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Especialidad en Biodiversidad del Neotrópico

Análisis Multicriterio para la identificación de áreas prioritarias de restauración del paisaje forestal en la Mixteca Alta, Oaxaqueña.

T E S I S

QUE PARA OBTENER EL GRADO DE:

M A E S T R O E N C I E N C I A S

P R E S E N T A:

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Directores de Tesis:

Dr. Rafael F. Del Castillo Sánchez

Dr. Davide Geneletti

SANTA CRUZ XOXOCOTLÁN, OAXACA, JUNIO 2011

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SECRETARIA DE INVESTIGACION Y POSGRADO

ACTA DE REVISION DE TESIS

En la Ciudad de Oaxaca de Juárez siendo las 13:00 horas del día 30 del mes de Mayo del 2011 se reunieron los miembros de la Comisión Revisora de Tesis designada por el Colegio de Profesores de Estudios de Posgrado e Investigación del **Centro Interdisciplinario de Investigación para el Desarrollo Integral Regional, Unidad Oaxaca (CIIDIR-OAXACA)** para examinar la tesis de grado titulada: "**Análisis multicriterio para la identificación de áreas prioritarias de restauración del paisaje forestal en la Mixteca Alta, Oaxaqueña"**

Presentada por el alumno:

Uribe	**Villavicencio**	**David**
Apellido paterno	materno	nombre(s)

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aspirante al grado de: **MAESTRÍA EN CIENCIAS EN CONSERVACIÓN Y APROVECHAMIENTO DE RECURSOS NATURALES**

Después de intercambiar opiniones los miembros de la Comisión manifestaron ***SU APROBACION DE LA TESIS***, en virtud de que satisface los requisitos señalados por las disposiciones reglamentarias vigentes.

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En la Ciudad de Oaxaca de Juárez el día 30 del mes mayo **del año 2011,** el (la) que suscribe **David Uribe Villavicencio** alumno (a) del Programa de **MAESTRÍA EN CIENCIAS EN CONSERVACIÓN Y APROVECHAMIENTO DE RECURSOS NATURALES** con número de registro **A090535,** adscrito (a) al Centro Interdisciplinario de Investigación para el Desarrollo Integral Regional, Unidad Oaxaca, manifiesta que es autor (a) intelectual del presente trabajo de Tesis bajo la dirección de los Dres. Rafael Felipe del Castillo Sánchez y Davide Geneletti y cede los derechos del trabajo titulado: "**Análisis multicriterio para la identificación de áreas prioritarias de restauración del paisaje forestal en la Mixteca Alta, Oaxaqueña"** al Instituto Politécnico Nacional para su difusión, con fines académicos y de investigación.

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RESUMEN

Una pregunta urgente que surge durante la planeación de una intervención de restauración es: ¿En qué sitio comenzamos? Encontrar una respuesta satisfactoria, bajo un enfoque multidimensional que incluya las preferencias de diferentes actores involucrados, es una tarea muy compleja. El Análisis de Decisión Multicriterio (MCDA) es un conjunto de técnicas desarrolladas en un ambiente SIG, orientadas a la toma de decisiones espaciales. Esta propuesta se basa en la definición y ponderación de múltiples criterios para la evaluación de aptitud del territorio tomando en cuenta diversas opiniones. Utilizamos la metodología MCDA para la identificación de áreas prioritarias para la restauración del paisaje forestal de la Mixteca Alta, Oaxaca (México). Criterios medioambientales y socioeconómicos fueron seleccionados y evaluados. Se tomó en cuenta la opinión de gente local y expertos de cuatro sectores de la población: habitantes, académicos, ONG y servidores públicos. Se modelaron espacialmente las preferencias de estos grupos e identificaron las áreas de mayor prioridad. El resultado final se representó en un mapa de alternativas que nos permitió localizar con precisión los sitios donde, de acuerdo a los actores involucrados, es prioritario enfocar los recursos y esfuerzos de restauración. El MCDA fue una herramienta muy útil dentro de la planeación colectiva que generó y priorizó diversas alternativas de sitios para encauzar los trabajos de restauración.

ABSTRACT

A pressing question that arises during the planning of a restoration intervention is: Where to restore first? Find a satisfactory answer, under a multidimensional approach that includes the preferences of different stakeholders is a complex task. Multicriteria Decision Analysis (MCDA) is a set of techniques developed in a GIS environment, oriented to the spatial decision making. This proposal is based on the definition and weighting of multiple criteria for evaluating land suitability, taking into account various point of views. MCDA methodology used to identify priority areas for forest landscape restoration of the Mixteca Alta, Oaxaca (Mexico). Socioeconomic and environmental criteria were selected and evaluated. We took into account the opinion of local people and experts in four sectors of the population: public, academic, NGOs and governmental. We modeled spatilly the preferences of these groups and were identified the most priority areas. The final result is represented on a map of options that allowed us to pinpoint the sites where, according to stakeholders, we should focus the resources and restoration efforts. The MCDA was a very useful tool in collective planning in which were generated and prioritized several alternatives sites to guide restoration work.

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GIS-based multicriteria decision analysis for area prioritization to landscape forest restoration in High Mixtec region, Oaxaca (Mexico).

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Abstract

A pressing question that arises during the planning of a restoration intervention is: Where to restore first? Find a satisfactory answer, under a multidimensional approach that includes the preferences of different stakeholders is a complex task. Multicriteria Decision Analysis (MCDA) is a set of techniques developed in a GIS environment, oriented to the spatial decision making. This proposal is based on the definition and weighting of multiple criteria for evaluating land suitability, taking into account various point of views. MCDA methodology used to identify priority areas for forest landscape restoration of the High Mixtec, Oaxaca (Mexico). Socioeconomic and environmental criteria were selected and evaluated. We took into account the opinion of local people and experts in four sectors of the population: public, academic, NGOs and governmental. We modeled spatially the preferences of these groups and were identified the most priority areas. The final result is represented on a map of options that allowed us to pinpoint the sites where, according to stakeholders, we should focus the resources and restoration efforts. The MCDA was a very useful tool in collective planning in which were generated and prioritized several alternatives sites to guide restoration work.

Keywords: Multicriteria decision analysis, Forest Landscape Restoration, GIS, priority areas.

1. *Introduction*

Deforestation is one of the most serious environmental problems. The scale of forest loss of is alarming. During 2000-2010 approximately 130 000 Km^{2} $^{y-1}$ of forest have been lost around the world (FAO, 2010). In response, the efforts to support and promote the recovery of forest ecosystems have increased (Berger, 1990; Hobbs and Harris, 2001). One of the most comprehensive approaches of forest restoration is the Forest Landscape Restoration (FLR) (WWF and IUCN, 2000). The term was defined as a process of restoration of goods, services and ecological processes that forests can provide at a broader landscape level. It fosters a forest restoration based on the better assets for both people and environmental, focusing in regain of ecological integrity and enhancing human well-being at landscape scale (UICN, 2008)

The landscape is not a geographical unit but a human concept. The ecological, political, socioeconomic, and cultural dimensions influence its size and shape. The FLR provides a perspective to implement large-scale and long-term restoration attempts with the incorporation of diverse dimensions within them. It is a collaborative process that involves a wide range of stakeholders since the planning stage through decision making process (Bekele-Tesemma and Ababa, 2002).

Multicriteria Analysis (MCA) is a set of techniques oriented to aid in a process of decision making (Moore, 1975). It provides a single analysis framework to integrate contradictory opinions and multiple criteria to weighs them and select the alternative with the highest score (Nijkamp y Van Delft, 1977; Carver, 1991). Malczewski (2006) documented the increase of use of MCA in synergy with the capabilities of the geographical information systems (GIS) in the last two decades. The spatial multicriteria decision analysis (MCDA), used for territorial decisions, has a broad range of applications, such as water management (Wang *et al* 2004; Sánchez *et al* 2004), land use planning (Geneletti, 2007a), transportation infrastructure (Jha *et al* 2001; Caloni, 2003), waste disposal (MacDonald, 1996; Lea□o *et al* 2004), urban planning (Gomes and Lins, 2002; Zucca, *et al* 2008), environmental planning (Pereira and Duckstein, 1993; Bojórquez-Tapia *et al* 2001) and restoration (Cipollini *et al.* 2005; Orsi and Geneletti, 2010).

