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SYSTEM BASED ON FUZZY RULES AS A SUPPORT TOOL FOR THE APPLICATION OF CONAMA RESOLUTION 04/94.

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Resumo

Sistemas baseados em Regras Fuzzy como ferramenta de suporte para a aplicação da resolução CONAMA nº 04/94. Os estágios de regeneração da floresta secundária e a floresta primária são definidos pela Resolução CONAMA nº 04/94, no caso do Estado de Santa Catarina, e possuem um papel fundamental na correta aplicação da Lei Federal nº 11.428/2006 e consequentemente na gestão dos recursos florestais do Bioma Mata Atlântica. Contudo, diante da complexidade e das incertezas que envolvem o processo de sucessão florestal, Sistemas Baseados em Regras Fuzzy, elaborados a partir dos parâmetros legais e contemplando o conhecimento de especialistas, podem ser importantes ferramentas de apoio na definição dos estágios sucessionais. Para isso foi elaborado um modelo especialista composto por dois indicadores, um para os parâmetros estruturais (DAP, Área Basal e Altura) e outro para os qualitativos (fisionomia, estrutura do dossel, diversidade, epífitas, trepadeiras, serapilheira e sub-bosque). Para a verificação do modelo proposto foram usados os dados de 466 unidades amostrais provenientes do Inventário Florístico Florestal de Santa Catarina – IFFSC. Os resultados obtidos pela execução do modelo apontaram que a estrutura adotada consegue expressar o processo de regeneração, auxiliando no processo de tomada de decisão. Foi observado uma maior concentração na classificação de estágios intermediários de regeneração florestal (médio e avançado). Comparando os estágios de regeneração provenientes da aplicação do modelo com os definidos pela aplicação da fórmula proposta pelo IFFSC houve uma correspondência em 72% dos casos. O modelo aparenta ter uma sensibilidade à adoção de escalas de interpretação dos valores defuzzificados.
Palavras-chave: Floresta Secundária. Lógica *Fuzzy*. Licenciamento ambiental. Mata Atlântica

Abstract

The regeneration stages of secondary forest and primary forest are defined by CONAMA Resolution nº 04/94, in the case of the State of Santa Catarina, and play a fundamental role in the correct application of Federal Law nº 11,428/2006 and consequently in the management of forest resources of the Atlantic Forest Biome. However, given the complexity and uncertainties surrounding the forest succession process, Fuzzy Rule-Based Systems, developed from legal parameters and incorporating expert knowledge, can be important support tools in defining successional stages. For this purpose, a specialist model consisting of two indicators was developed, one for the structural parameters (DBH, Basal Area and Height) and the other for the qualitative ones (physiognomy, canopy structure, diversity, epiphytes, climbers, litterfall and understory). To verify the proposed model, data from 466 sampling units from the Forest Floristic Inventory of Santa Catarina – IFFSC were used. The results obtained by executing the model showed that the adopted structure can express the regeneration process, assisting in the decision-making process. A higher concentration was observed in the classification of intermediate stages of forest regeneration (medium and advanced). Comparing the regeneration stages resulting from the application of the model with those defined by applying the formula proposed by IFFSC, there was a correspondence in 72% of the cases. The model appears to be sensitive to the adoption of interpretation scales for defuzzified values..
Keywords: Secondary Forest, *Fuzzy* Logic, Environmental Licensing, Atlantic Forest.

INTRODUCION

The Atlantic Forest Biome, which originally covered 8% of the South American landmass specifically the territories of three countries: Brazil, Argentina, and Paraguay has undergone a significant reduction in its natural occurrence, particularly from the 20th century onward. This decline has been intensified by urbanization, the expansion and development of agricultural and livestock activities, leaving only 37% of its original coverage, now predominantly composed of fragmented forests in secondary stages of regeneration (MOHEBALIAN *et al.*, 2022; ARMENTERAS *et al.*, 2017). In Brazil, this pattern is repeated, with the remaining 28% of native coverage in the Atlantic Forest Biome consisting predominantly of secondary and fragmented remnants (REZENDE *et al.*, 2018; ROSA *et al.*, 2021). Similarly, the forest cover in the state of Santa Catarina, estimated at 38.05%, is composed of approximately 95% secondary vegetation in either medium or advanced stages of regeneration (VIBRANS *et al.*, 2021; VIBRANS *et al.*, 2012; VIBRANS *et al.*, 2013a; VIBRANS *et al.*, 2013b).

Federal Law No. 11,428/2006, also known as the Atlantic Forest Law, was enacted to guide conservation and protection measures for the Atlantic Forest Biome. It regulates the potential removal of native vegetation based on regeneration stages for both secondary and primary forests, establishing, according to these stages, the activities subject to permissions and restrictions (Mota *et al.*, 2019; BRASIL, 2006; RESENDE *et al.*, 2024). As stipulated by Federal Law No. 11,428/2006, these stages are defined based on Resolutions issued by CONAMA (National Environmental Council) (BRASIL, 2006). Among the Brazilian states that encompass the Atlantic Forest Biome, 16 have a specific CONAMA Resolution applicable to their territories, incorporating qualitative and quantitative parameters that guide the classification of secondary and primary forest regeneration stages (CONAMA, 2007; RESENDE *et al.*, 2024). However, there are issues related to the lack of standardized criteria for data collection and the grouping of phytogeographic regions by regeneration stage (RESENDE *et al.*, 2024, BRESSANE *et al.*, 2023a).

