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Integrating ecological and socioeconomic criteria in a GIS-based multicriteria-multiobjective analysis to develop sustainable harvesting strategies for Mexican oregano *Lippia graveolens* Kunth, a non-timber forest product

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ABSTRACT

Mexican oregano is a non-timber forest product harvested in natural vegetation and represents an important source of income for rural families. Recent reports have highlighted decreases in natural populations caused by increased harvest intensity. Oregano leaf harvesting is a complex problem, involving different components and views, and has a clear spatial dimension. We proposed an analytical framework based on multi-criteria-multi-objective analyses. GIS tools were used as the platform for managing, displaying and analyzing ecological and socioeconomic information from different sources in order to evaluate land suitability of three different management strategies for two competing land objectives: oregano Harvest and oregano Regeneration.

The incorporation of environmental evaluation criteria in the analysis allowed the identification of new potential oregano harvesting areas which were neither reported by harvesters, nor registered during harvesting trips. Socio-economic criteria, such as land tenure, highlighted the fact that a substantial proportion of current oregano harvesting areas are located outside ejido limits resulting in potential conflicts for resource access. The proposed Balanced oregano management strategy, in which the same proportion of suitable area (50%) was assigned to both objectives, represents the most favorable management strategy. This option allows harvesters to continue earning an income from oregano leaf harvest; and at the same time helps in the selection of the best areas for oregano regeneration. It also represents a management strategy with a smaller impact on oregano populations and on the harvesters´ income, as well as lower monitoring costs. The proposed analytical framework may contribute to advance the application of systematic approaches for solving decision-making problems in areas where oregano leaves and other NTFP are harvested.

1. Introduction

Non-timber forest products (NTFP) are biological resources harvested from forest vegetation for various purposes. -multiobjectiveHarvest of NTFP has been considered an opportunity for ecosystem conservation and rural development given that, if properly done, its potential negative impact is lower than that of timber extraction or other land uses, such as intensive agriculture or livestock production (Peters, 1994; Godoy and Contreras, 2001; Vedeld et al., 2004; Ticktin, 2004; Ruíz-Pérez et al., 2004; Belcher et al., 2005; Kamanga et al., 2009; Uberhuaga et al., 2012). Although the harvest of NTFP can potentially improve livelihoods while conserving ecosystem services (Belcher and Ruíz-Pérez, 2001), under particular circumstances, the ecological impacts of NTFP harvest can cause significant losses of wild populations or generate ecosystem impacts which compromise biodiversity conservation (Dangi, 2008; Homma, 1992;

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Ticktin, 2004).

Aromatic plants are a particularly well known NTFP on a global scale and represent an important source of income for rural families, especially in indigenous forest communities (Karki et al., 2003; Rasul et al., 2012). Mexican oregano (*Lippia graveolens* Kunth) is an aromatic shrub of the Verbenaceae family which is distributed in arid and semiarid climates from south Texas to Costa Rica (Pool and Rueda, 2001). Oregano leaves are traditionally used and commercialized as flavouring and the essential oil is used in different industries. Mexican oregano is mainly harvested from wild populations, with approximately 4000 tons harvested annually and exported to the U.S. market. Although there are only a few *L. graveolens* cultivars in Mexico, it is an economically important species (Huerta, 1997).

Recent reports have highlighted decreases in natural oregano populations caused by increased harvest intensity which results in lower densities, changes in population structure and compromised regenerative potential in the form of fewer reproductive individuals and lower seed production (Soto et al., 2007; Osorno-Sánchez et al., 2009; Osorno-Sánchez et al., 2012). Harvesting of wild oregano populations for sale is regulated in Mexico by the General Law for Sustainable Forest Development (*Ley General de Desarrollo Forestal Sustentable* - LGDFS) and the environmental regulation NOM-005-SEMARNAT-1997. These legal instruments establish the procedures, criteria and specifications for leaf harvest. A simplified management plan is required to legally harvest and commercialize this NTFP. This management plan must include a detailed description of harvest quantity and procedures in a particular territory, and the survey mechanisms applied to guarantee sustainable harvests (DOF, 2005, 2012a, 2012b, 2013).

Mayan communities have traditionally used oregano for culinary and medicinal purposes (Hopkins, 2011; Salazar et al., 2016). Nowadays, in northwest Yucatan, Mexico, oregano leaves are intensively harvested for commercial purposes (Calvo-Irabien, 2009). Oregano harvesting in the region involves manual removal of the leaves from the branches, packing leaves in sacks, transport and sun-drying. Harvest occurs in the rainy season as *L. graveolens* normally sheds its leaves in the dry season. Women are largely responsible for collecting oregano leaves in forested areas, fields and home gardens. Harvesters have the generalized perception that, due to more intensive harvesting, natural oregano densities have been declining, making it difficult to find oregano near their hometown. In order to design and implement successful and sustainable oregano harvesting strategies which will enable both income generation and biodiversity conservation, a better understanding of oregano use and management practices requires quantitative studies. These studies need a detailed assessment of oregano availability, current harvesting areas and their ecological characteristics, as well as user´s perceptions of the socio-economic factors affecting oregano harvesting in this region.

Oregano leaf harvesting is a complex problem, involving different components (e.g., environmental, socioeconomic) and views (e.g., local people, harvesters, experts) and has a clear spatial dimension. Dealing with this kind of problems requires the application of proper tools to provide robust and informed decisions. Land suitability mapping, based on geographical information systems (GIS), is one of the most useful applications for spatial planning and management of natural resources (Malczewski, 2006). In association with multi-criteria decision analysis (MCDA) and multi-objective analysis, GIS can be defined as a process which integrates and transforms geographic data (input map criteria) and value judgments (decision makers' preferences and uncertainties) to obtain an overall assessment for choosing between alternative land uses, actions and objectives (Eastman, 1995; Malczewski, 2006; Boroushaki and Malczewski, 2008). In addition, these tools also provide a digital database for long-term monitoring (Moeinaddini et al., 2010).

Multi-criteria and multi-objective analyses have been successfully applied in land use planning in diverse contexts, including agriculture (Ceballos-Silva and López-Blanco, 2003), timber management and design of natural protected areas (Bojórquez-Tapia et al., 2001; Rosete and Bocco, 2003; Orsi and Geneletti, 2010). In the reviews carried out by Mendoza and Martins (2006) and Malczewski (2006) on multi-criteria methods applied to the management of natural resources, non-timber forest products have been included as an evaluation criterion in different MCDA assessments; however, to our knowledge, these analytical tools have not been employed for planning sustainable management of aromatic species.

The study goal was to develop a proposal for sustainable management of Mexican oregano in a rural area in the Northwest portion of the state of Yucatan, Mexico. We propose an analytical framework based on multi-criteria/multi-objective analyses. GIS tools were used as the platform for managing, displaying and analyzing ecological and socio-economic information from different sources in order to develop three alternative strategies for oregano management, using harvest and regeneration activities as competing objectives. The results constitute an oregano harvesting strategy to guide actions and generate economic benefits, while ensuring resource conservation.

The paper structure is as follows: Section 2 presents a description of the study area, Section 3 explains the methodological approach and Section 4 presents and discusses the main results of the GIS based on multi-criteria/multi-objective assessment. Finally, Section 5 outlines conclusions and perspectives of research.

2. Study area

The study area is located in the northwest portion of the state of Yucatan, Mexico (Fig. 1). Climate is sub-humid with 738 mm annual average rainfall and 26 °C average annual temperature, with a well-defined dry season (November–May) (INEGI, 2009; Orellana et al., 2010). Soils are young, very rocky and shallow (INEGI, 2009). The vegetation mosaic consists of patches of managed vegetation, unmanaged tropical dry forest, fallow areas, home gardens, cultivated fields and scattered livestock pastures (González-Iturbe et al., 2002). In the late 19th century, a large portion of the area was cleared and cultivated with sisal (*Agave fourcroydes*). Currently, however, only small areas are still used to produce this crop and as a result, secondary vegetation is the main source of oregano leaves and other NTFPs (González-Iturbe et al., 2002; Jiménez et al., 2010).

