UNIVERSIDAD NACIONAL AUTÓNOMA DE MÉXICO

POSGRADO EN CIENCIAS BIOLÓGICAS

INSTITUTO DE ECOLOGÍA

El análisis de aptitud del suelo como herramienta para definir la distribución de las especies y su uso en el diseño y manejo de las áreas naturales protegidas

T E S I S

QUE PARA OBTENER EL GRADO ACADÉMICO DE

MAESTRA EN CIENCIAS BIOLÓGICAS
(BIOLOGÍA AMBIENTAL)

P R E S E N T A

GEORGINA ALCANTAR LÓPEZ

DIRECTOR DE TESIS: DR. LUIS ANTONIO BOJÓRQUEZ TAPIA

MÉXICO, D.F. MARZO, 2006

Ing. Leopoldo Silva Gutiérrez
Director General de Administración Escolar, UNAM
Presente

Por medio de la presente me permito informar a usted que en la reunión ordinaria del Comité Académico del Posgrado en Ciencias Biológicas, celebrada el día 7 de noviembre del 2005, se acordó poner a su consideración el siguiente jurado para el examen de grado de Maestría en Ciencias Biológicas (Biología Ambiental) de la alumna **Alcantar López Georgina** con número de cuenta **90087051** con la tesis titulada: **"El análisis de aptitud del suelo como herramienta para definir la distribución de las especies y su uso en el diseño y manejo de las Áreas Naturales Protegidas"**, bajo la dirección del **Dr. Luis A. Bojórquez Tapia.**

Presidente:	Dr. Víctor Sánchez-Cordero Dávila
Vocal:	M. en C. Salvador Sánchez Colón
Secretario:	Dr. Luis A. Bojórquez Tapia
Suplente:	Dr. Rurik Hermann List Sánchez
Suplente:	Dr. Mariano Hernández Narváez

Sin otro particular, quedo de usted.

Atentamente
"POR MI RAZA HABLARA EL ESPIRITU"
Cd. Universitaria, D.F. a, 9 de marzo del 2006

Dr. Juan Núñez Farfán
Coordinador del Programa

c.c.p. Expediente del interesado

Agradezco el apoyo económico recibido por parte de:

- Programa de Beca Crédito del Consejo Nacional de Ciencia y Tecnología (CONACYT) para estudios de Maestría en la Facultad de Ciencias, UNAM.

Agradezco la asesoría proporcionada por los miembros de mi Comité Tutoral y del jurado:

- Dr. Luis Antonio Bojórquez Tapia
- Dr. Mariano Hernández Narváez
- M. en C. Salvador Sánchez Colón

Agradezco el tiempo dedicado a la revisión y comentarios de otros miembros del jurado:

- Dr. Víctor Sánchez Cordero
- Dr. Rurik List Sánchez

Gracias al Dr. Luis Bojórquez, al Dr. Mariano Hernández y al M. en C. Salvador Sánchez por sus valiosos comentarios y por permitirme aprender de cada uno pero, sobre todo, por su entrañable amistad.

Gracias al Dr. Victor Sánchez Cordero y al Dr. Rurik List Sánchez por creer en el trabajo y aceptar integrarse al jurado.

Gracias al propio proceso de trabajo que me ha permitido conocer, colaborar y aprehender de tanta gente. Espero también haber dejado cosas positivas en cada uno de ellos.

Gracias a Ivan por compartir mi vida, mi tiempo y mi espacio pero principalmente por creer en mi trabajo y capacidades, incluso más que yo.

Finalmente, Gracias a mi universidad por ser el espacio en donde encontré formación, aprendizaje, a mi pareja, a mis amigos para toda la vida y a Luis mi maestro.

Índice

Índice

Resumen

El aumento en la explotación de los recursos naturales como consecuencia del crecimiento poblacional provoca la pérdida de la diversidad biológica. Para limitar los efectos de estos procesos es necesario identificar las áreas naturales que deban ser conservadas por la biodiversidad que alojan. Sin embargo, para poder conservar es necesario, primero, conocer los sitios que ocupan las especies. Para conseguirlo, es necesario conocer la distribución de las especies en el territorio. En este trabajo se utilizó el análisis de aptitud del suelo para definir la distribución de las especies a partir de las características bióticas y abióticas de los lugares donde las especies se encuentran; así como en la importancia que tiene cada factor para determinar dicha aptitud. Así, se utilizaron los métodos multicriterio-multiobjetivo para evaluar la potencialidad del suelo para albergar las poblaciones de las especies y a partir de ella, definir los límites y la zonificación de diferentes Áreas Naturales Protegidas. Estos métodos y la consulta a expertos permitieron obtener los atributos del paisaje necesarios para que las especies permanezcan en la región y así determinar cuales son las áreas necesarias para su conservación. Finalmente, estudios como estos establecen las bases en la definición de políticas de conservación, así como los objetivos de dichas políticas, es decir, definen qué se debe conservar y dónde se encuentra.

Introducción

La planeación del uso del suelo es un instrumento que permite resolver el dilema existente entre el desarrollo y la conservación (Hale et al. 2005). El aumento en la demanda de recursos naturales y en la superficie ocupada por las actividades humanas dificulta la delimitación de nuevas zonas de protección. Por ello, resulta cada vez más importante contar con el mejor sustento técnico sobre los objetos de conservación y que, en muchas ocasiones, se refiere a la distribución de las especies y los hábitats que ocupan.

Uno de los principales insumos para la protección de las especies es el conocimiento sobre su distribución en el espacio, así como las condiciones ambientales que la determinan y que influyen en su permanencia (Fleishman et al. 2003, Larson et al. 2003). En este sentido, los modelos que permiten describir y predecir la distribución de las especies han resultado herramientas importantes para determinar los impactos de diversos factores en la distribución de los organismos, entre ellos el cambio en el uso del suelo (Guisan et al 2000, Larson et al. 2003). La combinación de información espacial con diversas herramientas estadísticas y los sistemas de información geográfica ha hecho posible el entendimiento de los patrones espaciales sobre la aptitud del hábitat para diferentes especies. Los modelos estadísticos son utilizados con frecuencia para relacionar la presencia, la presencia-ausencia o la abundancia de las especies con las condiciones ambientales, a partir de la información de sitios inventariados. Además, hacen posible predecir la distribución geográfica de las especies en una región.

Al respecto, Guisan y Zimmerman (2000) hacen una revisión de las diferentes metodologías utilizadas para predecir la distribución geográfica de las especies. En general, se pueden distinguir dos grandes grupos (1) los mapas construidos a partir de los datos depositados en las colecciones científicas y (2) la evaluación del hábitat con el propósito de identificar los sitios más aptos para la presencia de alguna especie. La evaluación de la aptitud del hábitat tiene como objetivo principal la identificación de las variables ambientales que se correlacionan con la presencia de las especies (Van Horne 2003). Básicamente, la aptitud del hábitat se refiere a la potencialidad que tiene el hábitat para mantener las poblaciones de la especie que se modela (Conroy et al 2003).

La aptitud del hábitat comprende tanto los factores bióticos como los abióticos, sus relaciones y su concurrencia en el espacio, mayor aptitud facilita la continuidad en la distribución de las especies (Larson et al. 2003 y Fleishman et al. 2003). Los métodos que determinan la aptitud del hábitat están basados en la evaluación de los atributos que definen el hábitat que la especie ocupa desde la estructura hasta la distribución de cada uno de ellos, (p.ej. tipo de vegetación, altitud, pendiente, insolación, etc). En estas evaluaciones, los estados de las variables que componen el hábitat son relacionados con la calidad del hábitat para cada especie, utilizando escalas de 0 (no apto) a 1 (máxima aptitud).

Sin embargo, estos modelos requieren de información de campo, opiniones de expertos, así como de registros suficientes y de buena calidad de las variables que definen el hábitat. En este sentido, los sistemas de información geográfica eliminan la necesidad del registro puntual de los datos, pues permiten la utilización de la información con que se dispone; así como la generación de información regional a partir de datos de campo (Larson et al. 2003).

Muchos de los modelos de aptitud del hábitat que se han construido están basados en la información de las variables tomada directamente en el campo, a diferencia de los modelos que utilizan sistemas de información geográfica y que pueden manejar la información a nivel de paisaje o región. Actualmente, esta nueva condición favorece que en la construcción de este tipo de modelos se consideren diferentes escalas de análisis, se incorporen nuevas variables y, en consecuencia, se obtengan mejores resultados (Larson et al. 2003). Este tipo de modelos permiten identificar aquellos otros sitios que pueden resultar igualmente aptos para mantener las poblaciones de la especie evaluada, a partir de la información de los sitios donde de hecho se presenta. Por ello, representan una buena herramienta en la toma de decisiones sobre los sitios que es necesario conservar pues, en principio, pueden ser capaces de mantener las poblaciones y la biodiversidad en el ámbito regional.

Los modelos que permiten analizar y predecir la presencia y riqueza de especies, así como la viabilidad de poblaciones pueden servir como apoyo práctico para varios objetivos, incluidos los de conservación. Idealmente, planificadores urbanos, biólogos y tomadores de decisiones debieran analizar los escenarios de crecimiento urbano, de distribución de los usos del suelo y de limites de reservas para predecir los posibles impactos de cada uno en la biodiversidad. Estos esfuerzos se han iniciado desde diferentes áreas del conocimiento, por lo que el reto principal es reconciliar e integrar los diferentes principios, semántica, métodos y escalas de análisis (Cogan 2002). Cuando el comportamiento de las variables predictivas puede ser modificado por las actividades humanas, entonces los modelos deben ser utilizados para modelar los efectos de las diferentes alternativas de manejo (Fleishman et al. 2003).

Actualmente, los SIG y las computadoras de gran capacidad y velocidad han permitido mejorar el manejo de los modelos que permiten describir los sistemas que se estudian. Gracias a esto, la utilización de mejores fuentes de información permite una mejor descripción de las variables que definen el hábitat, por ejemplo, uso del suelo, tipo de vegetación, la topografía, el clima, la frecuencia y magnitud de disturbios, así como el patrón del cambio de uso de suelo resultado de las actividades humanas, etc. Con esto, el entendimiento sobre las relaciones entre las especies y su hábitat ha ido avanzando, principalmente a escala regional (Donovan *et al.* 1987, Rickers *et al.* 1995, Robinson *et al.* 1995 y Fleishman et al. 2003). Además, este tipo de modelos pueden ser utilizados para comparar diferentes propuestas de manejo del territorio y evaluarlas (Larson et al. 2003).

Desde una perspectiva regional, la planeación del uso del suelo debe contemplar la concentración de especies, así como los sitios donde cada especie puede encontrarse. Para esto, los inventarios de campo proveen de datos empíricos esenciales en el desarrollo de modelos y estrategias de manejo efectivas. Por otro lado, los modelos analíticos permiten identificar los lugares donde es necesario realizar estudios de campo más detallados. Sin embargo, incluso cuando existen grandes bases de datos, los modelos predictivos resultan útiles para los tomadores de decisiones pues permiten ponderar los riesgos o beneficios potenciales de cada una de las alternativas de manejo propuestas (Fleishman et al. 2003)

Métodos multicriterio-multiobjetivo

Los métodos multicriterio-multiobjetivo son un conjunto de metodologías utilizadas para identificar los criterios que determinan el cumplimiento de una meta particular, así como para evaluar diferentes alternativas de decisión. En general, estos métodos tienen seis componentes. Primero, tienen una meta o un conjunto de metas en función del problema planteado. Segundo, la definición y evaluación de criterios las preferencias de los tomadores de decisión que se ven reflejadas. Tercero, el conjunto de criterios de evaluación (objetivos o atributos) a partir del que se hace la selección de alternativas. Cuarto, el conjunto de alternativas. Cinco, el entorno del proceso de decisión, las variables que influyen en el proceso pero que no se pueden controlar. Y seis, los resultados asociados a cada una de las alternativas en evaluación (Malczewski 1999).

