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FIRE MANAGEMENT AND RESTORATION PLAN IN THE SIERRA DE MANANTLÁN BIOSPHERE RESERVE, MÉXICO

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1. INTRODUCTION

Wildfires are a common disturbance in forested ecosystems around the world (Chandler *et al.* 1983, Whelan 1995), and a controversial issue for biological conservation and protected area management (Pyne 1996, SCBD 2001, Jardel *et al.* 2003 a).

In the case of México, fire is a frequent phenomenon in protected areas such as national parks and biosphere reserves, especially those found in mountainous areas. Wildfires tend to be associated with deforestation, since fire is used to convert forests and other types of vegetation into agricultural fields or pastures. Even though high wildfire frequency is indeed associated to degradation processes in remaining vegetation, there is evidence from ecological studies around the world that demonstrates that fire—whether originated by natural causes such as lightning or by humans for agricultural burning and other historical uses of fire—is and has been part of forested ecosystem dynamics as well as the evolutionary environment of their biota (Agee 1993, Whelan 1995, Pyne *et al.* 1996).

Prevention, combat and suppression are the mainstream policy approaches to wildfires in forests and protected areas in México. These are based on a negative perception of the role of fires in forest ecosystems, which prevails among the public opinion, policy makers in the forestry and environment sectors, and among Mexican conservationists and foresters.

Despite the attempts to suppress fires, the area burned annually is increasing. According to official reports, the average area burned between 1970 and 2002 was 218,627 ha year^{-1}, with critical years like 1988 or 1998 with 518,265 and 849,632 ha burned respectively (www.semarnat.gob.mx).

In many forest ecosystems, fire suppression can be considered as a disturbance that changes the species composition, structure and function of ecosystems, as well as causes an increase in fuel loads, thus affecting the severity of fire effects Whelan 1995, Pyne *et al.* 1996).

In Mexican subtropical mountain forests, the absence or the lack of fire may result in alterations to ecological patterns and processes (González-Cabán and Sandberg 1989, Fulé and Covington 1996, 1999, Rodríguez-Trejo 1996, Heyerdahl and Alvarado 2003, Jardel *et al.* 2003 b, Rodríguez-Trejo y Fulé 2003). Therefore, research and experimentation on fire ecology and management in Mexican forests are a fundamental need to develop scientific knowledge, techniques and experience that can be applied to the sustainable use, conservation or restoration of these forest ecosystems.

The persistence of high forest fire incidence indicates that the suppression approach must be reconsidered. Current knowledge on fire ecology, together with forest and protected area management experience, points out that it is essential to change the current paradigm of fire prevention, control, and reforestation of burned areas to one that incorporates fire management and ecological restoration strategies.

Furthermore, the fact that most forest fires are of anthropogenic origins implies that the understanding of fire as a social and cultural phenomenon is fundamental in any management or conservation strategy.

This paper presents and discusses the conceptual framework of a fire management and forest restoration strategy for a mountainous protected area in Western México, the Sierra de Manantlán Biosphere Reserve (SMBR). It also presents some ideas for the development of a fire management model applicable to México's forests, which are characterized by their environmental heterogeneity, high biological diversity and social complexity (Jardel 1990, Challenger 1998).

2. THE SIERRA DE MANANTLÁN BIOSPHERE RESERVE

The Sierra de Manantlán is located in the states of Jalisco and Colima, in Western Central México. It is found between 19°25'-19°45' N latitude, and 103°45'-103°30' W longitude (**Fig. 1**). The Biosphere Reserve, established in 1987, covers 139,577 ha of heterogeneous mountainous landscape, with an altitude ranging from 300-600m to 2500-2860m above sea level (INE, 2000).

Present along this wide altitudinal gradient are warm to temperate climates with summer rains (June-September). Because of the rain shadow effect, the southern slopes, oriented towards the Pacific Ocean, are more humid than north and east facing slopes.