One important question that arises in restoration planning is Where to restore first? or Where should we focus the available resources and efforts? The decision should come from collective consensus between stakeholders and select the best option sites, or, at least, the most suitable for restoration. But individual opinions are often in conflict between each other, and economical and technical restrictions limit the total surface to consider in a restoration plan (Maginnis et al., 2007). MCDA should be a useful tool to deal such problems by allowing the incorporation of related systematic procedures that reveal the stakeholders preferences and incorporate such preferences into a GIS-based decision making (Malczewski, 1999; Gómez y Barredo, 2006).

We applied MCDA on the Upper Mixtec region, in southern Mexico, one of the highly degraded regions of Latin America, where the lack of environmental data and resources go together with the urgency of implementing of a regional plan for restoration. Our study illustrates step-by-step a sequence of methods of priority-setting performed in a GIS environment. It was based on the preferences of stakeholders from different population sectors and on the evaluation of both environmental and socioeconomic criteria, to ultimately, represent spatially the results as a map of priority areas for forest landscape restoration.

2. Study area

The High Mixtec region was the focus of our study. This region lies on northwest side of the state of Oaxaca, in south-eastern Mexico. It covers 8,100 Km^2, corresponding to 13% of the state area (Ferrusquía-Villafranca, 1976). Most of the information that we needed for our study were available at municipal level.

However, some municipalities belonged to more than one region. As a result, we have to arbitrarily set the limits of our study area by including only those municipalities in which at least 50% of their area belonged to this region following the municipal and regional division available for the state (INEGI, 2005b). In this way, we incorporated 124 municipalities in our study and a total of 11,633 Km² (Fig. 1).

The region is characterized by high topographic diversity with canyons, hills, intermountain plateaus, and valleys. The elevation ranges from 550 to 3,300 m a.s.l. Tropical dry forest, pine-oak forest and xerophyte scrubs area comprise the native vegetation (Garcia-Mendoza et al. 1994). However, crops and eroded areas are common throughout the entire area Mean annual precipitation is 692 mm with rainfall concentrates during July and August with intense showers.

The high Mixtec is a region with severe socio-economic and environmental problems derived, in part, from wrongful strategies of land management. There is a critic problem of water supply, degraded areas and bare soils. The human population is highly impoverished and dispersed (Garcia-Mendoza et al. 1994; Toledo y Solís, 2001). Approximately 50% of the original forest cover was lost with a deforestation rate of 52.7 km^{2} $^{y-1}$ (Rivera *et al.* 2011). Although some governmental and non-governmental efforts against deforestation have been successful, resources available to combat reforestation cannot include all the areas that require reforestation (Carabias *et al.* 2007;, 2010; Altieri *et al.* 2006). In 2005, only 26 km^2 were reforested in the whole Oaxaca State (Céspedes-Flores and Moreno-Sánchez). Clearly, there is an urgent need to optimize the resources available for reforestation in this area. Selecting the best areas for reforestation is complicated on the bases of the many factors that should be taken into account and the particular points of view of different stakeholders that participate in the process.

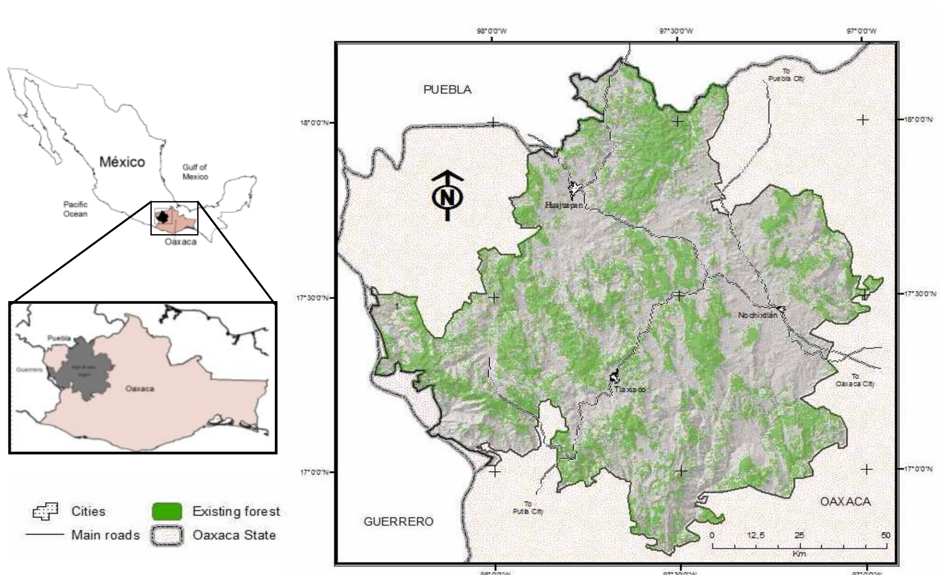

Figure 1. The study area, *High Mixtec region* in the State of Oaxaca, Mexico.

The use decision-making tools performed in a GIS environment to generate a map of priority areas for forest landscape restoration is an option that can minimize the subjectivity in the selection process, but this has not been tried yet in this region.

3. Methods and materials

Stage	Steps and Activities	Tool
Intelligence	a. Define and evaluate relevant criteria	Interview
	• Defining relevant criteria.	
	• Assign interval values of desirability.	
	• Assign values of importance	
	b. Create criteria layers set: factors and constraint	GIS
	• Acquire, compile and process availability thematic data.	
	c. Modeling preferences	MCE
	• Deriving commensurate criteria layers.	
	• Weight assignment.	
	• Aggregation	
Design	d. Design restoration options	MCE-GIS
	• Define threshold based on forest loss rate.	
	• Identify and eliminate unsuitability area.	
	• Create reforestation options maps for each stakeholder.	
Choice	e. Development of priority maps	GIS
	• Priority maps by population sectors.	
	• Map of priority areas for landscape forest restoration.	

Based on: Barba-Romero & Pomerol (1997) and Zucca *et al.* (2008).

A decision-making process was performed in a GIS environment to generate a map of priority areas for forest landscape restoration. For this end, we implemented a sequence of methods to identify the priorities for reforestation, to design sites as options, and to select the better ones. Judgment of stakeholders, expert and local people, were integrated with thematic spatial data through a multicriteria decision analysis (MCE) technique for land suitability evaluation (Bojórquez-Tapia, 2001 and 2003; Cipollini *et al.* 2005; Pereira and Duckstein, 1997). Prioritization was based on values of suitability of land (Store and Kangas, 2001) and the fulfillment of rules of exclusion related to surface demand, that is, the maximum area able to be prioritized (Eastman *et al.* 1995). Our study was situated in the temporal dimension of the year 2005. It integrated tools and techniques within a methodological framework of three main stages: intelligence, design and choice (Table 1, see annex 1).

At the intelligence stage, we sought the opinion of experts to identify and rank both socioeconomic and environmental criteria (Bojórquez-Tapia *et al.* 2003). These criteria were evaluated through value judgment of experts and local people about the desirable condition and relative importance of each criterion (Bojórquez-Tapia *et al.* 2001). Following Eastman *et al.*

Table 1. Framework for spatial multicriteria analysis followed in this study. Sequence of steps and activities performed.

(1995), a thematic raster layer for each of the criteria were developed based on the available data for the study region to generate criteria factor layers and the constraint layer that represent the areas in which restoration activities are not feasible: urban, existing forest and water zones. Finally, we normalized and assigned weights for each criterion through a MCE fashion to generate composite index maps of suitability land (Pereira and Duckstein, 1993). We generated a suitability

map for each stakeholder.