Agrarian law in Mexico recognizes three types of land tenure: communal, private and social. The latter is classified as *ejido* land and comprises territories granted to peasant and/or indigenous populations for their use and management. This land cannot be confiscated or declined, and is the sole property of *ejido* members. *Ejido* political organization consists of an assembly where communal decisions are taken on issues regarding land and natural resources, among other matters (DOF, 2012a; 2012b). The *ejido* studied here has a surface area of 4454 ha. Within the *ejido*, small plots (ca. 1 ha) are granted by the general assembly to individual members who then cultivate them until a new land use agreement is established. Access to resources within these plots is limited, whereas forest resources within the *ejido* territory are open-access for community members.

The *ejido* studied here was chosen because it is representative of oregano leaf harvest and management practices in Yucatan. In addition, a high percentage (90%) of the households in the *ejido* are involved, to a lesser or greater degree, in harvesting oregano. This *ejido* has an ethnically Mayan population of 777 inhabitants distributed in 176 households, most (n = 155) with a male head of household (INEGI, 2010). Education level is generally low, and less than 20% of the inhabitants (> 15 years old) have completed a basic education (6 years). The municipality which contains this *ejido* has a Human Development Index (HDI) value of 0.674. The municipality's value is lower than the averages for Mexico (0.739) and Yucatan (0.723; INEGI, 2010). The economically-active population is mostly male (76%), who engage in primary sector activities such as agriculture, livestock and NTFP harvest. Families supplement their income with NTFPs (honey, oregano, firewood, palm leaves) and subsistence agriculture, including crops

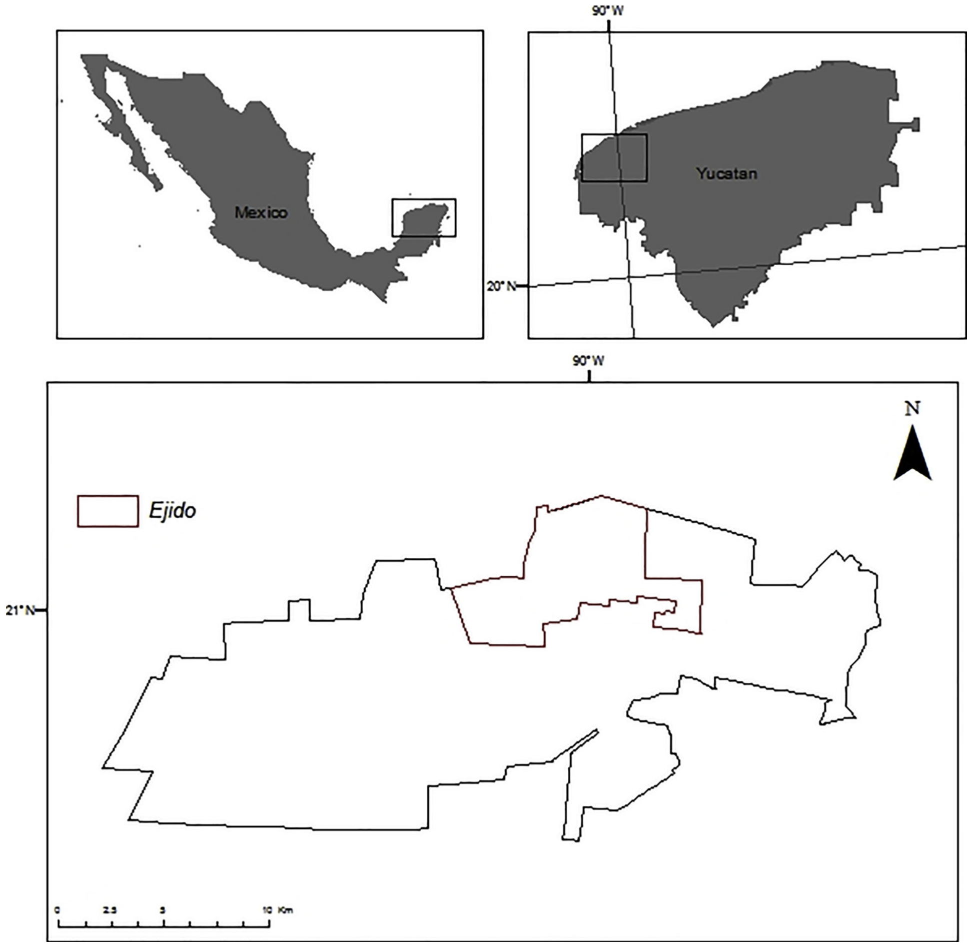


Fig. 1. Location of the Ejido in northwest Yucatan, Mexico.

such as corn, henequen and dragon fruit, among others (INEGI, 2010).

3. Materials and methods

The analytical framework presented in this study integrated the knowledge and opinions of oregano harvesters, as well as ecological and socioeconomic factors which influence the use and conservation of this NTFP. The logical sequence of this study can be described as a two-stage process; in the first stage, land suitability assessment models for two types of oregano management, Harvest and Regeneration, were generated using MCDA (Fig. 2A). In the second stage, we developed three management strategies using a multi-objective land allocation (MOLA) approach. The previously generated suitability maps for oregano Harvest and Regeneration were used as competing objectives (Fig. 2B).

3.1. Suitability maps for oreganoharvest and regeneration

These two types of oregano management were defined in conjunction with oregano harvesters and other community members based on the resource management context at the time of the study. The two types of management were defined as:

Harvest areas: locations designated for oregano leaf harvesting.

Regeneration areas: locations where harvesting is prohibited so they can be used to promote oregano population recovery. Harvest prohibition remains in place until estimated average density (2862 ± 560 ind. ha^{-1}) is attained. Reforestation activities (seeding) to facilitate population recovery are to be enhanced in these areas.

3.1.1. Selection of evaluation criteria and map generation

Land suitability analysis, for oregano Harvest and Regeneration, was performed using the following evaluation criteria grouped into two categories, environmental and socioeconomic factors. Evaluation criteria were chosen based on the objective of the study and data availability.

3.1.2. Ecological aptitude of the territory for oregano leaf biomass

The assessment of the ecological aptitude of the territory for *L. graveolens* leaf biomass was carried out using the environmental variables rockiness, stoniness and vegetation cover (NDVI), registered during field work. These variables have been previously reported to influence oregano abundance and distribution (Blanco and Ordoñez, 2003; Soto et al., 2007; CONAFOR, 2011; Martínez-Ríos et al., 2014). We generated three maps (percentage stoniness, rockiness and NDVI) which were incorporated into a GIS and multicriteria decision analysis in order to have a spatial representation of the ecological aptitude of the territory for oregano leaf biomass (Fig. 4). This map was later incorporated as one of the environmental evaluation criteria (Fig. 2A.I).