Two main landscape units can be differentiated in the Sierra's geology and geomorphology. The Western-Central portion, formed by igneous extrusive rocks from the Tertiary, and the eastern portion, formed by a calcareous dome from the Cretaceous, with strong karst development. In both parts, igneous intrusive rocks from the Cretaceous form the basement, while Quaternary sediments cover the Sierra's lower slopes and intermontane valleys (Jardel *et al.* 1996).

Figure 1. Location of Sierra de Manantlán Biosphere Reserve.

Given the variety and complexity of physical conditions described above, as well as to the natural disturbance patterns and human influence, a complex vegetation mosaic covers the SMBR, where forests represent 76% of the protected area. Tropical dry forests are found below 1200 meters above sea level (masl), deciduous oak forests between 1200-1800 masl, and pine and oak forests over 1800 masl. In more humid and sheltered conditions, such as those of narrow valleys, ravines and karstic depressions, tropical sub-humid forests are found in the lower parts, montane broadleaved forests (cloud forest) are found in middle altitudes (1400-2200 masl), and fir-pine-oak forests in higher altitudes (above 2200 masl). Scrub and pastures cover sites disturbed by agricultural clearing and burning (INE 2000).

The area provides habitat for a rich biological diversity. More than 2900 vascular plant species and 560 vertebrate species have been registered, including many rare, endemic and endangered (INE 2000). The SMBR is host to unique biotic communities and species found at the limits of their latitudinal distribution range, given its location in a transition zone between the Neotropical and Nearctic biogeographic realms.

The SMBR project was onset by the discovery of an endemic plant, a wild relative of corn that was named *Zea diploperennis*. This discovery led to botanical and zoological explorations that called the attention of experts to the biological richness of the Sierra de Manantlán. Thus, a protected area was proposed and in 1985 the Government of the State of Jalisco and the University of Guadalajara established a research station in the heart of the Sierra. The SMBR was decreed by the federal government in 1987, given the area's importance for biological conservation and watershed protection, as it is a water source for more than 400,000 people living in its proximity (Jardel *et al.*1996).

The SMBR management approach integrates ecological conservation and social development goals (Jardel *et al.*1996). An estimated 32,000 people inhabit the protected area, where social conditions are characterized by poverty and marginalization. The federal decree did not modify land tenure, and the existing land ownership prevailed after the decree: 68% of the reserve's area is owned by agrarian communities, and 32% by private landowners. However, the decree and management program (INE, 2000) establish management rules and restrictions over land and natural resources, based on zoning. The Reserve has three core zones, which cover approximately 30% of the protected area (41,898 ha), designated to protect headwaters and critical habitats for biodiversity conservation. Strict protection is enforced in core zones through various mechanisms negotiated with landowners (Jardel *et al.* 2003 a). A buffer zone surrounds the core zones, where management goals are directed to implement sustainable practices in forestry, agriculture, cattle rising, tourism and other natural resource management activities.

The basis of management in the SMBR are co-management mechanisms negotiated between the federal authority (National Commission for Natural Protected Areas, CONANP), represented by the Reserve's Direction, and agrarian communities and local organizations (INE 2000, Graf *et al.* 2002). These instances work together in the establishment of institutional arrangements and the execution of management programs directed to sustainable use of natural resources, rural development and ecological conservation.

Thus, a complex ecological and social setting and a management strategy that combines ecological conservation and social development goals are the context for this fire management and forest restoration program.

3. WILDFIRE IN THE SMBR

3.1. Incidence of forest fires

As in many Mexican mountainous zones, there is a high incidence of wildfires in the Sierra de Manantlán. Fire in the area has been mainly associated with agricultural burning, and it is considered one of the most influential factors in the composition and structure of vegetation as well as in forest succession (Jardel 1991, 1998). Forest fires occur in the dry season, between the end of December and early June, peaking in March, April and May.

Preliminary studies on fire history reconstruction in pine-oak forests in the SMBR indicate that in individual stands the mean interval between fires is between 5 and 14 years (Jardel 1991, Enríquez 1998). This is similar to that reported for other pine-oak forests in México (Fulé and Covington 1996; 1999; Heyerdhal and Alvarado 2003).