Toda decisión involucra el análisis de los valores de quienes se verán afectados por la decisión. Esta valoración es recogida a partir de la importancia relativa que cada persona, involucrada en el proceso, asigna a cada uno de los criterios evaluados. Por su parte, un criterio es aquel elemento de juicio que permite la evaluación de cada alternativa en función de la preferencia de los tomadores de decisión. En general, los criterios pueden ser tanto objetivos como atributos. En consecuencia, un problema de decisión multicriterio implica un conjunto de objetivos o de atributos o ambos (Malczewski 1999).

Los atributos son las variables que reflejan el estado del sistema en evaluación y sobre el que se quiere tomar una decisión. Específicamente, un atributo es una entidad de medición cualitativa o cuantitativa y que, en el contexto de un problema de decisión, es el objeto de decisión. Por el contrario, un objetivo es la oración que refleja el estado deseado del sistema que se analiza. Asimismo, este objetivo puede ser conseguido a partir de uno o varios atributos (Malczewski et al. 1997, Malczewski 1999).

Por su parte, las alternativas involucradas en un problema de decisión multicriterio están definidas en términos de las variables de decisión y son evaluadas en función de los objetivos. Estas alternativas se evalúan a partir de los criterios identificados. Dentro de los métodos multicriterio-multiatributo existen diferentes grupos de técnicas que pueden ser clasificadas en 2 grandes categorías: *multiple attributes decision making* (MADM) y *multiple objetives decision making* (MODM). Los métodos MADM son utilizados para seleccionar una alternativa entre un pequeño grupo, donde cada alternativa está claramente definida. Mientras que, los MODM se utilizan para elegir esa alternativa de entre muchas otras definidas por un conjunto de restricciones. Los métodos MADM se enfocan en la selección de un problema, mientras que los MODM son utilizados para definir el problema (Malczewski et al. 1997, Malczewski 1999).

En un problema MADM, el análisis está enfocado en la elección de la alternativa, de entre un número discreto de ellas. El problema MODM es aquel donde el espacio de solución es continuó y definido por ciertas restricciones, esto es, existe un infinito número de posibles soluciones. El MODM reconoce que los atributos de las alternativas son sólo los medios para alcanzar un fin, los objetivos de los tomadores de decisiones. Mientras los MADM obtienen las preferencias reflejadas en función de los pesos y los estados de los atributos; los MODM derivan estas preferencias en función de los objetivos relacionando los atributos a objetivos (Malczewski et al. 1997, Malczewski 1999).

Sin embargo, si existe una correspondencia entre atributos y objetivos, el problema multiobjetivo se convierte en multiatributo. Los problemas de decisión multiatributo implican la elección de alternativas definidas en función de sus atributos. Sin embargo, si la relación objetivo-atributo es clara, los atributos pueden ser considerados tanto objetivos como variables de decisión (Malczewski 1999).

Así pues, el análisis de aptitud del suelo (*Land Suitability Analysis*, LSA) es visto como un problema multicriterio, pues involucra la satisfacción de los intereses de varios tomadores de decisión o grupos de interés, reflejados en objetivos, en atributos o en ambos (Steiner 1983, Bojórquez et al. 1994 y Malczewski et al. 1997). Un objetivo es el estado deseado como resultado del proceso de planeación sobre el uso del suelo. Particularmente, todo proceso de decisión sobre los usos del suelo involucra una disyuntiva entre proteger o aprovechar y su impacto en los diferentes grupos de interés (Malczewski 1999). Esta disyuntiva se define entonces como conflicto ambiental. Un conflicto ambiental se presenta cuando las actividades de un sector reducen la capacidad del suelo para que otro sector realice sus actividades (Malczewski 1999). Por ello, en la planeación del uso del suelo deben considerarse los valores e intereses de los distintos grupos de interés para determinar la alternativa que minimiza el conflicto entre ellos.

En este sentido, es claro que la definición de áreas que deben ser conservadas o protegidas entra en conflicto con aquellos sectores cuyo principal objetivo es aprovechar los recursos naturales de esas áreas (Christensen et al. 1996, Myers et al. 2000, Pimm et al 2001 y Fitzsimons et al 2004). Por ello, en este trabajo se evalúan dos problemas de decisión desde el enfoque multicriterio para determinar el valor de conservación de los sitios en cuestión a partir de la evaluación de aptitud del hábitat. En ambos ejercicios, el objetivo primordial es proteger la biodiversidad en dos Áreas Naturales Protegidas (ANP): La Reserva de la Biosfera de la Mariposa Monarca y el Parque Nacional de San Pedro Mártir. En ambos casos, los métodos multicriterio se utilizaron para evaluar diferentes delimitaciones de cada ANP en función de maximizar el valor de la conservación y minimizar los conflictos ambientales con los otros sectores. El análisis se enfoco en identificar los límites alternativos que cumplieran con la conservación del hábitat de la Mariposa Monarca y evitaran la evaluación de diseños poco prácticos. Esto se pudo conseguir a partir de modelos de optimización, con lo que se logro que los expertos pensaran primero en los principios y objetivos relacionados a la conservación y después en la configuración espacial de las alternativas.

En particular, en este trabajo se utilizan los métodos multicriterio-multiobjetivo en la determinación de la aptitud de los hábitats para albergar las especies que se quieren proteger. Como lo menciona Van Horne (2003) los métodos para explicar la relación entre las especies y las variables que determinan su presencia dependen de los objetivos planteados en cada estudio. Por ello, en los trabajos aquí presentados se utilizaron los métodos multicriterio-multiobjetivo y la consulta a expertos para delinear los criterios que son importantes en la definición de las áreas importantes de ser conservadas.

Caso 1. El análisis de aptitud del suelo en la redefinición de los límites de la Reserva de la Biosfera Mariposa Monarca.

Mapping Expert Knowledge: Redesigning the Monarch Butterfly Biosphere Reserve

LUIS A. BOJÓRQUEZ-TAPIA,*‡‡ LINCOLN P. BROWER,† GUILLERMO CASTILLEJA,‡ SALVADOR SÁNCHEZ-COLÓN,§ MARIANO HERNÁNDEZ,* WILLIAM CALVERT,** SALOMÓN DÍAZ,†† PAOLA GÓMEZ-PRIEGO,†† GEORGINA ALCANTAR,†† ERIKA DANIELA MELGAREJO,†† MARÍA JOSÉ SOLARES,†† LILIANA GUTIÉRREZ,†† AND MARÍA DEL LOURDES JUÁREZ††

*School of Renewable Natural Resources, Biological Sciences East, Room 207, University of Arizona, Tucson, AZ 85721, U.S.A.

†Department of Biology, Sweet Brier College, Sweet Brier, VA 24595, U.S.A.

‡World Wildlife Fund, Av. México 51, 06100 México, D.F.

§Departamento de Botánica, Escuela Nacional de Ciencias Biológicas, Instituto Politécnico Nacional, Carpio y Plan de Ayala S/N, 11340 México, D.F.

**Texas Monarch Watch, 503 E. Mary Street, Austin, TX 78704, U.S.A.

††Instituto de Ecología, Universidad Nacional Autónoma de Mexico, Apartado Postal, 70–275, 04510 México, D.F.

Abstract: *Expert consultation has been used to fill the information gaps that hamper conservation planning and nature reserve design. The use of expert knowledge in conservation planning is difficult, however, because it is subjective, biased, and value-laden. Decision theory provides a systematic and comprehensive means for addressing experts' subjective—and sometimes contradictory—judgments in the design of nature reserves. Thus, the experts can separate the objective criteria from the subjective components of decision making that place value on those criteria. When linked to a geographic information system (GIS), these techniques foster consensus among experts by allowing the exploration of alternative designs in an iterative way. We used such a decision-analysis approach to redesign the Monarch Butterfly Biosphere Reserve (MBBR) in central Mexico. We examined three reserve scenarios to identify the optimal overwintering habitats considering (1) an area equivalent to the previously defined boundaries of the core zone of the MBBR (4500 ha); (2) an area equivalent to the previously defined boundaries of the whole MBBR (16,000 ha); and (3) the maximum possible extent for a new core zone. This last scenario produced an area of 21,727 ha. These results were transferred to the GIS to create the respective nominal maps that were presented to the environmental authorities, who selected the third scenario for the core zone of the new MBBR. Our results allowed us to locate the prime overwintering habitats precisely and to delimit a core area for the reserve that would minimize the inclusion of forest stands valuable to local loggers.*

Mapeo del Conocimiento Experto: Rediseño de la Reserva de la Biosfera Mariposa Monarca

Resumen: *La consulta a expertos se ha utilizado para llenar los vacíos de información que obstaculizan la planeación de la conservación y el diseño de reservas naturales. Sin embargo, el uso de conocimiento experto en la planeación de conservación es difícil porque es subjetivo, sesgado y conlleva una carga moral. La teoría de decisiones proporciona medios sistemáticos y exhaustivos para evaluar los juicios subjetivos y a veces contradictorios de expertos en el diseño de reservas naturales. Por lo tanto, los expertos pueden separar los criterios objetivos de los componentes subjetivos de la toma de decisiones que asignan valores a esos criterios. Cuando se vinculan a un sistema de información geográfica, estas técnicas fomentan consensos entre expertos al permitir la exploración iterativa de diseños alternativos. Utilizamos ese enfoque de análisis de decisiones para rediseñar la Reserva de la Biosfera Mariposa Monarca (RBMM) en México central. Examinamos tres escenar-*

‡‡*email l_boj@yahoo.com*

Paper submitted June 29 2001; revised manuscript accepted June 20, 2002.

ios de reserva para identificar los hábitats de hibernacíon óptimos considerando (1) un área equivalente a los límites previamente definidos del área núcleo de la RBMM (4,500 ha); (2) un área equivalente a los límites previamente definidos de toda la RBMM (16,00 ha); y (3) la máxima extensión posible de una nueva zona núcleo. El último de estos escenarios produjo un área de 21,727 ha. Estos resultados fueron transferidos al SIG para crear los respectivos mapas nominales que fueron presentados a las autoridades ambientales, quienes seleccionaron el tercer escenario para la zona núcleo de la nueva RBMM. Los resultados nos permitieron localizar con precisión los hábitats de hibernacíon de mayor importancia y delimitar un área núcleo para la reserva que minimizaría la inclusión de bosque de valor para leñadores locales.

Introduction

The design of nature reserves involves assessment of the conservation value of alternative sites. The goal is to maximize the protection of critical biological entities and simultaneously to minimize the inclusion of tracts of land considered valuable for incompatible economic activities. Achieving this goal is difficult because of the inherent complexity of ecological systems, the lack of quantitative information, and biased data (Margules & Usher 1981). Given the urgency for in situ biodiversity protection in these circumstances, expert consultation has been used to fill critical gaps in objective information. In Mexico for example, the Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (http://www.conabio.gob.mx; accessed February, 2000) consulted experts in establishing both a national strategy and the identification of priority areas for conservation.

Expert consultation is a process through which a group of experts define objectives, identify alternatives, and assess feasible solutions to a problem. The assessment of alternatives is based on a set of decision criteria, and a solution is selected through the development of a consensual framework (Bojórquez-Tapia et al. 2001). In spite of its usefulness for conservation planning, expert knowledge is problematic because it is typically incomplete, imprecise, and value-laden (Shrader-Frechette & McCoy 1993). Thus, the decision criteria generated by different experts in a group may be contradictory or incompatible.

Integrating disparate expert opinions and criteria with available ecological data is a challenge for park planners. Failure to achieve such integration in a transparent and systematic way can result in a reserve design that does not accomplish the goal of biodiversity protection, exacerbating land-use conflicts rather than mitigating them.

There is a need for approaches that combine available quantitative data with the more subjective knowledge of experts. Decision-theory techniques, linked to geographic information systems (GIS), have been successfully used for contrasting expert judgments and making educated choices about land uses (Bojórquez-Tapia et al. 2001). This method provides a rigorous analytical approach to expert consultation and can be adapted for the design of a nature reserve.

