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A multi-criterion index for the evaluation of local tropical forest conditions in Mexico

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ABSTRACT

Despite the ecological and economical importance of tropical forests they are currently affected by human activities, mainly through deforestation and selective extraction. With the aim of making an opportune diagnosis of the condition of forests, we developed an ecological index based on qualitative and semi-quantitative data, allowing a quick diagnosis in order to manage and conserve tropical forests. We evaluated 44 plots of tree vegetation, measuring canopy height, number of strata, tree cover, dominant trees, number of tree species, as well as the management of and damage to the forest. The data of each parameter was classified in categories of 3, 4 or 5, which were normalized between 0 and 1 for the worst and best characteristics, respectively. For the purpose of analysis, the average, a set of IF–THEN rules, and fuzzy logic were applied and as a result we obtained a model that measures the ecological condition of the tropical forests. The model has the advantages of having an ecological basis, allows data to be gathered quickly and is clear and easy to manage and interpret. When running the model, the value of each intermediate variable is displayed, thus allowing the detection of where necessary action is required to improve the ecological condition of the forest. We expect this index to contribute in evaluating the effectiveness of forest management and possibly offer advice for the short-term management and conservation of the remnants of tropical forests.

1. Introduction

The tropical humid rain forests are ecosystems located around the Equator between the Tropics of Cancer and Capricorn, in areas with a minimum annual rainfall of 1500 mm and mean monthly temperatures above 18 °C during all months of the year (Woodward, 1997). The dominant plants are tall, broad-leaved evergreen trees. The upper portion of the canopy often supports a rich flora of epiphytes, including orchids, bromeliads, mosses, and lichens, who live attached to the branches of trees. The undergrowth or understory in a rain forest is often restricted of sunlight at ground level, and generally consists of shade-tolerant shrubs, herbs, ferns, small trees, and large woody vines which climb into the trees to capture sunlight (Woodward, 1997; Ritter, 2006). Shrub or tree fallows are common in tropical areas, as a result of shifting cultivation systems, in which agricultural fields are abandoned temporarily and during the fallow different stages of natural regrowth develop over time (Brown and Lugo, 1990).

Tropical forests cover approximately 7% of the earth's surface (12 million km^2); however, these forests contain about 75% of the total species known on our planet (Bierregaard et al., 1992; Turner and Corlett, 1996). In Mexico, 24% of the forest area corresponds to tropical forest (Cairns et al., 1995; Masera et al., 1997). These forests have undergone a rapid process of degradation and deforestation in the last 60 years, with most of them being converted to agricultural areas or pasturelands. These changes are much faster and more extensive than in any other period in history (Hansen et al., 1992; Houghton, 1994; Tilman and Lehman, 2001). Land use change produces – among other processes – disturbance, which is referred to as a relatively discrete series of events in time – such as slash and burn, forestry interventions, and low scale fires – that modify ecosystems, communities or populations. These events, in turn, generate changes in the physical environment and the availability of resources (Horn, 1974; Pickett and White, 1985). As plant species possess a differentiated ability to recover from disturbances, known as resilience (Huston, 1994), plant communities will experience changes in structure and composition, generally expressed by a selective decrease in species numbers and densities (Vázquez-Yanes and Orozco-Segovia, 1995; González-Espinosa et al., 1997).

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Table 1
Input variables used in the model to evaluate local tropical forest condition.

Variable	Values of 5 levels				
	Best		Intermediate		Worst
	1	0.75	0.5	0.25	0
Vegetation height	>20 m	16–20 m	11–15 m	6–10 m	<=5 m

Variable	Values of 4 levels			
	1	0.66	0.33	0
Vegetation type	Natural forest	High secondary forest (>5 m)	Low secondary forest (<=5 m)	Plantation
Dominance of tree and shrub strata	Dominant	Sub-dominant	Present	Absent
Abundance of DBH classes	Abundant	Regular	Few	Absent
Canopy cover	>=76% (dense)	51–75%	25–50%	<25% (open)
Seedling abundance	High	Sufficient	Low	Absent
Recruitment (DBH ≤5 cm)	High	Sufficient	Low	Absent

Variable	Values of 3 levels		
	1	0.5	0
Tree species richness	>15	6–15	<=5
Seedling species richness	>3	2–3	0–1
Burning	Small, rare or fires with low intensity	Moderate size, frequency or intensity of fires	Large, frequent or fires with high intensity
Grazing and/or trampling	Rare, little or spatially restricted	Moderate	Frequent, much or spatially unrestricted
Firewood extraction	Little or none	Moderate	Much
Timber extraction	Little or none	Moderate	Much
Dead standing trees	Few or none	Some	Many

Variables with five levels are coded as 1, 0.75, 0.5, 0.25 and 0, variables with four levels as 1, 0.66, 0.33 and 0, and variables with three levels as 1, 0.5 and 0, in decreasing order of quality.

Measuring the extent of forest change is not simple and presents many challenges, the first of which is in selecting the criteria to be used to identify a forested area. This could be based on many things such as, a minimum area, crown cover and/or tree height (FAO, 2000; Neeff et al., 2006), location, time, societal use (Helms, 2002), or on land tenure (Ok and Kayacan, 2005). The next challenge is in defining how forest change is monitored. For large or inaccessible areas, the more effective approach is to utilize remotely sensed imagery, while in smaller areas it may be possible to do a plot-by-plot inventory to determine rates of change or the state of the forest (De Sherbinin, 2002). However, to generate the basis for the structural characterization of the plot inventory, the establishment of field plots requires measuring stand structure attributes, including age, basal area, mean diameter at breast height (DBH), maximum height, and the density of stems of different DBH (Smith and Killeen, 1998; Lefsky et al., 2001), all of which are time consuming and demand large investments, time and money. The actual dynamics of disturbance or forest loss call for urgent activities such as sustainable forest management, forest conservation and restoration, and the need for efficient and inexpensive methods to evaluate the ecological state of tropical forests. The Conference of the Parties to the Convention on Biological Diversity (COP, held in 1996), identified eight priorities for biodiversity research, and decided to focus its immediate attention on developing criteria and indicators for forest quality and biodiversity conservation as part of sustainable forest management (Stork et al., 1997). The aim of this study is to generate an index that allows for a rapid and cost-effective evaluation of the ecological condition of the forest, based on qualitative and semi-quantitative attributes that do not require an expert knowledge, such as species composition or ecological processes.