In the design stage, we established a threshold to extract group of cells that fulfill definition rules on the minimum area possible to be reforested. Defined maps displayed landscape-scale reforestation sites options by stakeholder (Orsi and Geneletti, 2010). At the final choice stage, we grouped and integrated the stakeholders' maps of reforestation site options by sectors: academic, governmental, non-governmental and public. Based on a definition process, we created the maps of priority areas for each population sector. Finally, a map of priority areas for forest landscape restoration was developed by an integration of the four sector maps.

3.1. Identify and evaluate relevant criteria

We carried out interviews to seek the opinion about forest restoration priorities (Cipollini *et al.* 2005). Following Bojórquez-Tapia *et al.* (2001 and 2003), the consultation was conducted with expert people with widely known work on environmental issues or professional experience in the study region and with local people. Both, experts and public were treated as stakeholders. The selection of experts was made following the method described by Geneletti (2008). We elaborated a preliminary list of experts and sought advice from them to include additional suitable people. The final list included members of governmental (G), non-governmental (NGO) and academic institutions (A). Local people (P), with knowledge about governmental programs for restoration and inhabitants from the region, were also included on criteria evaluation.

The goals of the consultation were to define and evaluate criteria, based on the judgment of stakeholders about forest restoration priorities, in a regional context. The process was carried out in two stages. First, we identified environmental and socio-economic criteria through the experts' consultation; and defined the criteria to be used in the study. At second stage, the selected criteria were evaluated according with the experts and public preferences. The interviews were conducted individually to avoid bias in judgment influenced by dissimilar opinions (Bojórquez-Tapía *et al.* 2003). We interviewed the stakeholders in a direct (face to face) and/or indirect (internet, telephone) way, on more than one personal session.

3.1.1 Defining the relevant criteria

Following the method applied for Orsi *et al.* (2010), we aimed to experts the question: Which variables should be considered to select a site for forest restoration? The answers were compiled by similarity within a criterion. A preview list was created of socioeconomic and environmental criteria with the frequency of cite or number of times that experts suggest one criterion. The criteria were ordered by the number of citations. Finally, relevant criteria were defined as the ten most cited criteria that fulfilled the following requirements: spatiality, that is, capable to be displayed in a map; availability of the data; and significant variability of this character over the study area.

3.1.2 Interval values of desirability

We sought the expert and local people opinion about which are the optimal conditions for each relevant criterion (Geneletti, 2005a). The central question was what would be the suitable condition of -criterion- for a restoration site? The question was made for each one of the criteria expecting answers into three key options: (1) lower, (2) intermediate and (3) higher ranges. For example, in a criterion of distance to forest, a person could chose: short distances, intermediate distances, or long distances to forest as desirable conditions to select a site for reforestation. The answers gave us three way to maximize the desirable values of each criterion, corresponding with a type of factor: 1, *cost factor* (the lower values the higher the desirability); 2 *intermediate factor* (the more intermediate values the higher the desirability); and 3 *benefit factor* (the higher values the higher the desirability).

3.1.3 Value of importance

The occurrence of different levels of importance between criteria is often in multicriteria decision making problems. So, prioritization of criteria must be performed (Geneletti, 2005b; Gómez and Barredo, 2006). For this purpose, it was essential the generation of information about the relative importance of the criteria according to the value judgment of the stakeholders (Belton and Gear, 1997). In order to know their preferences, we asked them to assign a value of importance for each criterion. The formulated question was *How important is the – criterion- in the selection of a restoration site?* The answers were ranked from low to high level of importance using a five-point scale from not relevant (key 1), to very important (key 5).

3.2. Criteria layers set: factors and constraint

A criteria raster layer set was generated according with the relevant criteria selected by experts. Two types of criteria layers were constructed: factors and constraint. For this end, we acquired, compiled and processed a set of available spatial thematic data from the study area. Tabular, vector and raster data were acquired from governmental sources. In addition, we acquired a supervised-classified spot'05 satellite image (30 m resolution) analyzed by personnel of the GIS Laboratory of CIIDIR Oaxaca, Instituto Politécnico Nacional (Rivera *et al.,* 2011). We generated raster-base layers using ArcGis 9.2 software (ESRI, 2006). A resample of 30m pixel resolution and WGS84-UTM-14N system re-projection were applied for each layer output. A pixel represents the spatial unit or evaluation alternative*,* which would be valued by criteria in terms of suitability.

The index of marginalization and the human density factor layers were processed from tabular data to raster format at municipal scale area. For the marginalization index (taken as an indicator of poverty) layer we adopted the four-point range of marginalization used by National Population Commission (CONAPO, 2005): from 1 (little marginalization) to 4 (very high marginalization). The human density layer was generated using data from the 2005 population census (INEGI, 2005a) and feature data of municipal area extent (INEGI, 2005b) to calculate the human density values (people/Km²).

The distance factor layers were developed applying the Euclidian distance algorithm with 30 meter of pixel resolution. Euclidian distance was calculated (meters) from the center of the source pixel to the center of each of surrounding pixels. The solar insolation (Watt-Hour m^{-2}) and slope (%) layers were obtained processing a digital elevation model (DEM) 30 m resolution from High Mixtec region. The risk of erosion layer was modeled following the methodology of The Revised Universal Soil Loss Equation –RUSLE- (Renard *et al.* 1997, Lewis *et al.* 2005). We generated the factor layers with available data. R factor (rainfall erosivity) with precipitation tabular data (Serrano-Altamirano *et al.* 2005). K factor (soil erodability) with edaphology vector data (INIFAP and CONABIO, 1995). LS factor (length and steepness slope), calculated using a DEM input with C++ executable free-software (Van Remortel *et al.* 2004). C factor (land cover) generated with the supervised-classified *spot* satellite image.

The constraint layer was constructed with the land cover layers of urban zones, water and forest to indicate the sites that won´t be considerate in a reforestation process.

3.3 Modeling preferences

In this stage we integrated preferences and criteria layers and generated individual suitability maps*,* one for each stakeholder. For this purpose, we assembled a criteria tree*,* which is a framework wherein we introduce the preferences of the stakeholders and noted a sequence of procedures of the multicriteria analysis technique (Barba-Romero and Pomerol, 1997; Zucca *et al 2005*). The criteria tree was generated by naming the outcome raster map and criteria (branches), and uploading the criteria raster layers for their proper branch. Completing the previous steps allow us to generate the suitability maps for each stakeholder by following the basic steps multicriteria decision analysis (Carver, 1991): 1) transformation of the original attribute values of criteria layers into comparable units (standardization), 2) prioritization of the criterion based on its relative importance (weight assignment), and 3) calculating and assigning suitability scores to each pixel (evaluation alternative) by using a decision rule (aggregation).

We used the Spatial Multicriteria Evaluation Module (SMC), of ILWIS 3.6®, to build a *criteria tree* and to develop multicriteria procedures (ITC, 2009)

3.3.1 Deriving commensurate criteria layers

For a multicriteria decision analysis process, in which we combine criteria and preferences, it is essential to combine criteria in the same scale of values. Therefore, original values of criteria must be transformed into comparable units (Malczewski, 1999). For this end, a standardization process was performed by generating a value function according the type of factor (Geneletti, 2005a). The standardization process was conducted using the SMCE module and the interval method of linear scale standardization following the formulas 1, 2 and 3. The procedure generated a linear relationship between the raw values of original attributes and the desirability values, in which they were, transformed (Figure 2). The standardized values of each criterion were distributed in a 0 to 1 scale being the maximum desirable value equal to 1 (Geneletti, 2004).

(1) *Benefit* $= (v - minv)/(maxv - minv)$

(2) *Cost* $= 1 - (v - minv)/(maxv - minv)$

(3) *Intermediate* $= -av^2+bv+c$

Where *minv is the minimum input value, maxv is the maximum input value; a, b* and *c* are constants, and *v* is the original input value.

