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Article

Extinction Risk of *Pseudotsuga Menziesii* Populations in the Central Region of Mexico: An AHP Analysis

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Abstract: Within the Analytic Hierarchy Process (AHP) framework, a hierarchical model was created considering anthropogenic, genetic and ecological criteria and sub-criteria that directly affect Douglas-fir (*Pseudotsuga menziesii* (Mirb.)) risk of extinction in central Mexico. The sub-criteria values were standardized, weighted, and ordered by importance in a pairwise comparison matrix; the model was mathematically integrated to quantify the degree of extinction risk for each of the 29 populations present in the study area. The results indicate diverse levels of risk for the populations, ranging from very low to very high. Estanzuela, Presa Jaramillo, Peñas Cargadas and Plan del Baile populations have very low risk, with values less than 0.25. On the other hand, Vicente Guerrero, Morán, Minatitlán, La Garita and Tonalapa populations have very high risk (>0.35) because they are heavily influenced by anthropogenic (close to roads and towns), ecological (presence of exotic species and little or no natural regeneration) and genetic (presence of mature to overmature trees and geographic isolation) factors. *In situ* conservation activities, prioritizing their implementation in populations at most risk is highly recommended; in addition, germplasm collection for use of assisted gene flow and migration approaches, including artificial reforestation, should be considered in these locations.

Keywords: Douglas-fir; risk analysis; conservation of populations; Analytic Hierarchy Process (AHP); multi-criteria evaluation; assisted gene flow

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1. Introduction

Pseudotsuga menziesii (Mirb.) Franco barely survived in Mexico after the last ice age; the gradual increase in temperature forced this species to migrate from south to north and towards higher altitude in the mountains [1], which resulted in a fragmented and discontinuous distribution. In Mexico, this conifer is mainly distributed in the northern region, although in the central part of the country the species exists in small isolated stands [2]. At the southernmost limit, two isolated populations are located in the state of Oaxaca [3,4].

Added to this, the improper use and exploitation of natural resources affects forest species to the extent that some of them are endangered or threatened [5,6]. This is the case of *P. menziesii* located in the central region of Mexico, where the species grows in 29 small, fragmented populations suffering high anthropogenic pressure due to land-use changes, overgrazing, forest fires, inappropriate cone collecting, pest attack and illegal tree cutting and timber [7,8]. Also, Mexican populations of *P. menziesii* are exposed to high environmental stress due to their location at the southern end of its natural distribution [7,9]. The above-mentioned situation has caused a reduction in the size and density of populations, as well as low natural recruitment [8]; these circumstances are causing a reduction in genetic diversity and reproductive capacity associated with increased inbreeding [2,10].

P. menziesii is a valuable species for timber and wood production, but in Mexico this conifer is listed as protected by the Mexican government [11], so it is mainly used for Christmas-tree plantations. Therefore, the protection and proper management of each remaining population of the species is important for both natural recovery and establishment of commercial Christmas-tree plantations. It is imperative to implement *in situ* and *ex situ* conservation activities to ensure the preservation of the *P. menziesii* stands in its natural habitat, thereby allowing continuous evolution of the species and conservation of the remaining gene pool.

When designing conservation strategies for the species, we must understand and prioritize the current extinction risk experienced by the remaining populations. Risk of extinction is related to population viability and can be defined as the probability of the continued existence of populations over specified time periods [12], which can be estimated by qualitative and quantitative means. It refers to the likelihood of global or local extinction of target taxa. In this sense these authors suggest that no single measure is sufficient to assess population viability (risk) but different pools of data and type of analysis are necessary. Therefore, several methods to assess population risk might exist based on factors that potentially influence the viability of a species and upon its intrinsic characteristics.

The purpose of this study was to estimate, using a multi-criteria analysis technique, the Analytic Hierarchy Process (AHP), the degree of extinction risk faced by each natural *P. menziesii* population located in Central Mexico (states of Hidalgo, Tlaxcala and Puebla) influenced by anthropogenic, genetic, and environmental factors. Based on AHP, priorities to define a conservation strategy for the species in the region were determined.

