

Comparative analyses of these stand parameters in Table 6 and Fig. 5 indicates that RTB is the best forest stand parameter to use for successional stage classification. RTB represents the forest stand structure characteristics. In initial successional stages (SS1), saplings and seedlings account for the majority of the total biomass (over 90%). As vegetation grows, trees gradually replace seedlings and saplings and until SS4 trees account for the majority of total biomass (over 91%). When a successional stage arrives at SS4, then RTB appears stable and has a similar value as mature forest, indicating that the forest stand structures of SS4 become stable as mature forest. It is more feasible to attribute SS4 to a mature forest category in practice because SS4 has a similar function as a mature forest in affecting the components of atmosphere and ecosystem. In particular, when remotely sensed data are used for successional forest and mature forest classification in the Amazon basin, three successional forest stages (SS1, SS2, and SS3) and one mature forest class (including SS4 and primary forest) are feasible to identify.

This research indicates that the CDA approach can be used to classify successional forest stages. The first two CDA functions can distinguish successional forests into four stages as SS1, SS2, SS3, and SS4. However, using CDA is not a convenient method for successional forest classification in practice. Thus, using RTB or a combination of two stand parameters such as AGB and ASD are more feasible for practical use.

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