For the state of Santa Catarina, CONAMA Resolution No. 04/94 was established to define the criteria and thresholds for delineating the characteristics of primary and secondary forests, with the latter being classified into regeneration stages described as initial, intermediate, and advanced (CONAMA, 1994). However, the regeneration process depends on multiple factors and may exhibit different responses, making its accurate classification complex and allowing for varying classification outcomes regarding its regeneration stage within the same area (CHAZDON *et al.*, 2016; SIMINISKI *et al.*, 2013; PASTÓRIO *et al.*, 2020).

This set of factors creates uncertainty in the application of CONAMA Resolution No. 04/1994 and complicates the alignment of its parameters with the characteristics of forest remnants in the state of Santa Catarina (SIMINSKI *et al.*, 2013; ANDREACCI; MARENZI, 2017; PASTÓRIO *et al.*, 2020). Since the generalized structure of CONAMA Resolution No. 04/94 does not prioritize the differences among regeneration stages and provides vague information in its proposed parameters adding complexity to its implementation—misclassifications may occur, interfering with the proper application of Federal Law No. 11,428/2006 (BRESSANE *et al.*, 2022; RESENDE *et al.*, 2024).

Given the difficulties and complexities involved in updating CONAMA Resolution No. 04/94, it is essential to identify mechanisms that support its implementation and mitigate its shortcomings, thus contributing to the management of land use in the Atlantic Forest Biome. To this end, it is crucial to make the definition of successional stages less subjective and less susceptible to technical errors and external influences resulting from urbanization and agricultural and livestock activities (BRESSANE *et al.*, 2022; SIMINSKI *et al.*, 2013; RESENDE *et al.*, 2024).

Several studies have sought methods to make the determination of forest succession more objective, including those conducted by Siminski *et al.* (2013), Vibrans *et al.* (2012), Vibrans *et al.* (2013a), Vibrans *et al.* (2013b), Bressane *et al.* (2022), and Pastório *et al.* (2020). However, these studies do not fully integrate CONAMA Resolution No. 04/94 to establish regeneration stages, even though this is an essential measure for guiding environmental licensing processes and applying Federal Law No. 11,428/2006.

In this context, the adoption of Fuzzy Rule-Based Systems as a decision-support tool can be beneficial for implementing CONAMA Resolution No. 04/94, as this method allows for the incorporation of expert knowledge and the definition of membership degrees for different classes of regeneration stages. This contributes to a more precise analysis aligned with the interactions present in the regeneration process of forest remnants (MOTA *et al.*, 2019; BRESSANE *et al.*, 2022; BRESSANE *et al.*, 2023a).

The objective of this study was to apply artificial intelligence, in conjunction with the development of an expert model based on a Fuzzy Rule-Based System, to assist in defining secondary forest regeneration stages and characterizing primary remnants in accordance with CONAMA Resolution No. 04/1994. This, in turn, contributes to the application of Federal Law No. 11,428/2006 in Santa Catarina.

MATERIAL AND METHODS

Study Area

The study was conducted within the area governed by CONAMA Resolution No. 04/94, which encompasses Dense Ombrophilous Forest (FOD), Mixed Ombrophilous Forest (FOM), and Deciduous Seasonal Forest (FED) phytogeographic regions associated with the Atlantic Forest Biome in the state of Santa Catarina (Figure 01).

For the analyses, data from 466 sample units were used, obtained from the Santa Catarina Forest Floristic Inventory (IFFSC) (VIBRANS *et al.*, 2012; VIBRANS *et al.*, 2013a; VIBRANS *et al.*, 2013b). This inventory includes qualitative information (such as epiphytes, lianas, understory, canopy cover, litter, and species count) and structural attributes (such as basal area, diameter at breast height (DBH), and total height) of forest remnants in the state of Santa Catarina, distributed across the Dense Ombrophilous Forest, Mixed Ombrophilous Forest, and Deciduous Seasonal Forest phytogeographic regions.