2. Materials and Methods

2.1. Analytic Hierarchy Process (AHP)

Ventura-Ríos *et al.* [2] determined the spatial distribution of *P. menziesii* in central Mexico by characterizing 29 small, isolated populations. The present study examines the extinction risk of those populations located in the states of Hidalgo, Tlaxcala and Puebla (Figure 1). The extinction risk analysis was performed using the methodology known as Analytic Hierarchy Process (AHP), a structured approach to complex decision-making defined by Saaty [13] for decision-making in business environments based on the simultaneous analysis of multiple criteria. AHP is one of the most used tools in what is known as multi-criteria decision-making [14]. The tool has been successfully used to define strategies to mitigate the risks associated with decision-making in forestry [15,16] and environmental issues [17]. Theoretical details of the methodology can be found in Saaty [13] and Malczewsky [18]. Saaty and Niemira [14] presented a thorough summary of the technique. We describe the AHP applied to define extinction risk of *P. menziesii* populations located in central Mexico.

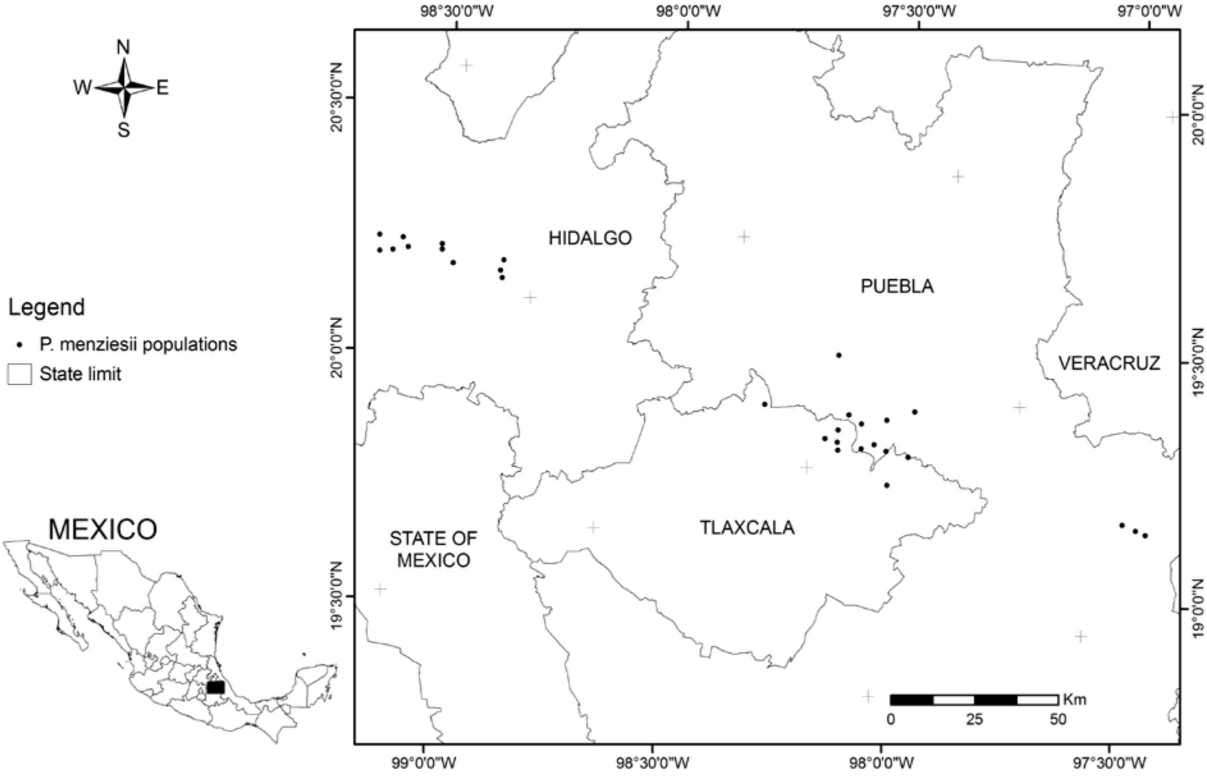

Figure 1. Geographical location of *Pseudotsuga menziesii* (Mirb.) Franco populations in central Mexico.

A model with three hierarchies was developed: definition of goal or objective, identification and definition of criteria for evaluating alternatives, and identification of decision alternatives (Figure 2). Three criteria or decision variables (anthropogenic, genetic and ecological) were considered to estimate the extinction risk of *P. menziesii* populations, each of them composed by several sub-criteria, 14 in total (Figure 2). The three criteria employed are not exhaustive, but these were considered as the most important issues to conduct an assessment of the current risk for these populations.