2. Material and methods

2.1. Study area

The study was carried out in the municipality of Tenosique (17°15′00″–17°40′48″ lat. N; 90°59′09″–91°38′16″ long. W) occupying an area of 2098 km^2 in the eastern part of Tabasco, SE Mexico (INEGI, 2000). The region is characterized by a warm and humid climate with precipitation throughout the year. The average temperature is 26 °C and the mean annual precipitation is 2000 mm (INEGI, 2001). The main part of the municipality is characterized by slightly hilly areas with elevations from 20 to 200 m. In the south, where the field work was realized, there are partly steep mountains of up to 640 m (INEGI, 1994). The dominant soils in the hilly areas are Vertisols, Cambisols, Luvisols and Acrisols over Miocene or Oligocene sediments, whereas, in the mountains the dominant soil types are Leptosols and Regosols over Limestone (INEGI, 1985).

Forest fragments are immersed in a mosaic of secondary vegetation of different ages derived from agricultural activities and abandoned pasture land (Isaac-Márquez et al., 2005). These evergreen forest remnants can reach up to 30 m of height and generally three tree layers are present, and an herbaceous layer with araceae, marantaceae and ferns, as well as lianas and various types of orchids (Gobierno del Estado de Tabasco, 1997). The most common tree species include *Swietenia macrophylla*, *Cedrela odorata*, *Andira galeottiana*, *Spondias mombin*, *Tabebuia rosea*, *Ceiba pentandra*, *Nectandra ambigens*, *Castilla elastica*, *Calophyllum brasiliense*, and *Cordia alliodora* (Ochoa-Gaona et al., 2008).

2.2. Data collection

A data sheet was designed to systematically collect qualitative and semi-quantitative data on vegetation structure, forest composition, natural regeneration, and forest management. The data collected include the following categorical variables (a) vegetation type: shrub fallow, tree fallow, tropical forest or plantation and its height; (b) presence and dominance of the following strata: high trees of >20 m, medium sized trees of 10–20 m, small trees of <10 m and shrubs of < 3 m, each stratum is classified as dominant, co-dominant, existent, or absent; (c) canopy with the following cover classes: 25%, 26–50%, 51–75%, or 76–100%; diameter classes of trees present in the plot of each class: <5 cm, 6–10 cm, 11–20 cm, 21–40 cm and >40 cm, classified as: abundant, medium number, few individuals, or absent; (d) approximate number of adult tree species, based on morphological characteristics of leaves and tree architecture; (e) approximate number of tree seedling species also based on morphological characteristics; (f) forest uses and damages: Grazing/trampling intensity, firewood extraction, wood extraction, soil fire and standing dead trees in classes of intensity or frequency: without or low, medium, and high (Table 1). The plots were selected during field visits to obtain a set of samples that represented different degradation or successional stages of tree vegetation (25 tree fallows, eight shrub fallows, one plantation, and ten tropical rain forests). In each plot, a circular area of 1000 m^2 was delimited and used as the basis to fill in the field data sheets. Within each plot, two 1 m^2 quadrants were established to analyze the natural seedling regeneration. A total of 44 plots of tree vegetation were evaluated and all data were saved in spreadsheets for further analysis.

2.3. Model development

A hierarchical model was developed to describe the state of the forests, based on ecological principles, criteria, and indicators (Prabhu et al., 1996; Stork et al., 1997; Campbell et al., 2001). Two or more indicators were aggregated to higher level intermediate variables, which at the end were aggregated into a simple index that valuated the ecological condition of the forest on a scale from 0 (worst condition) to 1 (best condition); the number of intermediate value classes depended on the number of categories defined in the field data sheet (Table 1).

2.4. Indicators

The indicators that were used in the ecological appraisal are those commonly applied by ecologists (Sutton and Harmon, 1977; Braun-Blanquet, 1979; Hubbell et al., 1999; Peña-Claros, 2001; Lindenmayer et al., 2006; Martínez-Ramos and García-Orth, 2007) when carrying out a forest inventory or a vegetation analysis in the field, such as vertical and horizontal structure of the forest, natural regeneration of the tree species, vegetation cover type, species richness, and disturbance factors (Fig. 1).

2.4.1. Forest structure

The maintenance of stands with high structural complexity is critical for forest biodiversity conservation; it facilitates a more rapid return from logging damage to a regenerated stand with a suitable habitat for species that have been displaced by the disturbance (Lindenmayer et al., 2006). These authors also found that complexity within a landscape enhances dispersal of some animals through a cutover area, by means of the so-called connectivity function and can provide the within-stand variation in habitat conditions required by some taxa, the so-called habitat heterogeneity function. The structural elements of forests can be distinguished as vertical and horizontal attributes in the model, each one considered as a key factor in describing that particular part of the overall structural complexity (Newton, 2007). Height and cover, together with the number of layers, are the most important structural and functional variables of many components of forest ecosystems, such as spatial heterogeneity, temporal dynamics of the understory vegetation, pattern and mosaics of natural regeneration and variation of microclimatic conditions (Song et al., 1997; Figueroa-Rangel and Olvera-Vargas, 2000).