Integration of decision analysis and spatial modeling techniques enables experts to articulate, in a step-by-step fashion, a rank ordering of the potential configurations of a new reserve and to justify their preferences. Such integration allows a comprehensive exploration of alternative reserve designs in a consultative and iterative way. The analytical tools ensure the transparency of the final selection because the conclusions can be linked to the original data and judgments. The advantage of this approach is that the process is systematic, coherent, and defensible. Consequently, it fosters consensus among experts by allowing them to evaluate alternative reserve designs on the basis of strictly defined decision criteria.

Our purpose here is to present the approach we used to redesign the Monarch Butterfly Biosphere Reserve (MBBR) in central Mexico. The approach entailed the implementation in a raster geographic information system (GIS) of a multicriteria, group decision-making model (MCGDM), a multivariate statistical model, and a 0–1 mathematical programming model. Experts were consulted through two participatory planning workshops.

Conservation Issues

The migration of the monarch butterfly is a unique phenomenon of global interest because the butterflies travel up to 4000 km during the fall from southern Canada and the eastern United States to their overwintering sites in central Mexico. The butterflies, which breed east of the Rocky Mountains in a region larger than 2.6 million km^2, migrate into Mexico and concentrate in an area of 1800 km^2 (De la Maza & Calvert 1993). In late March and early April the butterflies that survive the overwintering period migrate to the Gulf coastal states, where they produce an early spring brood. The ensuing generation then migrates northward to Canada and reestablishes the eastern North American breeding range (Brower 1995, 1999).

The overwintering sites are located on 11 separate mountains of the Transverse Neovolcanic Belt in the states of Mexico and Michoacán. The butterflies form densely aggregated colonies in oyamel (*Abies religiosa*, Pinaceae) forests, at elevations between 2400 m and 3600 m elevation (Calvert & Brower 1986; De la Maza & Calvert 1993).

The microclimatic conditions of the oyamel forest allow the butterflies to survive the winter and conserve their energy reserves, which they need to return north. The tree canopy protects the butterflies from wind, rain, snow, and freezing cold and, together with fog and clouds, creates the humid conditions that prevent the butterflies' desiccation. Because the overwintering period coincides with the dry season in central Mexico, the forest's function in the hydrologic cycle is also crucial. The forest maintains the supply of water the butterflies drink along small creeks on clear, hot days (Calvert & Brower 1986; Anderson & Brower 1996; Alonso-Mejía et al. 1997).

Protection of the overwintering habitat has been a top priority for conservation because the butterflies must survive the winter to be able to return to their spring and summer breeding ranges. In 1986, a presidential decree created the MBBR and protected five overwintering areas, which were known as the butterfly sanctuaries (Anonymous 1986) (Fig. 1). The decree specifically designated core zones for strict forest protection, and controlled forestry was allowed in the buffer zones surrounding the core zones. All forestry activities were subject to the approval of a management plan, and tree removal from the buffer zones was thus contingent upon proof that logging would not damage the butterflies. Later, environmental authorities delineated the seven proposed sanctuaries that were never formally decreed.

The reserve generated unanticipated conflicts between logging groups and conservation organizations. Economic and political circumstances generated resentment of the reserve among the loggers and the local inhabitants, which resulted in illegal extraction of forest resources. The response to these activities was a call from conservation groups for the prohibition of forestry operations within prime overwintering habitat in the buffer areas, and a strict enforcement against illegal cutting. The position of the conservationists was justified by the evidence of widespread removal of trees within and adjacent to the officially protected overwintering habitats (L.P.B., 1997. Biological necessities for monarch butterfly overwintering in relation to the oyamel forest ecosystem in Mexico. Keynote address, North American Conference on the Monarch Butterfly).

During the North American Conference on the Monarch Butterfly in November 1997, conservationists, local loggers, and environmental authorities endorsed a proposal for redesigning the MBBR. These groups acknowledged that the 1986 system of sanctuaries did not protect all the overwintering colonies and included areas that could be allocated to sustainable forestry.

The Mexican authorities were thus compelled to modify the 1986 presidential decree. They were uncertain of the characteristics of the new MBBR because of the opposing viewpoints of loggers and conservationists. The loggers wanted prime habitat to be to where the colo-

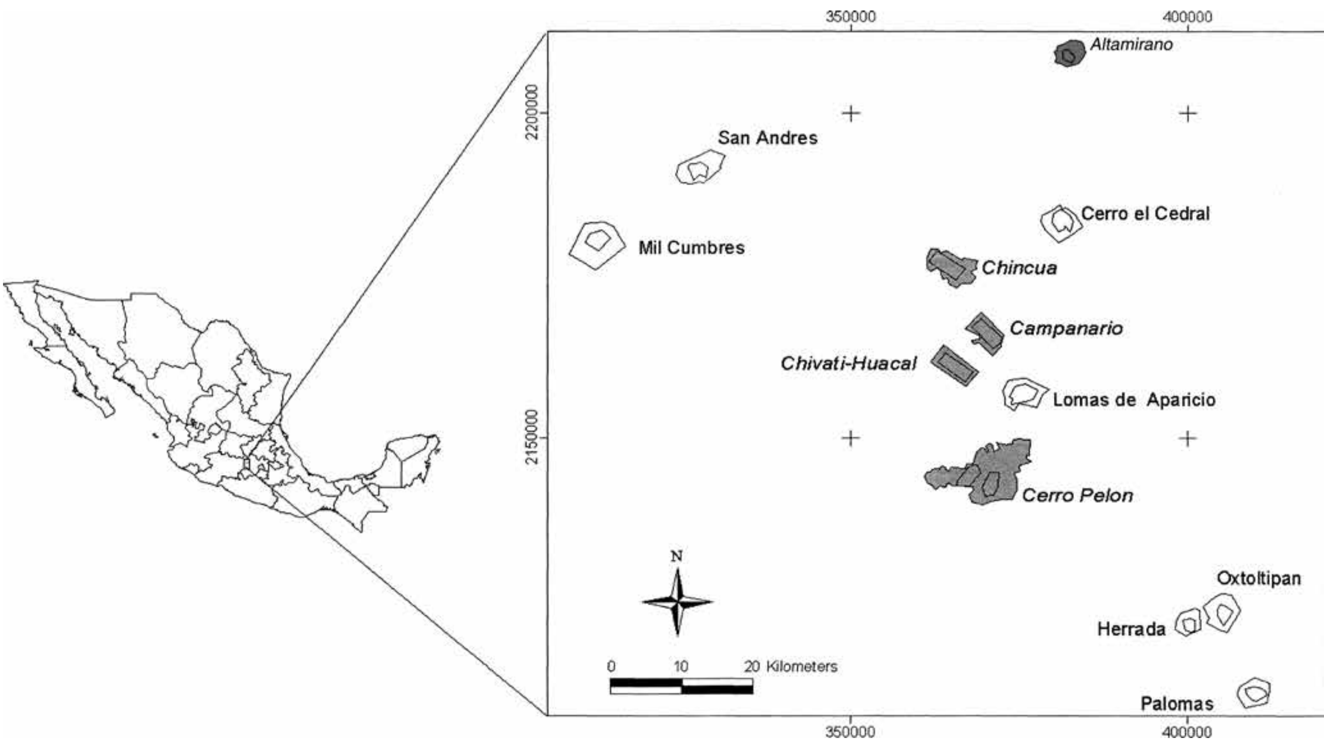


Figure 1. Study area, covering portions of the states of México and Michoacán in central México. Polygons in gray and names in italics refer to the five decreed sanctuaries. Polygons in white and names in roman type refer to the seven proposed sanctuaries. The interior polygon demarcates the core zone, and the exterior polygon demarcates the buffer zone of each sanctuary.

nies were located, and they maintained that a series of disconnected core zones encircling those colonies would satisfy the conservation objectives. The conservationists advocated a continuous core zone surrounding the oyamel stands, allowing the overwintering butterflies to select other suitable locations in case of major disturbances by fire, drought, or illegal cutting.

Methods

The redesign of the MBBR involved the development of a digital cartographic database and a two-stage analytical procedure. In stage 1 the distribution pattern of the overwintering monarch butterfly in central Mexico was established, and in stage 2 this pattern was used to delineate a reserve that covered the maximum possible area of overwintering habitat. At each stage, the experts reviewed the results of the spatial analyses in an iterative way until consensus was attained.

GIS Database

We compiled a cartographic database of the available digital map layers, indicating the positions of 149 colony sites, the boundaries of the 12 sanctuaries (Fig. 1), a digital elevation model, landforms, vegetation, and land use (Anonymous 1995). This final layer was obtained through the interpretation of a 1993 Landsat thematic mapper satellite image that covered the areas surrounding the five decreed sanctuaries (vegetation and land-cover data were not available for the whole region). In addition, we derived a set of raster layers from meteorological data (precipitation and aridity index) and a digital elevation model (watersheds, aspect, slope, and potential solar radiation).

Potential solar irradiation under clear-sky conditions for the overwintering period was computed from the standard formulae (Jones 1983). We calculated the sun's relative position at the respective dates with spherical geometry (Vorontsòv-Veliamínov 1979). The aridity index was estimated after that of Guttman (1998). We obtained both the aridity index and the total precipitation layers for the overwintering period by interpolating data from 19 weather stations located throughout the study region (Instituto Mexicano de Tecnología del Agua 1996).

We implemented all the spatial modeling in the raster-based software Geographic Resource Analysis Support System, Grass 4.2 (US Army Construction Engineering Research Laboratory 1991), through a set of UNIX shell scripts in a Sun Ultra 10 workstation.

Stage 1

We applied two spatial analysis approaches to mapping all potential overwintering habitat of the monarch butterfly. The first was based on the habitat-suitability evaluation (Pereira & Duckstein 1993) and consisted of the development of a multicriteria group decision-making model (Lahdelma et al. 2000).

The second approach entailed the development of a logistic model from the geo-referenced records of overwintering colonies and the GIS database. This model was initially generated for comparative purposes. At the end of the spatial analysis, however, the experts were asked to judge which model—or combination of models—provided the best representation of the potential monarch butterfly overwintering habitat. The final decision was attained by consensus.

EXPERT CONSULTATION

Expert consultation was carried out in a group decision-making workshop (October 1998). The goal was to attain consensus among 20 experts, all of whom have been involved in research and monitoring of overwintering sites in Mexico, on the biological requirements of the monarch butterfly. The specific objective was to generate a map of potential overwintering habitats. Consequently, deliberations were restricted to biological issues, and conflicts with the logging sector were not considered at this point.

The experts were separated into three working groups to prevent dominant personalities or authorities from biasing the judgments of the entire group. A facilitator guided discussions in each group to clarify the key issues, identify problems, and formulate the decision criteria in a format usable for the spatial analysis. Decision criteria were those measurable physical or biological attributes characterizing the overwintering habitats and that could be mapped (Smith & Theberge 1987).

Each group used the computer program Expert Choice (Decision Support Software 1995) to independently define and rank the decision criteria following the analytic hierarchy process (AHP; Saaty 1980). The AHP weighted each decision criterion by its importance on a [0–1] interval scale. Next the experts agreed on the value function that best translated each decision criterion into a relative, standardized score of habitat suitability. The resulting scores were also on a [0–1] interval scale (Pereira & Duckstein 1993).

MULTICRITERIA MODEL OF POTENTIAL HABITAT

We based the multicriteria model on the ideal-point technique (Szidarovszky et al. 1986; Jankowski 1995). We implemented it in the GIS to assess the worth of each pixel as habitat for the monarch butterfly, so the decision criteria were represented by I thematic map layers. For each pixel, a habitat-suitability score was obtained by means of the relative distance of departure from the ideal point, d_T, in a scale of 0 (worst) to 1 (best). The ideal point is an abstract site possessing the most desirable values of each of the n

decision criteria. Departures were computed with a Euclidean and two nonlinear distance measures (Szidarovszky et al. 1986; Pereira & Duckstein 1993):

$$d_\tau = \left[\sum_i^I w_i^{\tau} (1 - x_i)^{\tau} \right]^{1/\tau}, \qquad (1)$$

where w_i and x_i are the weight (derived by the AHP) and the standardized score (obtained by the value function) for decision criterion i, respectively; $(1 - x_i)$ is the deviation from the ideal point of the ith criterion; and τ is an exponent that ranges from 1 to ∞ and defines the kind of distance metrics used in the analysis.