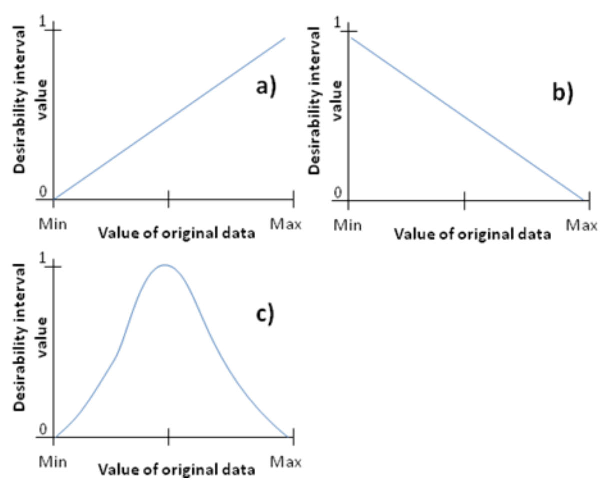

Figure 2. Value functions that represent the interval value of desirability to make the standardization of: a) *Benefit* factor, b) *Cost* factor and c) *Intermediate* factor.

3.3.2 Weight assignment

The relative importance value assigned to each criterion, known as *weight,* was used for criteria prioritization (Belton and Gear, 1997; Geneletti, 2005b). We followed the rule: the higher the importance value, the higher the weight (Belton and Gear, 1997). We applied the rank order method for translating the stakeholders' preferences into quantitative values of importance that they were normalized to sum 1 (Malczewski, 1999, Gómez and Barredo, 2006). The procedure was set up in SMCE module using the information of the interviews. At first, the criteria were put in order of importance, from the most important to the irrelevant criterion (Zucca *et al.* 2005). Then, the expected value algorithm (formula 4) was applied to calculate the weight (*Wk)* for criterion (*k*), where *n* is the number of criteria and *i* is the position of criterion within the ranking.

(4) $$w_k = \sum_{i-1}^{n+1-k} \frac{1}{n(n+1-i)}$$

3.3.4 Aggregation

The aggregation brings together the results of previous steps, combining normalized criteria values and weights for each alternative (Pereira and Duckstein, 1993). This is done by applying a decision rule that dictates the basis of aggregation and decides which alternatives are preferred to another, based on the overall assessment of the alternatives (Malczewski, 1999; Geneletti, 2005b).

The aggregation was performed using the weighted linear summation method from the SMCE module. This method calculated the overall score for each alternative multiplying their standardized criterion value by the weight of the criterion. This product is added with the calculated products for each criterion for the same alternative (Geneletti, 2005b). The outcome must be a composite index map with normalized values. Consequently, we were able to rank alternatives according to the overall performance score, being the alternatives with higher scores the most suitable sites (Pereira and Duckstein, 1993). The decision rule evaluated each alternative, *Ai,* by the following formula:

(5) $$A_i = \sum w_j x_{ij}$$

Where x_{ij} is the score of i [th] alternative with respect to the j^{th} standardized criterion value, and w_j is a normalized weight, so that $\sum w_j = 1$. The most preferred alternative was the maximum value of A_i.

3.4 Design of option sites for reforestation

The design of suitable sites, as options for reforestation, was done by a definition process of the suitability maps through an exclusion threshold that discriminates suitable areas from unsuitable areas. Definition maps were generated, one for each interviewed people, displaying only the better sites for reforestation according to the individual judgment of the stakeholders. Logical-based commands were applied to dictate the instructions on command line module of ILWIS 3.6 (ITC, 2009).

The definition process began with the establishment of the definition rules: Total area able to be prioritized ≤ 15,000 ha (1.3% of total study area), minimal area of suitable patch ≥ 0.54ha (6 contiguous suitable cells). These rules were agreed on the basis of the required area to be reforested to overcome the deforestation process according to the forest loss rates calculated by the National Forestry Commission (CONAPO, 2003). The twofold percentage of deforested area per year was adopted as the amount of area to be prioritized.

Following Orsi and Geneletti (2010), we set a threshold to extract the most suitable pixels from suitability maps. The threshold was defined on the basis of the fulfillment of definition rules. The identification, selection and extraction of suitable pixels were done by the study of the histogram of suitability map data. We filtered the selected pixel to eliminate isolate pixels and groups with 5 or least pixels. Finally, we generated the defined maps for each stakeholder that display only the qualified area (group of cells) considered as reforestation options, being the representation of individual preferences of priority areas for reforestation.

3.4 Development of priority areas maps

After generating the maps of reforestation option by each stakeholder, we integrated them by the sector to which they belonged. Sector-maps were generated to meet the scenario for academic, governmental, NGO and public population sector. Then we performed a definition process to select the sites that fulfilled the definition rules of area. After that, we integrated those sector-maps to obtain a map that should contain the areas considered as the highest important. We took into account the four priority scenarios and, in essence, the overall judgment and preferences of the participants. To make the spatial model, we used the command line module to perform the map sum calculation (Formula 6 and 7); where *d, e, f* to *n* were the input maps of the stakeholders*; A, G, N* and *P* were the input maps of each population sector. Definition process was applied to fulfill the area requirements. We selected the sites with overlap among two, three and four sectors and they were designed as the 3th, 2nd and 1st priority sites, respectively.

(6) *Sector-map = d + e + f +…n*

(7) *Priority Areas-map = A + G + N + P*

4. Results

A total of 54 interviews were fully completed from four different sectors of the society involved in the decision making of reforestation planning: academic (9), governmental (10), NGO (9) and local people (26), here defined as the as the public sector.

We identified 34 different criteria through expert consultation, 21 environmental criteria and 13 socioeconomic. The table 2 shows the most cited criteria by the experts. The higher number of cites was given for the criterion “distance from forest”, with the consensus of 18 experts. On the other hand, the 41% of the listed criteria were mentioned only one time by experts (3.6% of citation). The ten most cited criteria were considered as relevant, of this, five were environmental and five were socioeconomic (table 3). The criteria without available data as rate of land use change, soil depth, land tenure, forest fragmentation, among others; were discarded in the selection.

The overall trends in opinion of the stakeholders with respect to maximization of a desirability interval value (type of factor) and the relative importance (weight) for each criterion classified by population sector are shown in Figure 3 and 4 respectively. In general, the opinions regarded the desirable type of factor and weights of criteria were divided among population sectors.

In the selection of the type of factor to maximize the desirability interval value (figure 3), the criteria “distance from rivers” and “risk of erosion” were the most divided, in both, between criteria and sector approaches. Also, the overall opinion was divided from the public sector about the entire environmental criteria. On the other hand, there were similar opinions among the four sectors considering the “marginalization index” criterion as a benefit factor (maximize higher input values), with the 90% of opinions. The “distance from forest”, with the 82.5% of the total opinions, got the second most unanimous response in considering as cost factor (maximize lower input values) that criterion. There was an absolute consensus between the experts (academic, governmental and NGO) with the 100% of opinions regarding to maximize the lower distances from existing forest.

The selection of the importance category is shown in Figure 4. The 66% of opinions included the environmental criteria in categories of important and very important, while only the 46% of opinions included socioeconomic criteria in the same categories. The criterion “distance from forest” had the highest frequency of qualifications of “very important” category, with 31 of 54 opinions, of which the 100% of experts supported this designation. In the public sector, the higher frequency of the category “very important” was given for the criterion “index of marginalization” with 18 opinions of 26.

The set of criteria layers was constituted for eleven layers (Figure 5, see annex 2). Ten of them were the factors that represent spatially the relevant criteria. The minimum and maximum attribute values presented by factor layer is shown for the study area in table 4.The constraint layer was generated to represent an area extent of 6,891km^2 of restricted sites for a reforestation plan, representing the 59% from the total study area. The non- restricted sites comprise the 41% of the study area, and were the only ones which were evaluated by the multicriteria analysis.

