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Use of Fuzzy Logic for Modeling the Effect of Climate on the Reproductive Phenology of a Tropical Tree

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Abstract

Most of the models for analyzing the relationship between phenology and climatic variables rely on quantitative data on flowering and fruiting, while the use of semi-quantitative information such as the categorical Fournier Index remains a challenge to phenological data analysis. Fuzzy logic has been recently used for modeling climate data and its effects on different environmental aspects as it can handle vague situations, few and nonlinear data, multiple variables, categorical data, and semi-quantitative information, typical in long-term phenological records. Therefore, the objective of this research was to use fuzzy logic to model the relationship between climate and phenology of a tropical timber tree species, and to forecast whether this species phenology can be affected by global warming. To this end, we developed a fuzzy logic model (type Mamdani) to associate data on the species' reproductive phenology (flowering and fruiting) recorded from 2007 to 2012, with monthly mean, minimum and maximum temperature, monthly mean solar radiation, relative humidity, and monthly precipitation obtained for the same period and location. Based on the model achieved and three locally predicted climatic variables for the period 2027 - 2032 under A2 and B2 climate change scenarios we estimated the future phenological behavior of the species. The fuzzy logic modeling showed that the flowering intensity index was strongly associated with the combination of maximum temperature, minimum temperature, solar radiation, and precipitation. Regarding fruiting, a strong association was observed with precipitation, while a weak relationship was found with mean temperature. The model calibration and validation showed a greater precision for fruiting than for flowering. Under the future climate change scenarios, the model predicted a decrease in the flowering and fruiting intensity indices. We discuss that although fuzzy logic is not a "traditional" tool in the field of ecology, it performed satisfactory, despite a low number of individuals.

Keywords: Aniba perutilis, Mandami Type triangular, output variables, input variables, defuzzing, Fournier index, tropical tree.

INTRODUCTION

Plant phenology is highly related to climate both in temperate and tropical regions; thus, its analysis is highly relevant in the face of current and future climate change. In tropical forests, researchers have studied which climatic variables are the most important drivers of phenological processes (*e.g.,* Borchert et al. [1]; Zimmerman et al. [2]); however, evidence is still inconclusive. For instance, solar radiation has been found to strongly influence phenology of tropical species [3,4], while Dunham et al. [5] have addressed the importance of annual precipitation and its annual distribution in forest phenology. Other researchers have found a relation between phenology and temperature [6], whereas Borchert et al. [1] and Calle et al. [7] have suggested daily isolation as the main factor controlling phenology of several tropical plant species.

Although multiple climatic variables seem to determine phenological processes, analyses have been generally focused on simple correlations (e.g. De Paiva-Farias et al. [8]; Morellato et al. [6]; Ordóñez-Blanco and Parrado-Rosselli [9]). Also, conventional mathematical models are not actually appropriate since responses to climate are non-lineal and highly auto correlated [10,11]. Moreover, phenological data has an excess of zero values due to the absence of a particular phenophase. Therefore, novel analytical approaches in phenology studies should be developed, in order to generate models for predicting the effect of climate change on plant populations [12].

Some researchers have developed new approaches for analyzing the relationship between phenology and multiple climatic variables. These include generalized additive models, mixture transition distribution models and Bayesian models (*e.g.* Hudson et al. [10]; Mendoza et al. [12]). These models, however, rely on quantitative data on flowering and fruiting, while information obtained through the widely used Fournier's method [13], which is a semi-quantitative description of the intensity of phenophases, remains a challenge to phenological data analysis.

Fuzzy logic is an approach that has been recently used for modeling climate data and its effects on different ecological and environmental aspects (*e.g.* Orlandini et al. [14]; Real et al. [15]; Segura and Obregón [16]). This is because it can handle

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vague situations, few and non-linear data, multiple variables, categorical data and semi-quantitative information, which is also typical in long-term phenological records obtained through the Fournier Index. Therefore, fuzzy logic can be an interesting approach for modelling the relationship between climate and phenology and hence, to forecast whether plant phenology can be affected by global warming. According to Morelatto et al. [17] assessing the impacts of climate change on phenology of vulnerable or threatened plant species, is certainly one of the mechanisms to integrate research on phenology to conservation science, as it might help to set effective priorities for conservation agenda and to guide mitigation actions [17].

In Colombia, particularly in protected areas, phenology monitoring of plant conservation targets has been done from 2007 following Fournier's method [13]. Thus, in order to integrate this information into management plans and conservation agendas, it should be analyzed in light of future climate change. In that way, the objective of this paper was to use fuzzy logic to model the association between climate and data on reproductive phenology of *Aniba perutilis* Hemsl. (Lauraceae) a conservation target and a threatened timber tree species of some Andean protected areas in Colombia. To this end, data on the species' reproductive phenology (flowering and fruiting) recorded from 2007 to 2012 in the Otún Quimbaya Flora and Fauna Sanctuary, was associated to monthly mean, minimum and maximum temperature, monthly mean solar radiation, relative humidity and monthly precipitation obtained for the same period and location. Based on the model achieved and three locally predicted climatic variables for the period 2027 to 2032 under A2 and B2 climate change scenarios [18], we estimated the future phenological behavior of the species.

