Ciência Florestal

UFSM

Ci. Fl., Santa Maria, v. 29, n. 2, p. 519-530, abr./jun. 2019
DOI: https://doi.org/10.5902/1980509830688
ISSN 1980-5098

Artigos Submissão: 04/01/2018 Aprovação: 04/05/2018 Publicação: 30/06/2019

Classification of successional stages in atlantic forests: a methodological approach based on a fuzzy expert system

Classificação de estágios sucessionais de florestas atlânticas: uma abordagem metodológica baseada em sistema fuzzy

Maurício Tavares da Mota[I], Adriano Bressane[II], José Arnaldo Frutuoso Roveda[III], Sandra Regina Monteiro Masalskiene Roveda[IV]

Abstract

A method based on fuzzy modeling was developed for the classification of the stages of a forest succession. The construction of the model considered the criteria established by CONAMA, which define secondary vegetation in the initial, middle, and advanced stages of regeneration of the Atlantic Forest, as guidelines for the management of native vegetation in the state of São Paulo. The proposed model was applied for classifying cases reported in the literature, where floristic and phytosociological analysis of the forest structure had been performed employing the judgment of experts. The fuzzy modeling approach provided good agreement with the conclusions of the experts, according to the Kappa index. In conclusion, fuzzy modeling is a promising technique for addressing subjectivity and uncertainty in the classification of successional stages in the Atlantic Forest.

Keywords: Ecological succession; Fuzzy logic; Atlantic Forest

Resumo

O presente trabalho tem como objetivo propor e avaliar um método baseado em modelagem *fuzzy* para classificação de estágios de sucessão florestal. A construção do modelo considerou critérios estabelecidos pela Resolução CONAMA nº 01 de 31 de janeiro de 1994, que define vegetação secundária nos estágios inicial, médio e avançado de regeneração da Mata Atlântica, como diretrizes para o licenciamento de exploração da vegetação nativa no Estado de São Paulo. O modelo proposto foi aplicado para classificação de casos reportados na literatura, nos quais uma análise florística e fitossociologica da estrutura florestal havia sido realizada segundo o julgamento de especialistas. Como resultado, a modelagem *fuzzy* proporcionou uma concordância substancial quando avaliado por meio do índice Kappa. Portanto, conclui-se que a proposta do método baseado em modelagem *fuzzy* representa uma alternativa promissora para tratar a subjetividade e a incerteza associadas à classificação dos estágios sucessionais de uma formação florestal.

Palavras-chave: Sucessão ecológica; Lógica fuzzy; Floresta atlântica

I Biólogo, Dr., em Ciências Ambientais pela Universidade Estadual Paulista, Av. 3 de Março, 511, CEP 18087-180, Sorocaba (SP), Brasil. mauriciotavaresmota@gmail.com (ORCID: 0000-0003-4844-1457)

II Engenheiro Ambiental, Dr., Professor da Universidade Estadual Paulista, Av. Eng. Francisco José Longo, 777, CEP 12245-000, São José dos Campos (SP), Brasil. adriano.bressane@unesp.br (ORCID: 0000-0002-4899-3983)

III Matemático, Dr., Professor da Universidade Estadual Paulista, Av. 3 de Março, 511, CEP 18087-180, Sorocaba (SP), Brasil. jose.roveda@unesp.br (ORCID: 0000-0002-0158-1586)

IV Matemática, Dra., Professora da Universidade Estadual Paulista, Av. 3 de Março, 511, CEP 18087-180, Sorocaba (SP), Brasil. sandra.regina@unesp.br (ORCID: 0000-0003-3390-8747)

Introduction

In the recent decades, there has been a significant reduction in the area occupied by tropical forests, around 35%, due mainly to anthropic action. As a consequence, it is estimated that over half of the existing tropical forests are now secondary (WRIGHT, 2010). Forests, as well as other physiognomic formations, present different stages of development. These are known as successional stages, which can be characterized using several methods reported in the literature (SIMINSKI; FANTINI; REIS, 2013). These include vegetation age (SALDARRIAGA *et al*., 1988), structural parameters (MORAN; BRONDÍZIO, 1988; SIMINSKI *et al*., 2004), and phytophysiological characteristics (LANA *et al*., 2010), among others. However, most studies have focused on the characterization of the ecological process of natural succession, while few have correlated academic methods with legal norms. Therefore, there are divergences between the different methods described in the literature and the existing legal regulations, which in Brazil are generally implemented by means of resolutions of the National Environment Council (CONAMA).

In order to classify the forest stages of the Atlantic Forest in the state of São Paulo, CONAMA Resolution #01/1994 is the accepted legal framework. This regulation is based on the physiognomy, number of tree strata, tree height, diameter at breast height (DBH), litter, understory, and species diversity (BRASIL, 1994). Although some authors such as Siminski *et al*. (2004), Siminski and Fantini (2004), Magnano *et al*. (2012) and Siminski, Fantini and Reis (2013), consider that there is no coherence between the ecological and legal parameters of the CONAMA resolutions, these resolutions remain the only accepted references for legal purposes.