We generated a total of 54 composite index layers, one for each stakeholder (figure 6a) that represent the suitability value of each pixel in a gradient color palette. The range of suitability values for reforestation was between 0.16 and 0.94. We defined the thresholds of area for each individual map of stakeholder. The lower limits of the thresholds between maps had different values of land suitability between 0.42 and 0.86, with an average of 0.70. The percentage of area selected for reforestation option sites was an average of 1.35% of the total area, varying between stakeholder maps in a range of ± 0.5 %. (Table 5). The maps by stakeholder of reforestation option sites represented the individual opinion about the best area for reforestation (figure 6b).

Four maps of reforestation option sites, one by each sector, resulted from the aggregation of the individual stakeholder reforestation option maps. These maps showed the sites considerated by each population sector as the most suitable areas for reforestation as restoration intervention (Figure 7). A high concentration of suitable sites were in the souther portion of the High Mixtec region in the four sector maps . For the map of public sector, 97% of its priority sites fell on the south of the study area. While for the maps of experts, 87% (NGO), 85%(governmental) and 80% (academic) of its priority sites were also in the south.

The map of priority areas for landscape forest restoration showed an extention of 216.3 km^2 of reforestation sites, 1.8% of total study area. That map represents the areas with high priority for restoration considering the opinion of all the members from the four population sectors. Both, ponderation of assigned weights and maximized interval values, as well as, restrictions of area amount able to take into consideration; determined the final selection of suitable sites.

The weights given to environmental criteria were more determinant for the selection of the priority sites, with 60% of importance (Table 6). The greater weight was given for the criterion “Distance from forest”, 0.15 over other criteria. Tha criterion “marginalization index” was the most importat among socioeconomical criteria with a weight of 0.12. In other hand, the priority areas were located on sites with low attribute values in 7 of 10 criteria. On the contrary, these , high levels of insolation and marginalization characterized the areas for restoration (table 4)

The priority areas were displayed in three colour-level to represent the type of priority (Figure 8). Most of the priority sites, the 87.8 %, fell on the southeastern part of the High Mixtec region. The sites with third priority (blue) covers an area of 131.5 km^2, the sites with second priority (yellow) a total of 74.9 Km^2 and the sites with first priority (red) covers an extention of 9.87 Km^2, with 97.7 % of these sites located on the southern. The 50% of the 1st priority sites, 4. 9 km^2, was concentrated within the territory of two municipies, San Mateo Sinduhi and San Pablo Tijaltepecthe.

5. *Discussion*

With a continuous call for restore landscapes that support the continuity of ecological functions and services in addition to the human well-being, increases the urgency for innovative tools and methods to assist in decision making. Our focus in identifying of most suitable sites for restoration responds to the need of optimizes efforts and resources. In addition, the selection of areas under a Forest Landscape Restoration approach implies the involvement of stakeholders' opinion from the planning stage. The end result of our study is a spatial representation of the most consensual preferences among experts and local people at the High Mixtec region. Spatial multicriteria decision analysis allowed us the land suitability assessment under environmental and social criteria based on value judgment of stakeholders. This was achieved through the integration of interviews, MCA and GIS techniques into a systematic and transparent procedure (Annex 1). Barba-Romero and Pomerol (1997) pointed that the sequence of steps depends on the problem situation because there is a numbers of ways in which the activities can be organized. The main obstacle in our study was the availability of data, since a lack of ready-to-use list of criteria until outdated or non-existent thematic data from the study area. Successful decision making process depends on the quality and quantity of information. For this reason, most of the time was invested in the acquisition, generation and updating of information needed for the study. We emphasize this to be considered in the reproduction of this methodology.

The expert consultation is a helpful and widely practices to fill gaps of information (Keeney ad Raiffa, 1976, Store and Kangas, 2001; Bojórquez-Tapia *et al* 2003, Geneletti, D. 2007; Orsi *et al* 2010). Our results reveal that there is a poor agreement between experts about which criteria should be use for a land assessment to select restoration sites. Only three criteria, "Distance from forest, rate of land use change and risk of erosion" were cited for more than the 50% of experts (Table 2). Orsi *et* al (2010) obtain similar results of low percentage of criteria citation. Identifying relevant criteria by mean of expert opinions should be taken with caution because the expert knowledge uses to be incomplete, imprecise and value-biased (Bojórquez-Tapia *et al* 2003). However, expert consultation is not necessarily bad source of advice (Malczewski, 1999). The availability of information was determinant in criteria selection because less than half of the cited criteria had insufficient data to be considered. The number of criteria to use is another controversial question. We decide to use the ten more relevant criteria based on computational load. However Barredo (1996) suggest the use of not more than seven criteria, there aren't rules that specify how many criteria we must to include in a MCA study. In other studies the set of criteria consist in three (Caloni, 2003) until thirteen (Zucca *et al* 2008) criteria. Another option is presented by Orsi and Geneletti (2010), who used fourteen criteria divided in two analysis stages.

The relationship established between value judgments and value functions gave us the benefit to complement the opinion about the relative importance of each criterion with the desirable way to maximize the values of attributes. The use of value functions has the advantage of providing a clear recording of the judgments and the choices that make up the final scores of suitability (Geneletti, 2005a). Both judgments, were independent each other and influenced a marked differentiation between plots (pixels) in land assessment.

The integration of GIS capabilities (acquire, store, manipulate, analyze and represent spatial data) and multicriteria decision analysis (MCDA) techniques gave us a user-friendly and powerful tool for handle conflicting interests and find points in common. GIS-based MDCA had the advantage to deal with multiple criteria, which represents the real-state of our study area; and can include conflicting opinions that describe the decision problem from different angles. Another feature of the proposed methodology is its flexibility to incorporate new or updated data. Basic or fundamental GIS operations provide the tools for generating data inputs to spatial multicriteria decision analysis (Annex 2). In addition, concrete and easy-understand outcomes (spatially represented) are generated by stage until the final map. Malczewski (1999) and Gómez and Barredo (2006) argued that the incorporation of GIS in decision making process help in minimizing conflict among competing parties by providing useful outcomes (digital or printed maps) to continuing the negotiation. However, Obermeyer and Pinto (1994), remind us an important assumption of the GIS use in decision making; it is assumed that there is no disagreement among stakeholders over the validity and acceptance of spatial model results. In the practice could be different.

The approach of Forest Landscape Restoration (FLR) is pragmatic (UICN, 2008). It was developed in response to the unclear results of traditional efforts of forest restoration, which have been focused mainly to ecological integrity (Dudley and Aldrich, 2007). Reforestation has been the restoration action more used during the last decades (Dorado and Arias, 1998) and there is a tendency to focus it on developing decision-making authority to the stakeholders, an important element of FLR (Bekele-Tesemma, 2002; Carabias *et al* 2003). The involvement of stakeholders within decision making process and building consensus among them should promote a balance between the focus of ecological integrity and human well-being. Spatial MCDA tools emerge as a methodological option to promote the active participation since the modeling of preferences until the negotiation with the alternatives resulted through the process.

An important drawback of the application of MCDA methodology is the inherent presence of uncertainty. Uncertainty exists in many decision situations in which its amount varies greatly (Malczewski, 1999). Broadly speaking, there are two main sources of uncertainty involve in making a decision: the factor of opinion-change of the people and the accuracy of available information (Keeney and Raiffa, 1976). In the first case, the inability of the stakeholders for provides accurate and unchangeable judgments regarding with the evaluation of relevant criteria. Delphi surveys have been applied in MCDA studies to reveal the change-in-opinion index of stakeholders (Bojorquez *et al* 2003, Geneletti, 2007). This forecasting method involves an iterative process of interchanges of opinions and arguments among participants, who then had to supporting with new arguments their judgment or can change the original opinion (Taylor, 1984). In the second source, the available data to the decision makers is often uncertain and imprecise. Thus even when uncertainty is recognized, it may have to be ignored because of insufficient data for evaluation, the evaluation would require too much time or due to software limitations. The performance of sensibility analysis is suggested to identify if our model is robust, if present errors was propagated and the way in which error of input data affect the final output.