As part of the SMBR's fire management planning process, a database and a Geographic Information System (GIS) were integrated, using the available information from fire-fighting crew reports and field inspections. The information included in fire-fighting crew reports includes location, burned area and vegetation types, and fire-fighting operations. These reports are collected and filed by the SMBR Direction since 1995. Since 2001, burned areas are inspected in the field and located in topographic maps with coordinates obtained with a Global Positioning System (GPS).

Between 1995 and 2003, 327 fires were registered, adding up to a total burned area of 61,664.8 ha. The mean area burned per year was 6,851.6 ± 1,291.1, and 36 ± 4 fires were registered. Thus, the burned area per year equals 4.9% of the total SMBR area, and 5.6% of its forested area. **Figure 2** shows as an example the location of the fires registered in 2002.

Pine-oak and oak forests comprise 53.7% of the SMBR area, where 37% of the registered fires occurred in pine-oak forests and 27% in deciduous oak forests (Jardel *et al* 2003).

Since 2001, the burned areas have been delimited and incorporated into the GIS as polygons. In average, 29.5% of the affected area is registered in pine-oak forests, 27.8% in deciduous oak forests, 13.8% in oak-pine forests and 16.2% in scrub, grasslands, and slope agriculture (Castillo *et al*, 2003). Most scrub vegetation is found in abandoned or fallowing agricultural fields.

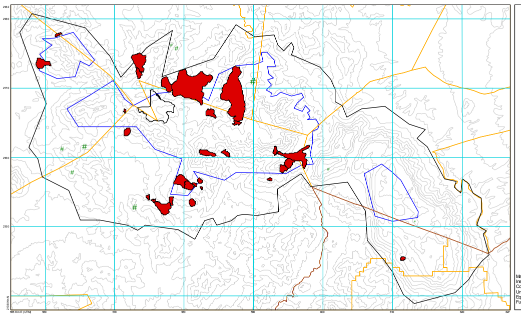

Figure 2. Area burned in 2002.

Fire distribution patterns allowed the identification of critical areas of high fire incidence . From the total area affected by fire in the last three years, 882.6 ha burned in two subsequent years, and 223.1 ha in three subsequent years (Castillo *et al*. 2003).

33.5% of fires are associated to agricultural burning, 15.8% to illegal crop cultivation, namely marihuana and poppies, 11.9% were intentionally caused and 3.2% were caused by visitors, while 32.4% of reported fires had undetermined causes.

Compared to anthropogenic fires, natural fires are very rare. Lightning is associated to rainstorms, causing the death of individual trees and small gap openings. There is anecdotic evidence of wildfires produced by lightning at the beginning of the rainy season, when early rainfalls and thunderstorms are followed by some dry days.

3.2. Fire effects

Generally, areas affected by fires in México are not systematically evaluated. Furthermore, there are few fire ecology studies conducted in Mexican forests, resulting in a gap of the information and knowledge needed for the design of fire management strategies (see for example González-Cabán and Sandberg 1989, Fulé and Covington 1996, Rodríguez-Trejo 1996).

In order to evaluate the effects of wildfires in the forests of the SMBR, as part of the planning process for fire management and restoration activities, information was compiled, systematized and integrated from different sources. In addition to the GIS and the database made from the fire-fighting crew reports, the affected sites were inspected and interviews were conducted with local people, researchers and personnel involved in the Reserve's management and fire prevention and control. A revision of ecological research concerning the effects of fire on the regional flora and fauna was made, focusing in pine-oak and mountain cloud forests. Empirical knowledge acquired through 16 years of fieldwork and observations, in the case of the first two authors, was also taken into account. Following is a summary of the most relevant findings.