MATERIALS AND METHODS

Study species

Aniba perutilis Hemsl. (Lauraceae) is a representative species of the Andean region [19, 20]. It is extensively distributed throughout Colombia and Bolivia [21, 22] and generally grows in primary montane and submontane wet tropical forests in zones with mean temperatures from 3 to 26°C and annual precipitation from 1900 to 4000 mm [23]. Locally known as "comino crespo," this timber-yielding species commands attention on the international furniture market. This demand, which translates into overexploitation, coupled with habitat loss, explains the categorization of the species as critically endangered (CR A2cd) [21]. For these reasons, it has been considered a conservation target of the Otun-Quimbaya Fauna and Flora Sanctuary (OQFFS: 4°43′30" N, 75°34′30" W), a protected area of the Colombian National Park System, and hence, it has been included in the monitoring strategy of the protected area.

Phenological data

We used monitoring data from ten *A. perutilis* individuals with a DBH greater than 15 cm from 2007 to 2012. Although Morellatto et al. [24], asserted that 15 individuals is the minimum number to obtain similar patterns to the sample population, as this phenological monitoring began in 2006, ten individuals was a common sample size for phenological researches (*e.g.* D'Eça and Morellato [25] ; Fournier and Carpantier [26]). The trees were chosen at least 100 m apart from each other along an existing path, considering that during initial sampling they were in a reproductive state (flowers or fruits). For each individual, phenological activity was recorded on a monthly basis in line with the method proposed by Fournier [13] and Fournier and Charpantier [26]. The Fournier's method was chosen for phenological monitoring because it is simple, applies to any type of tree, does not depend on plant architecture or size and facilitates field data collection and analysis particularly in protected areas where low budget and few staff is a constant [27]. Moreover, the Fournier's method remains one of the most useful tools for describing phenology both at the population and community levels, as is still widely used in recent phenological studies [28, 29, 27].

According to Fournier [13], the intensity of the phenophases is estimated for each individual through a semi-quantitative scale as follows: 0 (absence of the phenomenon); 1 (presence of the phenomenon with an intensity between 1 and 25% of the crown); 2 (presence of the phenomenon with an intensity between 26 and 50% of the crown); 3 (presence of the phenomenon with an intensity between 51 and 75% of the crown); 4 (presence of the phenomenon with an intensity between 76 and 100% of the crown).

Per analysis done by Bencke and Morellato [30], two variables can be used to describe phenological event intensity. The first is the Fournier intensity index (referred to as the intensity index), in which values are attributed to each tree according to the semi-quantitative scale for each observation date using the following formula [13]:

$$\%FI = \left[\sum_{i=1}^{n} xi/\left(\mathrm{n} * 4\right) \right] * 100$$

Where n is the number of individuals sampled in a population and xi is the value of the semi-quantitative scale assigned to the individual i [24].

We also calculated the percentage of trees per species displaying a phenological event in each observation period [30]. Based on Newstrom, Frankie, and Baker [31], phenological events were characterized in terms of frequency (*i.e.* continuous, sub-annual, annual and supra-annual) and duration (*i.e.* short, or less than a month; intermediate, or between 1 and 5 months; extended, or more than 5 months). For the sake of clarity, open flowers and floral buds were categorized as flowering and green and ripe fruit as fruiting.

Climate data

Data for monthly mean minimum, maximum and mean temperatures, solar radiation, precipitation and relative humidity for the sampling period were obtained from the Automatic Climate Station IDEAM - PNN Quimbaya situated at 1,881 m and at 4°43'30" N, 75°34'30 W. Projections of monthly mean temperature, monthly precipitation and monthly mean relative humidity for the period 2027-2032 were obtained using climate modeling for Colombia done by Alarcón and Pabón [18] with a regional distribution and horizontal resolution of 900 x 900 m in two climate change scenarios from the IPCC Fourth Assessment Report (A2 and B2; [32] IPCC 2007). The A2 and B2 scenarios were chosen because they represent medium-high and medium-low greenhouse gas emissions, respectively, and because most climate models generally rely on them [18]. Climate prediction site was located 8.41 km from the study site (4°47'31" N, 75°32'24" W). The 2027-2032 forecast period was determined with the goal of avoiding temporally distant predictions, where the effect of factors inherent to the individual's biology and the probability of stochastic events occurring were unlikely to be predicted [33]. Furthermore, we chose six years as the time period for predictions in order to address a possible multiannual pattern of the species.