In spite of the limitations, MCDA arises as a practical, flexible, adaptable and perfectible methodology in the use of spatial decision making. Its practical applications are not confined to a planning stage, but also could be a management tool through its ability to incorporate new data, updated data and new criteria. The next bound step should be the creation of a spatial decision support system to serve as manager tool in the implement of adaptive policies for restoration at regional or minor scales and seek strategies and solutions more consistent with the complex involved in the socio-environmental problems.

6. Conclusions and recommendations

The search for rapid solutions to complex socio-environmental problems, as forest loss, is not an easy task since decision making processes involve dealing with different points of view and limited information of the environment. Our study clearly shows that it is possible the integration of different methods and technological tools, namely interviews, GIS and MCA within a systematic framework to select the most suitable sites for reforestation based on spatial analysis considering multiple criteria and conflicting preferences. The followed sequence of steps, led us through a logical, transparent and repeatable way since the incorporating of available data to the generation of essential inputs for the creation of the outcomes for the different stages of methodology. This methodology allowed us to identify the priorities of stakeholders from different population sectors and to meet the possible scenarios to be considered as reforestation option sites. At the end, a tangible result, the map of priority areas, represents the most consensual sites to implement a reforestation in High Mixtec at regional scale based on the stakeholder's judgment. Multicriteria decision analysis within a GIS environment is a helpful tool in restoration planning for its capabilities to deal with multiple criteria, to model spatially conflicting preferences of stakeholders, and to generate tangible outcome maps. Also, it fulfills the objectives of FLR involving value judgment by experts and local people related with ecological integrity and social needs. However, uncertainty and limited number of criteria to evaluate are some drawbacks. Uncertainty is inherent in any model. The implementation of sensitivity analysis to assess uncertainty on the decision making process is a viable option to take into account. On the other hand, the high computational load required could force to decrease the number of criteria per target. Finally, it is important to note that the final map is not meant to be an optimal solution, but only the most suitable according to the stakeholders' value judgments. This map is a useful tool to continuing the negotiations between stakeholders and it is susceptible to be improved with their feedback. Future researches lines and practical applications could point to the implementation of MCDA techniques on the management of adaptive policies of restoration at regional and local scale.

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TABLAS Y FIGURAS

Table 2. Criteria ranking, based on the percentage of citation by experts.

Rank	Criteria	Citation (%)
1	Distance from forest	64.3
2	*Rate of land use change	57.1
3	Risk of Erosion	53.6
4	*Biodiversity index, *natural corridors	46.4
5	Slope of terrain (%), *rate of deforestation.	42.9
6	Distance from crops	39.3
7	Human density, Insolation, distance from roads, distance from rivers.	35.7
8	Distance from urban settlements, marginalization index, *social capital	32.1
9	*Soil Depth	28.6
10	*Land tenure	17.9
11	Distance from ANPs, distance from reforested sites	10.7
12	*Soil fertility	7.1
13	Distance from greenhouses, migration rate, *forest fragmentation, humidity, *biotype, *presence of pest, *social stability, precipitation, *forest fires, *seed dispersion, *presence of cattle, *biodiversity use, temperature, elevation above sea level.	3.6

* Criteria without available data for the entire region

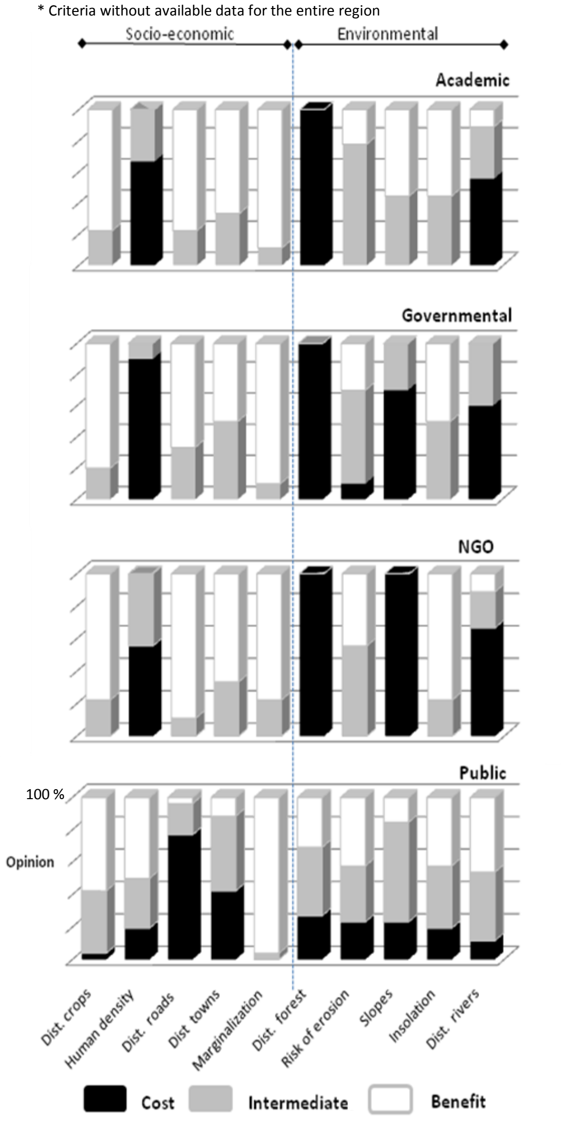


Figure 3. Type of factor (Cost, Benefit or Intermediate) selected by stakeholders by four population sector, to maximize the desirability interval value of each one of the criterion through standardization process.

Tabla 3. Relevant environmental and socioeconomic criteria selected by consultation of experts.

Dimension	Decision Criteria	Description
Socio-economic	Distance from Crops	Euclidian distance (meters) from existing areas used for agriculture
	Human density	Number of people per Km^2. Based on extent of municipal area.
	Distance from roads	Euclidian distance (meters) from highways, roads and trails.
	Distance from urban	Euclidian distance (meters) from the existing urban zones.
	Marginalization index	Summary of nine socio-economic indicators of social exclusion (CONAPO, 2005).
Environmental	Distance from forest	Euclidian distance (meters) from the existing forest.
	Risk of erosion	Index of risk for soil erosion per water action.
	Slope of terrain	Percentage of maximum change in z-value of the surface from each pixel.
	Insolation	Units of hour-watt per m^2 of sun insolation. Calculated for the, summer and winter, solstice and equinox.
	Distance from rivers	Euclidian distance (meters) from the not intermittent rivers.

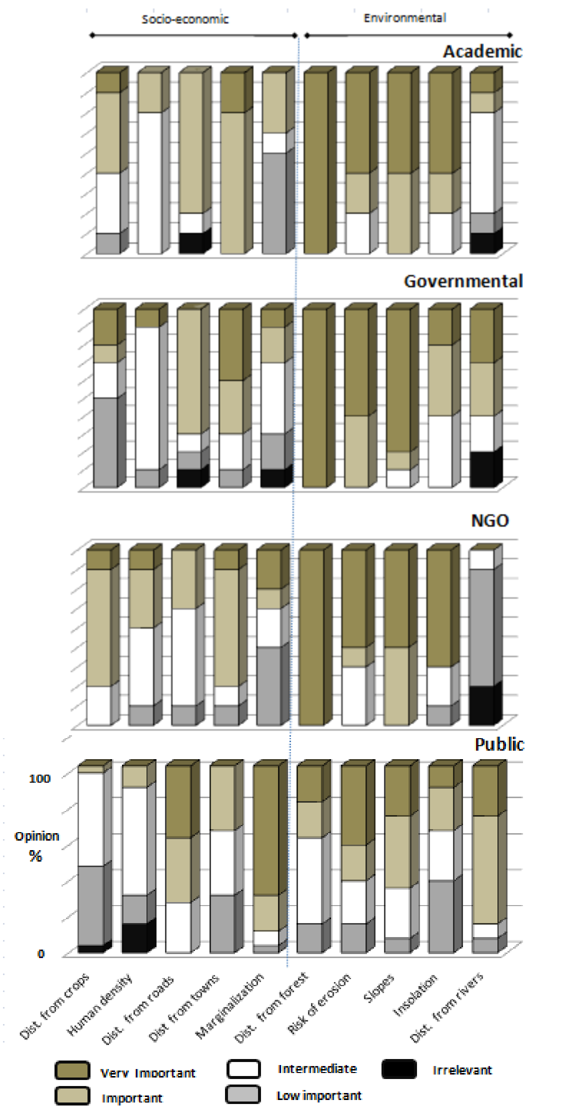


Figure 4. Percentage of opinions for category of importance given to the socioeconomic and environmental criteria by each sector.