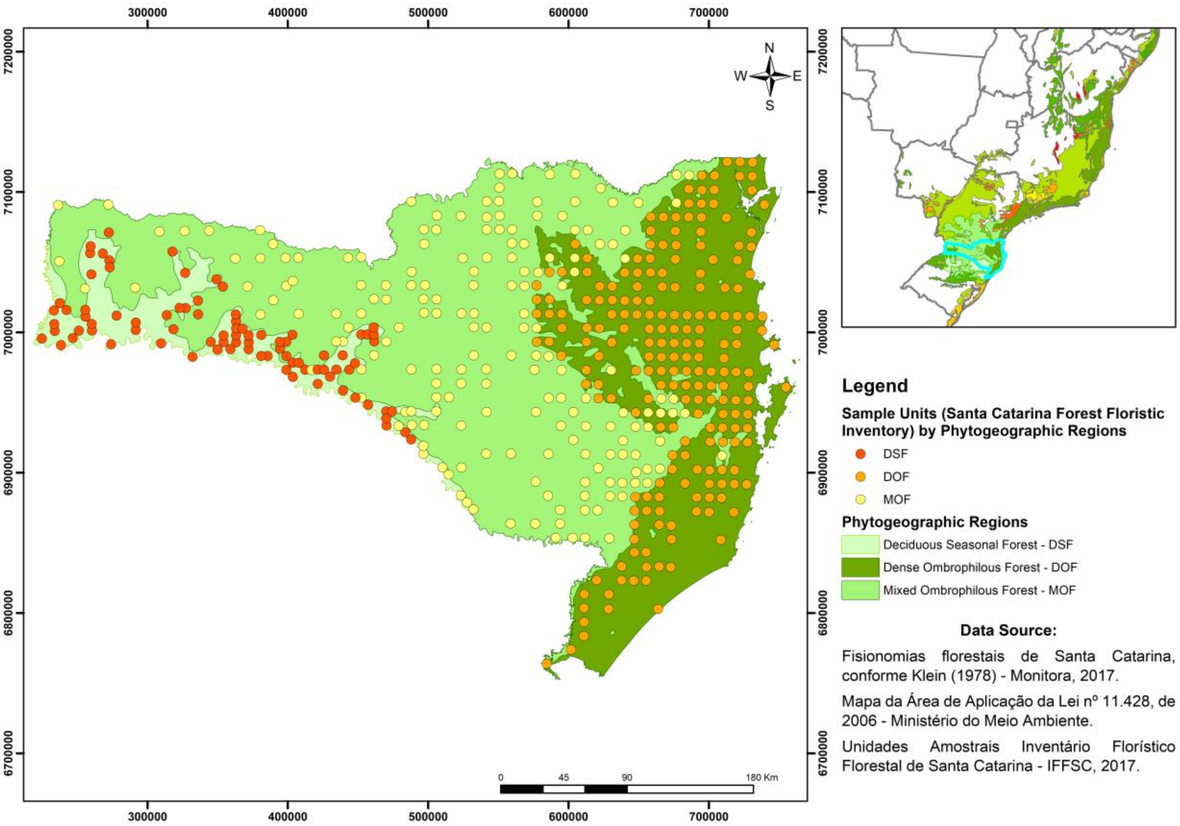

Figure 1. Map of the area of application of CONAMA Resolution No. 04/94 with the location of Sample Units by Phytogeographic Region.

Figura 1. Mapa da área de aplicação da Resolução CONAMA nº 04/94 com a localização das Unidades Amostrais por Região Fitogeográfica.

Design of the Fuzzy Rule-Based Expert System

For the development of the Fuzzy Rule-Based System (FRBS), the structure proposed by Mota *et al.* (2019) for the application of CONAMA Resolution No. 01/1994, which defines the successional stages of native forest vegetation in the state of São Paulo, was used as a reference. This structure consists of a Fuzzy Rule-Based System (FRBS), comprising the following stages: Fuzzification, Rule Module, Inference Module, and Defuzzification. These stages were adopted in the present study for the development and calibration of a Fuzzy Rule-Based System to meet the specifications established in CONAMA Resolution No 04/94. For the implementation and operation of the Fuzzy Rule-Based System, the open-source software "InFuzzy" was used.

In the fuzzification module, the information from CONAMA Resolution No. 04/94 was converted into membership functions. The input variables were composed of two indicators: one for structural attributes (including Basal Area, Mean Total Height, and Mean Diameter) and another for qualitative attributes (encompassing parameters such as physiognomy, canopy structure, diversity, epiphytes, vines or lianas, litter, and understory). The proposed structure is described in the Supplementary Documentation.

Some attributes from CONAMA Resolution No. 04/94 were excluded from the composition of the qualitative indicator due to their specificity to certain regeneration stages or the difficulty of establishing them in the field. Indicator species were not used, as data from the Santa Catarina Forest Floristic Inventory (IFFSC) indicated inconsistencies between the species listed in CONAMA Resolution No. 04/94 for each regeneration stage and those observed in the field (VIBRANS *et al.*, 2012; VIBRANS *et al.*, 2013a; VIBRANS *et al.*, 2013b).

For each parameter outlined in CONAMA Resolution No. 04/94, composing both the structural and qualitative indicators, a variable weight was assigned according to the corresponding regeneration stage. The weights were defined as follows: “3” for the initial regeneration stage, “5” for the intermediate regeneration stage and “7” for the advanced regeneration stage. Additionally, for the composition of the Structural Indicator, a value of "10" was assigned to attributes related to Primary Forest. The numerical arguments for each membership function, referred to as the Structural and Qualitative Indicators, were obtained by summing the attributes, as illustrated in Figure 02.

The linguistic terms that make up the membership function of the output variable correspond to the regeneration stages of secondary forests, classified as initial, intermediate, and advanced, in addition to the Primary Forest category. These linguistic values were converted into a numerical domain ranging from 0 to 10, with this range being evenly partitioned to assign a specific value to each attribute of the output function, as demonstrated in Figure 02. The choice of this range and the partitioning methodology were adapted from the work of Mota *et al.* (2019).