The environmental variables percentage stoniness and rockiness were registered during field work using a systematic design consisting of 51 sampling sites (10 x 10 m), located at an average distance between sites of 1.75 km (± 100 m). Each sampling site was divided into 16 quadrants (2.5 x 2.5 m). Sampling sites were distributed throughout the *ejido* and surrounding lands where oregano is usually harvested. Percentages of soil rockiness and stoniness (following Bautista and Zink, 2010) were estimated as an average of the 16 quadrants inside each sampling site. In order to produce a continuous map of the distribution of soil characteristics in the total study area, punctual values

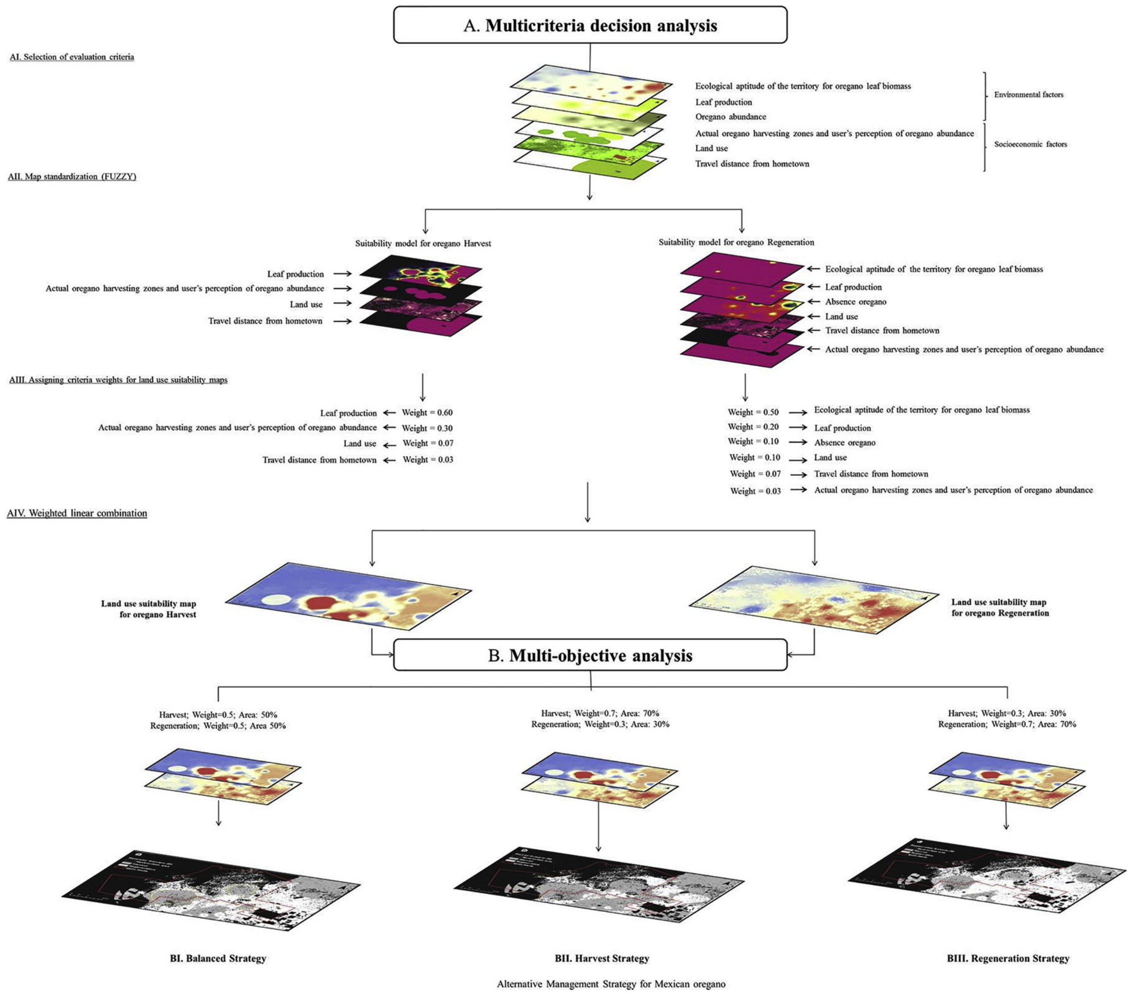


Fig. 2. Flow chart of the analytical framework based on multicriteria-multiobjective analyses. (A) MultiCriteria Decision Analysis (MCDA) incorporating ecological and socioeconomic information from different sources. (B) Multi Objective Land Allocation (MOLA) approach to develop three management strategies for oregano. A) Development of suitability assessment models. (A.I) Selection of evaluation criteria according to fieldwork described in the methodology. Criteria maps were incorporated to next step (A.II) Standardized continuous maps for each criterion were elaborated using the FUZZY module in IDRISI™ software. (A.III) Relative weights were assigned to the criteria to allocate the most suitable areas for each type of land use. Weight values varied from 0 to 1, zero indicating minimal and maximum contribution to the land use suitability. (A.IV) To elaborate land use suitability maps for each type of oregano Harvest and Regeneration, we utilized the weighted linear combination (WLC) method available in the MCE module in IDRISI. The resulting Harvest and Regeneration suitability maps (A.IV) were considered the competing objectives and were used as inputs for the multi-objective analysis (B). The multiple objective land allocation algorithm (MOLA), available in the IDRISI™ software, was utilized to develop alternative management strategies for oregano. Three alternative strategieswere produced (B.I, B.II, B.III), by assigning different goal areas and weights to each objective.

Table 1
Fuzzy membership function type, control points and function shape for the evaluation criteria selected to asses the ecological aptitude of the territory for oregano leaf biomass.

Criteria	Control points				Function
	a	b	c	d	
Stoniness (%)	36	77			Sigmoidal, monotically increasing
Rockiness (%)			18	60	Sigmoidal, monotically decreasing
Cover (NDVI)	-0.24	0.1	0.2	0.57	Sigmoidal, symmetric

registered during field work were interpolated (Hernández-Stefanoni et al., 2004; Li and Heap, 2011) by using the Inverse Distance Weighting (IDW) method available in the IDRISI INTERPOL™ module (Eastman, 1997, 2012). It is well known that interpolation techniques to elaborate continuous maps of soil variables increase uncertainty in non-sampled areas (Hernández-Stefanoni et al., 2004), nevertheless, as we will discuss later, the lack of inventories at fine spatial scale and the limited budget to conduct a larger field survey in the area, made it necessary to choose the interpolation alternative.

Vegetation cover was estimated using the Normalized Vegetation Index (NDVI) (Carlson and Ripley, 1997) from a January 2011 SPOT5 (*System Pour l'Observation de la Terre 5*) image with 10 m spatial resolution. Values for NDVI vary between 1 and -1 in direct relation to green vegetation cover in each pixel of a studied area. Values for dense vegetation vary from 0.5 to 0.8, while bare soil values range from 0.1 to 0.2 (Carlson and Ripley, 1997). NDVI map was used as a proxy to estimate vegetation cover in the studied area.

Each map was then standardized with the FUZZY module in IDRISI™, using a membership function fuzzy set on a scale of 0–1 (Eastman, 1997). Function inflection points and weights for each criterion were assigned according to multiple linear regression results (Table 1). Linear multiple regression analysis were run to assess the effect of percentage of soil rockiness, percentage of stoniness and vegetation cover on oregano leaf biomass. Previous tests were run to fulfil regression analyses assumptions.

3.1.3. Oregano leaf productivity

Oregano plant total height and leaf crown diameters were measured for all plants inside each quadrant, in the 51 sampling sites. Leaf biomass (kg) was estimated from a sample of 30 individuals from which all leaves were harvested, dried and weighed. Correlation analyses between leaf biomass and different plant variables (height, leaf crown area, leaf crown volume) showed that the leaf crown area was the best variable for predicting leaf biomass. The following equation was used to estimate dry leaf biomass (g) = -3.8075 + 0.0366*leaf crown area ($R2 = 0.95$, $p = 0.0001$) in each of the sampling sites. Leaf biomass was interpolated to create a leaf production map (Fig. 2AI) by using the Inverse Distance Weighting (IDW) method available in the IDRISI™ INTERPOL module (Eastman, 1997, 2012).