Definition of the successional stage of the forest is of paramount importance, since it has direct implications for possible uses of the land. The Atlantic Forest Law (Law #11.428/2006) provides for rigorous protection of the advanced stages and gradually becomes more lenient and permissive in relation to areas where the growth stages are less advanced (SIMINSKI; FANTINI; REIS, 2013). This highlights the great importance of the correct definition and the interpretation of the successional stage of the forest, requiring a qualified professional with the competence and ability to identify the characteristics that are constant at each of the stages described in the law. There are situations where, in the same area, it is possible to find characteristics attributed (in the law) to different stages, which can lead to uncertainty in the decision-making process.

The present work aims to assist the professionals responsible for forest management, by providing a logical and structured procedure, using fuzzy modeling, as a tool to support decision-making. The choice of fuzzy modeling was based on its capacity to handle subjectivity, thus allowing the creation of a system based on rules. The model can assist in decision-making by associating the reasoning of experts with parameters of distinct natures associated with uncertainties. In classical logic, the elements are defined as belonging or not to a certain set, assigning them the values 1 and 0, respectively. In contrast, in fuzzy logic an element may belong to a fuzzy set with a degree of membership ranging from 0 to 1, with 0 being non-relevant and 1 corresponding to full membership of the set. Hence, the successional stage of a given forest fragment can be classified considering the occurrence of characteristics of different stages of succession, enabling the system to assign the degree of membership of a particular stage. In this approach, the exact reasoning corresponds to a limiting case of the approximate reasoning, being interpreted as a process of composition of nebulous relationships in which degrees of truth or uncertainty are considered (GOMIDE; GUDWIN; TANSCHEIT, 2014).

Since definition of the forest stage can often be complex, fuzzy logic can provide an appropriate tool to aid in decision-making. As the complexity of a system increases, the human ability to accurately describe its behavior decreases (ZADEH, 1973). Complex problems do not translate into numbers, but rather into linguistic expressions, mathematically defined as labels of fuzzy sets (ZADEH, 1973). Therefore, this theory is highly suitable for use in decision-making processes that must follow a sequence of linguistic commands or expressions, translated by a set of rules, which are capable of being decoded by a fuzzy inference system. This, in turn, is a typical case of a fuzzy rules-based system (FRBS) that uses fuzzy logic to produce outputs for each condition evaluated.

This change in thinking opens up new and refined ways of looking at old issues. Fuzzy theory allows the expression of uncertainties and subjectivities, so that both qualitative and quantitative information can be used. The vagueness arising from linguistic terms (much, little, low, high, etc.), traditionally seen as unscientific, is admissible in the fuzzy approach, often enabling the system to closely represent reality itself. In the present work, a method based on fuzzy modeling was developed and evaluated for the classification of the stages of forest succession.

Materials and methods

The model constructed was developed using criteria that characterize the successional stages of forest formation in the Atlantic Forest of São Paulo state, established by CONAMA Resolution #01/1994. These characteristics were adapted to provide the input variables of the developed fuzzy system. Each input (evaluated condition) was linked to to an output (classification of the successional stage), using a fuzzy inference system composed of four essential parts: fuzzification module, rule base, inference module, and defuzzification module (Figure 1). In the elaboration of this model, aggregation operators were used for the integrated analysis of the indicators contained in CONAMA Resolution #01/1994, modeled to assess the successional stage, as described below.

Fuzzification module

Fuzzification was the first part of the modeling process, consisting of the conversion of the numerical input into fuzzy sets, characterized by membership functions. It was at this stage that the functions were constructed, allowing definition of the degree of relevance to the modeled set. The values employed in this model were extracted from CONAMA Resolution #01/1994 and were applied to average tree height, diameter at breast height (DBH), and indicators (represented by values corresponding to the sums of scores attributed by the experts). The sum of the scores ranged from a maximum of three, for the pioneer stage, to fifty-six, for the advanced stage (see Table 1).

Table 1 – Description of vegetation characteristics and assignment of values for input variables (indicators) based on CONAMA Resolution #01/1994.

Tabela 1 – Descrição de características da vegetação e atribuição de valores para as variáveis de entrada, "Indicadores", com base na Resolução CONAMA nº 01 de 1994.

In the pioneer stage:	**Score**	
a) Discontinuous and/or incipient litter.	1	3
b) Presence of creepers, usually herbaceous.	1	
c) Most abundant plant species are typically heliophilous, including forage, exotic, and invasive crops, such as *Baccharis* spp., *Vernonia* spp., *Gochnatia polymorpha*, *Peschieria fuchsiaefolia*, *Guapira* spp., *Ricinus communis*, *Acacia* spp., *Gleichenia* spp., *Pteridium* spp., etc.	1	

Continued...

Table 1 – Continued...
Tabela 1 – Continua...