Fuzzy Logic modelling

In order to integrate all climatic variables and *A. perutillis* flowering and fruiting phenology, a fuzzy logic model (type Mamdani) was developed [34, 35]. The fuzzy logic approach was adopted as there was no certainty of which climatic variable was the better predictor of the phenological behavior of the species. Moreover, fuzzy logic allows to embrace multitude of variables, to face the complex, rather than linear, nature of the relationship between climate and phenology and to factor in any uncertainty the semi qualitative Fournier method may entail [36].

The model consisted of six input variables: 1) monthly mean minimum temperature, 2) monthly mean maximum temperature, 3) monthly mean temperature, 4) monthly mean solar radiation, 5) monthly rainfall and 6) monthly mean relative humidity. There were four output variables: 1) percentage of flowering individuals, 2) flowering intensity index, 3) percentage of fruiting individuals, and 4) fruiting intensity index. From these ten variables, we defined sets (fuzzy sets) using membership functions conditioned such that at least one element of the fuzzy set exhibited the highest grade of membership [37]. To obtain the membership value, real numerical values of input and output variables were transformed into a membership grade to the fuzzy set. A membership function is a curve that maps each point in the input space to a membership value between 0 and 1, and may take many forms (trapezoidal, triangular, and bell-shaped [38]. In this particular case, triangular membership functions were used for mathematical simplicity, user-friendliness and facilitation of defuzzification process.

The system established low, intermediate and high quantifiers for most of the input and output variables except for the percentage of flowering individuals, for which the system established low, low- intermediate, intermediate, intermediate-high or high quantifiers. As the main principle of fuzzy logic is the allowance of partial belongings of any object to different subsets (fuzzy set) of the whole data set, one object can belong to two fuzzy sets at the same time. For instance, a minimum temperature of 17.5°C in Figure 3 (see below) belongs to low and intermediate sets with 0.25 and 0.75 membership degrees, respectively.

The follow up step was the formulation of the rules that included all possible fuzzy relations between input and output variables. Fuzzy control rules can be formulated based on expert knowledge or created by the system itself, that is, the model itself imposes the rules mathematically [11, 39]. In response to the lack of prior information regarding the species' phenology in a time-scale greater than one year and, to avoid *a priori* hypotheses, we opted to have rules set by the model. Thus, 73 fuzzy rules were developed per phenophase based on the original data matrix, which correspond to the 73 months spanned by our data set.

These rules are generated using **If-Then** propositions to be resolved by the model, so they describe—in linguistic variables—the quantitative relationships among the variables. For instance, **if** mean, minimum and maximum temperature are low, solar radiation and rainfall are intermediate and relative humidity is high, **then** flowering intensity index will be high. Here, it behooves us to clarify that each rule represents a cause-effect relationship; in other words, for a given operating condition (cause), there is a corresponding step (effect) that must be taken to control the process [40,11].

For calibration, 70% of the data from the original matrix was used with the input and output data to verify learning ability [41]. The remaining 30% of the database was employed for validation. Data obtained for the model were compared to measured data to confirm similarity by means of the mean squared error [42, 41]. Once the model was calibrated, we forecasted the species phenology for the period 2027-2032 in the A2 and B2 climate change scenarios. As for these scenarios, the regional climate model developed by Alarcón and Pabón [18] only used three variables (i.e. monthly mean temperature, monthly precipitation and monthly mean relative humidity); these were considered as the output variables. The Fuzzy Logic Toolbox 7.10.0, included in the MATLAB ® (R2010a) software package, was used for the fuzzy model [43]. Finally, we performed the traditional Spearman Rank Correlation Coefficient (r_s) in order to examine if the typical one by one variable analysis between climate, fruiting and flowering coincided with those obtained through the fuzzy logic model.

RESULTS

Aniba perutilis flowering and fruiting

The flowering pattern of *A. perutilis* recorded between 2007 and 2012 was supra-annual, every three years (Figure 1). As different individuals flowered over one and four months, we considered this phenophase to be intermediate, in spite of one specific individual not flowering for longer than a month. In regards to *A. perutilis* fruiting, patterns were also found to be supra-annual (every three years), and its duration oscillated between one and three months; consequently, it was considered intermediate (Figure 2).