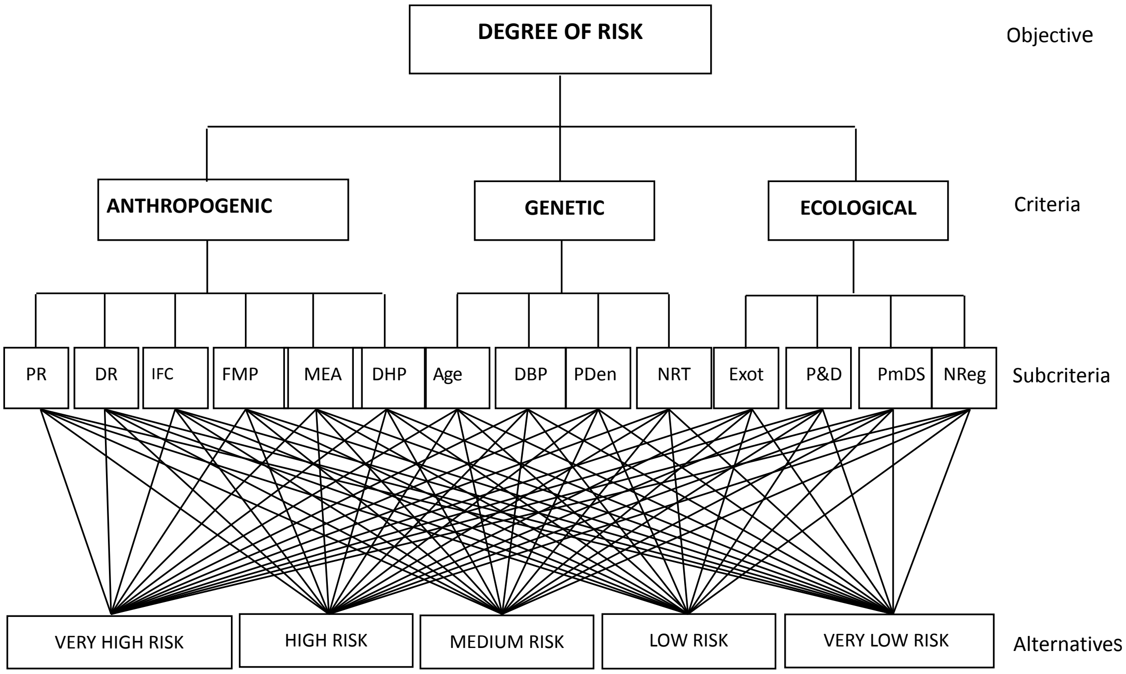

Figure 2. Decision problem hierarchization and sub-criteria considered. PR: Property regime; DR: Distance to roads; IFC: Interest in forest conservation; FMP: Forest management program; MEA: Main economic activity; DHP: Distance to human population; Age: Estimated age of Douglas-fir trees; DBP: Distance between populations of *Pseudotsuga*; PDen: Population density; NRT: Number of trees at reproductive age; Exot: Introduction of exotic species; P & D: Presence of pests and diseases; PmDS: *Pseudotsuga menziesii* is the dominant species; NReg: Natural regeneration.

2.2. Description and Application of Criteria and Sub-Criteria

In order to make a proper comparison using mathematical procedures, sub-criteria were standardized to a common scale or value range from 1 (low contribution) to 9 (high contribution) following the logic for the scale defined by Saaty [13], as shown in Table 1. The value assigned to each sub-criterion, considering the 1-to-9 scale (Table 1), was defined based on scientific literature and considering the results of the survey developed for the owners of *P. menziesii* populations under study (this is indicated following the description of the sub-criteria, according to the case). We used this combination of data sources in order to broaden the perspective of the analysis by including relevant social criteria in the Mexican context. Also, local and site-specific sampling provides more realistic information for the analysis.

Table 1. Standardized values for the sub-criteria used to determine the risk of 29 populations of *Pseudotsuga menziesii* in central Mexico.

DR	***Value***	**MEA**	***Value***	**DHP**	***Value***	**DBP**	***Value***	**NRT**	***Value***
>5	1	Conservation	1	>7.0	1	<2	1	>800	1
3.1–5.0	3	Ecotourism	3	4.1–7.0	3	2–5	3	401–800	3
1.6–3.0	5	Silviculture	5	2.1–4	5	5.1–10	5	201–400	5
0.5–1.5	7	Agriculture—livestock	9	0.5–2.0	7	10.1–30	7	51–200	7
<0.5	9			<0.5	9	>30	9	<50	9
PR		FMP		PDen		Age		NReg	
Communal	1	Yes	1	<10	7	Young	1	Good	1
Ejidal	3	Use rules	3	11–20	5	Mature	4	Low	5
Private	5	No	7	21–30	3	Overmature	4	None	9
				>30	1				
IFC		Exotic		P & D		PmDS			
Yes	1	Yes	7	Yes	7	Yes	1		
No	7	No	1	No	1	Moderate	4		
						No	7		