Most forest fires in the SMBR are surface, low-intensity fires. Crown fires are restricted to small areas located in hilltops and ridges. 98% of the fires registered between 1995 and 2003 were surface fires, and the remaining 2% were classified as crown fires. Fires are relatively small in size (**Fig. 3**), averaging a burned area of 189.2 ha per fire and a mode of 50 ha, while 84% of the registered fires were less than 300 ha (Jardel *et al*, 2003).

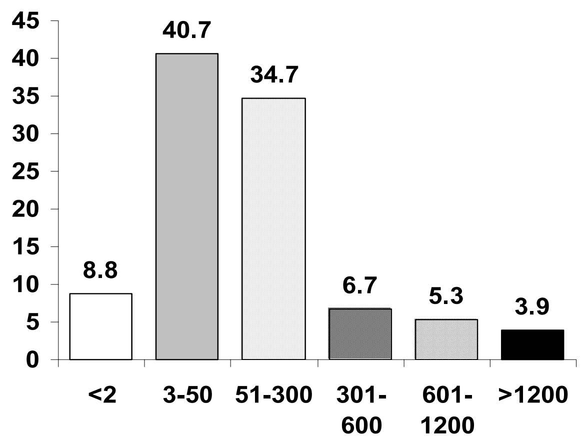

Figure 3. Percentage of total number of fires registered between 1995-2003, classified by size (ha).

The most severe fire damages in terms of tree mortality and gap opening are associated to topographic conditions —hilltops and ridges, steep slopes and windy sites— or vegetation structure —very dense stands with vertical fuel continuity—. Fire can cause relatively large gap openings (from hundreds of square meters to a few hectares) in crown burned patches, when severely damaged trees die after fires, or when fire occurs in association to agricultural clearings or intensive logging with slash accumulation. Abundant pine tree regeneration is established in these gaps. Pines, such as *Pinus pseudostrobus, P. douglasiana, P. oocarpa, P. devoniana*, some oaks, such as *Quercus scytophylla* and *Q. castanea*, and madrone (*Arbutus xalapensis*) regenerate well in fire-opened gaps (Anaya 1989; Jardel 1991; Saldaña and Jardel, 1992).

Surface fires also favor pine dominance over other shade-tolerant species that are less resistant to fire, such as firs (*Abies religiosa* and *A. religiosa* subsp. *emarginata*) and hardwoods (such as *Carpinus tropicalis, Cornus disciflora, Fraxinus uhdei, Magnolia iltisiana, Persea hintonii, Zinowiewia concinna* and others) that are the successional replacement of pines in the absence of fire (Saldaña and Jardel 1992, Sánchez-Velásquez and García-Moya 1993, Jardel 1998, Jardel *et al* 2001b).

Observations in permanent plots established for research on succession (Jardel *et al*, 2001b) suggest that surface fires accelerate self-thinning processes in pine stands, eliminating suppressed trees. Furthermore, shade-tolerant broadleaved species tend to increase in dominance in sites where fire has been excluded for many years.

In summary, field observations indicate that fire favors dominance of pine forests and some oak species, while it has negative effects on the regeneration of fir and mountain cloud forests. Given that these two forest types are considered priorities for conservation in México and the SMBR (INE 2000), fire control measures have been adopted to foster their conservation and restoration (Jardel *et al*. 2003 b).

Inasmuch fire favors the establishment of pine forests, when fires occur repeatedly in young stands, regeneration establishment is prevented and replacement by secondary scrub occurs. Furthermore, the combination of fire and factors such as logging, overgrazing or poorly constructed logging roads, leads to forest degradation and soil erosion. Under these conditions it is necessary to adopt restoration measures that imply erosion control and soil conservation practices, reforestation with native species and temporary fire suppression.

Prescribed experimental burning undertaken in Las Joyas Research Station (LJRS), in the central part of the SMBR, indicates that controlled fires can reduce fuel loads without causing significant tree mortality. A reduction of 65% to 70% of woody fuel load and 70% to 80% of litter depth was observed in pine-oak forests following prescribed burns.