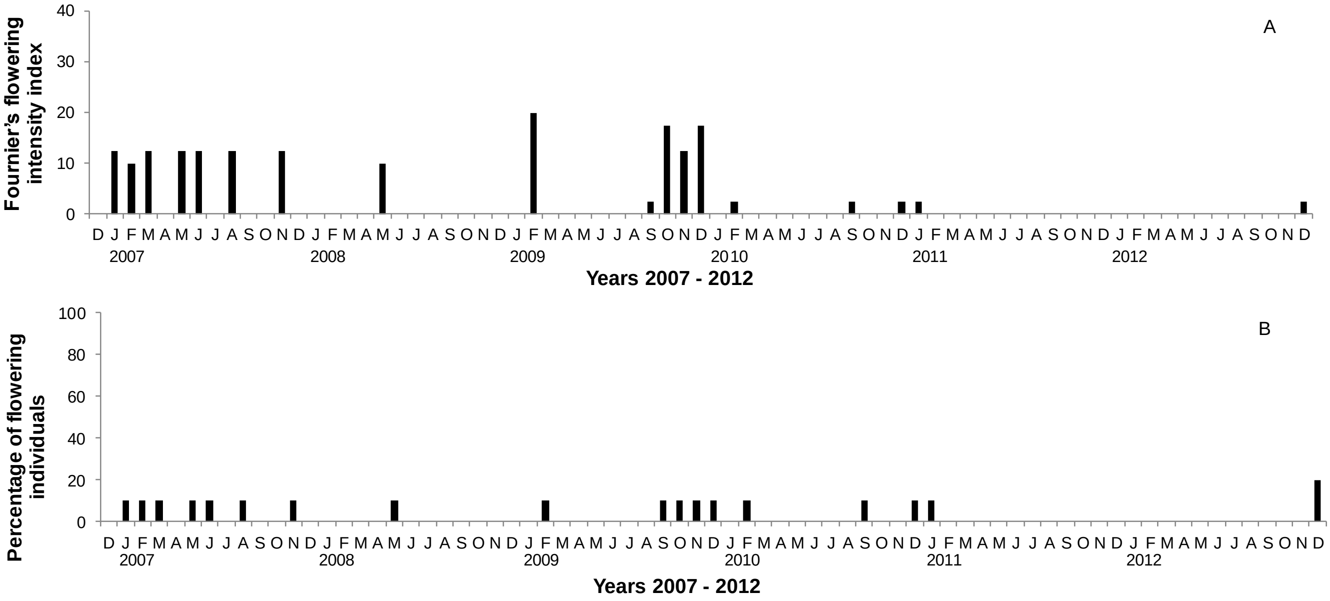

Figure 1. *A. perutilis* flowering from 2007 to 2012 in terms of A) Fournier's flowering intensity index, and B) Percentage of flowering individuals. N=10.

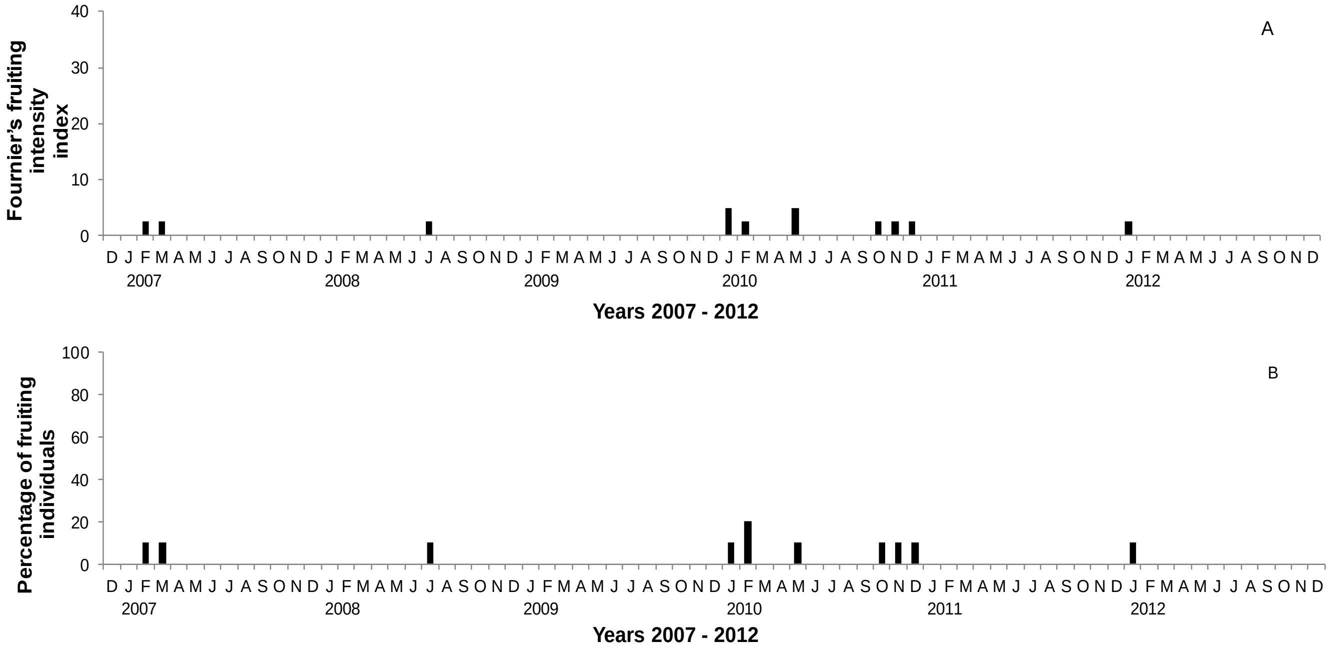

Figure 2. *A. perutilis* fruiting from 2007 to 2012 in terms of A) Fournier's fruiting intensity index, and B) Percentage of fruiting individuals. N=10.