DR: Distance to roads (km); MEA: Main economic activity; DHP: Distance to human population (km); DBP: Distance between populations of *Pseudotsuga* (km); NRT: Number of trees at reproductive age; PR: Property regimen; FMP: Forest management program and/or forest-use rules; PDen: Population density (No. trees ha^{-1}); Age: Estimated age of Douglas-fir trees; NReg: Natural regeneration; IFC: Interest in forest conservation; Exotic: Introduction of exotic species; P & D: Presence of pest and diseases; PmDS: *Pseudotsuga menziesii* is the dominant species.

2.2.1. Anthropogenic Criteria

Considering that human activities positively or negatively impact the conservation of *P. menziesii populations,* six sub-criteria were included in the criteria (Table 1):

Distance to roads: Distance (km) between the stands (*P. menziesii* populations) and roads; the shorter the distance, the greater the risk of extinction [19].

Property regimen: The type of ownership (communal, private or “ejido”) influences the conservation of populations. Based on conducted surveys, it is assumed that forest care is the best when the property regimen is communal, followed by the ejido. Forest in private ownership is the riskiest in the region. An ejido is a land concession given by the Mexican Government to a group of people after the Mexican Revolution (1918); is a collectively owned piece of land in which community individuals possess and farm a specific plot, but forestland is managed on a communal basis. Currently more than 70% of the forestland in Mexico is under this ownership regime.

Interest in forest conservation: If interest is expressed, a value of 1 was assigned; when such interest is lacking a value of 7 was designated. We used such extreme values because the lack of owners’ interest in forest conservation makes a great difference in terms of success of a conservation program. This criterion was assessed by the survey taken by owners.

Forest management program (FMP) and/or forest-use rules: Populations that have a FMP approved by the Ministry of Environment and Natural Resources (Secretaría del Medio Ambiente y Recursos

Naturales, SEMARNAT) or those under internal rules of management are most likely to be preserved. Data obtained by survey filled out by owners.

Main economic activity: Activities that cause the greatest impact to the forest are agriculture and livestock [20], followed by silviculture, ecotourism and conservation activities. Information based on field observations and survey taken by owners.

Distance to human population: Distance (km) between localities where *Pseudotsuga* grows and human population centers; the greater the distance, the less the risk of possible looting for wood and genetic material [19].

2.2.2. Genetic Criteria

The probability of continued existence is related to the gene pool of populations, because genetic variation helps species to adapt to environmental changes [21,22]. Reduced genetic variability is associated with increased vulnerability in the event of a sudden change in the environment. Four sub-criteria were considered (Table 1).

Estimated age of Douglas-fir trees: The younger the tree, the less the risk. An overmature population is at increased risk because of reduced vigor and decreased reproductive capacity [8]. Trees showing incipient reproductive events and vigorous growth were considered as young, and those that presented evidence of previous reproductive events were considered as mature. These data were obtained by sampling each population [2].

Distance between Pseudotsuga populations (genetic isolation): The longer the distance between populations, the greater the extinction risk. Isolated populations have limited gene flow [23] and genetic isolation may contribute to a reduced genetic variability.

Population density: The lower the density (Number of trees ha^{-1}), the greater the extinction risk. Decreased genetic exchange could generate low genetic variation and limited reproductive capacity, because the presence of few trees of the species leads to diminished pollen density. This criterion was assessed by field sampling.

Number of trees at reproductive age: The lower the number of individuals, the greater the extinction risk. A small population size increases the direct risk of extinction in the presence of a catastrophic event [24]. In addition, a small population has little gene flow and is subjected to random genetic drift, thereby increasing inbreeding, reducing genetic diversity and diminishing good development in the process of species evolution.

2.2.3. Ecological Criteria

Four sub-criteria linked to *P. menziesii* environment and organisms co-inhabiting with the species that could affect its performance and survival were included (Table 1).

Introduction of exotic species: It was considered that populations presenting evidence of *non-native* tree species are most at risk. Exotic species can displace native species by competition for resources [22]. Data evaluated through field surveys.

Presence of pests and diseases: Due to the high impact of cone and seed-feeding insects on Douglas-fir populations in Mexico, evidence that suggests the occurrence of some kind of pest or disease was graded with a higher level of extinction risk; absence of pests and diseases involves lower risk. Data are from field observation.