2.4.1.1. Vertical structure. The vertical structural attributes are essential elements when drawing the complexity of a forest profile. The main attributes used for the model are canopy height and the number of strata that can be distinguished in each profile. Tropical rainforests in Mexico can reach heights of more than 30 m (Pennington and Sarukhán, 2005), depending on the degree of disturbance or the succession stage. We distinguished four strata, high canopy trees (>20 m), medium sized trees (10–20 m), small trees (<10 m) and shrubs (<3 m). This structural factor influence the micro-environmental conditions within the forest, such as daily temperature fluctuations, relative humidity, and distribution of sunlight (Sutton and Harmon, 1977; Braun-Blanquet, 1979; Balandier et al., 2009). However, stratifying tropical forests into distinguishable layers is often difficult and sometimes even questioned (Parker and Brown, 2000). In our model, emphasis was placed on the presence and height of the dominant and co-dominant layers (Newton, 2007) by means of assigning relative weights to height of the different layers, taking into account that canopy height is an indicator of stand maturity and conservation phase of the forest. The presence of a separate shrub layer also generates specific microclimatic conditions, but only at the upper soil and litter level of the forest; as a result a lower weight was assigned to this attribute compared to the tree layers.

2.4.1.2. Horizontal structure. The horizontal structural (HSt) attributes assess the spatial distribution of the forest elements (mainly trees) over a certain area. That is, dense forests will present many trees close together or trees with extended crowns, with both factors contributing to high tree cover. In our model, HSt was measured by means of two attributes: (a) canopy cover and (b) presence of tree stratum within the stand, and the diameter at breast height (DBH) of the most dominant (Newton, 2007). We distinguished five diameter classes of trees (<5 cm, 6–10 cm, 11–20 cm, 21–40 cm and >40 cm) and we annotated for each class if the number of trees are abundant, medium number, few trees, or absent. The measurement of tree stem DBH is a standard operation in forest inventories and the use of data to develop frequency distributions of trees by DBH classes is an elementary tool to describe stand structure (Stork et al., 1997). The DBH of the dominant tree layer is an indication of the maturity of the forest. Stands whose upper canopies are predominantly trees with >40 cm DBH are considered as mature forests, whereas stands with dominant trees of DBH 20–40 cm are considered to be old secondary forests, and stands with dominant trees <20 cm DBH are considered as young secondary forests (Martínez-Ramos and García-Orth, 2007).

The canopy cover defines the amount of light that will reach the forest understory. This is extremely important on habitat quality because of its critical role in the determination of understory microclimate and other factors such as decomposition rates (Stork et al., 1997). If the canopy is very open, light demanding trees (generally secondary and pioneer species) will be favored in their growth, whereas dense canopy cover will create a more humid and dark environment, which will favor species typical of the forest interior. We differentiate the following cover classes: (a) 25, (b) 26–50, (c) 51–75, or (d) 76–100%.

2.4.2. Natural regeneration of the forest

Considering that natural regeneration is strongly driven by canopy gap dynamics, we used the abundance of seedlings (<50 cm height) present in each 1 m^2 sample plot, and sapling species (>50 cm height and <5 cm DBH) as a separate criterion in the model. Each gap usually contains some seedlings or sapling of shade-tolerant tree species, which remain beneath the closed canopy as a "seedling/sapling bank" (Szwagrzyk, 1990), until eventually one or several of them reach the canopy. We registered the number of tree seedling species based on morphological characteristics; the local name of native tree seedling species in the plot and their relative abundance (abundant, medium number, few individuals).

2.4.3. Vegetation characteristics

As attributes of the vegetation, the model includes (a) tree species diversity and (b) the vegetation cover type. Species diversity in this work refers to the number of different tree species in a