In the initial stage of regeneration:	Score	
a) Woody strata ranging from open to closed, presenting plants with variable heights.	3	21
b) Epiphytes, when present, are not very abundant and are represented, for instance, by mosses and lichens.	3	
c) Creepers, if present, may be herbaceous or woody.	3	
d) Litter, when present, can be continuous or not, forming a thin layer that is little decomposed.	3	
e) The sub-forest can include young plants of arboreal species of the more mature stages.	3	
f) Low biological diversity, with around ten dominant tree or shrub species.	3	
g) The most abundant and characteristic plant species, besides those mentioned for the pioneer stage, are: *Gochnatia polimorpha*, *Peschieria fuchsiaefolia*, *Guapira* spp., *Ricinus communis*, *Acacia* spp., *Stenolobium stans*, *Trema micrantha*, *Solanum granuloso-lebrosum*, *Psidium guaiava*, *Croton urucurana*, *Aloysia virgata*, *Pterogyne nitens*, *Cecropia* spp., *Xylopia aromatica*, *Byrsonima* spp., *Guazuma ulmifolia*, *Tibouchina* spp., *Miconia* spp., *Rapanea* spp., *Alchornea* spp., *Schinus terebinthifolius*, and *Casearia sylvestris*, among others.	3	
In the middle stage of regeneration:	**Score**	
a) Presence of layers of different heights, with each layer having a cover varying from open to closed, the top layer surface being uniform, and emergent trees appearing.	5	35
b) Epiphytes appear in a greater number of individuals and species, being more abundant and presenting more species in the Ombrophilous Forest domain.	5	
c) Creepers, when present, are generally woody.	5	
d) Litter may vary in thickness, depending on the season and location.	5	
e) The sub-forest shows common occurrence of Ombrophilous shrubs, mainly including Rubiaceae, Myrtaceae, Melastomataceae, and Meliaceae species.	5	
f) Significant biological diversity, with possible dominance of a few species, usually of rapid growth. In addition, various palms and ferns may appear.	5	
g) The most abundant and characteristic species, in addition to those mentioned for the previous stages, are: *Machaerium* spp., *Platypodium elegans*, *Cordia trichotoma*, *Pithecellobium edwallii*, *Myracroduon urundeuva*, *Schizolobium parahiba*, *Amburana cearensis*, *Casearia gossypiosperma*, *Cedrela* spp., *Cabralea canjerana*, *Luehea* spp., *Copaifera langsdorfii*, *Peltophorum dubium*, *Lonchocarpus* spp., *Pterodon pubescens*, *Ocotea* spp., *Nectandra* spp., *Crytocaria* spp., *Plathymenia* spp., *Centrolobium tomentosum*, *Tabebuia* spp., *Andira* spp., *Guarea* spp., *Acacia polyphylla*, *Zanthoxyllum* spp., *Enterolobium contorsiliquum*, *Didimopanax* spp., *Araucaria angustifolia*, *Podocarpus* spp., *Terminalia* spp., *Tapirira guianensis*, *Matayba* spp., *Tabebuia cassinoides*, *Myrcia* spp., *Machlura tinctoria*, *Piptadenia gonoacantha*, and *Patagonula americana*, among others.	5	
In the advanced stage of regeneration:	**Score**	
a) Closed forest physiognomy, with tendency for a contiguous distribution of crowns. The canopy may or may not present emergent trees.	7	56
b) Large numbers of strata, including trees, shrubs, terrestrial herbs, creepers, and epiphytes, etc., which abundance and number of species vary according to climate and location. The upper crowns are usually horizontally broad.	7	
c) Epiphytes including many species and in great abundance, mainly in the Ombrophilous Forest.	7	
d) Creepers are usually woody (mainly legumes, Bignoniaceae, Compositae, Malpighiaceae, and Sapindaceae), being more abundant and species-rich in the Seasonal Forest.	7	
e) Presence of litter, varying according to time and location, presenting intense decomposition.	7	

Continued...

Table 1 – Conclusion...
Tabela 1 – Conclusão...

In the advanced stage of regeneration:	Score	
f) In the sub-forest, shrub and herbaceous strata appear with greater or lesser frequency, with the shrubs being predominantly those already mentioned for the previous stage (Ombrophilous shrubs) and the herbaceous species consisting predominantly of Bromeliaceae, Araceae, Marantaceae, and Heliconiaceae, mainly in the humid areas.	7	56
g) Very high biological diversity, due to the structural complexity and the number of species.	7	
h) In addition to those already mentioned for the previous stages, common mature forest species include: *Cariniana* spp., *Hymenaea* spp., *Balfourodendron riedelianum*, *Machaerium* spp., *Chorisia speciosa*, *Esenbeckia leiocarpa*, *Ocotea porosa*, *Ficus* spp., *Manilkara* spp., *Persea* spp., *Erythryna* spp., *Calophyllum brasiliensis*, *Miconia* spp., *Gallesia integrifolia*, *Aspidosperma* spp., and *Dalbergia* spp., among others.	7	

Source: Autores (2018)

Rule base

The fuzzy rule base is a set of propositions describing the behavior of the parameters involved in the inference system. These rules were defined as follows:

IF (condition assessed) THEN (classification of forest formation)

where the evaluated condition and the classification of the forest formation are values representing the linguistic variables, modeled in the first module. It is precisely this aspect of fuzzy logic that enables the construction of models that behave properly, even when the decision-making process involves uncertainties, subjectivities, and inaccuracies. Therefore, in general, the rule base is constructed on the basis of expert knowledge.