Fuzzy logic modelling

Based on the triangular membership functions used for the fuzzy logic model, monthly precipitation was low up to 272.4 mm, intermediate between 0 and 544.8 mm and high when it exceeded 272.4 mm (Figure 3). As aforesaid, unlike conventional set theory, in fuzzy logic, one member of a given set can belong to that set to some degree and to other set in some other degree between 0 to 1. Concerning solar radiation, less than 263.6 W/m² was considered low, 263.6 to 497.8 W/m² intermediate and greater than 380 W/m² high. For maximum temperature, low values did not exceed 20.4°C, intermediate values fell between 16.9 and 23.9°C and high values surpassed 20.4 °C.

For output variables, membership functions were low when intensity index mean percentages were less than 5% (Figure 4). Intermediate values fluctuated between 0 and 10%. We observed a bifurcation of the high intensity index: the first group corresponded to percentages between 5 and 20% and the second to values greater than 10%, with differing grades of membership.

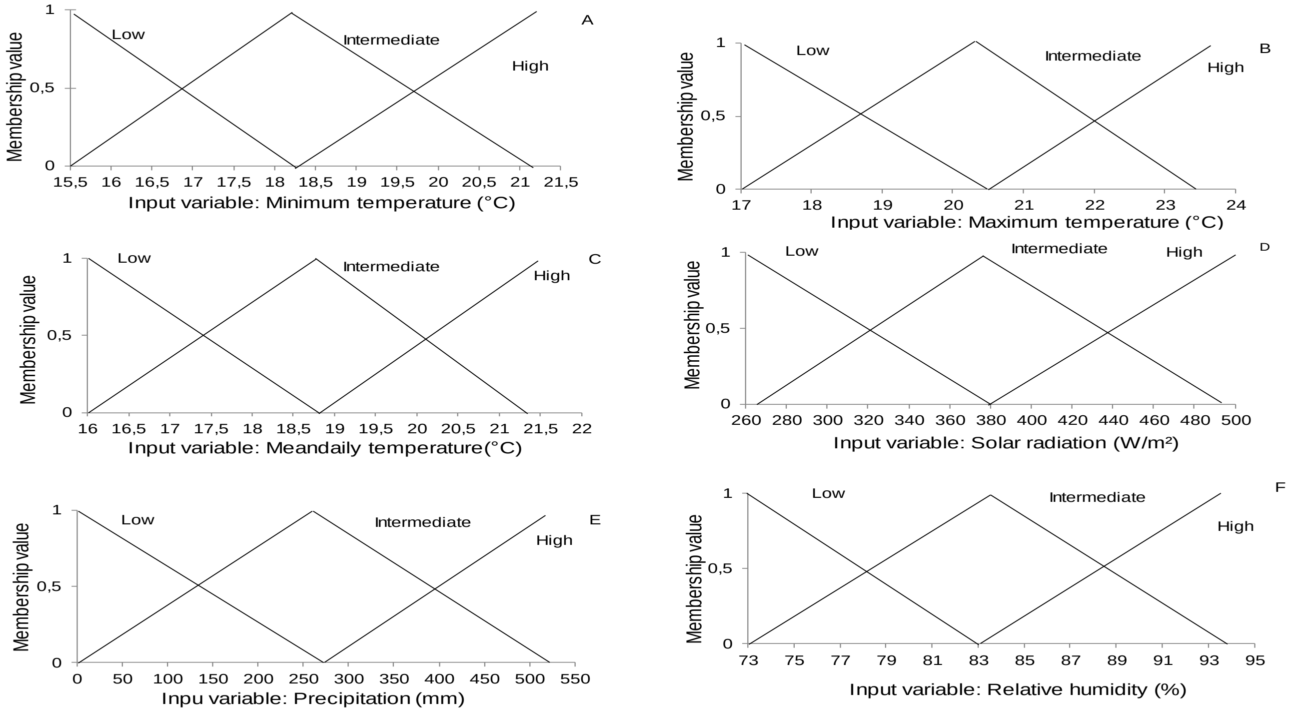

Figure 3. Membership functions of input climatic variables A) minimum temperature, B) maximum temperature, C) Mean daily temperature, D) Solar radiation, E) precipitation and F) relative humidity (low, intermediate and high).