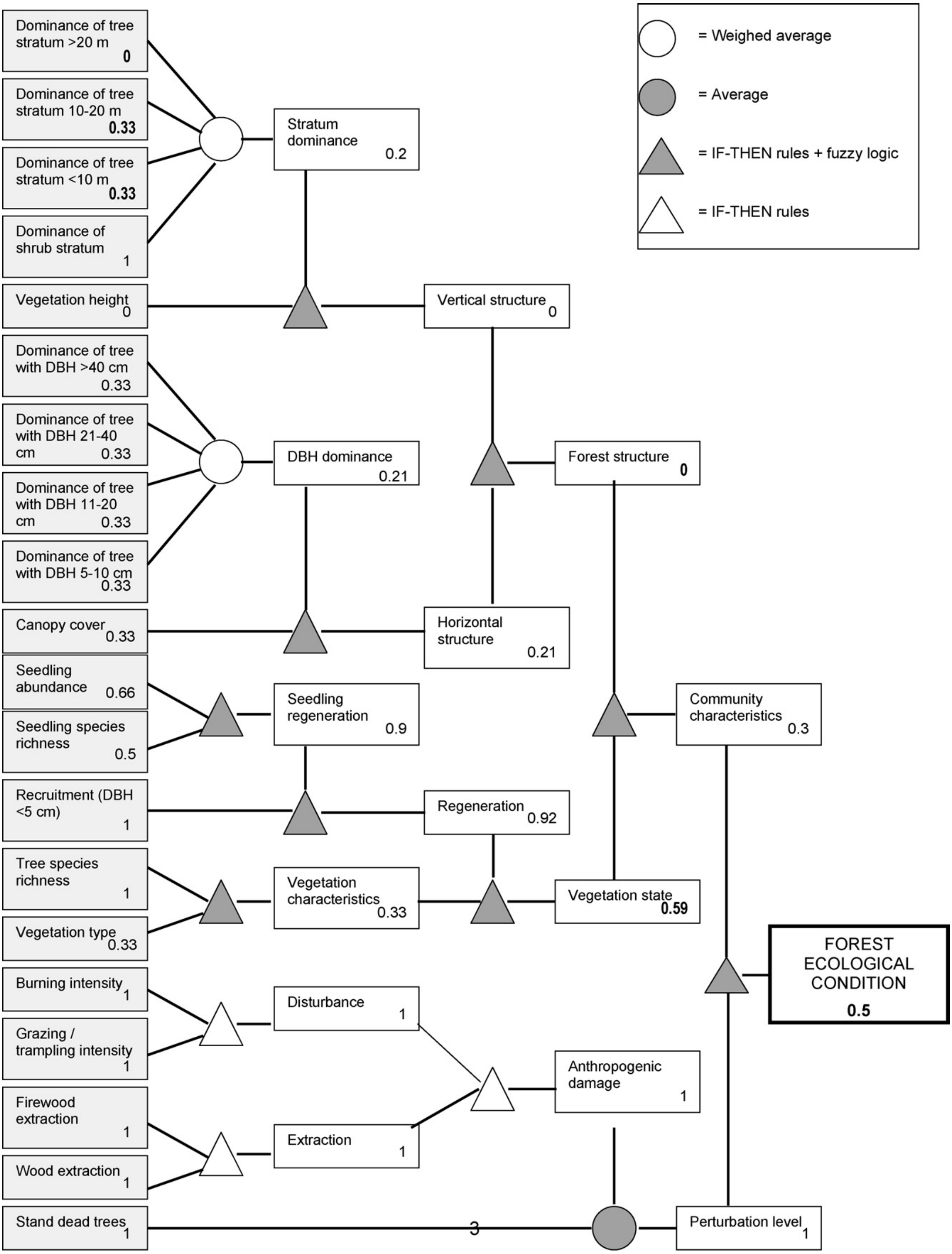

Fig. 1. Model to evaluate local tropical forest condition. The basic indicators used to run the model are shown in grey. The numbers in bold that appear on the lower right correspond to an example run of the model, with the initial (grey box), intermediate and final values of the ecological condition of the evaluated plot.

stand (Schmidt et al., 2006). Numerous studies have shown that the higher the levels of diversity in rainforest ecosystems, the higher the ecological stability (Lindenmayer et al., 2006). However, a widely accepted generalization in community ecology is that localized disturbances, such as tree-fall gaps, promote the coexistence of species that have different resource use strategies, dispersal and competitive abilities—a hypothesis known as the intermediate disturbance hypothesis (Hubbell et al., 1999; Molino and Sabatier, 2001). Some disturbances may also facilitate colonization and establishment of invasive, non-native plants when dominant native trees are removed (Brown and Gurevitch, 2004). In this sense, the species composition is an important factor that should have been included in our model. However, determining composition requires ample botanical knowledge of the successional status of the species, which in most cases is scarce in tropical regions, especially when there are more than 1000 tree species reported for the tropical forests of Mexico (Kineeland, 2007). Therefore, in our model we use the number of tree species (based on morphological characteristics of leaves and tree architecture) present in the plot as indicators of biodiversity. However, the above-mentioned limitations may apply.

To evaluate vegetation cover type we distinguished shrub fallow, tree fallow, tropical mature forest and plantations and registered the height of the community. It is well established that the presence of species depends on the forest type, disturbance, age classes (Hagan and Whitman, 2006) and the historical use of the plot (Peña-Claros, 2001; Thompson et al., 2002; Chinea and Helmer, 2003; Ochoa-Gaona et al., 2007). We distinguish between forest stages by assigning an increasing weight to the number of species, in the following order: plantations < shrub secondary vegetation < tree secondary vegetation < primary forest. Due consideration is given to the fact that there is a gradient on the complexity and number of species, and that primary forests include the species guilds typical of mature forests, as these guilds require more attention for conservation (Ochoa-Gaona et al., 2007).

2.4.4. Disturbance parameters

Disturbance is a relatively discrete event that can interrupt the structure of the forest and the species of communities or populations, as well as affect the physical environment and change the availability of resources (White and Pickett, 1985). In contrast to the more traditional approaches of assessing taxonomic diversity, measuring the effects of management practices on biodiversity is possible by examining the state of those processes that generate or maintain biodiversity (Stork et al., 1997).

Disturbance modifies the spatial and temporal pattern of species composition (presence or absence, relative and absolute abundance, richness), as well as the structure (vertical and horizontal spatial distribution of biomass and organisms, diversity, trophic networks, age and size structure of populations), and dynamics and functioning of the ecosystems (rates of energy transfer, nutrient cycling, species interactions, succession) (Pickett and White, 1985; Ramírez-Marcial et al., 2000). In our model we include anthropogenic and natural events that influence the condition of forest plots, but do not involve large-scale conversion to other land uses. The variables of anthropogenic origin include extraction activities, such as firewood extraction and wood harvesting, animal grazing/trampling, and the use of fire, all of which affect the seedlings and juveniles of the forests. Uses and damages observed were registered in three classes as a function of the intensity or frequency of each disturbance: absent or low, medium, and high

2.4.4.1. Extraction activities. Selective logging and firewood extraction are the most common forms of intervention in tropical forests (Stork et al., 1997), modifying the structure and floristic composition of the forests (González-Espinosa et al., 1995). These disturbances may promote the establishment of non-native, invasive plant species, potentially affecting forest structure and diversity even long after the perturbation has ceased (Brown and Gurevitch, 2004). It has been estimated that in Mexico at least 19 million people use firewood for cooking (Masera et al., 1997). Harvesting parts of trees or shrubs may involve their reproductive structures, such as fruits or seeds, which effectively reduces the size of the parental pool (Namkoong et al., 1996). After logging, the diameter classes of pioneer trees may be significantly larger than they would in primary forests. In addition, some light demanding, non-pioneer tree species exhibit higher growth rates after logging. These types of differential species responses to disturbance result in differences in tree composition (Verburg and van Eijk-Bos, 2003).

2.4.4.2. Grazing activities. Grazing/trampling can alter the spatial heterogeneity of vegetation, consequently influencing ecosystem processes and biodiversity (Adler et al., 2001). An evaluation of livestock impacts on natural resources requires an understanding of the context in which grazing occurs, including timing, duration, intensity, and species of grazing animals (Borman, 2005). Grazing sheep and cattle, in abandoned corn fields, is a common practice that interferes with the recruitment of seedlings and saplings of trees and shrubs, and may lead to the establishment of permanent grasslands (Nahed-Toral, 1989; González-Espinosa et al., 1997). Grazing could also help to re-establish the vegetation structure and food resources that attract wild seed vectors, which in turn affects the seed rain (Miceli-Méndez et al., 2008). In our model we evaluate differentially the presence and intensity of grazing that has left visible evidence in the forests.