Compromise programming (CP) was then used to determine the threshold distance of the combined criteria in a pixel from the ideal point for potential overwintering habitat (Pereira & Duckstein 1993). The pixels below the threshold were reclassified into a binary map layer that depicted the overwintering habitats.

LOGISTIC MODEL OF POTENTIAL HABITAT

The logistic model was used to predict the probability of occurrence of overwintering monarch butterfly colonies at each pixel. The general form of the model (Nicholls 1991) is as follows:

$$\text{logit}\, p = b_0 + b_1 x_1 + b_2 x_2 + \ldots + b_i x_i + b_{11} x_1^2 + b_{22} x_2^2 + \ldots + b_{ii} x_i^2, \qquad (2)$$

where p is the expected probability of occurrence of monarch butterfly colonies at a given pixel; x_i is the value of the ith predictor variable at the pixel; and b... are coefficients estimated from the sample.

The squared terms of the predictor variables were included to allow for possible nonlinear relations with the probability of occurrence. The logit transformation of the expected probability of occurrence (logit $p = \ln(p/(1 - p))$) was used to bound the linear part of the model within the interval [0–1] from its original range ($-\infty, +\infty$).

The variables included in the model were selected by a stepwise process, as suggested by Crawley (1993). At each step, the significance ($p < 0.05$) of the addition or deletion of a variable was assessed. Once a final model was achieved, its goodness of fit was evaluated by means of the significance ($p < 0.05$) of the difference between its residual deviance and the deviance of the null model (i.e., a model with no predictor variables included).

The data for estimating the model's coefficients were derived from a GIS dataset delimited by the region covered by the vegetation map layer. Thus, the model was generated from a sample of 117 georeferenced records of overwintering colonies and 58 georeferenced sites where no colonies have been recorded. The predictor-variable values—elevation, slope, vegetation, aspect, modal aridity index, total annual precipitation, potential irradiation, nearness to streams, nearness to human settlements, and nearness to roads—for these records were extracted from the GIS by overlay operations. We used the program GLIM 4 to fit the model. The model was transferred to the GIS and then compromise programming was used to derive the threshold probability value that fixed the limits of the overwintering layer of the habitat map.

Stage 2

Our goal at this stage was to elucidate a reserve design that could be implemented by the authorities. The idea was to include as much as possible of the overwintering habitats predicted in stage 1 and exclude forest stands that might be valuable for loggers. Following the suggestion of Anderson et al. (2001) for structuring the objectives of a decision analysis, we focused on the alternative designs that could accomplish the goal and avoided the examination of impractical reserve designs. This was achieved through the application of a GIS-based optimization model, which forced the experts to think first about the principles and objectives related to conservation biology and only later about the spatial configuration of the alternatives.

EXPERT CONSULTATION

A second group decision-making workshop was held to determine the new boundaries for the MBBR (January 1999). The potential overwintering habitat predicted in stage 1 shaped the study area used in stage 2. Hence, based on the map generated in stage 1 and the criteria that could be used, the experts were asked to divide the predicted potential overwintering habitat into the appropriate landscape units (i.e., tracts of land to be considered during the optimization procedure, described in the next section).

The experts acknowledged two sources of uncertainty in determining reserve size. First, there was no consensus among them about the minimum amount of overwintering habitat required by the monarch butterfly. Second, the experts ignored the size of the area that the authorities would be willing to allocate for conservation. These uncertainties were addressed by focusing on the area of conflict around the five decreed sanctuaries and exploring different total-area scenarios in the optimization model. The main considerations at this stage were to preserve the existing colonies, protect as much as possible of the predicted overwintering habitat, maintain the hydrologic cycle, preserve the microclimatic conditions of the forest stands, and avoid habitat fragmentation.

Because water courses were considered critical to the butterfly's survival, the experts concluded that an essential prerequisite to protecting the overwintering habitats was to maintain the hydrological conditions of the watersheds. In addition, the experts identified the biological requirements of the butterfly that determined habitat

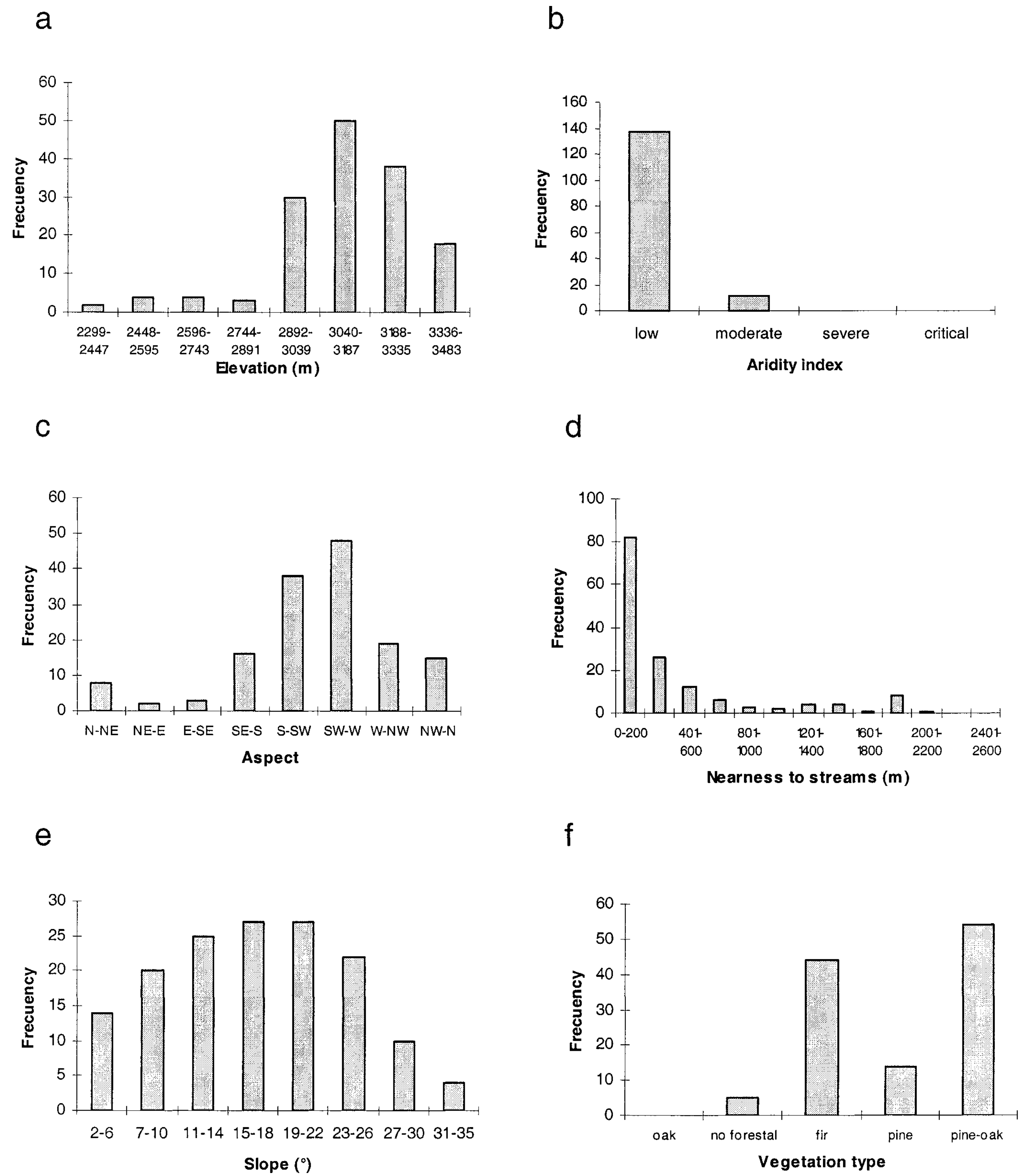


Figure 2. Observed frequency distributions of overwintering monarch butterfly colonies for the variables included in the cartographic database of the study area (a–e: n *= 149; f:* n *= 117).*

quality, which were synthesized in four factors determining conservation priorities for the landscape units: (1) locations of overwintering colonies and predicted overwintering habitat, (2) aspect (prioritizing southwestern facing slopes), (3) habitat characteristics (namely, degree of deforestation in a landscape unit), and (4) elevation (prioritizing higher elevations). Thus, factors 1 and 2 were satisfied by delimiting the landscape units by the area of predicted potential habitat contained within watersheds and determining the slope aspect of each watershed. Factors 3 and 4 were implemented by dividing the watersheds into segments of 100-m elevation intervals (e.g., 2600–2699 m, 2700–2799 m, 2800–2899 m, 2900–2999 m, and ≥3000 m). The 100-m interval was defined empirically by examining the minimal size of a landscape unit that could be produced on the most abrupt slopes.

SPATIAL ANALYSIS

We addressed the selection of the landscape units for the new MBBR as a 0–1 mathematical programming problem (Church et al. 1996; Appendix 1). The program What's Best, version 3.1 (Lindo Systems 1998), was used to run the optimization procedure. The objective function selected those landscape units that maximized the total overwintering habitat value, subject to the constraint of a fixed total area for the reserve (Appendix 1). Through overlay operations in the GIS, the landscape units were coded and associated with the potential overwintering habitats that resulted from the first phase of the analysis, with vegetation, and with aspect map layers. The results were transferred to the optimization software.

The location of overwintering colonies, habitat characteristics, and aspect (factors 1–3) were implemented in the optimization software as ranking weights for the landscape units. The highest ranking weight was given to units that presented overwintering colonies and intact habitats. The second ranking weight was given to landscape units that included overwintering colonies in which the extent of deforestation was <20% of their area. The lower ranking weight was assigned to landscape units that were located between two watersheds selected in a previous step in which the extent of deforestation was <20% of their area. Landscape units of southwestern aspect were ranked higher than those with north-northeastern aspect. Factor 4 was implemented as a model constraint and implied a sequential selection of the landscape units, from higher to lower elevations.

We analyzed three area-constraint scenarios: (1) an area (A) equivalent to the core zone decreed of the five sanctuaries decreed in 1986 (A = 4500 ha), (2) an area equivalent to the full extent of five decreed sanctuaries (A = 16,000 ha), and (3) no area restriction ($A = \infty$). We translated the results of these scenarios to the GIS to create the respective nominal maps.

Results

Stage 1

The georeferenced records of the colony sites revealed the main characteristics of the overwintering habitats (Fig. 2). The majority of the colony sites were at a high elevation (>2890 m; 91% of the sites); had low aridity (94% of the sites) and a south-southwest aspect (58% of the sites); and were located a short distance from streams (<400 m; 83% and 57% of the sites, respectively), on moderately steep slopes (11–26°; 41% of the sites), and in pine-oak forests (46% of the sites) and fir forests (38% of the sites).

Thirty percent of the 149 colony sites were outside the boundaries of the five sanctuaries decreed in 1986. Within those sanctuaries, 50% of the colonies were within the core zones, and 20% of the sites were located within the buffer zones. Considering the proposed sanctuaries, the percentage of sites under protection increased slightly (56% for the core zones and 25% for the buffer zones).

The three working groups generated AHP structures of two levels. At the first level, the experts stated that the goal of the study was to determine the characteristics of overwintering habitats for the new design of the MBBR. At the second level, the experts included the ecological attributes that determine the quality of the overwintering.