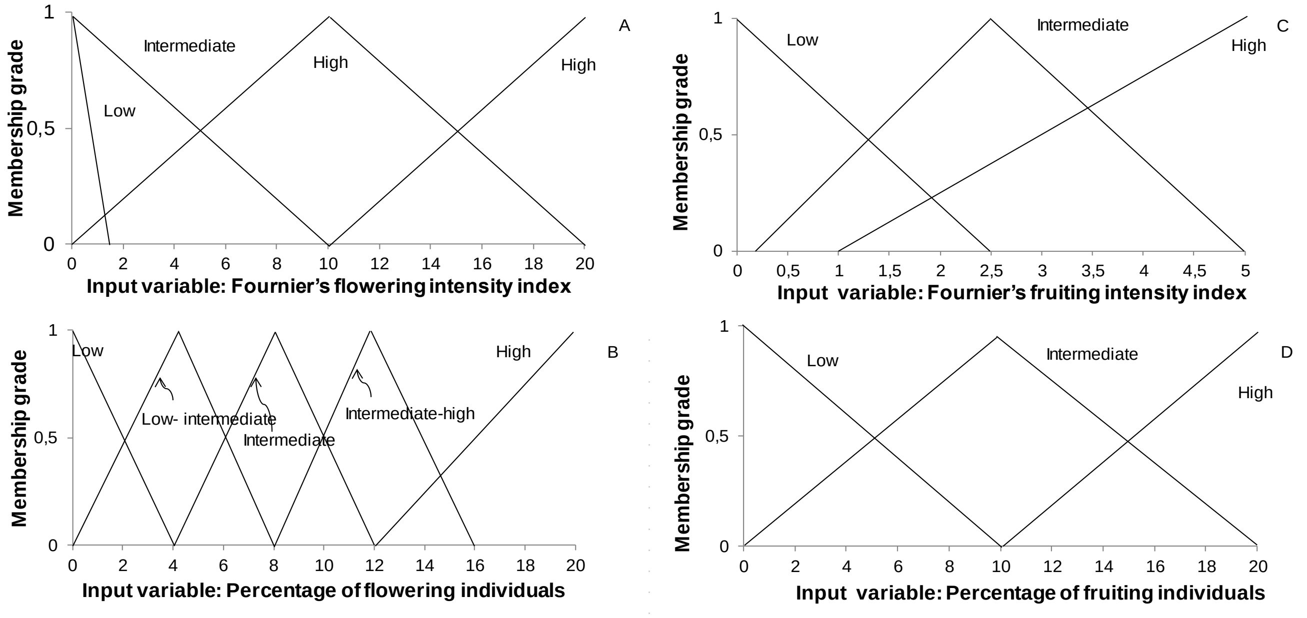

Figure 4. Membership Functions of output phenological variables: Fournier's flowering intensity index (Low, High-Intermediate and High), Percentage of flowering individuals (Low, Low-Intermediate, Intermediate, High-Intermediate and High), Fournier's fruiting intensity index (Low, High-Intermediate and High) and Percentage of flowering individuals (Low, Intermediate and High).

We obtained 73 fuzzy rules for each output variable. The **If-Then** propositions allow us to briefly shed light on how these rules work; for instance: **if**, minimum, maximum and average temperatures are high and solar radiation, precipitation and relative humidity values intermediate, **then** percentage of flowering individuals will be non-existent. Similarly, **if** the three temperature variables are high and solar radiation intermediate, rainfall and relative humidity low, **then** percentage of fruiting individuals will be low. According to this model, the majority of rules for the output variable fruiting intensity index are low, a situation consistent with the multiannual pattern observed.

Results of the fuzzy logic modeling showed that the flowering intensity index was strongly associated with the combination of maximum temperature, minimum temperature, solar radiation and precipitation. Yet, percentage of flowering individuals was only linked to precipitation. Regarding fruiting, a strong association was observed with precipitation while a weak relationship was found with mean temperature (Table 1). The model calibration and validation showed the greatest precision for fruiting intensity index (0.68) followed by flowering intensity index (1.35). Hence, despite the few phenological data obtained and its highly skewed distribution, the model was highly robust. In contrast, percentage of individuals in flower or fruit displayed higher mean squared errors (MSE 4.97, MSE=7.95, respectively).

In a similar fashion, according to the Spearman Rank correlation coefficient, flowering peaks were associated to high minimum and maximum temperature and a low relative humidity of one of two months prior (Table 2). Regarding fruiting, positive significant correlations were observed for minimum temperature of the same month and the maximum temperature two months prior (Table 3). Precipitation and relative humidity of the preceding month were negatively correlated with the fruiting intensity index and the percentage of fruiting individuals (Table 3).

Table 1. Summary of the relation among Climatic Variables and A. *perutilis* fruiting and flowering based on Fuzzy Logic. The symbol ↑means the climatic variable favors a phenological event, while the symbol ↓indicates the contrary.