2.4.4.3. Use of fire. For centuries, in many parts of the world, the burning of forests has been a common practice in order to make hunting easier, improve grazing and clear land for agriculture (Campbell, 1954; Tilman and Lehman, 2001). However, even low-intensity fires may be detrimental for some tree species and affect the dynamics of succession, as they may destroy seed banks, soil fauna and accelerate erosion (Alvarado et al., 2004; Quintana-Ascencio et al., 1996; Martínez-Ramos and García-Orth, 2007). Our model integrates the valuation of the use of fire in areas of forest, which in the tropical zones is applied mainly for renovating the herbaceous strata for grazing. Three levels of incidence are measured by observing burns of smoke at the base of the trunks.

2.4.4.4. Standing dead trees. A standing dead tree may be the result of natural senescence, and as such dead trees will always be present in natural forests. However, the number of standing dead trees may increase as a result of pathogens, insect attack, and crowns being broken by lightning, storm or fire (Arriaga, 2000; Gale and Hall, 2001). Normally standing dead trees disintegrate gradually with occasional branches falling to the forest floor and the trunk remaining upright. Variation in the way trees die and disintegrate is important since it affects the availability of light and nutrients and the sequential replacement and growth of the remaining vegetation (Arriaga, 2000; Gale and Hall, 2001). In our model, the abundance of standing dead trees is used as an indicator of the incidence of natural or anthropogenic disturbance, such as insect attack.

2.5. Statistical analysis

Once the data were normalized, different analytical procedures were applied to aggregate the values into one index (Fig. 1):

(a) In the case of linear interactions between two or more indicators, we applied average or weighed average. For example, let A and B represent two primary indicators that shall be aggregated to intermediate variable X, and X increases with increasing A and

B. If *A* has the value *a*, and *B* has the value *b*, then the value *x* of the intermediate variable *X* is determined as $x = (a + b)/2$, or as $x = (w1 \times a + w2 \times b)/(w1 + w2)$, where *w*1 and *w*2 are weights.

(b) In the case of non-linear interactions between two or more indicators, a set of IF–THEN rules were established and measured at an ordinal scale. For example, let *A* and *B* represent two primary indicators that shall be aggregated to intermediate variable *X*, and the relationship between *A* (or *B*) and *X* is unimodal – i.e. *X* receives low values when the values of *A* (or *B*) are low or high, *X* receives high values when the values of *A* (or *B*) are medium – then the value *x* of the intermediate variable *X* is determined by a set of *n* rules, where *n* is the product of the number of discrete values of *A* and the number of discrete values of *B*. When *A* has the ordered discrete values a_1, a_2 and a_3, and *B* the ordered discrete values b_1, b_2 and b_3, then *x* is determined by a set of nine rules:
   Rule 1: IF *A* = *a*1 and *B* = *b*1 THEN *X* = *x*1
   Rule 2: IF *A* = *a*1 and *B* = *b*2 THEN *X* = *x*2
   Rule 3: IF *A* = *a*1 and *B* = *b*3 THEN *X* = *x*3
   Rule 4: IF *A* = *a*2 and *B* = *b*1 THEN *X* = *x*4
   Rule 5: IF *A* = *a*2 and *B* = *b*2 THEN *X* = *x*5
   Rule 6: IF *A* = *a*2 and *B* = *b*3 THEN *X* = *x*6
   Rule 7: IF *A* = *a*3 and *B* = *b*1 THEN *X* = *x*7
   Rule 8: IF *A* = *a*3 and *B* = *b*2 THEN *X* = *x*8
   Rule 9: IF *A* = *a*3 and *B* = *b*3 THEN *X* = *x*9

(c) In the case of non-linear interactions between two or more indicators, a fuzzy logic-based set of rules was constructed within a continuous numerical or an ordinal scale with a large number of possible values. For example, if both primary indicators *A* and *B* can have numerical values from 0 to 1, then the value *x* of the intermediate variable *X* is determined by a series of fuzzy set rules representing the linguistic variables "low *A*", "medium *A*", "high *A*", "low *B*", "medium *B*", "high *B*", as well as the output "low *X*", "medium *X*", "high *X*", for example:
   Rule 1: IF *A* = low and *B* = low THEN *X* = [low, medium or high]
   Rule 2: IF *A* = low and *B* = medium THEN *X* = [low, medium or high]
   Rule 3: IF *A* = low and *B* = medium THEN *X* = [low, medium or high]
   Rule 4: IF *A* = medium and *B* = low THEN *X* = [low, medium or high]
   Rule 5: IF *A* = medium and *B* = medium THEN *X* = [low, medium or high]
   Rule 6: IF *A* = medium and *B* = high THEN *X* = [low, medium or high]
   Rule 7: IF *A* = high and *B* = low THEN *X* = [low, medium or high]
   Rule 8: IF *A* = high and *B* = medium THEN *X* = [low, medium or high]
   Rule 9: IF *A* = high and *B* = high THEN *X* = [low, medium or high]

In classic set theory an object can either be a member (membership = 1) or not (membership = 0) of a given set. The central idea of fuzzy set theory is that an object may have a partial membership of a set, which consequently may possess all possible values between 0 and 1. The closer the membership of an element is to 1, the more it belongs to the set; the closer the membership of an element is to 0, the less it belongs to the set. There are three steps involved in the calculation of the model output, when applying the fuzzy set theory: first, for any observed value of the primary indicators its corresponding membership value in the fuzzy set domain is calculated (fuzzification); second, the memberships of the intermediate variable *X* are calculated, applying the rules in the fuzzy set theory (fuzzy inference); third, the fuzzy results are converted into a discrete numerical output (defuzzification). For an introduction to fuzzy models see Wieland (2008). Fuzzy rule-based models have become popular in ecological modelling (Salski, 1996) and there exist numerous examples of their usefulness in the context of ecosystem evaluation, bio-indication and sustainable management (Mendoza and Prabhu, 2003; Kampichler and Platen, 2004; Ocampo-Duque et al., 2007). To keep the number of rules in the model as well as their complexity, as low as possible, we aggregated only two variables at a time when using methods (b) and (c).