Pseudotsuga menziesii is the dominant species: The greater the dominance, the less the risk. Dominated species are most likely to disappear due to the strong competition by dominant species. *Pseudotsuga* dominance was determined by field sampling [2].

Natural regeneration: The greater the amount of natural regeneration, the less the risk. Thirty or more seedlings (50 cm in height) per 40 m^2 (average from 3 samples sites) were considered adequate recruitment, whereas less than thirty were considered as scarce. The criterion was assessed by sampling each population [2].

2.3. Construction of Pairwise Comparison Matrices (PCM)

The criteria (Table 2) and sub-criteria (Tables 3–5) were placed in a double entry matrix (called pairwise comparison matrix, PCM) employing the same order for both columns and rows. Subsequently, each pair of criteria and sub-criteria was compared using the 1-to-9 scale defined by Saaty [13]. The cells in the matrices were assessed by comparing the relative importance of the criteria (or sub-criteria) in each row against the criteria (or sub-criteria) listed in each column of the corresponding matrix; due to the principle of reciprocity defined as part of the procedure [13,18], it is only necessary to compare the upper half (above the diagonal) of the PCM. For example, when comparing the importance or contribution of sub-criteria distance to human population (DHP) and distance to roads (DR) for the extinction risk of *Pseudotsuga* populations, it was considered that DHP sub-criteria is moderately more important than DR sub-criteria, so a value of 5 was assigned (Table 3, row 6 and column 2 intersection); in the reciprocal case, the value is 1/5 (Table 3, row 2 and column 6 intersection). All the comparisons listed in Tables 2–5 were similarly performed.

Table 2. Pairwise comparison matrix and relative weights of the criteria used to estimate the degree of risk of the populations of *Pseudotsuga menziesii* in central Mexico [†].

Criteria	Anthropogenic	Genetic	Ecological	*Weight*
Anthropogenic	1	3	3	0.60
Genetic	1/3	1	1	0.20
Ecological	1/3	1	1	0.20

[†] Consistency Ratio (CR) = 0.001; a quantitative measure of consistency associated with the defined pairwise comparisons of criteria.

Calculating the Criteria and Sub-Criteria Weight and Risk Estimation

Estimation of weights for each criterion and sub-criterion considered in the analysis (Tables 2–5) was performed using the algorithm implemented in the WEIGHT module of IDRISI; a software for the analysis and display of spatial data [25]. The weights result from computing a vector of priorities from each matrix; mathematically, the principal eigenvector is computed and normalized [13,14]. The algorithm computes a quantitative measure of consistency, a consistency ratio (CR), associated with the defined pairwise comparisons of criteria and sub-criteria. The CR evaluates the probability that the values in the

PCM are not randomly assigned; its value must be less than 0.10, indicating that pairwise comparisons were consistent [13]. In this case, all CR values were lower than 0.10 (Tables 2–5).

Table 3. Pairwise comparison matrix and relative weights of anthropogenic sub-criteria used to estimate the degree of risk of the populations of *Pseudotsuga menziesii* in central Mexico †.

Anthropogenic Sub-Criteria	**PR ‡**	**DR**	**IFC**	**FMP**	**MEA**	**DHP**	***Weight***
PR	1	1/3	1/3	1/5	1/9	1/9	0.0301
DR	3	1	1	1/3	1/5	1/5	0.0689
IFC	3	1	1	1/3	1/5	1/5	0.0689
FMP	5	3	3	1	1/3	1/3	0.1532
MEA	9	5	5	3	1	1	0.3394
DHP	9	5	5	3	1	1	0.3394

† Consistency Ratio (CR) = 0.017; ‡ PR: Property regime; DR: Distance to roads; IFC: Interest in forest conservation; FMP: Forest management program; MEA: Main economic activity; DHP: Distance to human population.

Table 4. Pairwise comparison matrix and relative weights of genetic sub-criteria used to estimate the degree of risk of the populations of *Pseudotsuga menziesii* in central México †.

Genetic Sub-Criteria	**Age ‡**	**DBP**	**PDen**	**NRT**	***Weight***
Age	1	1/3	1/5	1/7	0.0595
DBP	3	1	1/3	1/5	0.1279
PDen	5	3	1	1/3	0.3639
NRT	7	5	3	1	0.4487

† Consistency Ratio (CR) = 0.031; ‡ Age: Estimated age of Douglas-fir trees; DBP: Distance between populations of *Pseudotsuga*; PDen: Population density; NRT: Number of trees at reproductive age.