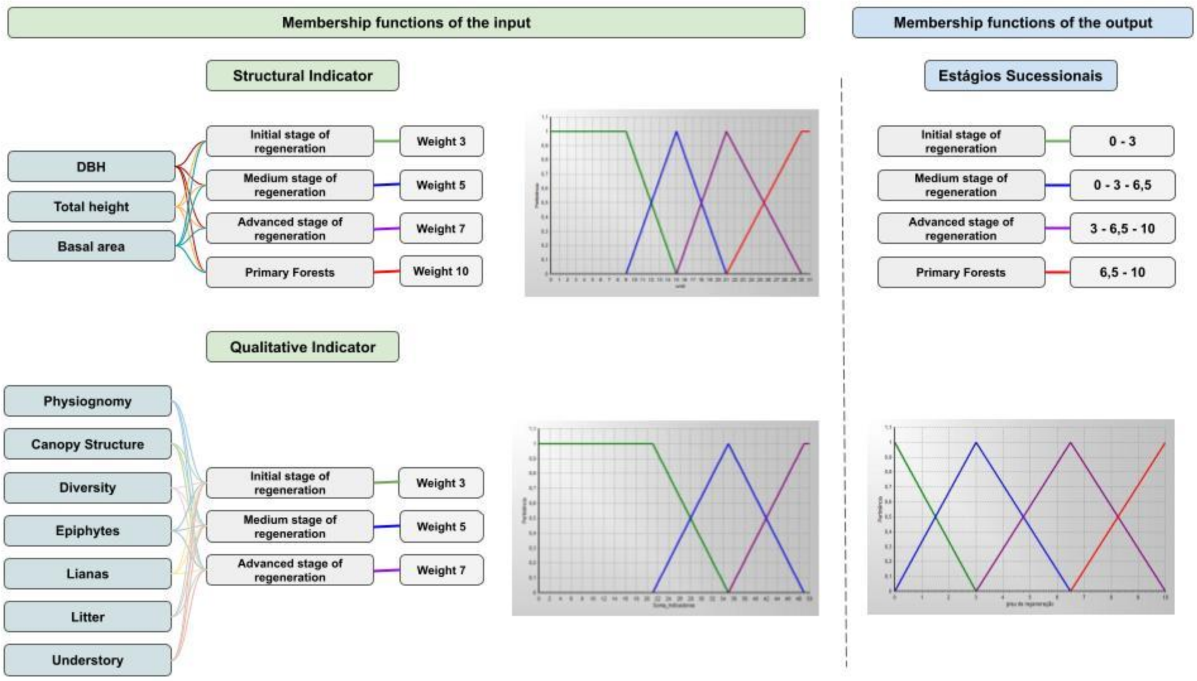

Figure 2. Example of the organization of the Membership Functions corresponding to the input and output of the Fuzzy Rule-Based System.

Figura 2. Exemplificação da organização das Funções de Pertinência correspondentes a entrada e a saída do Sistema Baseado em Regras Fuzzy.

In the Rule Base and Inference Module, conditional IF-THEN propositions were formulated based on expert knowledge to establish relationships between the input variables (parameters from CONAMA Resolution No. 04/94) and the output variable (regeneration stage). To achieve this, all possible combinations of the linguistic values of the input and output variables were considered, resulting in 12 rule blocks.

To avoid inconsistencies, redundancies, and subjectivity, the rule blocks were established using the product of the input and output values, compared against an arbitrarily defined scale, as illustrated in Figure 03. Subsequently, a review of the generated rules was conducted, identifying the need for corrections in three rules, resulting in the final distribution of two rules for the initial regeneration stage, five rules for the intermediate regeneration stage, four rules for the advanced regeneration stage, and one rule for primary forest.

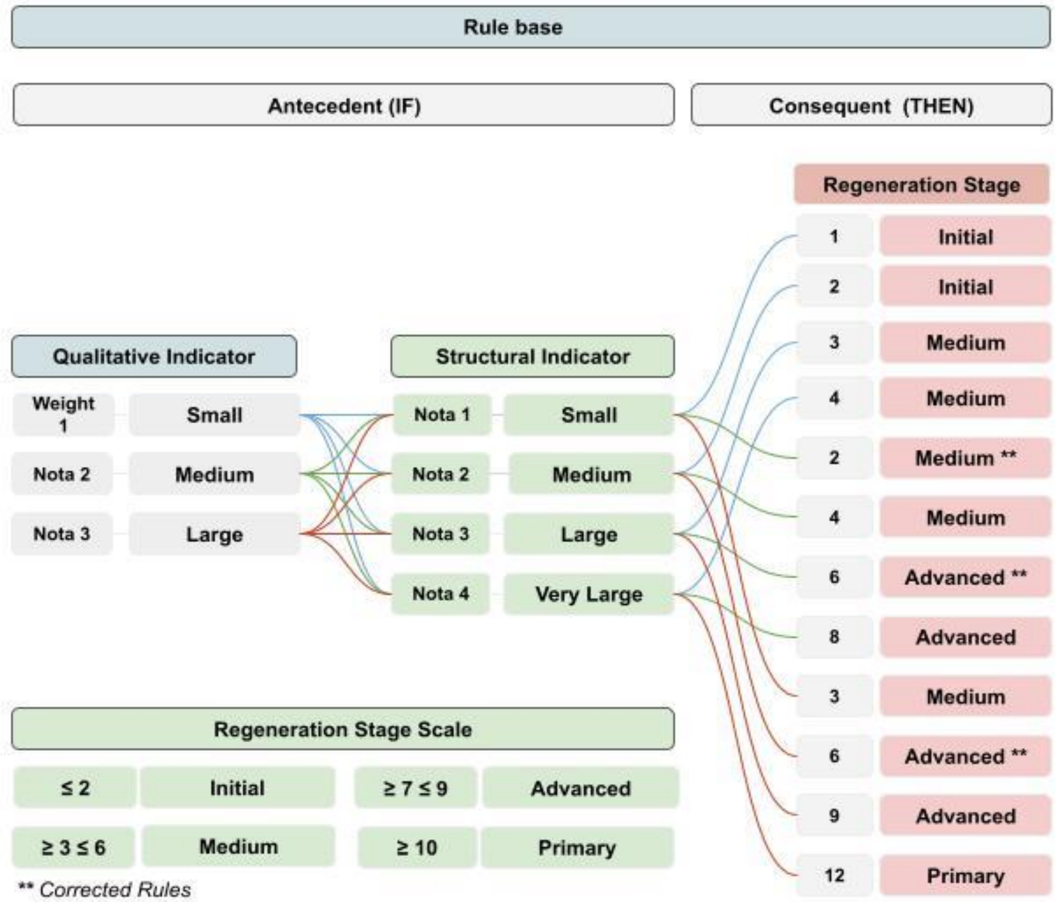

Figure 3. Development of the Rule Blocks for the Fuzzy Rule-Based System.
Figura 3. Elaboração dos Blocos de Regras do Sistema Baseado em Regras Fuzzy.