3.1.4. Oregano abundance

Inside sampling sites, oregano plant density was estimated using 16 quadrants (2.5 x 2.5 m). As in the case for leaf production, oregano abundance was interpolated by using the Inverse Distance Weighting (IDW) method available in the IDRISI™ INTERPOL module to create a continuous map for this criterion (Fig. 2AI).

3.1.5. Land use

A land use map was constructed using a supervised classification based on a SPOT image (January 4, 2011) following Mas and Ramírez, (1996). Five land use categories were included in this analysis following González-Iturbe et al., (2002): (1) human settlements, area where human population is located; (2) agriculture/livestock, areas where agricultural or livestock production occurs; (3) secondary vegetation cover, vegetation regrowth after henequen (*Agave fourcroydes*) cultivation; (4) bare soil, areas without vegetation cover and with rock outcrops; and (5) mature dry forest, areas of forest with no signs of disturbance (land use map Fig. 2AI).

3.1.6. Oregano harvesting areas and harvester's perception of oregano abundance

Qualitative research methods and GIS were used to locate and describe actual oregano harvesting areas and incorporate resource-user perceptions of oregano abundance in a map. Qualitative research tools include participant observation, open-ended interviews and participatory mapping (Taylor and Bogdan, 1986; Tarrés, 2001; Evans et al., 2006; FIDA, 2009). Participatory mapping is a valuable research tool which provides a visual representation of the perceptions of community members and/or resource-users, by collecting data of what they consider to be significant features within a territory (FIDA, 2009; Evans et al., 2006). The map to locate present oregano harvesting points was built using two approaches, one based on a focus group (6 members) and the other, on individual mapping with four experienced harvesters. Actual harvesting points were geo-referenced using field coordinates. In order to build the GIS harvest areas map (Fig. 2AI), a 1 km diameter area was added around each recorded harvesting point, because this was the observed maximum distance walked by harvesters so as to harvest oregano leaves, once they had arrived at an area. Additional information was obtained during oregano harvesting field trips, such as, participants' detailed knowledge of the landscape, harvester perception of oregano abundance (low and high) and the history of oregano management.

3.1.7. Travel distance from hometown

A GIS map was constructed, considering a radius of 5 km surrounding the hometown (Fig. 2A.I). This was the maximum recorded distance that harvesters walked during oregano harvesting trips; therefore, it was considered as the threshold distance to the hometown, in order to assign areas, either to Harvesting or Regeneration oregano management.

3.2. Standardization, weighting of evaluation criteria and assignment of suitability scores for oregano Harvesting and Regeneration

Given that the data of the selected evaluation criteria have been collected in different ways, and have different formats, in order to proceed with the MCDA we needed to transform the original attribute values of the previously selected evaluation criteria layers into comparable units (Malczewski and Rinner, 2015). Standardized continuous maps for each criterion were elaborated using the FUZZY module in IDRISI™ (Eastman, 1997; Fig. 2, AII). Fuzzy functions evaluate the possibility of each pixel belonging to a fuzzy set using different membership functions. A fuzzy set is characterized by a degree of fuzzy membership that ranges from 0 to 1, indicating a continuous increase from non-membership to full membership, respectively (Eastman, 2012). In the standardization process, we used different sigmoidal fuzzy membership functions depending on the specific evaluation criterion. In addition FUZZY requires control points which specify the positions along the X axis of four points governing the shape of the membership function: The first point (a) marks the location where the membership function begins to rise above 0. The second point (b) indicates where it reaches 1. The third point (c) indicates the location where the membership grade begins to drop again below 1, while the fourth point (d) marks where it returns to 0. (Eastman, 1997; Su Jeong et al., 2013). Fuzzy membership functions and control points for the selected evaluation criteria are reported in Table 2.

Even though the previously selected evaluation criteria define the requirements needed to develop the two types of oregano land suitability maps for oregano Harvest and Regeneration, the selected evaluation criteria do not have the same degree of significance for each type of management. Therefore, the next step in the MCDA was criteria prioritization. Based on the information obtained during harvesting trips, harvester interviews and participatory mapping, weights were subjectively assigned to the selected evaluation criteria in order to allocate the most suitable areas to each type of management, depending on their influence on oregano harvest or regeneration activities. Weight values varied from 0 to 1, indicating minimum and maximum contribution to the suitability (Fig. 2A.III).

Since oregano leaf is the NTFP being managed, leaf production was incorporated as one of the most important evaluation criteria for both types of management, either Harvest or Regeneration. Harvesters' decision to begin a harvesting trip is strongly influenced by their perception of the probability of the selected area having enough oregano to fill at least one sack (1–3 kg of dry leaves). Thus, to assess suitability for Harvest areas, using the leaf production criterion map, a considerably higher relative weight ($w = 0.6$) was assigned to this criteria for the Harvest management in comparison with that for Regeneration ($w = 0.1$; Fig. 2A.III).

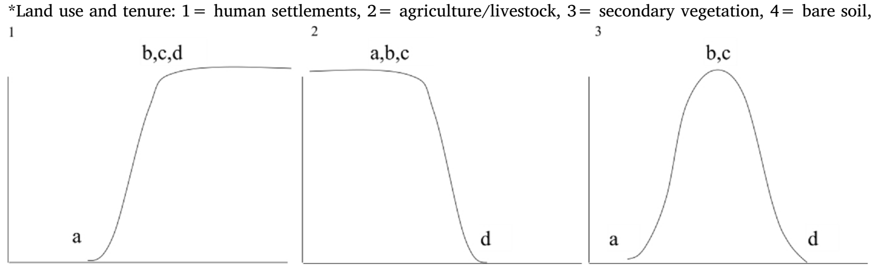
Oregano absence and ecological aptitude of the territory for oregano leaf biomass were selected as evaluation criteria only to determine the most suitable areas for oregano Regeneration management. Incorporation of these two criteria allowed us to identify areas where oregano is not present at the moment; however, these areas do represent a suitable habitat for oregano leaf biomass. Consequently, ecological aptitude of the territory was assigned the highest relative weight value ($w = 0.5$) for the Regeneration management (Fig. 2AIII)

Distance to the hometown was selected as an evaluation criterion for both types of management. Harvesters had stated that, in addition to oregano quantity, hometown proximity to oregano populations was also quite important. During interviews, the harvesters mentioned that they usually walk up to 5 Km, therefore, this distance was set as the maximum value to be used as threshold in the corresponding travel distance map. The criterion of distance from hometown was assigned a lower relative weight to determine suitable areas for Harvesting ($W = 0.03$); but it was assigned a higher value for the Regeneration management ($W = 0.07$; Fig. 2AIII). This differential ponderation allowed the areas close to the hometown; where oregano is currently

Table 2
Fuzzy membership function type, control points and function shape for the evaluation criteria selected to asses land suitability for the Harvest and Regeneration oregano management strategies.

	Criteria	Control points				Function
		a	b	c	d	
Harvest	Leaf production (kg)	0	5			Sigmoidal, monotonically increasing[1]
	Actual oregano harvesting zones and user's perception of oregano abundance (Hight = 1; Low = 2)	0	1	2	2	Sigmoidal, symmetric[3]
	Land use and tenure*	1	3	3	5	Sigmoidal, symmetric[3]
	Travel distance from hometown (km)	0	5	5	> 5	Sigmoidal, symmetric[3]
Regeneration	Ecological aptitude of the territory for oregano leaf biomass			0.3	1	Sigmoidal, monotonically increasing[1]
	Absence oregano			0	1	Sigmoidal, monotonically decreasing[2]
	Leaf production (kg)			5	20	Sigmoidal, monotonically decreasing[2]
	Land use and tenure*	1	3	3	5	Sigmoidal, symmetric[3]
	Travel distance from hometown	0	5	5	> 5	Sigmoidal, symmetric[3]
	Actual oregano harvesting zones and user's perception of oregano abundance			1	2	Sigmoidal, monotonically decreasing[2]

*Land use and tenure: 1 = human settlements, 2 = agriculture/livestock, 3 = secondary vegetation, 4 = bare soil, 5 = mature dry forest.



absent, to be preferentially assigned as Regeneration areas.