Table 5. Pairwise comparison matrix and relative weights of ecological sub-criteria to estimate the level of risk of the *Pseudotsuga menziesii* populations' in central Mexico †.

Ecologic Sub-Criteria	**Exot ‡**	**P&D**	**PmDS**	**NReg**	***Weight***
Exot	1	1/3	1/7	1/7	0.0541
P & D	3	1	1/3	1/3	0.1431
PmDS	7	3	1	1	0.4014
NReg	7	3	1	1	0.4014

† Consistency Ratio (CR) = 0.003; ‡ Exot: Introduction of exotic species; P & D: Presence of pests and diseases; PmDS: *Pseudotsuga menziesii* is the dominant species; NReg: Natural regeneration.

To facilitate subsequent arithmetic operations and the interpretation of results by having final values between 0 and 1, standardized values for each sub-criteria (Table 1) were transformed (re-scaled) to values from 0 to 1 (0 = No risk, 1 = Maximum risk). The value of extinction risk for each population was calculated by adding the products of the transformed standardized values of the sub-criteria and their respective weighting values (linear weighted sum). The estimated risk values were ordered from lowest to highest and classified into five categories or degrees of risk: very low (values from 0 to 0.24), low (values of 0.25 to 0.27), medium (values from 0.28 to 0.30), high (values from 0.31 to 0.34) and very high (values greater than 0.35). The risk categories were defined by the authors based on the range of risk values calculated for populations (0.15 to 0.45, Table 6) and the need to clearly prioritize the activities for the conservation of the species. Notice that only one population (Estanzuela) had a risk value below 0.22 (Table 6), in other words, most of the risk values are between 0.22 and 0.45.

Table 6. Degree of risk of extinction for the *Pseudotsuga menziesii* populations in central Mexico.

Population	Value	Risk Level [†]	Population	Value	Risk Level
Estanzuela	0.15	VLow	Barranca Canoita	0.29	Med
Peñas Cargadas	0.22	VLow	Cuyamaloya	0.30	Med
Presa Jaramillo	0.23	VLow	Zapata	0.30	Med
Plan del Baile	0.24	VLow	La Caldera	0.31	High
Cañada El Atajo	0.26	Low	El Llanete	0.32	High
Cruz de Ocote	0.26	Low	Apizaquito	0.33	High
San José Capulines	0.26	Low	La Rosa	0.33	High
Capula	0.27	Low	Las Antenas	0.33	High
Cuatexmola	0.27	Low	Tlalmotolo	0.34	High
El Salto	0.27	Low	Tonalapa	0.36	Vhigh
Villareal	0.27	Low	La Garita	0.38	Vhigh
Axopilco	0.28	Med	Minatitlán	0.42	Vhigh
Buenavista	0.28	Med	Morán	0.44	Vhigh
San Juan	0.28	Med	Vicente Guerrero	0.45	Vhigh
Tlaxco	0.28	Med			

[†] VLow: very low risk; Low: low risk; Med: Medium risk; High: high risk; Vhigh: very high risk.

3. Results

Four of the twenty-nine evaluated populations (13.8%) had very low risk of extinction showing values less than 0.25 (Table 6). These populations, Estanzuela, Peñas Cargadas, Presa Jaramillo and Plan del Baile, are influenced to a lesser degree by anthropogenic factors, because the average distance to human population centers is 3.0 km, the average distance to roads is 3.0 km and the main economic activity for the first three populations is tourism and for the last one is forestry. Moreover, there is interest in preserving populations because the owners of the stands established rules for forest use. *Pseudotsuga menziesii* is the dominant species in these populations, with healthy trees (free of pests and diseases), ages range from young to mature, and presence of natural regeneration from poor to good.

The average distance to the nearest *P. menziesii* population is 4.0 km, the average number of trees at reproductive age is over 500, and the average population density is 23 trees ha^{-1}.

Seven *Pseudotsuga* populations had low risk with values varying from 0.26 to 0.27, including Cañada El Atajo, Cruz de Ocote, San José Capulines, Capula, Cuatexmola, El Salto, and Villareal (Table 6). These populations are influenced by anthropogenic factors because the average distance to human population centers is 2.4 km, the average distance to roads is 2.0 km and the main economic activities are agriculture and silviculture. However, the owners have interest in conserving the populations, since 50% of them have a Forest Management Program and the rest are managed under internal rules for forest use. The *P. menziesii* trees are young, but some populations are infested by pests and diseases. In these locations, Douglas-fir is the dominant species, but its natural regeneration is scarce, the average distance to the nearest *P. menziesii* population is 6.4 km and the average number of trees at reproductive age is 383, while the population density is 18 trees ha^{-1}.