Inference and defuzzification modules

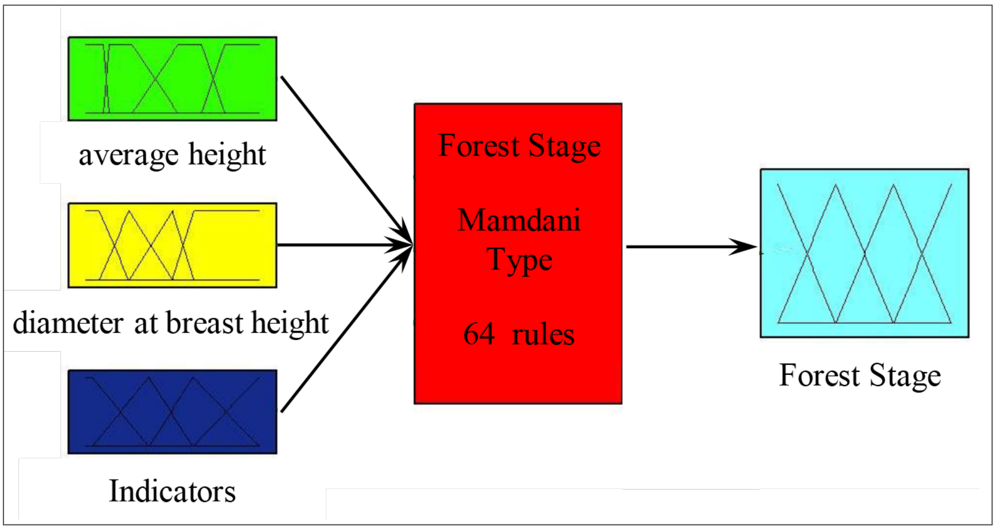
It is here that the propositions of the rule base are mathematically translated, by means of logical operators such as t-norms and t-conorms, enabling the process of inference necessary for the classification of successional stages. In turn, the defuzzification is an operation that converts a fuzzy output (from the inference process) into a real value which, in the case of the proposed model, corresponds to a certain stage of forest succession. The defuzzification method used in this work was the center of gravity technique, with the output being normalized on a scale from 1 to 10. Figure 1 illustrates the structure of the model.

The variables and their input values were: (1) Average height, with values corresponding to the pioneer stage (<1.5 m), initial stage (1.5 to 8 m), middle stage (4 to 12 m), and advanced stage (>20 m); (2) Stem diameter at breast height (DBH), with values corresponding to the pioneer stage (~3 cm), initial stage (<10 cm), middle stage (<20 cm), and advanced stage (>20 cm); (3) Indicators with values varying between 1 and 56 describing the attributes observed in the area, as indicated in Table 1. Each of the attributes corresponds to a specific value and the sum is related to the input of the variable in question, considering maximum values of 3 (pioneer stage), 21 (initial stage), and 35-56 (middle/advanced stages). Table 1 was constructed based on CONAMA Resolution #01/1994, where the presence of the described attributes characterizes the vegetation stage.

In this way, the Mamdani-type fuzzy system could assist in deciding on the successional stage of the vegetation. The system was built using Matlab® software. The membership functions for the variables are shown in Figure 2.

Figure 1 – Model structure, with illustration of input and output variables of the system for evaluation of the stage of forest succession.