Considering the structure for classifying successional stages developed by Mota *et al.* (2019), the Mamdani inference method was chosen for the inference module. This method is based on a min-max propositional relationship, where the logical operator "AND" (t-norm) corresponds to the minimum value applied to the antecedents (Structural and Qualitative Indicators), while the logical connector "OR" (t-conorm) represents the maximum value assigned to the consequents (Successional Stages).

In the Defuzzification Module, the Fuzzy output is converted into a real numerical value (crisp) within a domain containing intervals associated with each successional stage. To achieve this, the center of gravity method was adopted (Equation 01), which corresponds to the weighted average of the areas, where the weights represent the membership degrees in a fuzzy subset. Since the centroid tends toward the central value, to ensure that all values within the domain were reached, the output values were normalized using Equation 02 (BRESSANE *et al.*, 2017).

$$Y^* = \frac{\sum_{m=1}^{Ny} y_m \, \mu_0 \left(y_m\right)}{\sum_{m=1}^{Ny} \mu_0 \left(y_m\right)}$$

Where: $\boldsymbol{ym}$ corresponds to the central value of rule m, $\boldsymbol{\mu 0}$ represents the degree of membership, and $\boldsymbol{Ny}$ is the number of rules in the fuzzy system.

$$Y' = \frac{\mathrm{Y\,est} * (\mathrm{Y} - \mathrm{Y\,min})}{(\mathrm{Y\,max} - \mathrm{Y\,min})}$$

where: **Y est** is the highest value within the output variable interval, Y is the defuzzified value, and, **Ymin** and **Ymax** are the lowest and highest values, respectively, generated during the defuzzification process.

Since the defuzzification results do not provide a categorical classification for the output variable, meaning they do not explicitly indicate the regeneration stage of secondary forests or their classification as primary forest, the normalized numerical values obtained in this stage were compared with three arbitrarily defined scales, presented in Table 01. In the first scale (Scale 01), the intervals between the numerical values defining the Regeneration Stage output variable were considered. In the second scale (Scale 02), the 0 to 10 interval was divided into four equal parts. In the third scale (Scale 03), three equal intervals were assigned to secondary forests, while a separate interval was allocated for primary forest. This approach aimed to minimize potential classification errors in defining successional stages and to assess the sensitivity of the relationship between the Fuzzy Rule-Based System (FRBS) and the chosen scale.

Table 1. Interpretative scales adopted to classify defuzzified results into Regeneration Stages for Secondary Forest and Primary Forest.

Tabela 1. Escalas interpretativas adotadas para a classificação dos resultados defuzzificados em Estágios de Regeneração para a Floresta Secundária e Floresta Primária.

	Scale 01	**Scale 02**	**Scale 03**
	Values	Values	Values
Regeneration Stage			
Initial Secondary	≤ 1,50	≤ 2,50	≤ 2,99
Medium Secondary	1,51 - 4,50	2,51 - 5,00	3,00 - 5,99
Advanced Secondary	4,51 - 8,50	5,01 - 7,50	6,00 - 8,99
Primary Forest	≥ 8,51	≥ 7,51	≥ 9,00

RESULTS

The normalized results obtained from the execution of the proposed model are distributed within a range of 2.50 to 7.50, with the majority concentrated between 4.50 and 7.00, which can be interpreted as intermediate regeneration stages (medium and advanced). There is little representation in the peripheral classes, which could correspond to forests in an initial regeneration stage or primary forests. When grouped into frequency classes, approximately 47.63% of the results fall between 6.00 and 7.99, while 38.62% are between 4.00 and 5.99, indicating that 86.25% of the results are concentrated in intermediate ranges.

When compared to the interpretation scales used for selecting the regeneration stages (Table 02), the results demonstrate that the model successfully adapted and represented the structure of information present in the sample units, generating different regeneration stages in accordance with the values computed from the qualitative and structural indicators.

Regarding the regeneration stages recommended by the model, as illustrated in Table 03, the use of Scales 02 and 03 resulted in an accuracy of approximately 72% when compared to the regeneration stages suggested by the IFFSC, derived from Fisher's discriminant analysis. However, Scale 01 did not yield satisfactory results, as approximately 42% of the indicated stages were divergent, additionally leading to an overestimation of the medium and advanced regeneration stages.

Table 2. Classification of Defuzzified and Normalized Results in regeneration stages for Secondary Forest and Primary Forest according to Interpretation Scale

Tabela 2. Classificação dos Resultados Defuzzificados e Normalizados em estágios de regeneração para a Floresta Secundária e Floresta Primária conforme Escala de Interpretação.