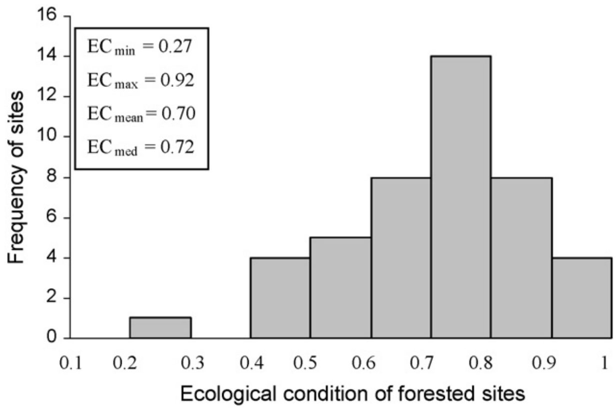

Fig. 2. Frequency of values obtained by the model applied to the plots of the study area.

Finally, the outcome of the model was compared with independent expert opinion from forest ecologists who are researchers and have experience in the study of tropical forests of south-eastern Mexico. They qualified the 44 plots between 0 and 1 on the basis of the collected parameters. Since the data did not have a normal distribution, we used a Spearman correlation coefficient to compare the results of the model with that of the independent experts. To validate the model's outcome we asked two experts to evaluate each plot, based on the collected parameters, using an adopted version of the Delphi technique. This technique has become a widely used tool for measuring, predicting and decision-making in a variety of disciplines (Armstrong, 1999; Rowe and Wright, 1999).

3. Results

The hierarchical model was tested, adjustments were made and the final result is presented in Fig. 1. After applying the model to the field data, the ecological index of forest condition of each plot was obtained, with values varying between 0.27 and 0.92 (Table 2). The plots with the higher values are in better ecological condition, showing a good vertical (canopy height, presence of various tree, shrub and herbaceous strata) and horizontal (high coverage, dominant DBH class >40 cm) structure, with abundant natural regeneration, high number of tree species present, and/or little visible disturbance. The majority of the plots (50%) obtained index values between 0.6 and 0.7, which indicates that most of the forests are at an intermediate ecological condition, and only 27% of the forests reached values above 0.8, indicating good ecological conditions (Fig. 2). A Spearman correlation coefficient of 0.82 ($p < 0.001$) was observed between the model outcome and the independently assigned values determined by external experts (Fig. 3). The model can be fed with independent data sets and run from the Internet website http://201.116.84.136:9500/index.html (Ochoa-Gaona et al., 2009).

4. Discussion

The concept of sustainable development has been popularized globally by the Brundtland Commission's report where sustainable development was defined as "meeting the needs of the present

Table 2
Normalized parameters of the evaluated forest sites and their ecological index value (EI).