Land use was chosen as a relevant evaluation criterion for oregano management because it influences both leaf harvest and regeneration. Land use was assigned a slightly higher relative value to determine the most suitable areas for Regeneration (W = 0.1) in comparison with that for Harvesting (W = 0.07; Fig. 2AIII). This allows the planning of oregano harvesting within the study area in a way that avoids future conflicts arising from harvesting on private or cultivated lands.

Finally, computation and assignment of suitability scores to each pixel, in order to elaborate suitability maps for oregano Harvesting and Regeneration management, was performed using the Weighted Linear Combination (WLC) method available in the MultiCriteria Evaluation (MCE) module in IDRISI™ (Greene et al., 2011; Fig. 2A.IV). This method is one of the most utilized methods in MCDA because of its relatively low complexity for implementation (Greene et al., 2011).

3.3. Alternative management strategies for oregano Harvest and Regeneration objectives

The previously described land suitability analysis (GIS-MCDA) allowed the identification of the most suitable areas for the two different types of oregano management, Harvesting and Regeneration (Fig. 1A.IV). However, some areas identified as suitable for Harvesting can be also be suited for Regeneration, implying that both uses might compete for the same spatial area, possibly deriving in conflicts, once a management program is implemented. To avoid such conflict, it is necessary to allocate the best suited areas for both uses while minimizing potential conflicts. Different strategies to solve these allocation conflicts are described in the literature and some of them are based on the best judgment of researchers (Villa et al., 2002), while others rely on the use of complex mathematical programming (Wu, 1998). In this study, the multiple objective land allocation algorithm (MOLA) proposed by Eastman (1995) and Eastman (2012), available in the IDRISI™ software, was utilized to develop alternative management strategies for oregano. To this end, the Harvest and Regeneration land suitability maps obtained in the previous stage (Fig. 2A.IV) were considered the competing objectives and were used as inputs for the multi-objective analysis (Fig. 2B).

Multi-objective land allocation (MOLA) is an automated algorithm for solving land allocation problems with multiple objectives, either conflicting or complementary. A multi-objective problem occurs when there are two groups (objectives) that share members (area) (Eastman, 1995). In this study Regeneration and Harvest are considered conflicting objectives because both land uses cannot be carried out in the same area, the activities associated with one of the objectives are opposed to those implemented for the other objective. MOLA is a procedure that employs a choice heuristic algorithm to allocate cells among conflicting objectives. As heuristic, MOLA can only approximate the optimal solution. Finding the optimal solution has high computational costs in order to achieve quality solutions in handling the objective of maximizing spatial compactness (Song and Chein, 2018). MOLA uses a compromise solution to maximize the suitability of resources and the amount of area assigned to each competing objective map according to their relative weight (Eastman, 1995). The procedure iteratively allocates best-ranked cells to objectives with major weight according to the total area expected (goal area), specified in advance, and then continues allocating lower priority pixels to the remaining objectives, according to their weights (Eastman, 1995; Greene et al., 2011; Eastman, 2012). The algorithm resolves for allocation conflicts between objectives (the same pixel required for more than one objective) based on weighted minimum distance-to-ideal-point logic (Van der Merwe, 1997). In cases of conflict, a pixel is allocated to the objective where its weighted suitability is highest.

Using MOLA, three alternative management strategies for oregano were produced (Fig. 2, BI, BII, BIII), by assigning different goal areas and priorities (weights) to each objective: For the Balanced strategy (B), both oregano land use objectives (Harvest and Regeneration) were assigned equal goal areas and weights (weight: 0.5 each objective; 50% of goal area per objective, 2800 ha); in the Harvest strategy (H), oregano leaf harvest was given higher weight (0.7) with 70% of area (3920 ha) assigned to this objective and 30% to regeneration (1680 ha; weight: 0.3); and the Regeneration strategy (R), in which oregano regeneration was given a higher weight (0.7) and with 70% of area (3920 ha) assigned to this objective and 30% to oregano leaf harvest (1680 ha; weight: 0.3). Additionally, a restriction layer was built to spatially locate areas where oregano harvesting or regeneration is not feasible due to human settlements, private and cultivated lands, or areas with low ecological aptitude for oregano leaf biomass. As a result, a total of

Table 3
Total estimated hectares, oregano leaf biomass and income derived from oregano leaf commercialization, associated with the Harvest and Regeneration objectives under the three modeled oregano management strategies, using MOLA. Values estimated only for the area within *ejido* are shown in bold.

	Balanced Scenario		Harvest Scenario		Regenertaion Scenario	
Objectives	Harvest	Regeneration	Harvest	Regeneration	Harvest	Regeneration
Area (ha)	2800	2800	3920	1680	1680	3920
	935.5	**1157**	**1262**	**824**	**579**	**1526**
Annual leaf biomass (tons)	25.2		35.3		15.1	
	8.4		**11.3**		**5.1**	
Income (thousands of Mexican pesos)	$378		$529		$227	
	$126		**$170**		**$77**	

Total area: 11,429 ha; *ejido* area: 4454 ha; restricted area: 5829 ha.

11,429 ha were considered in order to produce the maps of the alternative oregano management strategies.

The total area (hectares) associated with each of the two objectives, Harvest vs Regeneration, was estimated using the resulting maps, for each of the three alternative management strategies. Likewise, using the areas assigned to oregano leaf harvest in each strategy, the total oregano leaf production was estimated. For this purpose, we used a value of 90 kg ha^{-1}, which was the average estimated leaf production in the study area. Additionally, we estimated the income derived from the previously estimated leaf production, using $15 Mexican pesos as the price for 1 kilo of dried oregano leaves, reported in interviews (Table 3).

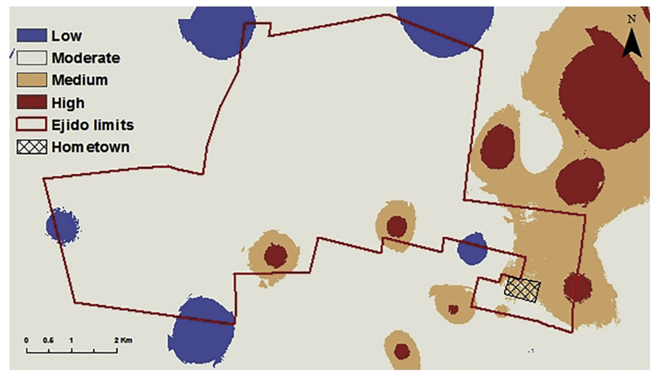


Fig. 4. Spatial distribution of the ecological aptitude of the territory for oregano leaf biomass. High suitability (ca. 1) and low suitability areas (ca. 0) are shown in red and in blue, respectively (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

4. Results and discussion

4.1. Evaluation criteria

Environmental evaluation criteria strongly determined land use suitability for oregano Harvesting or Regeneration. Average oregano plant density in the study area was 2862 ± 560 in. ha^{-1} (± standard error). Spatial distribution of oregano plants was strongly patchy and approximately half of the studied sites (26 of 51) contained individuals (Fig. 3). Likewise, average oregano leaf production was 1.84 ± 0.29 kg per studied plot, but varied widely among plots, with a range 0.01–4.9 kg (Fig. 3). In a hectare basis, the estimated average of oregano dry leaf biomass was 90.4 ± 2.9 kg ha^{-1}.