The decision criteria and their importance weights varied between the three working groups (Table 1). Ten decision criteria were identified by the experts, five of which were common in the three working groups. Working groups 2 and 3 decided to generate two versions for the multicriteria model. Experts in group 2 considered sepa-

Table 1. Criteria and criteria weights used in the multicriteria models for the overwintering habitats of the monarch butterfly in central Mexico.

	Weight	
Working group and criteria	*model a*	*model b*
Group 1		
elevation	0.214	not generated*
aspect	0.214	
vegetation type	0.037	
slope	0.180	
precipitation	0.185	
insolation	0.103	
nearness to streams	0.068	
Group 2		
elevation	0.379	0.338
aridity index	0.130	0.119
aspect	0.089	0.155
vegetation type	0.248	0.233
slope	0.037	0.030
nearness to streams	0.144	0.124
Group 3		
elevation	0.134	0.116
aspect	0.228	0.226
slope	0.025	0.024
vegetation type	0.179	0.177
temperature	0.061	0.084
nearness to streams	0.172	0.173
patch size of fir stands	0.201	0.200

**Group 1 generated one model only.*

rate models necessary to depict the period of colony formation and establishment (November to January; model a in Table 1) and the period of mating and departure (January to April; model b in Table 1). In group 3 the two models resulted from the lack of consensus about the relative importance of elevation and temperature (Table 1).

The analysis of habitat conditions was restricted to the areas surrounding the five decreed sanctuaries because of the coverage of the vegetation map layer. Therefore, it was necessary to conduct three different types of multicriteria analyses: (1) area of the vegetation map layer with land-cover data included, (2) area of the vegetation map layer with land-cover data omitted, and (3) entire study area with land-cover data omitted. Thus, 45 models were generated (Table 2).

Group 2's model a was selected as the best representation of potential habitat because it presented the best combination of exactitude, power, and efficiency (Table 2). The model corresponded to the compensatory decision-making mode ($\tau = 1$). It was designed to depict the areas corresponding to the period of formation and establishment of colonies at higher elevations; the corresponding model for the mating and departure period (model b of group 2) performed poorly and was then discarded (Table 2).

The location data of overwintering colonies showed differences in the value functions of the selected multicriteria model, especially for slope, aridity index, and vegetation type (Figs. 2 & 3). In the version restricted to the decreed sanctuaries, the area predicted was equivalent to the five sanctuaries (16,000 ha), but it extended over areas not protected by the sanctuaries. In the version for the entire study area, the model predicted an area equivalent to three times the current reserve system (Table 2; Fig. 4a).

The logistic model that best predicted the occurrence of monarch butterfly overwintering colonies was

$$\text{logit } p = -133.1 - 0.0181x_1 - 0.0336x_2 + 0.0001x_2^2 + 0.0914x_3 - 0.0000136x_3^2, \quad (3)$$

where x_1 is precipitation, x_2 is aspect, and x_3 is elevation.

This model accounted for a highly significant fraction of the null deviance ($p < 0.001$). The threshold value determined by compromise programming was equal to a probability of 0.45, which yielded the highest exactitude and power (80%) of the model in 40% of the study area (Fig. 4b). The model predicted the highest probability of occurrence of monarch butterfly colonies on southwestern-south slopes, at high elevations, and with low winter precipitation. The logistic model tended to include areas of the mating/departure period (January to April).

The representation of potential habitat for the entire overwintering period (November–April) required the combination of the two models of group 2 (because they were designed to depict independently the periods of formation/establishment and mating/departure of colonies). The combination of those two models performed poorly, however, because of the low exactitude and power of the latter (Table 2). A better representation of the habitat for the entire overwintering period was obtained by merging model *a* of group 2 and the logistic model (Fig. 4c). This union had the highest exactitude and power and delineated 226,000 ha of potential overwintering habitat.

Table 2. Results of the models for the three working groups of the monarch butterfly workshop.

		*Area corresponding to the vegetation map layer**										*Entire study area omitting land-cover data*				
		including land-cover data					*omitting land-cover data*									
Working group and model	*τ*	*T*	*1−α*	*1−β*	*E*	*A*	*T*	*1−α*	*1−β*	*E*	*A*	*T*	*1−α*	*1−β*	*E*	*A*
Group 1	1	6	72	78	67	14 (20)	6	72	78	62	15 (21)	5	84	76	79	202 (17)
	2	9	96	41	46	35 (50)	6	94	49	47	34 (47)	6	91	72	74	232 (17)
	∞	6	66	82	49	12 (17)	5	85	60	49	25 (36)	5	81	82	73	111 (8)
Group 2	1	4	76	62	66	18 (26)	5	79	70	65	16 (23)	5	82	88	88	54 (4)
model a	2	4	89	53	55	24 (34)	4	87	62	58	21 (29)	4	85	87	80	66 (5)
	∞	4	76	66	52	17 (24)	4	76	66	52	17 (24)	2	88	84	82	75 (5)
model b	1	3	48	35	24	44 (61)	3	6	51	24	29 (55)	3	37	34	34	799 (57)
	2	3	68	25	9	54 (76)	1	6	51	52	41 (58)	2	9	49	42	700 (50)
	∞	1	3	51	53	42 (59)	1	6	51	52	42 (59)	1	9	47	42	709 (51)
Group 3	1	4	60	66	57	20 (27)	6	65	51	22	30 (42)	6	74	64	66	355 (26)
model a	2	7	71	53	35	25 (35)	7	70	76	28	29 (42)	7	68	64	39	395 (28)
	∞	6	58	63	23	25 (35)	6	69	59	51	26 (37)	6	64	54	27	521 (37)
model b	1	4	51	59	59	16 (23)	6	68	60	46	27 (38)	7	59	79	66	162 (12)
	2	6	44	63	25	13 (19)	7	69	53	26	30 (43)	7	67	60	35	435 (31)
	∞	6	59	60	22	26 (37)	6	65	51	22	30 (43)	7	52	65	23	403 (29)

**Key: τ, exponent that determines the distance metric to the ideal point; T, threshold; $1-\alpha$, exactitude; $1-\beta$, power; E, efficiency; A, area $\times 10^3$ ha (% of the study area).*

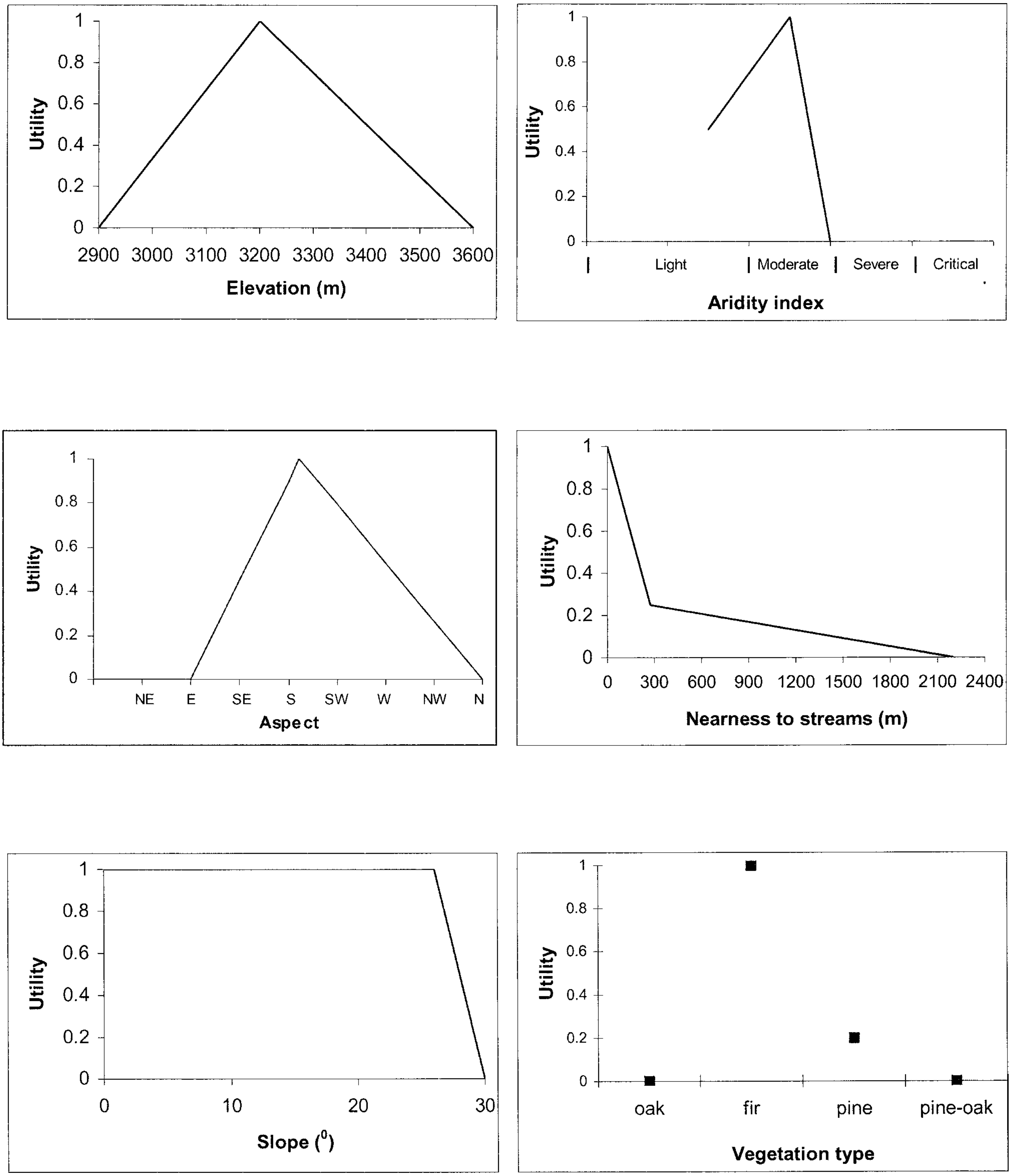
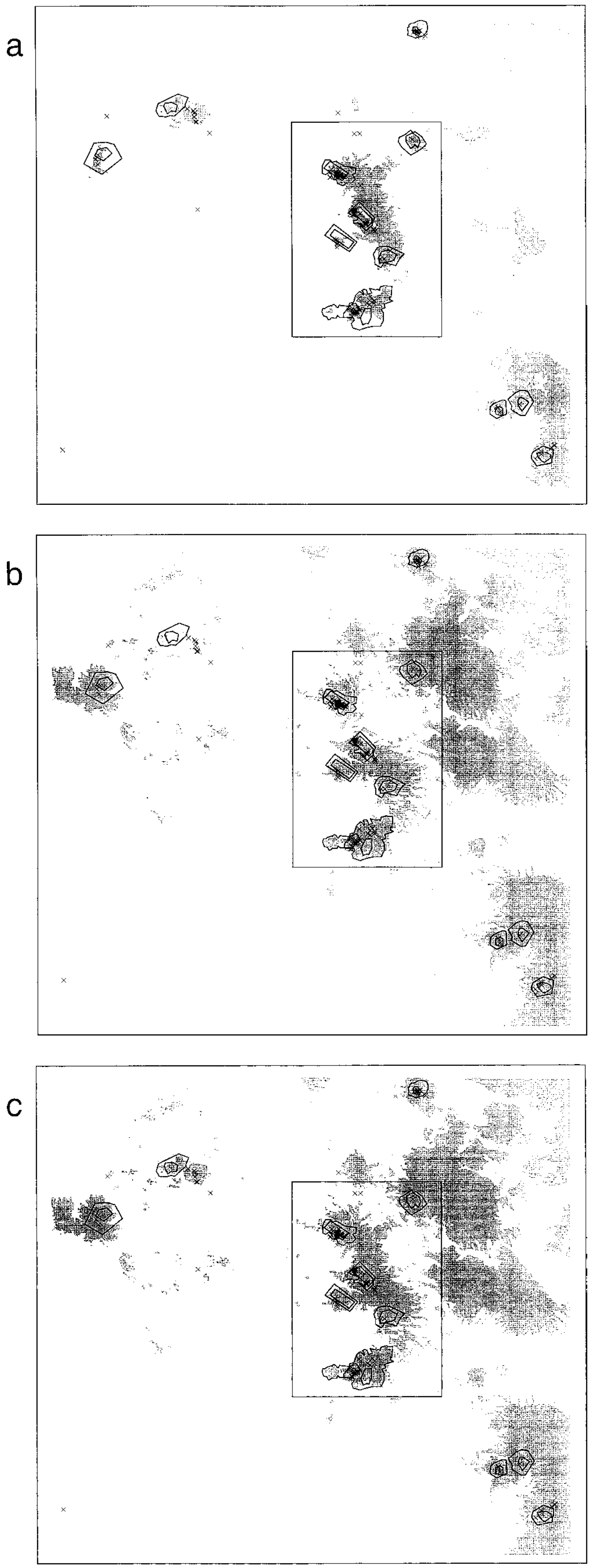


Figure 3. Value functions used for the best multicriteria model of overwintering habitats of the monarch butterfly in central Mexico.