	Scale 01		**Scale 02**		**Scale 03**	
	Values	Results	Values	Results	Values	Results
Regeneration Stage						
Initial Secondary	≤ 1,50	0	≤ 2,50	49	≤ 2,99	51
Medium Secondary	1,51 - 4,50	143	2,51 - 5,00	195	3,00 - 5,99	211
Advanced Secondary	4,51 - 8,50	323	5,01 - 7,50	222	6,00 - 8,99	204
Primary Forest	≥ 8,51	0	≥ 7,51	0	≥ 9,00	0

Table 3. Comparison between the Regeneration Stages described by the execution of the Fuzzy Rule-Based System and those informed by the application of the Formula proposed by the Santa Catarina Forest Floristic Inventory, developed from Fischer's Discriminant Analysis per sampling unit.

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Tabela 3. Comparativo entre os Estágios de Regeneração descritos pela execução do Sistema Baseado em Regras Fuzzy com os informados pela aplicação da Fórmula proposta pelo Inventário Florístico Florestal de Santa Catarina elaborado a partir da Análise Discriminante de Fischer por unidade amostral.

	Number of Sample Units with Equal Regeneration Stage Classification	Number of Sample Units with Different Classification of Regeneration Stages	Equal Rating Percentage
Scale 01	269	197	57,72
Scale 02	336	130	72,10
Scale 03	339	127	72,74

As indicated in Table 04, the regeneration stages suggested by the Fuzzy Rule-Based System combined with Scale 03 (FRBS/Scale 03), when compared to those listed by the IFFSC, Discriminant Analysis, and Expert Evaluation during the field measurement of sample units, demonstrate a higher predictive capacity for Dense Ombrophilous Forest and Deciduous Seasonal Forest. Conversely, the model exhibited the lowest predictive capacity for Mixed Ombrophilous Forest, with values around 52%, indicating the need for further studies to better understand this outcome.

Table 4. Percentage comparison between the Regeneration Stages described by the execution of the SBRF/Scale 03 and those informed by the Santa Catarina Forest Floristic Inventory, considering the proposed Formula developed from Fischer's Discriminant Analysis and the field classifications carried out by the Experts for Phytogeographic Region.

Tabela 4. Comparativo em porcentagem entre os Estágios de Regeneração descritos pela execução do SBRF/Escala 03 e os informados pelo Inventário Florístico Florestal de Santa Catarina, considerando a Fórmula proposta elaborada a partir da Análise Discriminante de Fischer e as classificações de campo realizadas pelos Especialistas por Região Fitogeográfica.

	Equivalence ratio of IFFSC Regeneration Stages (Fischer Discriminant Analysis) / SBRF/Scale 03 (%)	Equivalence ratio of IFFSC Regeneration Stages (Specialists) SBRF/Scale 03 (%)
Dense Ombrophylous Forest	85,43	79,12
Mixed Ombrophylous Forest	52,84	52,27
Deciduous Seasonal Forests	79,16	70,23

DISCUSSION

The structure of CONAMA Resolution No. 04/94 organizes the attributes for categorizing regeneration stages in a generalized manner, without considering the explanatory capacity of this information or the differences among phytogeographic regions (BRESSANE *et al.*, 2023a; BRESSANE *et al.*, 2023b). Furthermore, the resolution does not establish criteria or guidelines for conducting forest remnant surveys, lacking definitions for minimum plot areas, inclusion diameters, and guidelines for sample unit allocation. This results in conflicting classifications and increases subjectivity in decision-making regarding the proper categorization of regeneration stages (SIMINSKI *et al.*, 2013; PASTÓRIO *et al.*, 2020; RESENDE *et al.*, 2024).

The adoption of indicators that group qualitative attribute information could be an alternative to mitigate uncertainties, subjectivity, and the lack of criteria in CONAMA Resolution No. 04/94. As described by BRESSANE *et al.* (2022), these attributes have a limited capacity to express the regeneration process in stages. When analyzed individually, as proposed by CONAMA Resolution No. 04/94, there is a higher likelihood of misclassification in defining regeneration stages. Part of this issue is linked to the need for clear guidelines, as well as the adoption of standardized methods for data collection, classification, and normalization of the sampling process (SIMINSKI *et al.*, 2013; PASTÓRIO *et al.*, 2020).

The use of a structural indicator, incorporating Basal Area, Height, and DBH (Diameter at Breast Height), appears to be a plausible approach to addressing the rigid classification thresholds imposed by CONAMA Resolution No. 04/94 (SIMINSKI *et al.*, 2013; PASTÓRIO *et al.*, 2020; ANDREACCI; MARENZI, 2017). As pointed out by BRESSANE *et al.* (2022) and SIMINSKI *et al.* (2013), basal area is the most reliable parameter for representing forest succession processes, and the inflexibility of existing classification criteria can impact the correct definition of regeneration stages.

Similarly, Height and DBH also have predictive capacity for defining regeneration stages (BRESSANE *et al.*, 2023b). However, when evaluated individually, as suggested by CONAMA Resolution No. 04/94, these parameters present classification challenges when compared to field data, leading to inconsistencies with the resolution's descriptions. This results in the possibility of assigning different regeneration stages to the same forest fragment (SIMINSKI *et al.*, 2013; PASTÓRIO *et al.*, 2020; ANDREACCI; MARENZI, 2017; BRESSANE *et al.*, 2023a).

Regarding the results obtained from the execution of the Fuzzy Rule-Based System, the concentration of values in intermediate classes may be associated with the characteristics of forest remnants in Santa Catarina, where secondary forests in medium and advanced regeneration stages predominate. This pattern is also observed throughout the entire Atlantic Forest Biome, which may explain the absence of results in higher classes, representing primary forests (VIBRANS *et al.*, 2021; ROSA *et al.*, 2021).