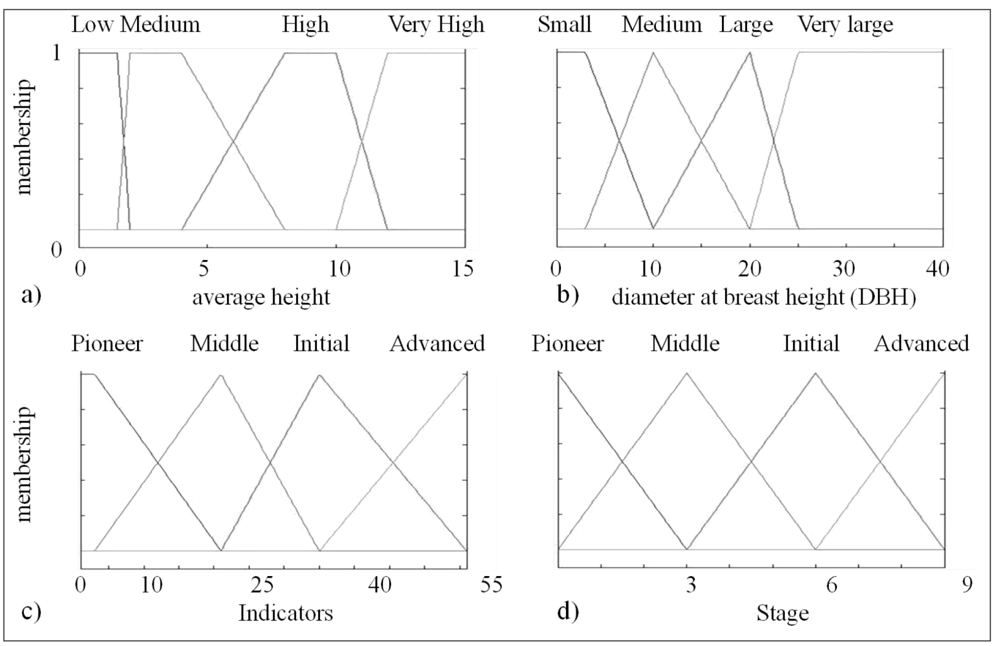
Figura 1 – Estrutura do modelo com ilustração das variáveis de entrada e saída do sistema que avalia o estágio de sucessão florestal.



Source: Authors (2018)

Figure 2 – Membership functions of the input variables (average height, DBH, and indicators) and the output variable (successional stage).

Figura 2 – Funções de pertinência das variáveis de entrada Porte, Diâmetro a Altura do Peito (DAP) e Indicadores, e da variável de saída Estágio Sucessional.



Source: Authors (2018)

From the membership functions of the input variables, a set of rules was elaborated to describe the behavior of the parameters involved in the system. The inference module then translated the propositions from the rule base. Finally, defuzzification converted the fuzzy set to a numerical value, using the center of gravity method. Figure 2 illustrates the membership functions for the output variable.

After identification of the input variables from the studies reported in the literature, the data were entered into the system. The measured results were normalized to values on a scale from 1 to 10, with 1 corresponding to the end of the pioneer stage and 10 corresponding to the extreme of the advanced stage. To test the model, in addition to real area data, dummy values corresponding to minimum and maximum were added to the system, in order to determine whether the model responded in a way coherent with expectations. The result of the model, considering the successional stage in which each formation was found, was compared to the conclusion of the experts (authors) using Kappa statistical coefficient, which provides a quantitative measure of the magnitude of the agreement between the observed and expected results. The interpretation of the results was performed according to the scale of values corresponding to the pioneer, initial, middle, or advanced stages, as shown in Table 2.

Table 2 – Ranges of values corresponding to the successional stages.

Tabela 2 – Faixas de valores correspondentes aos estágios sucessionais.

Score	Stage
1.0 - 2.9	Pioneer
3.0 - 4.9	Initial
5.0 - 6.9	Middle
7.0 - 10	Advanced

Source: Authors (2018)

After building the model, a search was performed using scientific articles, theses, magazines, books, and other publications. For this purpose, the research platforms Scielo, Periódicos Capes, Google Scholar, and Web of Science were used with the following keywords: phytosociology, floristic, successional stage, state of São Paulo, and CONAMA Resolution. This step was fundamental for validation of the model. Papers were selected that reported floristic and phytosociological analyses of Atlantic Forest formations in the state of São Paulo, with descriptions of the attributes that allowed the classification employing the model.

From the survey of cases reported in the literature, six papers were identified that included in their methodologies the description of characteristics contained in the CONAMA resolution. All the areas researched in this work were Atlantic Forest formations in the state of São Paulo, in different locations: Botucatu (SILVA, 2010), Cotia (ROSÁRIO, 2010), Guaiçara (MARDEGAN, 2006), São Paulo (BARRETTO, 2013), Ubatuba (RAMOS *et al.*, 2011), and Vale do Paraíba (D'ORAZIO, 2012). The forests at Botucatu and Guaiçara were classified as Seasonal Semideciduous, while those at the other locations were Dense Ombrophilous. Only Mardegan (2006) did not perform an analysis that involved splitting into subareas. The other authors subdivided the study area into subareas: Silva (2010) and Rosário (2010) assessed six subareas, Barretto (2013) evaluated three subareas, and Ramos *et al.* (2011) and D'Orazio (2012) assessed two subareas. Therefore, twenty sites in total were analyzed, with their data being entered into the system. Table 3 provides the conclusions of the authors regarding the forest stages at the sites assessed. These conclusions were compared with the results of the model developed in the present work, enabling the evaluation of the effectiveness of the model.

Table 3 – Comparison of the results of work carried out in São Paulo state and the classifications obtained with the fuzzy model.

Tabela 3 – Comparação entre resultados de trabalhos realizados em florestas do Estado de São Paulo e a classificação resultante de um modelo *Fuzzy*.