Phenological event	Minimum temperature	Maximum temperature	Men Temperature	Solar radiation	Precipitation	Relative humidity
Fournier’s flowering intensity index	↑	↑		↑	↑	
Percentage of flowering individuals					↓	
Fournier’s fruiting intensity index					↑	
Percentage of fruiting individuals			↓			

Table 2. Spearman rank correlation coefficient matrix for *A. perutilis* flowering and climatic variables in the OQFFS. N=73. For correlation to the month prior to flowering, N=72, and for two months prior N=71. In bold P < 0.05.

Climatic variable		**0 month prior**	**1 month prior**	**2 month prior**
Fournier’s flowering intensity index				
vs. Minimum temperature	r_s	0.064	**0. 249**	0.171
	p	0.296	**0.017**	0.077
vs. Maximum temperature	r_s	0. 129	0.321	**0.240**
	p	0. 139	0.003	**0.022**

Climatic variable		**0 month prior**	**1 month prior**	**2 month prior**
vs. Mean temperature	r_s	0. 032	0.121	-0.073
	p	0. 395	0.156	0.274
vs. Solar radiation	r_s	0. 018	0.156	-0.040
	p	0. 441	0. 096	0.022
vs. Precipitation	r_s	0. 073	0.062	0.042
	p	0. 270	0.302	0.365
vs. Relative humidity	r_s	-0. 191	**-0.235**	**-0.197**
	p	0. 053	**0.024**	**0.050**
Percentage of flowering individuals				
vs. Minimum temperature	r_s	0.121	0.300	**0. 222**
	p	0.154	0.005	**0.032**
vs. Maximum temperature	r_s	0.181	0.376	**0.270**
	p	0.063	0.001	**0.011**
vs. Mean temperature	r_s	0.071	0.149	-0.152
	p	0.275	0.105	0.102
vs. Solar radiation	r_s	0.042	0.127	-0.091
	p	0.361	0.143	0.225
vs. Precipitation	r_s	0.047	0.012	0.074
	p	0.346	0.460	0.271
vs. Relative humidity	r_s	**-0.243**	**-0.272**	**-0.211**
	p	**0.019**	**0.010**	**0.038**

Table 3. Spearman rank correlation coefficient Matrix for *A. perutilis* fruiting and climatic variables in the OQFFS. N=73. For correlation to the month prior to fruiting, N=72, and for two months prior N=71. In bold P < 0.05.

Climatic variable		0 month prior	1 month prior	2 month prior
Fournier's fruiting intensity index				
vs. Minimum temperature	r_s	**0.199**	0.169	0.179
	p	**0.046**	0.077	0.068
vs. Maximum temperature	r_s	0.115	0.179	**0.252**
	p	0.165	0.066	**0.017**
vs. Mean temperature	r_s	0.017	0.092	0.294
	p	0.444	0.221	0.006
vs. Solar radiation	r_s	0.133	0.018	-0.081
	p	0.132	0.441	0.251
vs. Precipitation	r_s	-0.017	**-0.213**	-0.061
	p	0.444	**0.037**	0.308
vs. Relative humidity	r_s	-0.135	-0.195	-0.175
	p	0.128	0.050	0.072
Percentage of fruiting individuals				
vs. Minimum temperature	r_s	**0.197**	0.174	0.171
	p	**0.048**	0.072	0.077
vs. Maximum temperature	r_s	0.123	0.185	**0.247**
	p	0.150	0.060	**0.019**
vs. Mean temperature	r_s	0.011	0.092	0.287
	p	0.464	0.221	0.008
vs. Solar radiation	r_s	0.126	0.029	-0.086
	p	0.144	0.406	0.237
vs. Precipitation	r_s	-0.019	**-0.217**	-0.069
	p	0.437	**0.034**	0.285
vs. Relative humidity	r_s	-0.144	**-0.205**	-0.180
	p	0.113	**0.042**	0.067

Predictions for 2027 – 2032.

The future climate modeling done for the zone (2027-2032) under climate change scenarios A2 and B2 predicted an increase in monthly mean temperature and a decrease in monthly relative humidity and precipitation (Table 4). When introducing these variables into the fuzzy model, a year-to-year variation was predicted for flowering and fruiting intensity index in both scenarios, such that during the years 2027, 2030 and 2031 the intensity index both for fruiting and flowering was predicted to be intermediate (Table 5 and 6). For the remaining years, the index of intensity was predicted to be low. After defuzzying the model (converting the fuzzy output into a numerical value), higher flowering intensity index was obtained for Scenario A2, while fruiting intensity index and percentage of flowering individuals showed low values for Scenario B2.

Table 4. Changes in Precipitation, Mean temperature and Relative humidity for the Period 2027-2032 (A2 and B2 Scenarios) in the OQFFS based on Alarcón & Pabón [18].

Climatic variable	Current (2007-2012)	2027-2032	
		A2	B2
Mean annual precipitation (mm)	1 751.4	709.14	747.69
Mean annual temperature (°C)	17.7	17.09	17.12
Relative humidity (%)	87.0	86.61	86.85

Table 5. Flowering and Fruiting prediction for 2027-2032 (Scenario A2) in the OQFFS.