Seven of the *Pseudotsuga* populations were at medium risk with values from 0.28 to 0.30, including Axopilco, Buenavista, San Juan, Tlaxco, Barranca Canoita, Cuyamaloya and Zapata (Table 6). These populations are negatively influenced by anthropogenic and ecological factors. They are at an average distance of 4.2 km away from human population centers and 3.3 km away from roads, but the main economic activity is agriculture. There is interest by owners to conserve the populations, since 50% of these have a Forest Management Program and the others have at least usage rules of the woodlands. Exotic species, pests and diseases are absent; *P. menziesii* trees are mature and dominant, but its natural regeneration is scarce to nonexistent. The average distance to the nearest *P. menziesii* population is 5.4 km, the average number of trees at reproductive age is 263 and the population density is 14 trees ha^{-1}, on average.

Six of the *Pseudotsuga* populations were at high risk, with values between 0.31 and 0.34, including La Caldera, El Llanete, Apizaquito, La Rosa, Las Antenas and Tlalmotolo (Table 6). These populations are strongly and negatively influenced by anthropogenic and genetic factors. They are at an average distance of 3.0 km away from human population centers and 1.8 km away from roads; also the main economic activity is agriculture. The populations are on private land; although some of these have a Forest Management Program and others have rules of use, two of the populations do not have any regulation. Three of these populations showed evidence of pests and diseases. Although *P. menziesii* trees are young and mature, they are not dominant and its natural regeneration is scarce. The average distance to the nearest *P. menziesii* population is 12.8 km, the average number of trees at reproductive age is 299 and the average population density is 11.8 trees ha^{-1}.

The five remaining populations had a very high risk, showing values above 0.35, including Tonalapa, La Garita, Minatitlán, Morán and Vicente Guerrero (Table 6). These populations are strongly and negatively influenced by anthropogenic and genetic factors, with an average distance of 1.2 km away from human population centers and 0.88 km away from roads; in addition, the main economic activity is agriculture. Four of these populations are privately owned and the other is part of an ejido, but none of them has a Forest Management Program. Although these stands varied from young to overmature and they are free from pests and diseases, natural regeneration is lacking and *P. menziesii* is not the dominant species. In this group are the smallest populations like Morán, La Garita and Vicente Guerrero with less than 20 reproductive trees; Minatitlán has 45 individuals, and Tonalapa shows 166 individuals of reproductive age. The average population density is 4.6 trees per ha, and the distance to nearest *P. menziesii* population is greater than 5 km. Furthermore, in these localities exotic pine species have been introduced through reforestation. A special case is the population of Morán, which is at very high risk. This relict of only four reproductive trees was originally described as *Pseudotsuga macrolepis* by Flous [26]. In addition, the owner is considering cutting down the trees because they are growing too close to his home and he is not interested in preserving them.

4. Discussion

The AHP, a mathematical process for measurement and decision-making, was used to evaluate the risk of extinction of fragmented *P. menziesii* populations in central Mexico. It allowed us to propose a hierarchy model that incorporates information from anthropogenic, genetic, and ecological factors or criteria, and offer a reference for future studies on the extinction risk of forest populations. The model was built considering elements that according to scientific literature and the authors experience on forest conservation practices are important to assess the risk of extinction of the species of interest in central Mexico. Neither the model, nor the criteria included in it are exhaustive or can be applied to other situations, but they might be used as a starting point to generate similar models for other tree species present in other latitudes.

AHP facilitated the task of calculating different weight values (importance) for each of the criteria identified as relevant for the risk assessment carried out, a critical issue in the modeling process. Both tasks, hierarchy model development and criteria weighting, are not trivial and must be carefully realized, AHP has widely demonstrated its value to perform such tasks [27,28].

Despite being a mature decision analysis methodology, the AHP is only one of many possible combinations of methods to standardize, weight, and rank available decision alternatives [18]. Other approaches to evaluate extinction risk exist, such as the so called population viability analysis [29]; however, it is also fair to mention that owing to its simplicity, ease of use, and theoretical foundation, the AHP has found wide acceptance among decision-makers [28]. It helps structure the decision problem in a manner that is simple to follow and analyze. Further, it has proved to be a methodology capable of producing results that agree with the decision-maker's expectations; that is the case of the study here reported.