Stage 2

The region corresponding to the vegetation map layer generated 99 landscape units. Global optimality in the first scenario (4500 ha) selected 34 landscape units of 4496 ha. These units were within the sanctuaries of Chincua and Cerro Pelón and bordered the sanctuary of Chivati-Huacal (Fig. 5a). Because their conservation scores were the highest, the experts considered these units the highest priority for the conservation proposal.



In the second scenario (16,000 ha), the global optimum selected 21 landscape units of 15,966 ha. Some of these landscape units formed a corridor between the sanctuaries of Chincua and Campanario, whereas others were located east and south of Campanario (Fig. 5b).

The third optimization scenario (infinite area) included 21,727 ha in 37 watersheds. The locations of the landscape units were within the Lomas Aparicio sanctuary, north of the sanctuary, and between two previously selected units (Fig. 5c).

Discussion

Our focus in redesigning the MBBR was to make the most of the available data and biological knowledge on the monarch butterfly overwintering phenomenon in central Mexico. One major limitation was that the biological research on the minimum area needed to maintain the migratory phenomenon had not been conducted. In addition, the sample of location data of overwintering colonies was not representative of the potential overwintering habitats in the study region.

We agree with Davis et al. (1990) that the solution to a conservation conflict cannot wait for exhaustive scientific research. Successful conservation planning has to be based on correct identification of relevant goals, issues, and limitations and has to produce realistic solutions (Davis & Johnson 1987). Therefore, we assert that conservation planning must be based on strictly defined decision criteria, incorporate the inherent uncertainty of species distribution data, and produce reproducible results.

Our study reveals some of the limitations of expert consultation methods that rely on relatively simple scoring procedures (i.e., Hanna et al. 1998). The differences among the three working groups demonstrate how imprecise the determination of the decision criteria and their importance weights can be (Table 1). Moreover, the ranges of the value functions show that, even for the best model, expert knowledge does not necessarily correspond to the available hard data. This is especially true in the case of vegetation type (Figs. 2 & 3), although it is unclear whether such a difference was caused by errors

Figure 4. Predicted overwintering habitat for the monarch butterfly in central Mexico (in gray) as generated by (a) the best multicriteria model, (b) the logistic model, and (c) a merger of the multicriteria model and the logistic model. The rectangle delimits the area used for the optimization model, as in Fig. 5. The georeferenced records of overwintering colonies are indicated by crosses. The 12 polygons correspond to sanctuaries, as in Fig. 1.

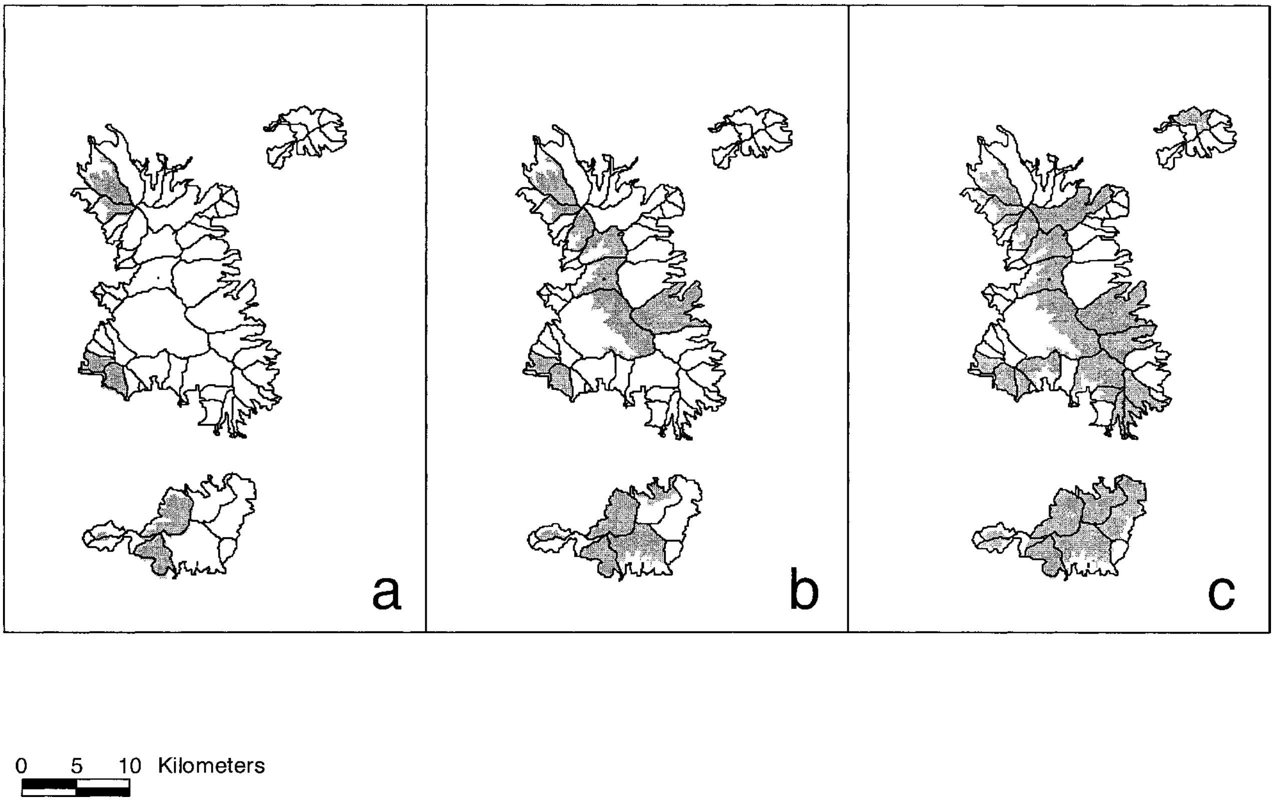


Figure 5. Results of optimization model for the new Monarch Butterfly Biosphere Reserve: (a) area constraint = 4500 ha; (b) area constraint = 16,000 ha; (c) area constraint = ∞. Black lines are the watershed boundaries, and the selected land units are shown in gray.

in the classification of the vegetation layer, by biases of the georeferenced records, or by misconceptions about habitat characteristics.

Smith and Theberge (1987) caution against the "spurious objectivity" that results whenever the theoretical assumptions of multicriteria modeling are not met. A multicriteria model is a representation of value priorities and trade-offs according to the decision-maker. It assumes that decision criteria are independent and that the experts have a precise knowledge about the potential outcomes of a criterion for different alternatives.

One means to overcome the practical and theoretical problems in multicriteria modeling is through the application of the ideal point technique and a sensitivity analysis. The first is not a value-laden evaluation of priorities and trade-offs and does not require assuming the independence among criteria or a particular decision mode (Pereira & Duckstein 1993). The latter is an indirect way to explore the effects of the uncertainties of decision criteria, priority weights, value functions, and map layers on the decision-making process (Malczewski 1999).

Based on the work of Pereira and Duckstein (1993), we conclude that the multicriteria models for representing overwintering habitats presented here are mathematically valid. Moreover, although the results shown in Table 2 cannot be considered a formal sensitivity analysis, they underscore the importance of comparing alternative models generated by different groups of experts to determine the best habitat-suitability representation.

Among others, the theoretical advantages of logistic models over multicriteria models are that they are generated directly from the data, in a way that allows the superfluous variables to be eliminated by means of quantitative statistical measurements. Therefore, logistic models could be perceived as unprejudiced representations of the phenomena under study. It must be stressed that model parsimony is important in spatial modeling to reduce error propagation.

The logistic model for the overwintering habitat had fewer explanatory variables than the number of decision criteria of the multicriteria models. According to the experts, however, both the logistic model and the best multicriteria model were biased. The first reflected the observation of colonies at lower elevations during the period of mating/departure. The second depicted the habitats of the formation/establishment period at higher elevations, whereas its complementary model for the mating/departure period was discarded because of its poor performance (Table 2). Hence, the most accurate representation of overwintering habitats was achieved by merging the best multicriteria model and the logistic model, as shown by the fact that this combination was more efficient than any other combination of models. The map generated in stage 1 was not a hypothetical model of the distribution pattern of overwintering colonies in central Mexico, however, but rather a decision-making tool to delimit the new MBBR in stage 2. Clearly, merging the models reflected the empirical nature of the analysis and not the theoretical explanatory power of any of the models.

The link between stages 1 and 2 was critical for the redesign of the reserve. The potential overwintering habitat predicted in stage 1 (Fig. 4c) shaped the study area for stage 2 (Fig. 5). This enabled the experts to delimit the landscape units in a way that was congruent with both pragmatic considerations and the biology of the monarch butterfly. The ranking system used on the landscape units forced the experts to be explicit about their judgments on conservation priorities, which facilitated the devising of unambiguous guidelines for a conservation agenda for the region. These guidelines were a key element in the ensuing negotiations with the environmental authorities on the final design of the MBBR.

The implicit assumption of the optimization process was that the total extent of the selected landscape units was enough for maintaining both a minimum viable overwintering population and a minimum dynamic area for the ecological processes related to habitat condition. As is typical in conservation planning, it was impossible to test these assumptions scientifically. The experts preferred the scenario that yielded the largest reserve area because it offered the greatest opportunity to meet those two assumptions. This area was recommended for the creation of the core zone of the biosphere reserve, and it encompassed about 10% of the potential overwintering habitat (Figs. 4c & 5c). The environmental authorities modified these results in the new presidential decree for the MBBR to match land-tenure patterns and to avoid conflict with local inhabitants. Nonetheless, the resulting reserve maintained the general shape and size of that in Fig. 5c. Additionally, the other scenarios helped set up conservation priorities. For example, if it were possible to implement conservation programs in only 4500 ha, they should be put in place in the landscape units selected by the first optimization scenario (Fig. 5a).

The spatial modeling approach we used proved a powerful consensus-building tool. At the beginning of the first phase, the experts' perceptions of the problem were defined loosely and did not by themselves provide a basis for thoughtful decision-making. At the end of the exercise, the experts were able to quantify the potential overwintering habitat and articulate a reserve design in terms of the goal and the binding limitations on action.

Acknowledgments

This research was supported by the World Wildlife Fund for Nature, Mexico, and the Monarch Butterfly Sanctuary Foundation. We thank the experts who generously participated in two planning workshops: A. Alonso, A. Angulo, G. Bocco, R. Campos, M. Franco, E. García, J. Hoth, M. Mejía, R. Solis, E. Rendón, and A. Torres. We acknowledge the work of M. E. Bravo, facilitator for the first participatory planning workshop, and M. Missrie, monarch butterfly specialist at the World Wildlife Fund–Mexico. We thank A. O. Nichols, R. I. Vane-Wright, H. Possingham, R. Pressey, and two anonymous reviewers for their critique of this paper. We also are grateful to H. Eakin for reading and correcting the English.