This patchy distribution can be explained, in part, by the fact that a considerable portion of the studied area presented moderate ecological aptitude for oregano leaf biomass (Fig. 4). The analysis that assessed the ecological aptitude of the territory for oregano leaf biomass, based on the selected habitat characteristics (rockiness, stoniness and NDVI), yields the following hectares available for each ecological aptitude level: high 612 ha; medium 1473 ha; moderate 8762 ha and low 581 ha (Fig. 4). Approximately 75% of the territory showed a moderate (0.36 > aptitude < 0.57) ecological aptitude for oregano leaf biomass. Areas with intermediate values (0.57 > aptitude < 0.77) were located surrounding the hometown. In general, lands with low suitability values (< 0.36) for oregano were located in the north and southwest areas (Fig. 4). Two areas of high ecological aptitude for oregano leaf biomass, located in the southern limits of the *ejido* (Fig. 4), coincide with actual

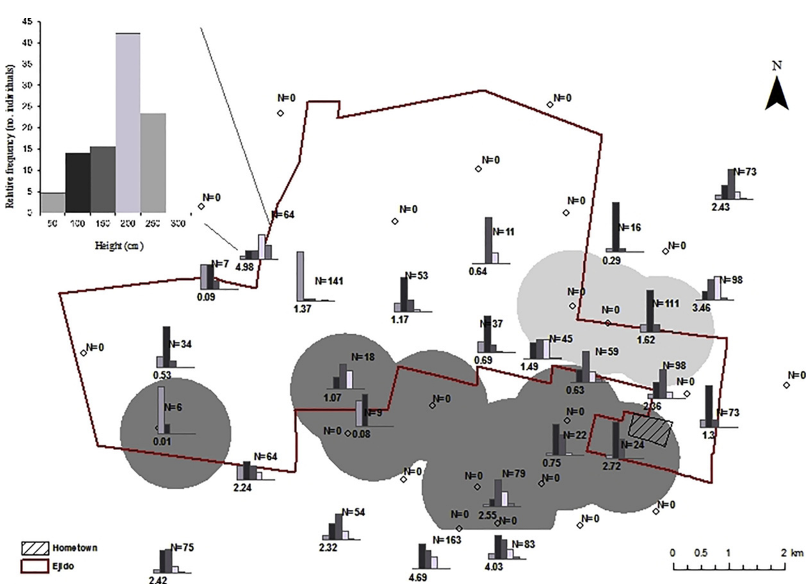


Fig. 3. Map showing sampling site locations of oregano populations. Estimated oregano leaf biomass (kg), and N = number of individuals/100 m2 are shown. Histograms represent the size (height) frequency distribution of oregano plants (enlarged in box in top left corner). Circles indicate oregano abundance based on harvesters responses in interviews: dark circles = high abundance; and light grey circles = low abundance Hometown location is indicated by a rectangle containing diagonal lines (bottom right corner) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

harvesting areas defined by interviewees as areas of high oregano abundance (Fig. 3). Our results agree with previous proposals which stated soil characteristics to be determinant in *L. graveolens* establishment and leaf production (Martínez-Ríos et al., 2014). Oregano population density in the study area was intermediate compared with reports from other regions of Mexico (Cavazos, 1991; Hernández, 1991; Soto et al., 2007).

Areas without oregano were frequently found in the northwest portion of the *ejido* and also near the hometown (Fig. 3). This result may be related with two different factors. In the northwest area of the *ejido* there is a low ecological aptitude of the territory for oregano leaf biomass (Fig. 4), which could explain the absence of oregano or its low abundance. In contrast, lack of oregano near the hometown is very probably due to over-harvesting, as confirmed by harvester observations in interviews and harvesting trips: “before we found a lot of oregano nearby” and “nowadays we need to go further and further away (in order to find the oregano)”. In addition, oregano density and leaf biomass were generally higher in areas far away from the frequently harvested zones reported by oregano harvesters (grey circles) and also from the hometown (Fig. 3). This coincides with previous reports of harvest impact on oregano populations (Osorno-Sánchez et al., 2012) and other non-timber forest products (Ticktin, 2004).

In order to reduce leaf harvest impact on natural populations, we suggest that in the Harvesting areas proposed in this study, management follows formal oregano leaf harvesting guidelines (NOM-005-SEMARNAT-2012; DOF, 2012a; 2012b), as well as the criteria established by local harvesters (e.g. no breaking of branches, no complete plant extraction, no harvest of small plants < 50 cm height, no harvest of flowers and fruits).

In relation to socioeconomic evaluation criteria, land use was deemed an important evaluation criterion for oregano Harvest and Regeneration. The analysis applied in the present study highlighted the fact that approximately half of the current oregano harvesting areas, reported by interviewees, is outside *ejido* limits (Fig. 3, grey circles). These areas involve potential resource access problems arising from conflicting interests among stakeholders. Land tenure has been frequently cited as an important factor driving NTFP harvest and conservation (Kamanga et al., 2009; Ruíz-Pérez et al., 2004; Bojórquez-Tapia et al., 2001). Land tenure in the studied area is mainly communal, although there are some private lands and cultivated areas. During the interviews and participatory mapping, harvesters mentioned that the main restriction for oregano leaf harvesting was access to private and/or cultivated lands. Indeed, it is uncommon for NTFP spatial distribution to fall strictly within political boundaries, making access to natural resources and land tenure conflict resolution a vital part of their exploitation (Bojórquez-Tapia et al., 2001; Ruíz-Pérez et al., 2004; Kamanga et al., 2009). In the study area, restriction of resource access due to land tenure is usually negotiated through personal arrangements with landowners.

Transportation to oregano harvest areas is mainly by foot; therefore, the distance to the hometown is particularly relevant for harvesters, especially when they must return carrying a load of 10–15 kg. The criterion distance to the hometown was comparatively less important to determine suitable areas for oregano Harvest, especially in areas with abundant oregano; but, was given a higher weight value for the allocation of areas to oregano Regeneration (Fig. 2A.III). This differential ponderation was based on field observations, during which we realized that if the harvest area is distant from the hometown (> 5 km) and the oregano is highly abundant, the harvesters usually resolve the situation by hiring a truck to transport the harvested leaves, thereby overcoming this limitation. In the case of the assessment of land suitability for oregano Regeneration, a higher weight value for this criterion will favour the land allocation of sites near the hometown, where oregano is currently absent.

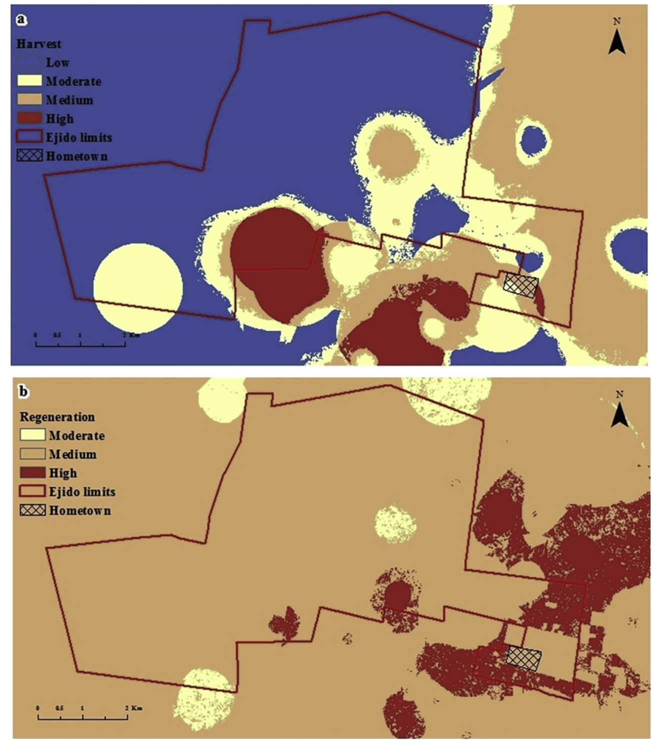


Fig. 5. Maps resulting from the Multicriteria Decision Analysis (MCDA) land use suitability analysis for oregano Harvest (a) and oregano Regeneration (b). High suitability (*ca.*1) areas are shown in red, low suitability areas (*ca.* 0) in blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