Different conditions are observed in burned sites:

a) Sites that have undergone crown or recurrent fires, in addition to the influence of logging and overgrazing, with scarce tree regeneration, few seed trees, seedlings or sprouts, and severe soil erosion.
b) Sites where frequent surface fires have halted regeneration of tolerant conifer or broadleaved tree species, disrupting successional processes

that lead to the establishment of endangered forest types such as cloud forests or fir forests.

c) Sites where abundant pine regeneration is established following forest fires, giving rise to oversaturated stands. High tree density leads to competition among trees, slowing growth and causing tree suppression and insect attack outbreaks. These stands have marked vertical and horizontal fuel continuity and they are very susceptible to severe fires.

Given these three conditions described above, different types of restoration management are needed. For sites in the first group, these measures range from fire suppression, elimination or control of damaging factors such as logging or grazing and protection to foster and protect natural regeneration, to the implementation of soil stabilization measures, and forest recovery through reforestation with native tree species. In the second group, fire and grazing must be controlled to favor successional replacement processes and thus to foster the establishment of cloud and fir forests. In the third case thinnings and prescribed burns are required to regulate density and to improve the health conditions of stands.

3.3. Fire regime

Ecological research has shown that there is an important variation in fire regimes and ecosystem responses to fire effects (Heinselman 1981, Agee 1993, Whelan 1995). Montane subtropical forests are characterized by a marked variation of site conditions, high species diversity and transition patterns between different vegetation units along climatic, topographic and soil gradients. Thus, it is essential to consider that the environmental heterogeneity of these forests is reflected in fire regime diversity and a variety of ecosystem responses to this disturbance, which in turn has important implications on fire management and restoration.

Using information generated through studies and observations made in the SMBR, and from available literature on fire ecology, a number of forest fire hypothesis for the area were developed, summarized in **figure 4.** These were based on the model proposed for Pacific Northwest forests in the United States by Agee (1981). This model relates potential vegetation types to temperature increase and moisture stress indices, taking into account climatic factors that determine plant biomass growth and fire incidence. Fire regimes in the Reserve were characterized based on fire frequency and the severity of their effects on vegetation. The hypothesis for the study area is that in “natural” conditions (i.e. absence of anthropogenic fires), four fire regimes would be observed:

1) Very rare or infrequent light surface fires, associated to droughts, windstorms or cyclones, that increase mortality, tree fall, and fuel load. This would be the characteristic fire regime in forests with more humid conditions, such as subdeciduous tropical forests and montane cloud forests, where broadleaved species are predominant. The severity of their effects can be high, since most tree species in these forests are very susceptible to fire. This fire regime is similar to that described for humid tropical forests (López-Portillo *et al* 1990, Uhl 1998, Cochrane 2003).

2) Infrequent (50-100 years return interval) surface or crown fires, with severe effects and stand replacement. This regime would correspond to fir forests, located in the coldest and moister upland sites in the study area and is similar to the fire regime of boreal forests (Johnson, 1992; Agee, 1993), although given the topographic conditions of the study area, fires cover small areas. Fires can occur associated to extreme droughts and insect outbreaks in old-growth, even-aged stands. This can also be the fire regime in mixed pine-broadleaved forests found in mesic sites where the potential vegetation is cloud forest.

3) Frequent surface fires (average return interval of less than 25 years) with low severity (understory consumption, individual tree mortality, generally concentrated in suppressed trees, with small gaps opened by fire crowning or tree mortality after fire). This would be the characteristic fire regime in pine and oak forests, similar to that described for pine forests in the Sierra Madre Occidental (Fulé and Covington 1996, 1999, Heyerdahl and Alvarado 2003).

4) Infrequent low severity fires. This regime would correspond to forests under drier conditions (deciduous tropical forests) where fuel accumulation is low and fires coincide with the dry season when plants such as deciduous trees and cryptophytes, are less susceptible to damage. In general, dry tropical forests of the region do not have natural fire regimes. Fire in these systems is associated to agricultural clearings or alterations due to tree removal and grass introduction (Mass 1995).