Site (authors)	Subdivision	AH	DHB	Indicators								Experts' classification		Fuzzy model	
				S	E	C	L	B	D	I	V	Stage	Formation	Score	Stage
	Minimum	1	1								3			1.0	P
Botucatu (SILVA, 2010)	Area 1	5.7	10.4	3	3	5	3	3	5	3	25	M	SSF	4.9	I
	Area 2	4.7	9.5	3	3	5	3	3	5	3	25	M	SSF	4.8	I
	Area 3	5.9	12.2	3	3	5	3	3	5	3	25	M	SSF	5.0	M
	Area 4	6.5	13.4	3	5	5	3	3	5	3	27	M	SSF	5.3	M
	Area 5	8.7	10.5	3	5	5	3	3	5	3	27	M	SSF	5.3	M
	Area 6	8.3	15.5	3	5	5	3	3	5	3	27	M	SSF	5.3	M
Cotia (ROSÁRIO, 2010)	I1	7.8	10.8	3	0	1	3	3	1	1	12	I	DOF	3.1	I
	I2	8.8	11.3	3	2	1	3	3	0	1	13	I	DOF	3.2	I
	M1	8	10.8	3	4	1	3	3	7	1	22	M	DOF	4.0	I
	M2	8.2	10.8	3	4	1	3	3	7	3	24	M	DOF	4.6	M
	A1	8.9	13.7	5	4	3	3	5	7	5	32	A	DOF	6.4	M
	A2	9.5	17.3	5	4	3	3	5	7	7	34	A	DOF	7.0	A
Guaiçara (MARDEGAN, 2006)	---------	6.5	12.5	5	3	3	3	5	3	5	27	M	SSF	5.3	M
São Paulo (BARRETTO, 2013)	Itapevi	9	9	3	5	5	5	5	7	7	37	A	DOF	7.4	A
	Marsilac	13	10	5	7	5	5	7	7	7	43	A	DOF	7.7	A
	Morro Grande	9.5	10	5	5	5	5	5	5	7	37	A	DOF	7.4	A
Ubatuba (RAMOS et al., 2011)	Portion F	14.5	14.4	5	5	5	3	5	5	7	35	A	DOF	7.4	A
	Portion H	13	13.3	5	7	5	3	5	7	7	39	A	DOF	7.5	A
Vale do Paraíba (D'ORAZIO, 2012)	São José dos Campos	7.5	12	5	3	5	3	5	3	3	27	M/I	DOF	5.3	M
	Tremembé	8.5	11.5	5	5	5	5	5	5	5	35	M/A	DOF	7.4	A
	Maximum	15	40								56			10.0	A

AH - average height; DHB - diameter at breast height; ; A = advanced; I = initial; M = middle; P = pioneer; S = forest stratum; Ep = epiphytes; C = creepers; L = litter; B = sub-forest; D = diversity; I = indicators; DOF = Dense Ombrophilous Forest; SSF = Seasonal Semideciduous Forest; V = total value

Fonte: Autores (2018)

Results

The CONAMA resolution does not distinguish between forest formations, referring only to the term Ombrophilous Seasonal Forest. Hence, it can be concluded that this covers all Atlantic Forest formations existing in São Paulo state. In all the selected works, there were descriptions of parameters in the CONAMA Resolution #01/94, defining the forest stage, which allowed the data to be inserted into the system. Table 3 shows the parameters identified for each site Only the data that were imported for use with the model were compiled, with the data for mean size, mean DBH, and the indicators (parameters described in CONAMA Resolution #01/1994) for each site being inserted into the fuzzy system.

The results obtained using the fuzzy model ranged from a value of 3.1 for the area identified by Ramos *et al.* (2011) as “I1” in Ubatuba, up to 7.5 for the area identified by Rosário (2010) as plot “H” in Cotia. The lower scores were associated with the earlier stages, while the higher scores corresponded to the more advanced stages. The responses for the minimum and maximum values used to evaluate the consistency of the results were as expected, with values of 1 and 10, respectively. Out of the twenty sites employed with the model, four presented results that differed from the conclusions of the authors regarding the successional stage. These included “Area 1” and “Area 2” in Botucatu (SILVA, 2010), which were classified by the author as being in the middle successional stage, while the model classified them as early stage, with scores of 4.9 and 4.8, respectively. Other divergences were for areas “M1” and “A1” in Cotia (ROSÁRIO, 2010), which were classified by the author as being in the middle and advanced stages, respectively, while the model classified them as early and middle stages, with scores of 4.0 and 6.4, respectively. Despite these differences, a Kappa index value of 0.69 was obtained, indicating substantial agreement between the classifications provided by the fuzzy model and the experts. Therefore, the model results were coherent with the stages described by the authors, as well as in relation to the minimum and maximum values (fictitious) inserted in the model in order to test the behavior of the system against the extremes.

Discussion

The main problem identified during the process of construction of the model was related to the generic way in which CONAMA Resolution #01/1994 provides the guidelines for defining successional stages. However, despite this difficulty, the model responded satisfactorily and proved to be fit for the intended purpose.