Literature Cited

Alonso-Mejía, A., E. Rendón-Salinas, E. Montesinos-Patiño, and L. P. Brower. 1997. Use of lipid reserves by monarch butterflies overwintering in Mexico: implications for conservation. Ecological Applications **7**:934–947.

Anderson, J. B., and L. P. Brower. 1996. Freeze-protection of overwintering monarch butterflies in Mexico: critical role of the forest as a blanket and an umbrella. Ecological Entomology **21**:107–116.

Anderson, R. M., B. F. Hobbs, J. F. Koonce, and A. B. Locci. 2001. Using decision analysis to choose phosphorus targets for Lake Erie. Environmental Management **6**:493–504.

Anonymous. 1986. Decreto por el que por razones de orden público e interés social, se declaran áreas naturales protegidas para los fines de la migración, invernación y reproducción de la mariposa monarca, así como la conservación de sus condiciones ambientales la superficie de 16,110–14–50 hectáreas, ubicadas en los municipios que se indican, pertenecientes a los Estados de Michoacán y del Estado de México. Diario Oficial **398**:33–41.

Anonymous. 1995. Estudio ecológico forestal en la Reserva de la Biosfera Mariposa Monarca en los estados de Michoacán y de México. Technical report. Instituto Nacional de Ecología, Universidad Nacional Autónoma de Mexico, Mexico.

Bojórquez-Tapia, L. A., S. Díaz-Mondragón, and E. Ezcurra . 2001. GIS-based approach for participatory decision making and land suitability assessment. International Journal of Geographical Information Science **15**:129–151.

Brower, L. P. 1995. Understanding and misunderstanding the migration of the monarch butterfly (Nymphalidae) in North America: 1857–1995. Journal of the Lepidopterists' Society **49**:304–385.

Brower, L. P. 1999. Para comprender la migración de la mariposa monarca (1857–1995). Instituto Nacional de Ecología, Mexico

Calvert, W. H., and L. P. Brower. 1986. The location of monarch butterfly (*Danaus plexippus* L.) overwintering colonies in Mexico in relation to topography and climate. Journal of the Lepidopterists' Society **40**:164–187.

Church, R. L., D. M. Stoms, and F. Davis. 1996. Reserve selection as a maximal covering location problem. Biological Conservation **76:** 105–112.

Crawley, M. J. 1993. GLIM for ecologists. Blackwell Science, Oxford, United Kingdom.

Davis, F. W., D. M. Stoms, J. E. Estes, J. Scepan, and J. M. Scott. 1990. An information systems approach to the preservation of biological diversity. International Journal of Geographical Information Systems **4**:55–78.

Davis, L. S., and K. N. Johnson. 1987. Forest management. McGraw-Hill, New York.

De la Maza, E. J., and W. H. Calvert. 1993. Investigations of possible monarch butterfly overwintering areas in central and southeastern Mexico. Pages 295–297 in S. B. Malcolm and M. P. Zalucki, editors. Biology and conservation of the monarch butterfly. Los Angeles County Museum of Natural History, Los Angeles.

Decision Support Software (DSS). 1995. Expert choice for Windows. Version 9.0 user manual. DSS, McLean, Virginia.

Guttman, N. B. 1998. Comparing the palmer drought index and the standardized precipitation index. Journal of the American Water Resources Association **34:**113–121.

Hanna, L., B. Rakotosamimanana, J. Ganzhorn, R. A. Mittermeier, S. Olivieri, L. Iyer, S. Rajaobelina, J. Hough, F. Andriamialisoa, I. Bowles, and G. Tilkin. 1998. Participatory planning, scientific priorities, and landscape conservation in Madagascar. Environmental Conservation **25:** 30–36.

Instituto Mexicano de Tecnología del Agua (IMTA). 1996. Extractor rápido de información climatológica (ERIC). IMTA, Cuernavaca, México.

Jankowski, P. 1995. Integrating geographical information systems and multiple criteria decision-making methods. International Journal of Geographical Information Systems **9:**251–273.

Jones, H. G. 1983. Plants and microclimate. Cambridge University Press, Cambridge, United Kingdom

Lahdelma, R., P. Salminen, and J. Hokkanen. 2000. Using multicriteria methods in environmental planning and management. Environmental Management **26:**595–605.

Lindo Systems. 1998. What's best! User manual. Lindo Systems, Chicago.

Malczewski, J. 1999. Spatial multicriteria decision analysis. Pages 11–48 in J. C. Thill, editor. Spatial multicriteria decision making and analysis: a geographic information sciences approach. Ashgate Publishing, Gower House, United Kingdom.

Margules, C., and M. B. Usher. 1981. Criteria used in assessing wildlife conservation potential: a review. Biological Conservation **21:**79–109.

Nicholls, A. O. 1991. Example of the use of generalised linear models in analysis of survey data for conservation evaluation. Pages 54–63 in C. P. Margules and M. P. Austin, editors. Nature conservation: cost effective biological surveys and data Analysis. Commonwealth Scientific, Industrial, and Research Organization, Canberra, Australia.

Pereira, J. M. C., and L. Duckstein. 1993. A multiple criteria decision-making approach to GIS-based land suitability evaluations. International Journal of Geographical Information Systems **7:** 407–424.

Saaty, T. 1980. The analytical hierarchy process. McGraw Hill, New York.

Shrader-Frechette, K. S., and E. D. McCoy. 1993. Method in ecology: strategies for conservation. Cambridge University Press, Cambridge, United Kingdom.

Smith, P. G., and J. B. Theberge. 1987. Evaluating natural areas using multiple criteria: theory and practice. Environmental Management **11:**447–460.

Szidarovszky, F., M. E. Gershom, and L. Duckstein. 1986. Techniques for multiobjective decision making in systems management. Elsevier, Amsterdam.

US Army Construction Engineering Research Laboratory. 1991. Geographic resource assessment support system, GRASS 4.0. User's manual. U. S. Army Corps of Engineers, Construction Engineers Research Laboratory, Champaign, Illinois.

Vorontsòv-Veliamínov, B. A. 1979. Problemas y ejercicios prácticos de astronomía. Editorial Mir, Moscow.

Appendix 1. The selection of landscape units to be included in the new Monarch Butterfly Biosphere Reserve was determined through the following 0-1 mathematical programing model.

$$\text{Maximize } Z = \sum_{i}^{I}\sum_{j}^{J} r_{ij}a_{ij}X_{ij}$$

subject to constraints

$$\sum_{i}^{I}\sum_{j}^{J} a_{ij}X_{ij} \le A,$$

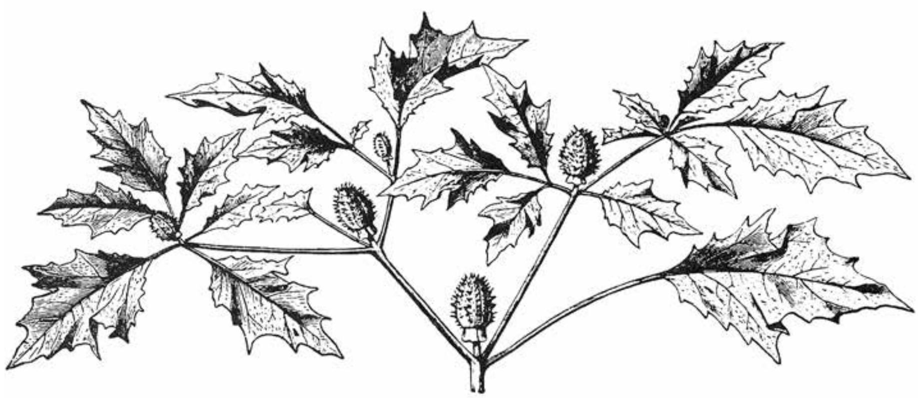
$$\sum_{i}^{I}\sum_{j}^{J} X_{ij} = U,$$

$$X_{ij} = 1{,}0, \text{ and}$$

$$X_{ij} \le X_{ij-1},$$

where i is the watershed index; j is the landscape unit index; r_{ij} is the rank weight of the jth unit in watershed i; a_i is the area of the ith unit; X_{ij} is the decision variable, $X_{ij} = 0$ if selection unit j in watershed i is not selected, or 1 otherwise; A is the total area allotted for a reserve design scenario; U is the number of landscape units to be included in the model; I is the set of watersheds, and J is the set of landscape units.

Equation 3 is the objective function; Eq. 4 is the area constraint; Eq. 5 is the constraint for the number of landscapes units (needed to identify global optimality); Eq. 6 is the binary restriction for the decision variable; and Eq. 7 enforces the sequential selection of landscape units from higher ($j - 1$) to lower (j) elevation in the ith watershed. The values of r_{ij} are proportional to the total number of colonies and the degree of deforestation in a landscape unit.



Caso 2. El análisis de aptitud del suelo en la delimitación y zonificación del Parque Nacional Sierra San Pedro Mártir.

Available online at www.sciencedirect.com
SCIENCE DIRECT®

Biological Conservation 117 (2004) 111–126

BIOLOGICAL CONSERVATION

www.elsevier.com/locate/biocon

Environmental conflicts and nature reserves: redesigning Sierra San Pedro Mártir National Park, Mexico

Luis A. Bojórquez-Tapia[a,*], Horacio de la Cueva[b], Salomón Díaz[c], Daniela Melgarejo[c], Georgina Alcantar[c], María José Solares[c], Gerardo Grobet[c], Gustavo Cruz-Bello[d]

[a]School of Renewable Natural Resources, Biological Sciences East, RM-325, University of Arizona, Tucson, AZ, 85719, USA
[b]Departamento de Ecología, Centro de Investigación Científica y Estudios Superiores de Ensenada. Km 107 Carretera Tijuana-Ensenada, Ensenada, B.C. 22860, Mexico
[c]Instituto de Ecología, UNAM, Ap. Postal 70-275, D.F. 04510, Mexico
[d]Instituto Nacional de Investigaciones Forestales, Agricolas y Pecuarias; km 4.5 Carretera Toluca-Zitácuaro, Zinacantepec, C.P. 51350, Mexico

Received 10 February 2002; received in revised form 22 June 2003; accepted 25 June 2003

Abstract

Nature reserves can be considered a land-use category that competes with other land-uses for territory. Therefore, one fundamental goal in conservation planning is to arrive at nature reserve designs that protect the most valuable lands for conservation, and avoid the inclusion of tracts of land valuable for other stakeholders. However, the complexity of conservation issues, the urgency for protecting critical biodiversity components and the lack of data have forced planners to rely on expert knowledge and public participation for designing nature reserves. Handling expert and public knowledge is challenging because it can be subjective, biased, value laden, context specific, and ambiguous. Here, we present a land suitability assessment (LSA) approach for designing the Sierra San Pedro Mártir National Park, Baja California, Mexico. The LSA allowed us the optimal configuration SSPM in terms of delimitation (inclusion of the most valuable biological resources) and zoning (segregation of incompatible land-uses).

Keywords: Conservation; Land suitability assessment; Multicriteria modeling; Analytical hierarchy process; Mathematical programming; Geographical information system; Baja, California

1. Introduction

The increasing demand for natural resources to meet the needs of a growing population has generated opposition both to already established nature reserves and to the creation of new ones. It is a truism that the protection of pristine ecosystems, prominent landscapes, particular species, or interesting biological phenomena face complex political, economic, social, and cultural challenges. Thus, biological conservation has become a land-use category in its own right that competes for available land with other uses, such as forestry, agriculture, recreation, and urban and infrastructure development (Margules and Usher, 1981).

Following Crowfoot and Wondolleck (1990), competition between conservation and resource extraction can be viewed as an environmental conflict generated by the opposing values of the stakeholders (with respect to nature and natural resources) that one should be able to resolve through negotiation. For this reason, participatory planning is considered as a necessary condition for attaining conservation goals under an ecosystem management framework (Christiansen et al., 1996; Grumbine, 1994). Negotiation is however a complicated process because, as observed by Shepherd and Bowler (1997), the roots of conflict are the inconsistent decisions by authorities at different levels of government and the irreconcilable demands of opposing interest groups.