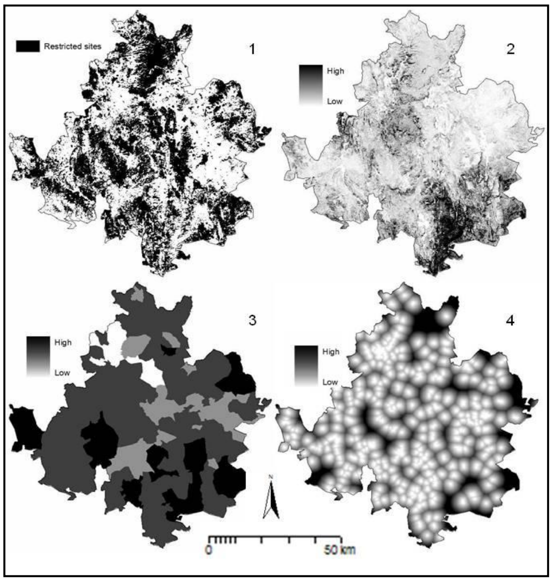


Figure 5. Sample of criteria layers generated through GIS operational process of thematic data: 1) constraint layer, 2) risk of erosion factor, 3) marginalization index factor and 4) distance from urban zones factor.

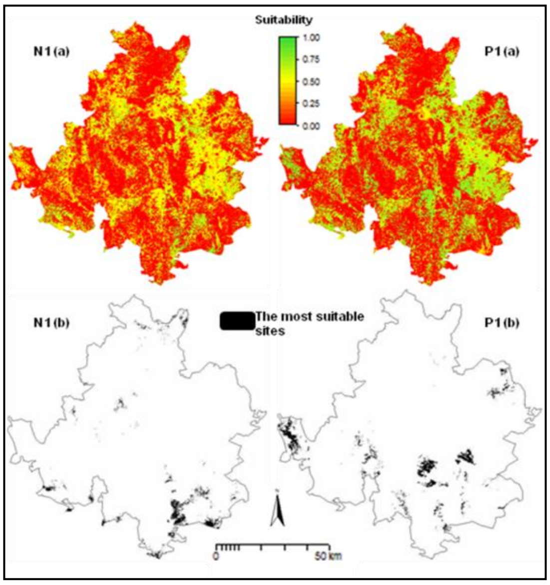


Figure 6. Sample of maps of suitability land for reforestation by the first member of NGO (N1a) and public sector (P1a). And maps of the most suitable sites extracted from the first ones (N1b and P1b respectively).

Table 4. Maximum and minimum values of attributes by criteria factor.

		High Mixtec	**Priority areas**	**1st priority areas**
Criteria	Unit	min & max values		
Dist. from crops	m	0 – 1706	0 - 29	0 – 28
Human Density	people/km^2	3 - 186	8 – 38	12 – 38
Dist. from roads	m	0 – 9421	86 – 4107	810 – 3526
Dist. from urban	m	0 – 14671	2995 - 8038	4060– 7672
Marginalization	Index	1 – 4	3 – 4	4
Dist. from forest	m	0 – 2010	13 – 102	21 – 87
Risk of erosion	T ha^{-1}year^{-1}	0 – 105	0.5 – 15	1 – 14
Slope	%	0 – 403	25 – 74	29 – 65
Insolation	Watt hour /m	4030– 7591	6111 – 6759	5969– 6752
Dist. from rivers	m	0 – 7198.2	107.3 – 2627	371 – 1979

Table 5. Sample of the area threshold established for the first three members of the academic (A), governmental (G), NGO (N) and Public (P) sectors.

Stakeholder map	**Threshold of area (%)**	**Value of suitability**
A_1	1.21	0.64
A_2	1.54	0.55
A_3	1.34	0.61
G_1	1.14	0.68
G_2	1.03	0.63
G_3	1.42	0.63
N_1	1.33	0.68
N_2	1.1	0.74
N_3	1.09	0.78
P_1	1.76	0.76
P_2	1.34	0.42
P_3	1.35	0.71

Table 6. Mean of assigned weight to socioeconomic and environmental criteria taking into account the overall opinion of stakeholders.

Dimension	***W***	**Factor**	***W***
Socio-economic	0.40	Distance from Crops	0.05
		Human density	0.05
		Distance from roads	0.10
		Distance from urban	0.08
		Marginalization index	0.12
Environmental	0.60	Distance from forest	0.15
		Risk of erosion	0.13
		Slope of terrain	0.14
		Insolation	0.09
		Distance from rivers	0.09

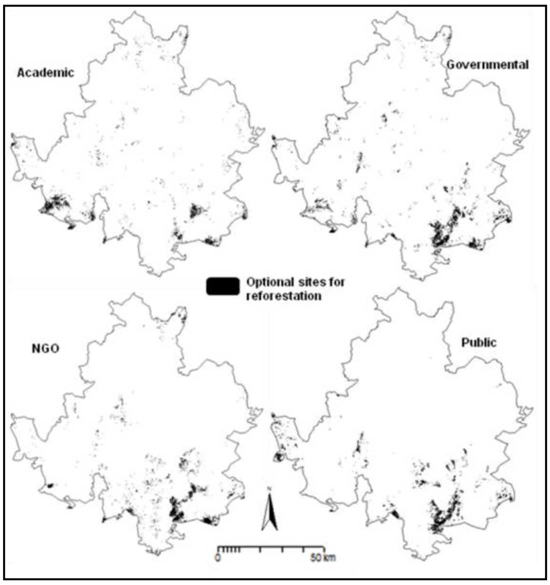


Figure 7. Maps of optional sites for reforestation by each population sector based on the preferences of its members.