The forest formations and ecosystems defined by Federal Law #11,428/2006 as being associated with the Atlantic Forest domain are Dense Ombrophilous Forest, Mixed Ombrophilous Forest, Open Ombrophilous Forest, Seasonal Semideciduous Forest, and Deciduous Seasonal Forest, together with Mangroves, Restinga Vegetation, Altitude Fields, Inland Marshes, and Northeast Forest Enclaves (BRASIL, 2006). Not all of these correspond to forest formations. According to the Brazilian Vegetation Technical Manual, the southeastern floristic region can be subdivided into the following forest formations: Dense Ombrophilous Forest, Semideciduous Seasonal Forest, Deciduous Seasonal Forest, and Savannah (IBGE, 2014). In these formations, there is great complexity involving different floristic and phytosociological structures. Therefore, the definition of specific parameters for each one is required in order to achieve better precision in establishing characteristics of each successional stage. The Savannah (Cerrado) formation has separate definition of its successional stages, but it is still necessary to define specific legal parameters for each of the three forest formations, as listed in the Brazilian Vegetation Technical Manual for São Paulo state (IBGE, 2014). Although Barretto and Catharino (2015) pointed out that there are considerable gaps in floristic and structural knowledge of the Atlantic Forest in certain regions, a combination of technical and scientific efforts could contribute to the establishment of technical norms for the classification of the successional stages specific to each formation. At the present time, given that the only legal reference for definition of the successional stages is CONAMA Resolution #01/1994, the fuzzy system, as described here, could assist in determining the successional stage of vegetation in a particular area.

In the study by Silva (2010) of forest in Botucatu, three of the six areas analyzed had different scores, making it possible to distinguish the successional stages of each of them and draw conclusions about the degree of development. In the work of Rosário (2010), the six areas in Cotia presented distinct scores, enabling identification of the characteristics of each area in terms of the successional stage in which it was found. In the study of Barretto (2013), two of the three areas in São Paulo showed divergent scores. Ramos *et al.* (2011) obtained different scores for the two areas in Ubatuba, and similar findings were reported by D'Orazio (2012) for forest in Paraíba Valley.

Although the structure of the fuzzy system developed in this study was elaborated considering the provisions of CONAMA Resolution #01/1994, it allows adaptations to be made, should this legal norm be revised to indicate parameters for a specific formation. The fuzzy model provided clear indications of the different degrees of membership that each area had, in relation to the stage in which it was classified. This was the purpose of the model: to enable evaluation of the degree to which the development in a certain area is close to the subsequent or previous stage. Disagreement between the author's evaluation and the outcome of the model, in terms of the successional stage, occurred for four areas. However, in two of these situations, the difference was very small: "Area 1" and "Area 2" of Botucatu were classified by the author as being in the middle stage, while the fuzzy system provided scores of 4.9 and 4.8, respectively. These values corresponded to the initial stage (see Table 2), but were very close to a score of 5.0, which would result in classification as an intermediate stage, in agreement with the author's evaluation. These divergences could be remedied if there were rules for each forest formation. For example, in the cases studied, there were Semideciduous Seasonal Forests and Dense Ombrophilous Forests with peculiarities that would make it possible to issue specific regulations. Notwithstanding, the fuzzy system was effective in providing variable membership for each of the stages, although some areas evaluated had similar scores, despite differences in the evaluation of some parameters. These areas included "Area 4", "Area 5", and "Area 6" in Botucatu, as well as the locations in Guaiçara and São José dos Campos. Overall, the results demonstrated that the use of fuzzy modeling offers a promising approach, capable of distinguishing successional stages and identifying how close they are to stages that are more advanced (mature) or less advanced.

Conclusions

Fuzzy modeling was satisfactorily applied as a tool to support the classification of forest stages in Atlantic Forest formations. The model allowed adaptation of legal parameters for use as the input variables in the system, providing results that were easy to interpret and that enabled distinction of the different forest stages.

Use of the system permitted evaluation of the degree of relevance of each identified stage, indicating trends towards more or less advanced stages. The conclusions of the model and the authors of the previous studies showed no significant divergences, confirming the capacity of the model for systematic classification. It should be noticed that it would be possible to improve the system, should specific regulations be available for the different formations that make up the Atlantic Forest.

References

BARRETTO, E. H.; CATHARINO, E. L. Florestas maduras da Região Metropolitana de São Paulo: diversidade, composição arbórea e variação florística ao longo de um gradiente litoral-interior, estado de São Paulo, Brasil. **Hoehnea**, São Paulo, v. 42, n. 3, p. 445-469, 2015.

BARRETTO, E. H. P. **Florestas climáticas da região metropolitana de São Paulo - SP**: caracterização florística estrutural e relações fitogeográficas. 2013. 157 f. Dissertação (Mestrado) - Instituto de Botânica da Secretaria de Estado do Meio Ambiente, São Paulo, 2013.