These fire regimes are hypothetical and represent extreme conditions within a gradient. They constitute a preliminary guide to design and experiment fire management practices and should be further studied.

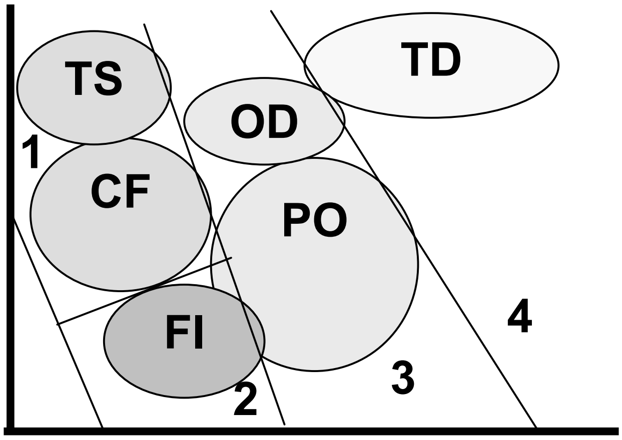

Figure 4. Potential vegetation units along a moisture stress index (X axis), a temperature gradient (Y axis), and hypothetic fire regimes (1–4). TS–tropical subdeciduous forest, TD–tropical deciduous forest, OD–deciduous oak forest, CF–cloud forest, PO–pine-oak forest, FI–fir forest. See text for description of fire regimes.

Moreover, it should be considered that fire regimes in the study area have been modified throughout centuries of human interventions, including a diversity of variables in space and time. Among these are increases on fire frequencies by agricultural burning, fuel load reduction caused by cattle grazing, vegetation structure and composition and fuel load alteration by agricultural clearings and logging, as well as fire suppression activities. Thus, setting restoration objectives is a complex issue, where a series of questions are posed concerning what would be an adequate fire regime for ecological conservation and forest production goals in a multiple use management unit (the SMBR) that has a great ecosystem diversity. Therefore it is necessary to define explicit objectives regarding the structure of vegetation, its composition and desirable conditions, taking into consideration management goals and the zoning of SMBR. It is also needed to design and implement a fire management program with an experimental or "learning by doing" approach based on the concept of adaptive management (Walters and Holling 1990), combining fire exclusion measures in some sites with prescribed burning in others, along with reforestation and soil restoration actions in the most degraded sites.

3.4. The social component

Fire in forested ecosystems is not only an ecological factor but it also is a social phenomenon. Most forested areas in the world have a long history of anthropogenic fire (Pyne 1997). Despite this, it is common that fire management and ecological restoration plans tend to focus in biophysical and ecological aspects.

Incorporation and consideration of social issues is essential to the success of any task related to management of natural resources. Deforestation and degradation processes are a consequence of social factors related to economic development policies, consumption patterns and market forces, land tenure structure and demographic growth. Depending on the ecological and social context, fire can be a destructive factor associated to land use change and deforestation, or a management tool for forestry or habitat management. It is therefore necessary to consider and understand the social processes, related to forest fire incidence as well as fire use and management.

Practically all the wildfires registered in the SMBR in the last years are of anthropogenic origins, and most of them are linked to agricultural burning and start in the interface between forests and croplands. Most agricultural fields are located in the lower slopes of the Sierra, with the exception of the eastern part of the reserve that corresponds to the Cerro Grande plateau.

Reducing the number of fires caused by agricultural burning involves the transformation of economic, cultural and social organization aspects that are behind agricultural practices. The use of fire to burn agricultural fields is a strongly rooted tradition among peasants. It is a cheap tool to clear land as well as to control, competing weed and insect populations, and it also helps to mobilize nutrients in fallows as part of swidden agricultural practices. However, burning ceases to be a sustainable practice in sites where traditional agricultural practices have been modified with time reduction on fallowing, abandonment of soil conservation practices and increased use of agrochemicals. In this situation, the use of fire contributes to cropland degradation, as it eliminates organic matter that should be incorporated to the soil. Fire use replacement in agriculture implies the need to introduce new cropping practices, such as soil conservation practices, use of green manures and establishment of cover crops. These practices need to be accepted by peasants and can be economically and socially viable depending on the profitability of agricultural production as well as work force and capital availability.