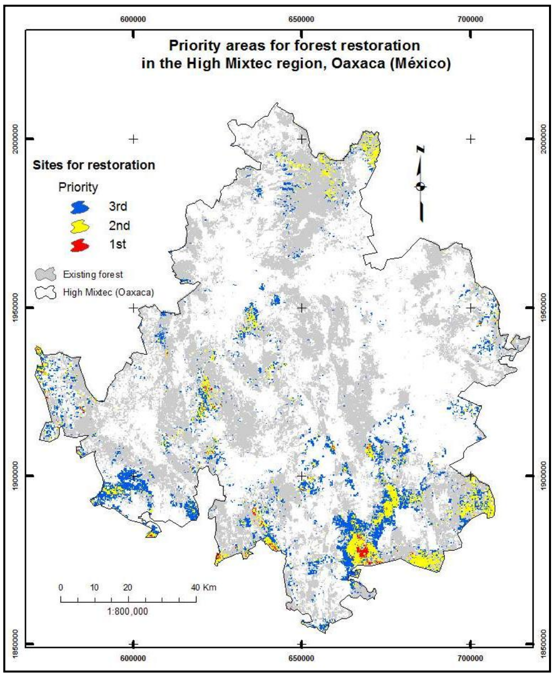
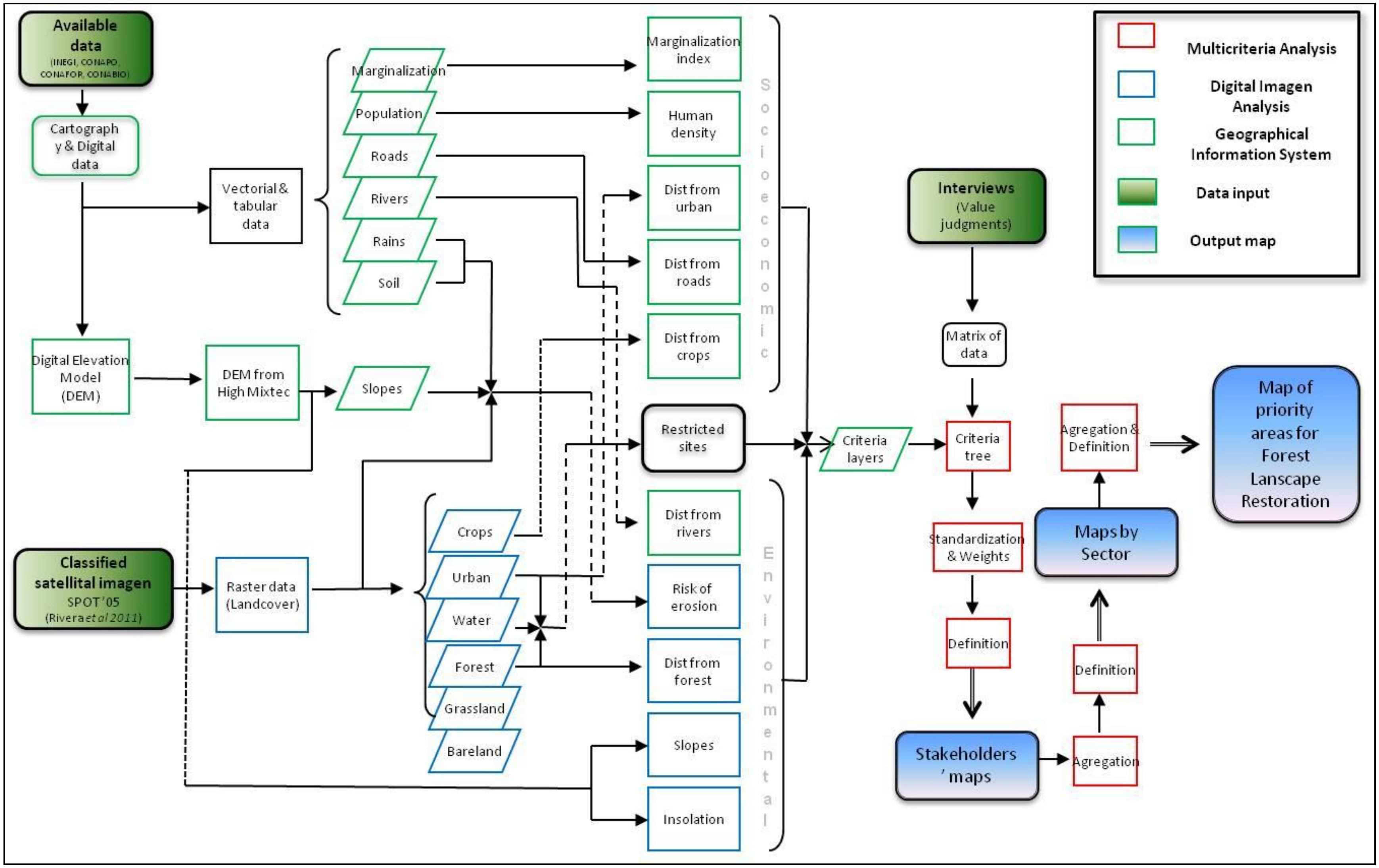


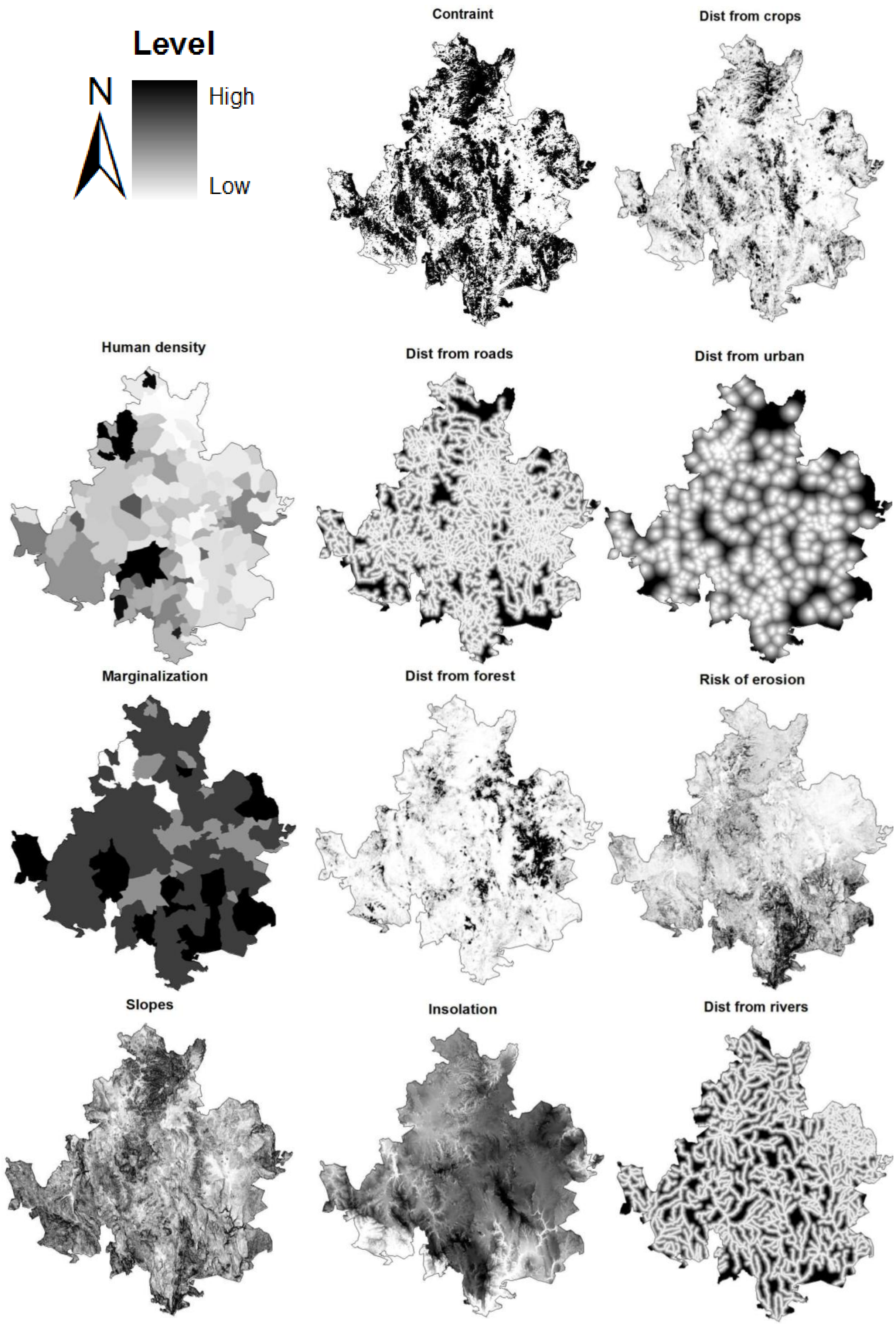
Figure 8. Map of priority areas for Forest Landscape Restoration in the High Mixtec region, Oaxaca (Mexico). It shows the areas in order of priority to implement actions of reforestation.

ANEXOS

Anexo 1.- Diagrama de flujo de la metodología de análisis de decisión multicriterio aplicada en un ambiente SIG para la generación del mapa de áreas prioritarias de restauración del paisaje forestal para la Mixteca Alta, Oaxaca.



Anexo 2.- Capas de criterios, diez factores y una restricción.



Anexo 3.- Mapa de áreas prioritarias para restauración de paisaje forestal en la Mixteca Alta.

Priority areas for Forest Landscape Restoration Hight Mixtec region, Oaxaca (Mexico)