Extinction of native forest tree species is caused by various processes, including reduction of and fragmentation of suitable environment, spread of diseases, genetic erosion and inbreeding [6]. The extinction of species also modifies and alters ecological processes involving it, affecting other species and causing changes in communities and ecosystems [20]. In the case of the *P. menziesii* populations in central Mexico, there is evidence of the effects of fragmentation and isolation by distance (9.4 km average distance between populations) as well as small size, from 4 to 1450 adult trees and 307 trees on average.

It is estimated that coniferous species require a population size of at least 180 reproductive trees to reduce the negative effects caused by low pollen levels and inbreeding, and to maintain seed production at sufficient levels [30]. In several of the stands included in the current study low natural regeneration of *P. menziesii* was observed [8]. In addition, seeds showed low germination and primary dormancy [7,31]. Moreover, a reduced level of genetic diversity with a high proportion of self-fertilization was found [10,32].

Habitat fragmentation in most of these populations is due to anthropogenic factors, but there is evidence that other factors such as environment and genetics play important roles in increasing the risks of extinction. The analysis conducted shows the relative effect of each of these factors over the current risks for each population, which is an important step to outline strategies for species conservation in the region. Risk factors for *Pseudotsuga menziesii* in the study area have their primary origin in the enormous social pressure that persists over populations as a result of historical changes in land use to fulfill human needs in the region, thereby increasing the fragmentation process of habitat.

One way to increase the genetic variability to counteract the effects of inbreeding over reproductive capacity [33,34] is through the promotion of gene flow between neighboring populations growing in similar environments (assisted gene flow as defined by Aitken and Whitlock [35]), which in turn could reduce adaptation problems (outbreeding depression). Populations from similar environments can also exchange genes through assisted migration by creating plantations that use more likely adaptable trees [32]; an action like this one is certainly possible to be carried out in central Mexico, which would increase genetic diversity by transferring new alleles or increasing the frequency of rare alleles in the recipient populations [23,33], and would provide long-term genetic stability to each population and a greater ability for adaptation to climate change or other risk factors. Performing movement of genetic material between related populations would counteract the effects of geographic isolation and fragmentation.

Conservation of remnant populations of *Pseudotsuga menziesii* in the central region of Mexico should be carried out in the natural environment where the species develops (*in situ*), because this would preserve the natural evolution processes of the species and its interactions with other organisms and ecological processes [22]. Such a conservation strategy is feasible in central Mexico due to the growing interest in managing the populations of the species as a genetic reserve—due to its current legal protection status. In this sense, the Mexican National Forestry Commission (CONAFOR), a federal agency, is currently promoting local and regional programs in order to enhance forest conservation to preserve the country's genetic resources.

The five populations with very high extinction risk and the six populations at high risk should have priority for conservation, due to the real possibility of losing their gene pool in case of extreme events. The populations at medium and low risk would also require protective actions such as grazing prevention, pest control and other actions to reduce current risks. *Ex situ* conservation should be considered as an alternative or complementary resource for populations at high and very high risk.

Other tree species present in central Mexico that are potentially relevant in this context and require studies of extinction risks include: *Pinus chiapensis*, *Fagus sylvatica*, and *Taxus globosa*, all of which have spatial distribution patterns and life history similar to that shown by *Pseudotsuga menziesii*.

5. Conclusions

The AHP-based analysis made it possible to show that 11 of the 29 studied populations were at high risk of extinction, seven were at medium risk and the remaining were at low risk; this suggest different strategies for conservation and protection of *Pseudotsuga menziesii* in the region. Tonalapa, La Garita and Minatitlán populations from the state of Puebla, as well as Morán and Vicente Guerrero from the state of Hidalgo, are at a very high risk of extinction because they are heavily impacted by anthropogenic and genetic factors. These populations are relatively small (less than 200 trees), they are very close to population centers (less than 1.5 km away) and to access roads (less than 1.0 km away) and these populations are located in areas where agriculture is the main economic activity. By contrast, the populations of Estanzuela, Presa Jaramillo, Peñas Cargadas and Plan del Baile are better preserved and they have a very low risk of extinction due to the lower human impacts because populations are at greater distance from human population centers and roads (more than 3.0 km away), in areas where ecotourism is the main economic activity, and some of them are within an ecological reserve.

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Author Contributions

Javier López-Upton and J. René Valdez-Lazalde conceived and designed the study and analyzed data; Aracely Ventura-Ríos generated the data; and all authors contributed in data analysis and discussion. The manuscript was written by J. René Valdez-Lazalde supported by Javier López-Upton and J. Jesús Vargas-Hernández.

Conflicts of Interest

The authors declare no conflict of interest.

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