Throughout the past years programs on environmental education concerning wildfires and the problems associated to them have been implemented directed to the population of the SMBR and its influence region. At the same time, organization and programming of agricultural burnings has allowed to reduce the number of fires caused by this activity.

Land tenure is another important factor related to fire management. There are three types of land ownership in the reserve: private, communal and *ejido*. The last two correspond to collective land tenure regimes. Private property represents only 32% of the total SMBR area, while 68% of its area are ejido and communal lands (INE 2000). The GIS was used to estimate fire incidence per land tenure type between 1995 and 2003, and it was found that 53% of the burned area was located in private lands, while 47% of the burned area was located in ejido and communal lands (Jardel *et al.* 2003). Thus, 5.6% of private lands burn every year, compared to 2.5% of area burned in collective lands, despite the fact that croplands are concentrated in ejido and communal land.

Contrary to a prevailing idea that collective property is more inefficient than private or state property regimes for natural resource conservation purposes, these results indicate that the circumstances are opposite in the SMBR. A possible explanation of this is that under communal and ejido regimes there is tighter community control as well as greater mobilization and performance capacity for control of wildfires. In contrast, most private owners do not live in the area and thus they do not have control over their land, in which there is an *open access* situation (Orstom 1990), which indicates that the property regime is dysfunctional.

Property is not an object; rather, it is a social construct that consists of social relations that define the rights and benefits of the property holder. A property regime is a structure of rights and duties characterizing the relationship of individuals to one another with respect to land and resources (Bromley 1991). There are different forms of land and resource property regimes, and their functionality depends on social relationships, as well as on the effectiveness of institutional arrangements and authority systems to protect the property holder's rights. Open access conditions arise when there are lands or resources over which no property rights have been recognized, or when there are no authority systems or institutional arrangements that can assure respect of property rights. Under these conditions, any property regime can be dysfunctional and overexploitation and degradation arise.

Many private lands in the SMBR are in open access conditions, where land owners are absent and do not control their land and resources, or subject to tenure conflicts with other land owners, and in some cases, private lands are invaded for production of illegal crops or logging (Jardel 1999). Thus, intentionally ignited fires and the lack of fire control interventions are frequent in private lands.

Land tenure conflicts and uneven land distribution are also factors that limit the possibility to establish long term agreements between the SMBR Direction and land owners to implement management and conservation activities on their lands, including fire management and restoration actions (Jardel *et al.* 2003 b). Hence, the solution to land tenure conflicts is a priority in the SMBR management strategy (INE 2000).

Another important factor is that in an area such as the SMBR, there are multiple social stakeholders involved in management. They have different goals, interests and action capacity. Among these are: peasants, cattle ranchers, communal or private forestry enterprises and NTFP gatherers, government agencies, research centers, environmentalists, and urban inhabitants of the region. These groups have different interests and perceptions of wildfire issues. For example, peasants use fires as a tool for agricultural practices, a city environmentalist perceives fire as a cause of forest destruction and a forester or reserve administrator may use prescribed burns as a tool to foster forest regeneration or to reduce fuel loads and severe fire hazard. Wildfires may also cause decrease in water quality or degradation of outdoor recreation places for urban people. Thus, a fire management program should consider mechanisms to solve conflicts or concilliate interests of different stakeholders.

4. FIRE MANAGEMENT STRATEGY

Fire management and restoration practices have to be developed in the complex context of social and ecological conditions described above, as part of the ecological conservation and social development strategies in a biosphere reserve such as the SMBR.