	Strata					Diametric classes					Regeneration					Disturbance and management					
Plot	TS20	TS10	TS0	SS	VH	D6	D11	D21	D41	CC	R	SR	SA	TR	VT	BI	GI	FE	WE	SD	FEC
1	0.33	0.66	0.66	0.33	0.75	0.33	0.66	0.66	0.66	0.66	0.33	1	0.66	1	1	1	1	1	0.5	1	0.75
2	0.00	0.33	1.00	0.33	0.25	1.00	0.33	0.33	0.33	1	1	0.5	0.66	0.5	0.66	1	1	1	1	1	0.78
3	0.00	0.00	0.33	1.00	0.00	0.33	0.00	0.00	0.00	0.33	0.66	0.5	1	0	0.33	1	1	1	1	1	0.50
4	0.00	1.00	0.66	0.66	0.50	1.00	1.00	0.33	0.33	1	1	0.5	0.66	0.5	0.66	1	1	1	1	1	0.72
5	0.33	1.00	0.66	0.33	0.75	1.00	1.00	1.00	0.66	1	0.66	0.5	0.66	0.5	1	1	1	1	1	1	0.92
6	0.00	0.00	1.00	0.33	0.00	1.00	0.00	0.00	0.00	0.66	1	0.5	0.66	0.5	0.66	1	1	1	1	1	0.67
7	0.33	1.00	0.66	0.33	0.75	1.00	1.00	0.66	0.66	1	1	1	1	1	1	1	1	0.5	0.5	1	0.77
8	0.00	0.00	1.00	0.33	0.25	1.00	0.33	0.00	0.00	0.66	0.66	1	1	0.5	0.66	1	1	0.5	1	1	0.67
9	0.00	0.00	1.00	0.33	0.00	0.33	0.00	0.00	0.00	0.66	1	0.5	0.66	0.5	0.66	1	1	1	1	1	0.71
10	0.00	0.33	1.00	0.66	0.25	1.00	0.66	0.33	0.00	0.66	1	0.5	0.33	0	0.66	1	0.5	1	1	1	0.72
11	0.33	1.00	0.66	0.33	0.75	1.00	1.00	0.66	0.33	1	1	1	0.33	0.5	1	1	0	1	1	1	0.86
12	1.00	0.66	0.33	0.00	1.00	0.33	0.66	1.00	0.33	1	0.33	0.5	1	1	1	1	1	1	1	1	0.85
13	0.00	0.00	1.00	0.33	0.00	0.66	0.33	0.00	0.00	0.33	1	0.5	0.33	0.5	0.33	1	0	1	0	1	0.27
14	0.00	0.33	1.00	0.33	0.25	1.00	0.66	0.66	0.33	1	0.33	1	0.33	0.5	0.66	1	0.5	0.5	0.5	1	0.65
15	0.00	1.00	0.66	0.33	0.50	0.66	1.00	0.33	0.00	1	0.33	0.5	0.33	0.5	0.66	1	1	0.5	0.5	1	0.67
16	0.00	1.00	0.33	0.33	0.50	0.66	0.66	0.33	0.00	0.66	0.66	1	0.66	0.5	0.66	1	1	1	1	1	0.83
17	0.00	0.00	1.00	0.33	0.00	0.33	0.00	0.00	0.00	0.66	1	0	1	0.5	0.66	1	1	1	1	1	0.71
18	0.00	1.00	0.66	0.33	0.50	1.00	1.00	0.33	0.00	1	1	1	1	0.5	0.66	1	1	1	1	1	0.84
19	0.33	1.00	0.66	0.33	0.75	1.00	1.00	0.66	0.33	1	0.66	1	0.66	0.5	1	1	1	1	1	1	0.91
20	0.33	0.33	1.00	0.33	0.00	1.00	0.66	0.33	0.33	0.66	1	1	0.66	0.5	0.33	1	1	1	1	1	0.68
21	0.33	0.33	1.00	0.33	0.00	0.33	0.33	0.33	0.00	0.66	1	0.5	0.66	0.5	0.66	1	1	1	1	1	0.75
22	0.00	0.33	1.00	0.33	0.25	1.00	0.66	0.00	0.00	0.66	1	0.5	0.33	0.5	0.66	1	1	1	1	1	0.74
23	0.00	1.00	0.66	0.33	0.75	1.00	1.00	0.66	0.00	1	1	0.5	1	0.5	1	1	1	1	1	1	0.87
24	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.66	1	0.5	0.66	0.5	0.33	1	0	1	1	1	0.55
25	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.66	1	1	0.33	0	0.33	1	1	1	1	1	0.42
26	0.00	0.33	1.00	0.33	0.25	1.00	1.00	0.33	0.00	0.66	1	1	0.66	0.5	0.66	1	1	0.5	1	1	0.75
27	0.00	0.00	1.00	0.66	0.25	1.00	1.00	0.33	0.00	0.66	1	0	0.66	0.5	0.66	1	1	1	1	1	0.78
28	0.00	0.00	1.00	0.33	0.00	1.00	0.00	0.00	0.00	1	1	1	0.66	0.5	0.66	1	1	1	1	1	0.71
29	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.33	0.33	1	0.33	0.5	0.33	1	1	1	1	1	0.42
30	0.00	0.33	1.00	0.66	0.25	1.00	0.66	0.33	0.00	1	1	1	0.66	0.5	0.66	1	1	1	1	1	0.76
31	0.00	0.00	1.00	0.66	0.25	1.00	0.66	0.33	0.00	0.66	1	0.5	1	0.5	0.66	1	1	0.5	0.5	1	0.55
32	0.33	1.00	0.66	0.33	0.50	1.00	1.00	0.66	0.33	1	1	1	1	0.5	0.66	1	1	1	1	1	0.88
33	0.00	0.00	1.00	0.33	0.25	1.00	0.33	0.00	0.00	0.66	1	1	0.33	0.5	0.66	1	1	1	1	1	0.69
34	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.33	1	0	0.33	0	0.33	1	1	1	1	1	0.43
35	0.00	0.00	1.00	0.33	0.25	0.00	1.00	0.00	0.00	0.33	0.33	1	0.33	0.5	0	1	1	1	1	1	0.41
36	0.33	1.00	0.33	0.33	0.75	1.00	1.00	1.00	0.33	1	0.66	1	0.66	0.5	1	1	1	1	1	1	0.92
37	0.00	1.00	0.66	0.33	0.50	0.33	1.00	0.66	0.33	1	0.33	0.5	0.33	1	1	1	1	1	1	1	0.88
38	0.00	0.33	1.00	0.66	0.25	1.00	0.33	0.33	0.33	1	1	1	0.66	0.5	0.66	1	1	1	1	1	0.81
39	0.00	0.00	0.33	1.00	0.00	0.33	0.00	0.00	0.00	0	0.66	0.5	1	0.5	0.33	1	1	1	1	1	0.58
40	0.33	0.33	1.00	0.66	0.25	1.00	0.66	0.33	0.00	0.66	1	0.5	0.33	0.5	0.66	1	1	1	1	1	0.72
41	0.00	0.33	1.00	0.00	0.25	0.33	1.00	0.33	0.00	0.66	0.33	0.5	0.33	0.5	0.66	1	1	1	1	1	0.69
42	0.00	0.33	0.33	1.00	0.00	0.33	0.33	0.33	0.00	0.33	1	0.5	0.66	0	0.33	1	1	1	1	1	0.55
43	0.00	0.33	1.00	0.66	0.25	1.00	1.00	0.33	0.00	0.66	1	1	0.66	0.5	0.66	1	1	1	1	0.5	0.64
44	0.33	1.00	0.66	0.33	0.75	1.00	1.00	1.00	0.33	1	1	1	0.66	0.5	1	1	1	1	1	1	0.91

TS20 = Higher tree stratum >20 m; TS10 = Tree stratum 10–20 m; TS0 = Lower tree stratum <10 m; SS = Shrub stratum; VH = Vegetation height (m); D6 = DBH 6–10 cm; D11 = DBH 11–20 cm; D21 = DBH 21–40 cm; D41 = DBH >40 cm; CC = Canopy cover %; R = Recruitment (young trees with DBH ≤5 cm); SR = Seedling richness; SA = Seedling abundance; TR = Tree richness; VT = Vegetation type; BI = Burning intensity; GI = Grazing/trampling intensity; FE = Firewood extraction; WE = Wood extraction; SD = Standing dead trees; FEC = Forest ecological condition.