4.2. Land suitability maps for oregano Harvest and Regeneration

A visual analysis of the suitability maps showed that areas presenting a high suitability for oregano Harvest were concentrated in the south (Fig. 5a). These areas coincided principally with zones presenting a high leaf production, as well as high oregano abundance, as reported by harvesters (Fig. 3). Areas with low suitability for oregano Harvest represent, approximately, half of the *ejido* territory (Fig. 4). The presence of mature forest, together with a long distance from the hometown (> 5 km) were the main limiting factors. The presence of vegetation cover has been previously reported as an environmental factor limiting oregano development (Soto et al., 2007).

In the case of the areas suitable for oregano Regeneration, most of the *ejido* territory showed moderate and medium land suitability. Results from the MCDA showed that the areas surrounding the hometown generally exhibited high suitability for Regeneration (Fig. 5b). These areas are suggested as a priority for the development of reforestation activities as a strategy to recover oregano populations which once existed near the hometown, as mentioned by interviewees.

The land suitability maps showed that some areas are suitable for both oregano Harvest and Regeneration (Fig. 5a, b). Therefore, MOLA algorithm was used to solve these conflicts. A visual inspection of the three modelled strategy maps showed that the pixels assigned for the two objectives, Harvest and Regeneration, are spatially dispersed over the entire study area (Fig. 6). However, there are adjacent areas containing a higher proportion of pixels corresponding to either the Harvest or the Regeneration objectives. In order to facilitate the description and discussion of these different oregano management strategy maps, five contiguous pixels zones were visually delimited as land sets for oregano Harvest (Fig. 6 grey areas), and were named Central (C), southwest (SW), near hometown (NT), south (S) and northeast (NE). The remaining contiguous pixels zones (white areas) were considered land sets for oregano Regeneration. Restricted areas (e.g. human

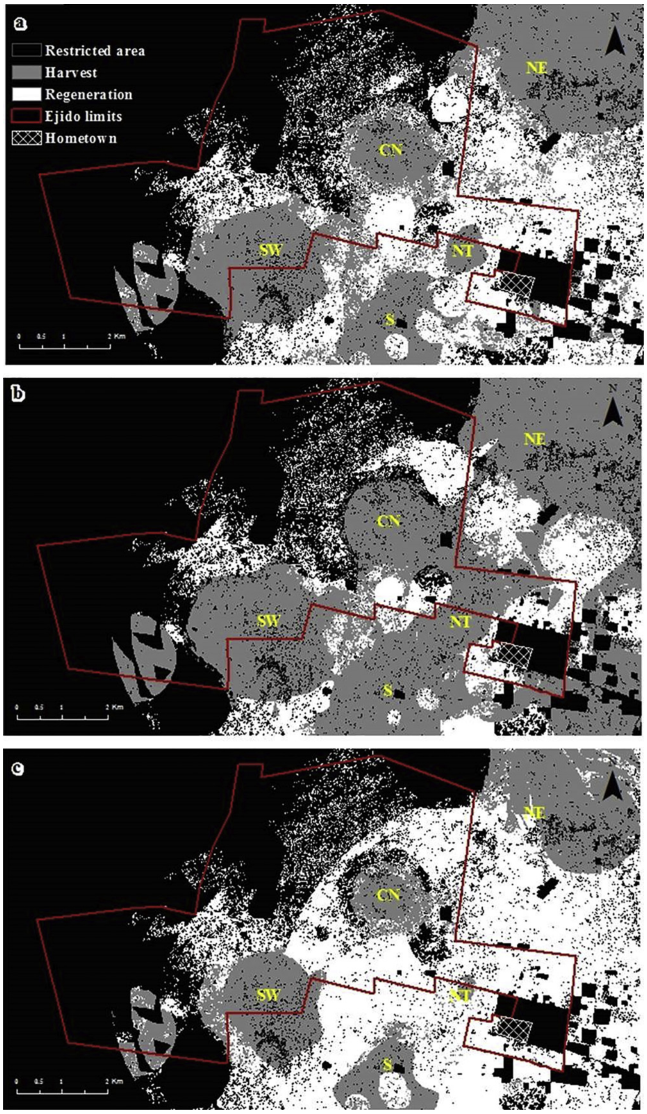


Fig. 6. Spatial distribution of the three alternative management scenarios: (a) Balanced (B), (b) Harvest (H) and (c) Regeneration (R) produced by the Multi-Objective Land Allocation Analysis (MOLA). Oregano Harvest areas are shown in grey, Regeneration areas in white and restricted areas in black. Yellow letters highlight proposed adjacent harvesting zones for implementing oregano management strategies (see text for details). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

settlements, private and cultivated lands, areas with low ecological aptitude for oregano leafbiomass)are shown in black (Fig. 6). The total area studied represented 11,492 ha; half of this area was designated as restricted. The territory of the*ejido*was 4454 ha. In terms of oregano management, it is important to highlight that in the three management strategy maps, Harvest zones CN and partially NT and SW are within the *ejido*limits (Fig. 6).

The first oregano management strategy, the Balanced (B) option, addressed the implications of a proposal where the assignation of land for oregano Harvest and Regeneration has the same importance (Fig. 6a). This option implies a balance that will allow harvesters to continue earning an income from oregano leaf harvest; and in addition, will help select the best areas for oregano regeneration. The oregano Harvest areas CN, NT and SW are particularly important because they represent the territory where settlers are entitled to decide on the use of and access to natural resources, in particular to decide on the rules that define the access to oregano leaves. In addition, harvest zones SW, NT and S are located in areas reported by harvesters for high oregano abundance (Fig. 3 dark grey circles), while zones NE and CN were not reported by users as actual oregano harvesting lands. It is interesting to note that a direct result of this study was the location of new potential oregano harvesting areas which were not reported by harvesters, nor registered during participant observation in field trips. The Harvest CN area is especially important because it is located inside *ejido* limits.

In this strategy (B), harvesting activities will be concentrated away from the hometown, while activities to promote oregano regeneration will be concentrated in the areas surrounding the hometown, where oregano populations have been overexploited and have become scarce. In the future, these regenerated areas could be incorporated into harvest, once the oregano population recovers. In this case, we proposed that a density of 2862 ± 560 in. ha^{-1}, representing the observed average density, could be used as a criterion to rotate areas from oregano Regeneration to Harvest.

In the Harvest (H) strategy map, the area allocated to the oregano harvesting goal clearly increased. The previously defined harvest zones CN, NT and S are now a continuous space and a minor increase can be also observed for harvest zones SW and NE (Fig. 6b). The areas designated for oregano harvest in this strategy extend south outside the *ejido* limits; this area is currently where leaf biomass is highest and harvesting activities are most intense (see Fig. 3 grey circles). Oregano harvesting areas outside *ejido* limits represent conflict points, since harvesters are not entitled to harvest oregano leaves in this territory, because it is part of another *ejido* land. Strategy H places the highest priority on leaf harvest, increasing revenue from oregano and motivating harvesters, but with the uncertainty if the resulting Regeneration land use area will still allow for recovery of the heavily impacted populations, especially those closest to the hometown. Maximizing the area allocated to oregano Harvest, and minimizing Regeneration areas, could have serious consequences on the species sustainability. Especially in areas surrounding the hometown, where the present process of rapid decrease in oregano abundance will be aggravated. Interviewees constantly mentioned the need to cover greater distances from the hometown each year in order to find oregano. They also mentioned that oregano used to be very abundant near the hometown, 10 to 15 years ago. Although this land use strategy could considerably increase the income obtained from oregano leaf harvest (see Table 3), it could also compromise the species persistence in the long term. This management strategy will require thorough monitoring of harvest impact on oregano wild populations.