Management decisions are presented by the SMBR Direction for their validation by the Advisory Council. Leaders of agrarian communities, local non-governmental organizations, municipal authorities and representatives of the region's state universities integrate this council, who asked the SMBR Direction and the Instituto Manantlán de Ecología y

Conservación de la Biodiversidad to design a *Fire Management and Restoration Plan*, as described in the reserve's management program (INE 2000). This plan establishes the conceptual framework, general guidelines, and actions for fire management and restoration of degraded areas.

Management goals are different for core and buffer zones. The objective of core zones is to protect headwaters and to maintain biological diversity and rare or endangered species or habitat types. Fire management should contribute to these goals, implying a strategy that includes fire suppression in some sites to foster conservation and regeneration of fire-sensitive forests, such as montane cloud forests or fir forests, and prescribed burns in other sites to reduce severe fire hazard or to improve regeneration, structure or health conditions of pine-oak stands.

Restoration in core zones is focused in the recovery of sites affected by repeated fires and intensive logging in the past, to increase forest cover, preserve biodiversity and to maintain the production of environmental services. Thus, the management approach implies control of the factors that cause degradation to protect sites to allow their natural recovery through regeneration and successional processes, or to intervene where soils have been strongly altered and natural regeneration is inadequate.

Fire management and restoration are directed to productive activities in the buffer zone. This implies the use of prescribed burning in silvicultural practices for timber production, and rehabilitation of high-graded forests to improve their productivity and economic value.

The SMBR *Fire Management and Forest Restoration Plan* includes the following action lines:

1) Wildfire prevention and control, where the goal is to reduce the number of wildfires and burned area.
2) Regulation or substitution of fire use in agriculture, including programmed and controlled agricultural burning as well as the undertaking of alternative agricultural practices that do not require fire use.
3) Experimental prescribed burning for fuel management, habitat conservation and silvicultural treatments. There is a need to develop knowledge and practical experience to manage fire in order to reach management prescriptions in the complex ecological conditions of the SMBR. A "learning by doing" approach is proposed, based in the concept of adaptive management.
4) Restoration of sites degraded by frequent fires and associated factors such as agricultural clearing, poor logging practices and livestock grazing, with an experimental management approach.

5) Applied research on fire ecology and management, and restoration ecology, and development of monitoring and information systems to support management decisions.

6) Improvement and strengthening of local capacities through education and training in fire management and ecological restoration at different levels.

7) Environmental education and public outreach. It is important not only to create consciousness about wildfires as a problem, but to convey knowledge and foster the understanding about the ecological role of fire, and to promote changes in attitudes and behavior towards fire management. The challenge is to move from a negative perception of forest fires , which has been promoted by most public outreach and environmental education programs, to an understanding of the ecology of fire and the use of fire as a management tool.

8) Development of institutional arrangements and operational mechanisms, since the implementation of any management plan requires the establishment of agreements among stakeholders, as well as organization, in order to make possible effort coordination and resource optimization.

9) Long-term funding to implement the fire management and restoration plan, which requires a coordinated and wellorganized use of available government resources and support programs, donations from non-governmental organizations and the design of long-term financial mechanisms, such as an endowment fund for the management of the SMBR.

These activities are planned and implemented in collaboration with government agencies, local communities, regional education and research institutions and international and national donors.

5. CONCLUSIONS

It is fundamental to understand the ecological role of fire in order to design sound management practices that include goals for biological conservation, ecological restoration, productive rehabilitation and sustainable silviculture. Given the current state of information about fire ecology, species diversity and the socio-ecological complexity of Mexican mountains, scientific research and experimentation are needed.

As it has been discussed, social issues are also a crucial component of a fire management strategy; therefore it is necessary to take into account stakeholder interests, land tenure, long-term institutional agreements, as well as decision-making and conflict resolution mechanisms.

This case study presents a complex socio-ecological context of fire management and ecological restoration in subtropical montane forests. It also reveals the importance of biosphere reserves as sites for experimentation with alternative natural resource management and conservation approaches and models that can be applied beyond their boundaries in order to create positive impacts on biodiversity conservation.

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