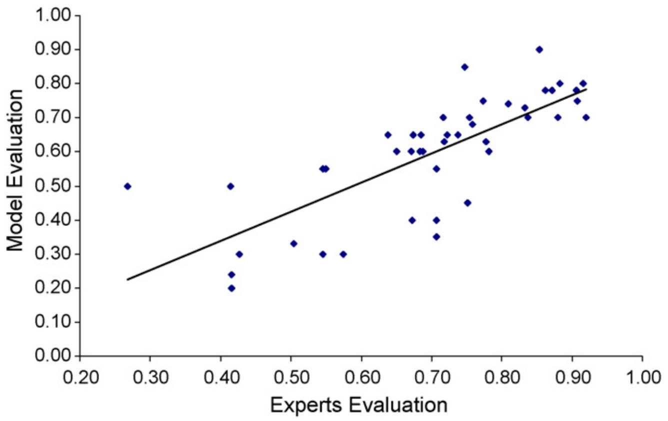

Fig. 3. Spearman correlation analysis between the model outcome (Y) and the independently assigned values determined by the external expert (X).

without compromising the ability of future generations to meet their own needs" (WCED, 1987; Gallopín, 2001; Hall, 2001). The concept has greatest application in biological systems, particularly, forestry and agriculture. As such, sustainable development is a term reflecting human, societal, and environmental values (Hall, 2001).

Namkoong et al. (1996), Prabhu et al. (1996), Stork et al. (1997) and Hall (2001), among others, developed between 50 to 1100 criteria and indicators for forest sustainability. Although comprehensive, their applicability is rather difficult and laborious due to the large number of indicators and data required. In many developing countries, such as Mexico, many of the data sources required to apply these methodologies to evaluate sustainability are not sufficiently available, such as productivity, social circumstances, and historical management. Much of the C&I reported in the literature are primarily developed for guiding and facilitating certification of forest management practices (Leskinen et al., 2003; Gomontean et al., 2008). On the other hand, there are few publications on C&I being used at a forest unit level (Gomontean et al., 2008). Santos Zelaya (2002) proposed 5 criteria and 51 indicators at the level of a forest management unit, which are adequate for tropical America; however, he emphasizes the need to adopt approaches that allow for indicators that are easier to measure and monitor in the field and that do not rely on external sources of information that are often difficult to obtain. This agrees with the findings of Gomontean et al. (2008) who eliminated C&I that are dependent on high technology, excessively time-consuming monitoring techniques; costly, ambiguous or unable to understand, or redundant.

The model that we are proposing is not, in fact, a model to evaluate sustainability because it does not include social, economic or other ecological parameters, such as soil or water. Instead, it focuses on evaluating the ecological condition of local forests and is designed to be a simple tool for assessing the biological part of a sustainability index. It can then be used to generate proposals for immediate action and possesses the following advantages: (1) it is based on structural, species diversity and management indicators that are collected directly in the field in a qualitative or semi-quantitative way and are not dependent on external sources, as recommended by Santos Zelaya (2002) (the indicators used in this work are explained in the methods section); (2) it can be considered as a tool for rapid ecological appraisal; and (3) it is clear and easy to interpret.

Despite the fact that rapid and low-cost assessments are frequently required to develop forest management and conservation activities, traditional forest inventories remain expensive and time consuming and require an ample botanical and ecological knowledge of the species, which is often scarce (Smith and Killeen, 1998; Lefsky et al., 2001). Data acquisition in our model was based on qualitative and semi-quantitative assessments of 20 categorical indicators, estimated at the plot level. Some indicators, such as vegetative cover classes and dominance index (that include both density and cover), have been proposed by Braun-Blanquet (1979) using qualitative measurements; others, such as the number of strata, may introduce some subjectivity of the observer; however, this variable has been used extensively to describe tropical forests of Mexico (Pennington and Sarukhán, 2005) and elsewhere. Other parameters, such as canopy height and tree DBH, can be estimated measuring a few characteristic trees, which is sufficient to distinguish the height of the different tree strata present in the forest and the presence and dominance of different DBH classes. The approximate number of adult tree species and tree seedlings is based on morphological characteristics that require only the ability to distinguish species by leaves or tree architecture for which easy guides can be readily developed. This avoids having to train personnel in plant taxonomy and identification.

It is likely that there will be limited skilled human resources or time for biodiversity assessment in any system of criteria and indicators, so it is important to design tools that are easy to understand, simple to apply and do not require special skills to measure or an expert interpretation (Stork et al., 1997, Hagan and Whitman, 2006). They must provide information to forest managers and policy makers that is relevant, scientifically sound and cost-effective (Stork et al., 1997, Kampichler et al., 2010).

Finally, the qualitative and semi-quantitative method can be accompanied by a more extensive exercise to measure in detail the forest plots, especially in the model validation stage. In our case, once the technical staff had been trained in the data collection procedures, they could collect data from two to three separate sites each day, mainly being limited by the time required to move between plots.

Once the model is run, intermediate values of the criteria are presented in the output, which in turn gives an insight into the factors that influence the final result of the evaluation (Fig. 1). This will aid decision makers in defining the appropriate measures needed to correct the forest deficiencies and to make recommendations for a particular stand or region. An index has utility, when it helps the forest manager or policymaker to make a decision with the indicator (Hagan and Whitman, 2006).

The final results give us relative values (0.0–1.0) of the ecological condition of the forest stand, with the highest values referring to the best conditions. Either, plot-by-plot or regional evaluations can be performed to gain a better perspective of the condition of the forest in a given area, and these can be monitored through time to evaluate the impact of policy measures. Once the model was created, there remained the question of whether or not the model gives an adequate estimate of the ecological status of the forests. However, the expert's evaluation correlated well with our index (Fig. 3), which provided us with greater certainty that the model gives an adequate estimate of the tree stratum of the forest.

5. Conclusion

The decision-making process of forest management and conservation activities require tools that can be readily applied in assessing the current condition of the forests. We expect that our model along with its ecological index can contribute in evaluating the sustainability of tropical forest management into an ecological framework, whilst taking into account indicators of the structure, tree diversity and management of the forest under evaluation.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.foreco.2010.05.018.

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