The low representativity of results in the higher ranges, classified as primary forests, is partly due to the limited availability of data with these characteristics used in the execution of the Fuzzy Rule-Based System (FRBS). Additionally, it is influenced by the constraints imposed by CONAMA Resolution No. 04/94, which restricts primary forests to fragments with minimal human intervention and maximum local ecological expression, linked to the concept of climax communities) (VIBRANS *et al.*, 2013a; VIBRANS *et al.*, 2013b; CONAMA, 1994).

The clustering of results within certain ranges or classes may be related to the structure of the sample unit data, which exhibits low variation. Mota *et al.* (2019), applying a similar methodology for classifying regeneration stages based on CONAMA Resolution No. 01/94 (São Paulo), also observed a concentration of results in intermediate classes and data clustering. This indicates that the generated results tend to be less sensitive to small changes in value structure, meaning that decimal-level differences tend to produce grouped results. This suggests that the system is not highly sensitive to minor variations, as small differences in decimal values tend to lead to result concentration.

When applying scales to interpret the regeneration stages based on the results of the Fuzzy Rule-Based System (FRBS), Scale 01 proved to be ineffective, as it tended to underestimate the classification of secondary forests in the initial regeneration stage, leading to an overconcentration of classifications in the medium and advanced regeneration stages. In contrast, Scales 02 and 03 provided a more balanced distribution of regeneration stages in the sample units, better reflecting the characteristics of forest fragments in Santa Catarina. These scales demonstrated sensitivity in the classification process and showed potential as a decision-support tool for defining successional stages. However, further studies are necessary to better understand the relationship between the resolution's parameters and regeneration stages, as well as to develop, test, and validate new models, systems, and scales.

Comparing the regeneration stages suggested by FRBS/Scale 03 with those determined using the formula proposed by the Santa Catarina Forest Floristic Inventory (IFFSC) (VIBRANS *et al.*, 2012; VIBRANS *et al.*, 2013a; VIBRANS *et al.*, 2013b), the classifications were identical in 72.74% of the sample units evaluated. This result is similar to Mota *et al.* (2019), who also applied FRBS as a decision-support tool for defining forest succession stages based on CONAMA Resolution No. 01/94. The accuracy of the FRBS/Scale 03 results falls within the estimated capacity of CONAMA Resolution No. 04/94 for defining regeneration stages using quantitative parameters, which Pastório *et al.* (2020) estimated at 81.87%. These results were expected since the model considers a combination of quantitative and qualitative attributes from CONAMA Resolution No. 04/94, which inherently limits the influence of qualitative attributes in defining regeneration stages (BRESSANE *et al.*, 2023b).

The divergences are mainly concentrated in the classification of medium vs. advanced regeneration stages and initial vs. medium stages, indicating an interaction between these regeneration stages. This may be associated with various factors, such as the classification criteria established by CONAMA Resolution No.

04/94, the lack of differentiation of regeneration stages by phytogeographic regions, and the absence of clear guidelines for the data collection process (BRESSANE *et al.*, 2023b; SIMINSKI *et al.*, 2013; PASTÓRIO *et al.*, 2020). As a result, attributes evaluated separately or collectively influence the classification process, leading to conflicts between qualitative and structural parameters (PASTÓRIO *et al.*, 2020). These conflicts may be further exacerbated by the lack of a prioritization system or weighting method for the parameters established in CONAMA Resolution No. 04/94, as all parameters are considered equally weighted (BRESSANE *et al.*, 2023b).

The results from the FRBS/Scale 03 application for each phytogeographic region suggest that CONAMA Resolution No. 04/94 may pose greater challenges in classifying the regeneration stages of Mixed Ombrophilous Forest, while achieving better performance for Dense Ombrophilous Forest, followed by Deciduous Seasonal Forest. This may, in part, reflect the structure of CONAMA Resolution No. 04/94, which does not account for differences among phytogeographic regions within its application area, nor does it consider the distinct characteristics of regeneration stages in these regions and the low predictive capacity of qualitative parameters (BRESSANE *et al.*, 2022; BRESSANE *et al.*, 2023a; BRESSANE *et al.*, 2023b).

The lack of differentiation of parameters by phytogeographic region is an issue observed in other CONAMA Resolutions aimed at classifying regeneration stages (BRESSANE *et al.*, 2023a; RESENDE *et al.*, 2024). This indicates that, in a potential update of CONAMA Resolution No. 04/94, it is essential that the attributes and parameters defining each regeneration stage be proposed individually for each phytoecological region (BRESSANE *et al.*, 2023a; BRESSANE *et al.*, 2023b).

The succession process, divided into regeneration stages, appears to be better explained through the analysis of membership degrees obtained from the execution of the proposed FRBS. In this context, the contribution of one stage to the subsequent and preceding stages would be acknowledged. Additionally, the FRBS identifies which regeneration stage is best represented within the evaluated dataset. Thus, the application of fuzzy logic demonstrates potential for resolving conflicts arising from the presence of multiple regeneration stages within a single forest fragment, as highlighted by Siminski *et al.* (2013), Andreacci and Marenzi (2017), and Pastório *et al.* (2020).