Phenological event	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**
Flowering						
Fournier's flowering intensity index	Intermediate	Low	Low	Intermediate	Low	Low
Percentage of flowering individuals	Intermediate	Low	Low	Intermediate	Intermediate	Low
Fruiting						
Fournier's fruiting intensity index	Low	Low	Low	Low	Intermediate	Low
Percentage of fruiting individuals	Low	Low	Low	Low	Intermediate	Low

Table 6. Flowering and Fruiting prediction for 2027-2032 (Scenario B2) in the OQFFS.

Phenological event	2027	2028	2029	2030	2031	2032
Flowering						
Fournier's flowering intensity index	Intermediate	Low	Low	Intermediate	Low	Low
Percentage of flowering individuals	Intermediate	Low	Low	Intermediate	Intermediate	Low
Fruiting						
Fournier's fruiting intensity index	Low	Low	Low	Intermediate	Low	Low
Percentage of fruiting individuals	Intermediate	Low	Low	Intermediate	Low	Low

DISCUSSION

Although fuzzy logic is not a "traditional" tool in the field of ecology and there are not similar studies with which to compare our results, recent investigations confirm its benefits, especially given its versatility, efficiency and relevance [44, 34, 14, 15, 45]. In this research, we developed a Mamdani-type fuzzy logic model to simulate flowering and fruiting patterns of *A. perutilis* under the influence of different climatic variables for the period 2007 – 2012 and to predict the species' reproductive phenology under future climatic conditions. Based on the MSE, the model performance was satisfactory, despite a low number of individuals monitored regarding other phenological studies [46, 47]. Even more, the model performed better when using the Fournier's index of both flowering and fruiting as output variables than when using percentage of individuals in a particular phenophase.

Results obtained by the model identified a strong relationship between a specific combination of climatic variables and flowering and fruiting of *A. perutilis*. In that way, flowering peaked when conditions included low humidity, high maximum temperature and low precipitation, while fruiting was highly associated with precipitation. Moreover, the fuzzy logic model was able to simulate reproductive phenology of *A. perutilis* for the years 2027 to 2032 in both climate change scenarios. Thus, regarding flowering, the model showed that some years will exhibit low flowering intensity and others intermediate flowering intensity coinciding with the supra-annual 2007-2012 pattern. Concerning fruiting, the model predicted that longer non-fruiting intervals will occur in both scenarios, as only one year will exhibit intermediate fruiting. Therefore, keeping in mind the uncertainties related to future predictions of climate change scenarios [48, 49] and that these models are preliminary and experimental, it seems that *A. perutilis* fruiting intensity will decrease, which make it imperative to take steps toward species management and conservation.

In addition, considering that the Fournier's method remains one of most useful tools for semi-quantitative description of the intensity of phenophases [26], and that integrative models that incorporate multiple environmental variables are scarce, fuzzy logic was found to be a capable method for analyzing long term phenological patterns, as it associated a particular combination of climatic conditions with a phenological event. In contrast to the Spearman rank correlation, which just detects one by one variable relationships, fuzzy logic can be a useful tool for explaining reproduction patterns of several multiannual tropical tree species, where a particular phenophase is triggered by a host of climatic variables, as occurring during an El Niño event [50, 51] .

FINAL CONSIDERATIONS

Despite of the aforementioned merits of fuzzy logic, it is important to recognize, that this study represents a first approach, which means our results should be taken with caution. In first place, although fuzzy logic models are more flexible to changes, rewriting the model is not an easy practice compared to existing mathematical methods. In addition, predictions for the 2027-2032 were based on only three of the six variables used in the 2007-2012, as local and regional climate models only consider mean temperature, humidity and precipitation. In that way, we advocate to include other variables such as maximum and minimum temperatures in climate models to improve the reliability of climate change projections not only for the Andean region but worldwide.

Finally, despite the model could handle few data and the nonlinear effects of input factors on the outputs, it is recommended that future model applications must be performed with more individuals, with data spanning more years, as in this research the small number of individuals, manifested as low robustness in the percentage of individuals fruiting and flowering after model calibration and validation. Moreover, notwithstanding that at the time when the monitoring was implemented ten was an appropriate number of individuals to study phenology at the species level [25, 26] , as well as recent phenological researches have continued to monitor less than 10 individuals [52, 7, 53], considering the suggestions made by Morellato et al. [24], long term monitoring strategies of plant conservation targets, particularly in the Colombian National Parks System, must increase to at least 15 the number of individuals, as it will certainly improve the model robustness and accuracy.

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AUTHORS' CONTRIBUTIONS

Doris Huertas Burgos and Ángela Parrado-Rosselli conceived the ideas, designed methodology; analysed the data and led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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