Finally, in the map corresponding to the Regeneration strategy (R; Fig. 6c), the Harvest zones S and NT are considerably reduced in comparison with the other two maps (Fig. 6a, b). In this strategy, the area surrounding the hometown, severely impacted by oregano harvest, is almost totally assigned to the Regeneration objective. Strategy R assigns priority to oregano regeneration of much of the areas in which oregano harvesting still takes place. We consider that this option will be more difficult to implement due to the economic reliance of a considerable proportion of the households on oregano income (Llamas-Torres, 2015) and also, because the Regeneration option represents a long-term benefit, rather than the immediate profit sought under the Harvest strategy. Additionally, this R option represents a higher cost associated to monitoring harvest prohibition in a considerably larger area compared to the Harvest or Balanced management options.

Oregano leaf biomass, and by consequence estimated derived income, varied between the three management strategies. As expected, strategy H, with a greater area assigned to the Harvest objective (3920 ha), resulted in the highest leaf biomass (35.3 tons) and highest income (Table 3). Strategy R, in contrast, placed higher priority on the Regeneration objective, and therefore resulted in an estimated oregano leaf biomass and income less than half that produced in strategy H (Table 3). Any restriction on harvest goal area will clearly have a greater impact on households which depend highly on the income from oregano, highlighting the need to consider all relevant criteria when analysing a NTFP management system. The differentiated impact of resource use restrictions on livelihood economy has been reported for charcoal production, fishing, hunting and resource extraction in tropical forests (Coomes et al., 2004; Coomes and Burt, 2001).

The fact that a substantial proportion of current oregano harvesting areas are located outside *ejido* limits, seriously affects the outcome of the different oregano management strategies in terms of economic benefits for harvesters. An important premise is that the benefits the community can obtain from the oregano management areas (for harvest and regeneration) correspond to areas within *ejido* limits, because, outside *ejido* limits, the community has neither the power to decide on the land use, nor the access to natural resources. In all three analysed management strategies, reduction of the harvest area to *ejido* boundaries resulted in a substantial income reduction (Table 3). If only the area within the *ejido* (4454 ha = 40%) is used in the leaf biomass and income estimations, both values notably decrease. For example, using these boundaries in the Balanced management strategy (B), reduces leaf biomass from 25.2 tons in the total area to 8.4 tons within the *ejido* limits; a three-fold decrease. Derived income from harvest, only within the *ejido*, declines to almost half that of income estimated for the total area. Likewise, in the Harvest management option (H), income is reduced by 32% compared to the total area, and in the Regeneration (R) option it is reduced by 34% (Table 3).

Our methodological framework relied on the use of GIS tools as the major basis for displaying and analysing spatial data and integrating digital products from different sources. It showed GIS coupled with MCDA and MOLA to be a feasible approach to incorporate information from different sources. The framework modelled the best suited areas to develop different types of oregano management practices in order to ensure income generation and also natural resource conservation. Similar land evaluation approaches have been used for selecting suitable areas for agriculture (Ceballos-Silva and López-Blanco, 2003), mapping species distribution (Store and Kangas, 2001) and for defining protected areas (Bojórquez-Tapia et al., 2001; Rosete and Bocco, 2003; Orsi and Geneletti, 2010); however, studies applied to the evaluation of non-timber forest products are scarce (Mendoza and Martins, 2006; Malczewski, 2006).

The areas allocated to one of the two competing objectives can be considered not only as ecologically suitable for that objective, but because the analyses incorporated socio-economic evaluation criteria, it also simulates three possible types of preferences by users that can guide the development of management plans for oregano.

The performances of suitability assessment models can only be as good as the data fed into them, nevertheless, in many cases, the availability of data with high resolution and detail is scarce. In our case, information was obtained from different sources and from previous studies (Blanco and Ordoñez, 2003; Soto et al., 2007; CONAFOR, 2011; Martínez-Ríos et al., 2014). Therefore, we are aware that not all relevant factors for evaluation could be included with the same quality or detail and, results could be substantially improved when higher quality, resolution and detailed data become available in the future. In addition, given that in our study, weights for the MCDA and the three alternative oregano management strategies were based on field data and participant observation, it would be desirable to derive such weights using also a participatory approach, during workshops or meetings with different stakeholders. When an inclusive method is used for balancing objectives of different groups of users, sharing costs and benefits, it is more likely that the final result will receive more public support (Sheppard and Meitner, 2005).

The methodological framework proposed is deemed systematic and flexible enough to incorporate new findings that might contribute to making adjustments to suitability models and, as in the case of the three harvesting management strategies, to develop and to compare alternative models according to the opinions of different experts. Limitations of our method have yet to be exposed when compared to other types of models, such as those which process multicriteria values in parallel (neural networks, Wolfslehner et al., 2004) rather than hierarchically; however, this is beyond the scope of this study.

5. Conclusions

This study presented results from the GIS-multicriteria-mulitobjective analyses used for evaluating the suitability of different oregano management strategies for two competing land uses, oregano Harvest and oregano Regeneration. The proposed management strategies represent an important support to guide actions in the decision making process for planning and using oregano populations to generate economic benefits while ensuring resource conservation. The three simulated management strategies generated different benefits and commitments. As a result of including environmental evaluation criteria, the analyses highlighted new potential oregano harvesting areas that were neither reported by harvesters, nor registered during participant observation in field trips. On the other hand, the inclusion of socio-economic criteria, such as land tenure, highlighted the fact that a substantial proportion of current oregano harvesting areas are located outside ejido limits. The community has neither the power to decide on land use outside ejido limits, nor the access to natural resources. Harvesting oregano in these areas generates land tenure conflicts with neighboring ejidos and seriously affects the income generated from oregano harvest.

We consider that the proposed Balanced management strategy, in which the same proportion of suitable area (50%) was assigned to both objectives, represents the most advantageous strategy. This option allows harvesters to continue earning an income from oregano leaf harvest; and at the same time represents a smaller impact on oregano populations in comparison with the Harvest option (70% area assigned to Harvest). Likewise, in comparison with the Regeneration management strategy (70% area assigned to Regeneration), the Balanced option represents a smaller decrease on the harvesters´ income, and lower monitoring costs, both derived from oregano harvest prohibition in a smaller area.

Independently of the proposed management strategies, there are risks of failure, inherent to the studied system, which could prevent the overall goal of sustainability in oregano management. Within the studied area, there are other land uses which compete with oregano harvesting and/or regeneration, such as livestock, agriculture, and urban development. The growth of these activities and their impact on oregano abundance and distribution need to be taken into account in order to develop long term land use planning, incorporating other productive activities within the territory. On the other hand, oregano leaf production depends on rainfall. Climatic fluctuations and considerably dry years could compromise the availability of this non-timber forest product.

In many developing countries, decision-making does not generally rely on quantitative data nor considers the involvement of local user groups. Frequently, it is based on single and often simplistic criteria responding to immediate needs, while resource management can be based more on political views than on scientific evidence. We consider that the proposed analytical framework may contribute to advance the application of systematic approaches for solving decision-making problems in areas where oregano leaves and other NTFP are harvested.

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