CONCLUSIONS

- The proposed FRBS demonstrated potential to overcome the challenges associated with the application of CONAMA Resolution No. 04/94 in defining the regeneration stages of secondary and primary forests. It enables the decision-making process to be conducted in a more standardized and less error-prone manner, minimizing subjective factors related to the interpretation of information in CONAMA Resolution No. 04/94 and the numerous factors influencing successional trajectories.
- Considering the specific characteristics of each phytogeographic region and the factors that may affect their successional trajectories, it would be important that, in the event of an update to CONAMA Resolution No. 04/94, the criteria and parameters guiding the classification of primary and secondary forests be defined according to each phytogeographic region. Additionally, due to the influence of topographic gradients, the resolution should also consider the subformations within each phytogeographic region.
- The study indicated the need to establish criteria that assist in the interpretation of qualitative parameters described in CONAMA Resolution No. 04/94.
- The proposed model presents several opportunities for enhancing the understanding of the succession process, taking into account ecological interactions. However, further studies are still needed to assess stage transition processes and the contribution of one stage to its predecessor and successor.
- Given the structure of CONAMA Resolutions, which were developed for the implementation of the Atlantic Forest Law, the model and its framework can be adapted for forest formations within the Atlantic Forest Biome in other states.

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REFERENCES

ANDREACCI, F; MARENZI, R. C. Avaliação da aplicação da Resolução CONAMA 04/94 na definição dos estágios sucessionais de fragmentos florestais da Floresta Ombrófila Densa de Santa Catarina. **Biotemas**, Florianópolis, v. 30, n. 4, p. 117-128, dez. 2017.

ARMENTERAS, D. *et al.* Deforestation dynamics and drivers in different forest types in Latin America: Three decades of studies (1980–2010). **Global Environmental Change**, [S.l.] v. 46, p. 139–147, set. 2017.

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, 22 dez. 2006.

BRESSANE, A. *et al. Fuzzy*-based methodological proposal for participatory diagnosis in the linear parks management. **Ecological Indicators**, [S.l.] v. 80, p. 153–162, mai. 2017.

BRESSANE, A. *et al.* Computer-aided classification of successional stage in subtropical Atlantic Forest: a proposal based on *fuzzy* artificial intelligence**. Environmental Monitoring and Assessment**, [S.l.] v. 195, n. 1, p. 184, dez. 2022.DOI.10.1007/s10661-022-10799-x

BRESSANE, A. *et al.* Atlantic Forest Ecosystems: Are There Significant Differences When Compared at the Same Stage of Regeneration? **Sustainability**, Basel v. 15, n. 8, 6823, abr. 2023a.

BRESSANE, A. *et al.* Prioritization of key indicators for the classification of successional stages in regenerating subtropical Atlantic forest, Southern Brazil: a proposal based on multivariate order statistics. **Environment Systems and Decisions**, [S.l.] v. 43, n. 2, p. 232–241, jun. 2023b.

CONAMA - CONSELHO NACIONAL DO MEIO AMBIENTE. Resolução n.4, de 04 de maio de 1994. **Diário Oficial da União**, nº 114, 17 jun. 1994. Seção 1, p. 8877-8878.

CHAZDON, R. L. *et al.* When is a forest a forest? Forest concepts and definitions in the era of forest and landscape restoration. **Ambio**, Stockholm v. 45, n. 5, p. 538–550, set. 2016.

MOHEBALIAN, P. M. *et al.* Deforestation in South America's tri-national Paraná Atlantic Forest: Trends and associational factors. **Forest Policy and Economics**, [S.l] v. 137, p. 102697, abr. 2022.

MOTA, M. T. *et al.* Classification of successional stages in Atlantic Forests: A methodological approach based on a *fuzzy* expert system. **Ciencia Florestal**, Santa Maria v. 29, n. 2, p. 519–530, jun. 2019.

PASTORIO, F. F; *et al.* Successional stages of Santa Catarina Atlantic subtropical evergreen rainforest: a classification method proposal. **Cerne** [online], [S.l.] vol.26, n.2, pp.162-171, set. 2020. DOI. 10.1590/01047760202026022651.

REZENDE, C. L. *et al.* From hotspot to hopespot: An opportunity for the Brazilian Atlantic Forest. **Perspectives in Ecology and Conservation**, [S.l.] v. 16, n. 4, p. 208–214, out. 2018.

RESENDE, A. F. *et al.* How to enhance Atlantic Forest protection? Dealing with the shortcomings of successional stages classification. **Perspectives in Ecology and Conservation**, [S.l] v. 22, n. 2, p. 101-111, abr. 2024.

ROSA, M. R. *et al.* Hidden destruction of older forests threatens Brazil's Atlantic Forest and challenges restoration programs**. Science Advances**, [S.l.] v. 7, n. 4, p. eabc4547, jan. 2021.

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, n. 3, p. 369-378, set. 2013.

VIBRANS, A.C.; *et al.* Monitora SC: um novo mapa de cobertura florestal e uso da terra do estado de Santa Catarina. **Agropecuária Catarinense**, Florianópolis, v. 34, p. 42-48, ago. 2021.

VIBRANS, A. C.; *et al.* (ed.). **Inventário Florístico Florestal de Santa Catarina: Floresta Estacional Decidual.** Blumenau: Edifurb, 2012. (Vol. II). 336 p.

VIBRANS, A. C.; *et al.* (ed.). **Inventário Florístico Florestal de Santa Catarina: Floresta Ombrófila Mista.** Blumenau: Edifurb, 2013a. (Vol. III). 440 p.

VIBRANS, A. C.; *et al.* (ed.). **Inventário Florístico Florestal de Santa Catarina: Floresta Ombrófila Densa.** Blumenau: Edifurb, 2013b. (Vol. IV). 576 p.