BRASIL. Conselho Nacional do Meio Ambiente. **Resolução CONAMA nº 01, de 31 de janeiro de 1994**. Regulamenta o art. 6º do Decreto nº 750, de 10 de fev. de 1993 para o Estado de São Paulo. Disponível em: <http://www.mma.gov.br/port/conama/res/res94/res0194.html>. Acesso em: 16 set. 2012.

BRASIL. Lei nº 11.428, de 22 de dezembro de 2006. Dispõe sobre a utilização e proteção da vegetação nativa do Bioma Mata Atlântica, e dá outras providências. **Diário Oficial da União**, Brasília, DF, 26 dez. 2006.

D`ORAZIO, F. A. E. **Composição e estrutura de florestas aluviais do médio vale superior do rio Paraíba do Sul**. 2012. 96 f. Dissertação (Mestrado) - Instituto de Botânica da Secretaria de Estado do Meio Ambiente, São Paulo, 2012.

GOMIDE, F. A. C.; GUDWIN, R. R.; TANSCHEIT, R. **Conceitos fundamentais da teoria dos conjuntos fuzzy, lógica fuzzy e aplicações**. 2014. Access in: <ftp://calhau.dca.fee.unicamp.br/pub/docs/gudwin/publications/ifsa95.pdf>.

LANA, J. M. *et al*. Análise dos estágios de sucessão de áreas de Mata Atlântica sob a influência de plantações florestais, Vale Do Rio Doce, Minas Gerais, Brasil. **Revista Árvore**, Viçosa, MG, v. 34, p. 733-743, 2010.

IBGE. **Manual técnico da vegetação brasileira**. [S.l.]: IBGE, 2014. Disponível em <ftp://geoftp.ibge.gov.br/documentos/recursos_naturais/manuais_tecnicos/manual_tecnico_vegetaca o_brasileira.pdf >. Acesso em: 31 maio 2017.

MAGNANO, L. F. S. *et al*. Os processos e estágios sucessionais da Mata Atlântica como referência para a restauração florestal. In: MARTINS, S. V. **Restauração ecológica de ecossistemas degradados**. 1. ed. Viçosa, MG: Editora UFV, 2012. p. 69-100.

MARDEGAN, C. M. **Estádio sucessional e estrutura fitossociológica de um fragmento de vegetação floretal existente às margens do Rio Dourado em Guaiçara, SP**. 2006. 85 f. Dissertação (Mestrado) – Universidade Estadual Paulista, Botucatu, 2006.

MORAN, E.; BRONDÍZIO, E. Land-Use change after deflorestation in Amazônia. In: LIVERMAN, D. E. **People and Pixels**: linking remote sensing and social science. Washington: National Academy Press, 1988. p. 94-120.

RAMOS, E. *et al*. Estudo do componente arbóreo de dois trechos da Floresta Ombrófila Densa Submontana em Ubatuba (SP). **Biota Neotropica**, Campinas, v. 11, n. 2, p. 313-335, 2011.

ROSÁRIO, R. P. G. **Estágios sucessionais e o enquadramento jurídico das florestas montanas secundárias na Reserva Florestal do Morro Grande (Cotia, SP) e entorno**. 2010. 153 f. Dissertação (Mestrado) - Instituto de Botânica da Secretaria de Estado do Meio Ambiente, São Paulo, 2010.

SALDARRIAGA, J. *et al*. Long-Term Chronosequence of Forest Succession. The Upper Rio Negro of Colombia and Venezuela. **Journal of Ecology**, Oxford, v. 76, p. 938-958, 1988.

SILVA, I. C. **Caracterização fisionômica de fragmentos vegetacionais do distrito de Rubião Júnior, município de Botucatu, São Paulo**. 2010. 116 f. Dissertação (Mestrado) - Instituto de Biociências, Campus de Botucatu, Botucatu, 2010.

SIMINSKI, A. *et al*. Sucessão florestal secundária no município de São Pedro de Alcântara, Litoral De Santa Catarina; estrutura e diversidade. **Ciência Florestal**, Santa Maria, v. 14, p. 21-33, 2004.

SIMINSKI, A.; FANTINI, A. C. Classificação da Mata Atlântica do litoral Catarinense em estádios sucessionais: ajustando a lei ao ecossistema. **Floresta e Ambiente**, Seropédica, v. 11, n. 2, p. 20-25, 2004.

SIMINSKI, A.; FANTINI, A. C.; REIS, M. S. Classificação da vegetação secundária em estágios de regeneração da Mata Atlântica em Santa Catarina. **Ciência Florestal**, Santa Maria, v. 23, p. 369-378, jul./set. 2013.

WRIGHT S. J. The future of tropical forests. **Annals of the New York Academy of Sciences**, New York, v. 1195, p. 1-27, 2010.

ZADEH, L. A. Outline of a new approach to the analysis of complex systems and decision process. **IEEE Transactions on Systems, Man, and Cybernetics**, New York, v. SMC-3, n. 1, p. 28-44, jan. 1973.