An additional problem in the design of nature reserves is the inherent complexity of ecological systems, limited data, and a lack of theory for both determining the relevant biodiversity elements to protect and setting

* Corresponding author.

0006-3207/$ - see front matter © 2004 Published by Elsevier Ltd.
doi:10.1016/S0006-3207(03)00265-9

up conservation priorities (Shrader-Frechette and McCoy, 1993). Given the urgency of protecting natural areas and settling the associated environmental conflicts, expert knowledge has been used to procure the necessary information within a consensual planning framework. As observed by Maddock and Samways (2000), the information available for conservation planning depends on the cumulative knowledge of different kinds of experts, including scientists, local peoples, advocates for particular sectors, and land managers.

Nonetheless, the use of expert knowledge can be problematic in decision making because it is subjective, value laden and often contradictory (Keeney and Raiffa, 1976). According to Shrader-Frechette and McCoy (1993), these problems can be related to three kinds of "value judgements": (1) the omission or misinterpretation of data (biased value judgments), (2) the use of data gathering techniques and assessment methods that support preconceived notions (methodological value judgments), and (3) the influence of personal, social, ethical or philosophical predilections in the interpretation of results (contextual value judgments). If these value judgments remain unchecked, nature reserves will not succeed in the long term because personal idiosyncrasies, prejudices, and interest positions will exacerbate conflicts between conservation advocates and other stakeholders.

Consequently, there is a need for formal approaches to make the best use of expert knowledge and readily available data in nature reserve planning. The goal should be to attain a design that results from an exhaustive and rational evaluation of the conservation issues and their inherent conflicts.

The multiple-use perspective (Brooks et al., 1992) provides a theoretical framework for implementing an appropriate identification of the issues, goals, and limitations of each stakeholder. Under this perspective, conflicts are reduced by the segregation of incompatible activities through a land suitability assessment (LSA). LSA is a formal decision-making technique to determine the fitness of the land taking into consideration the values and interests of the stakeholders (Bojórquez-Tapia et al., 2001; Malczewsky et al., 1997; Pereira and Duckstein, 1993).

The objective of this paper is to demonstrate how environmental conflicts in nature park design can be addressed through the application of an LSA approach. This approach allows planners to determine the optimal delimitation and zoning of a nature reserve in a way that maximizes consensus and minimizes conflict among the stakeholders. We present the case of Sierra San Pedro Mártir National Park (SSPM), Baja California, México, to show how a LSA can be implemented through the integration of mathematical models (multivariate classification, multicriteria modeling, and mathematical programming) into a geographical information system (GIS). The results of an LSA consist of a set feasible alternative reserve configurations, which in the case of SSPM allowed us to identify the one that (1) protected the critical biological entities, (2) avoided the inclusion of tracts land valuable to other stakeholders, and (3) segregated incompatible land uses within the reserve.

2. Study area

The SSPM was established in 1932 as a forest reserve and as a National Park in 1947 (Minninch et al., 1997). As it stands, the SSPM occupies a small but significant portion of the whole Sierra San Pedro Mártir. The current conflicts in SSPM originated from the ambiguities of the presidential decree that created the park and the history of land-use in the region. Over time, the disputes among conservationists, academic institutions, local inhabitants and park administrators became so intense that the Mexican environmental authorities were compelled to reconsider the configuration of the park as a means to settle the stakeholders' colliding demands.

2.1. Biological importance

Sierra San Pedro Mártir is located in northwestern Baja California, at the southern margin of the North American Mediterranean region (which includes southern California and northern Baja California, as far as 29°N), and along the southernmost portion of the Californian floristic region (Minnich et al., 1997). As any other mediterranean zone, wet-mild winters and warm-dry summers characterize it.

The sierra encompasses the last remnants of undisturbed habitats of the North American Mediterranean region. It presents an unmanaged forest fire regime and remains practically uninhabited. It still contains the habitats and endemic species that distinguish the Californian Mediterranean.

The SSPM has biologically important and charismatic animal species such as mountain bighorn sheep, (*Ovis canadensis cremnobates*), mule deer *(Odocoileus hemionus*), bobcat (*Lynx rufus*), mountain lion (*Felis concolor*), grey fox (*Urocyon cinereoargenteus*), coyote (*Canis latrans*), and golden eagle (*Aquila chrysaetos*). The species and subspecies endemic to the park and sierra are: pocket gopher (*Thomomys botae*), California pocket mouse (*Chaetodipus californicus*), Merriam chipmunk (*Eutamias obscurus*), California vole (*Microtus californicus*), long eared bat (*Myotis evotis milleri*), pinion mouse (*Peromyscus truei*), broad-footed mole (*Scapanus latimanus*), Douglas squirrel (*Tamiasciurus mearnsii*), and a rainbow trout (*Onchorhynchus mykiss nelsonii*) (Minnich et al., 1997). At present there are also plans to reintroduce the California condor (*Gymnogyps californianus*).

The vegetation presents clear altitudinal zones (Fig. 1). Chaparral on the lower western slope is replaced by mixed confer forest on the summit plateau. This is replaced by pinyon forest at higher elevations on the eastern escarpment, and by Sonoran Desert scrub at lower elevations. The most striking feature of the mixed conifer forests is its open park-like aspect. This old-growth forest consists of mature trees reaching 30–45 m,

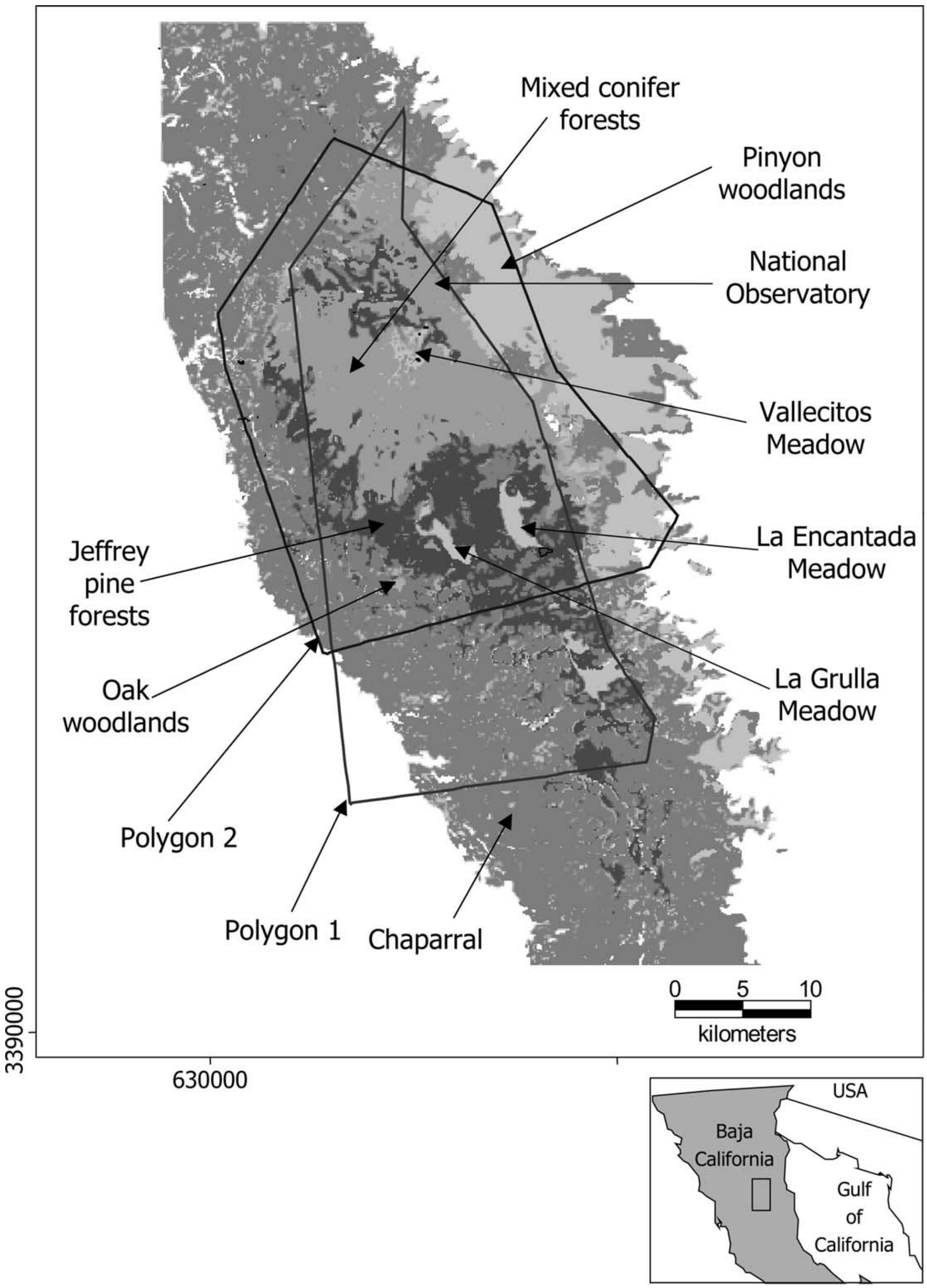


Fig. 1. Study area, vegetation and alternative interpretations of the presidential decree (polygons 1 and 2) that created the Sierra San Pedro Mártir National Park, Baja California, México.

with few pole-sized trees and saplings, and an open shrub cover (Minnich, 2001; Minnich et al., 2000; Minnich et al., 1997).

The best-known endemic species of the sierra is the mountain cypress (*Cupressus montana*), which covers 2400 ha within the SSPM. Silktassle bush (*Garrya grisea*) is the only shrub endemic to the sierra, but there are two other shrubs that are extremely rare in the area, desert sumac (*Rhus kearneyi*), and *Cercocarpus ledifolius*. All other endemic plants are annuals or herbaceous perennials: *Haplopappus wigginsii*, *Lesquerella peninsularis*, *Senecio martirensis*, *Mimulus purpureus*, *Ophiocephalus angustifolius*, *Astragalus gruinus*, *Trifolium wigginsii*, *H. martirensis*, *H. pulvinatus*, *Hedeoma martirense*, *Heterotheca martirensis*, *Sphaeralcia martirense*, *Stephenomeria monocephala*, *Draba corrugata*, *Eriogonum hastatum*, *Hemizonia martirensis*, *Galium diabloense*, and *G. wigginsii Minnich et al., 1997)*.

2.2. Land uses and threats to the park

Three communally owned lands or *ejidos* (Bramadero, Tepi, and Plan Nacional Agrario) set the northern, western and eastern boundaries of the park, while federal lands set its southern limit. The ejido lands are under a management regime oriented towards sustainable hunting of game species and the protection of natural habitats.

The only permanent residents of the park have been the staff of the National Astronomic Observatory (OAN, by its Spanish acronym). The OAN was established in 1975 with a presidential decree for an astronomical reserve in the area. The higher reaches of this sierra are considered to be one of the few remaining dark places in the planet with optimal characteristics for astronomical observation, namely atmospheric transparency, cleanliness, homogeneity, and low humidity.

Under present Mexican environmental law, natural resource development practices, such as forestry and cattle grazing, are prohibited within a national park. Therefore, the activities allowed in the SSPM are those directed to preserve the uniqueness of the sierra, the natural characteristics, and the atmospheric conditions for astronomical observation. Likewise, protection of the natural characteristics of the sierra is fundamental for the water supply of the agricultural and urban areas in the western lowlands.

Ranching can be considered a traditional land use of the SSPM. The Jesuit missionaries introduced cattle grazing to the area three centuries ago and this practice has continued ever since. Cattle roam freely through the park from early Spring to late Summer, and are driven to the ejidos and the lower western and southern reaches of the sierra during the Fall and Winter. The high altitude meadows within the park, Vallecitos and La Grulla (Fig. 1), are the grazing areas of the Ejido Bramadero. The conservationists have warned the environmental authorities that these grazing practices might be threatening endemic species of both small mammals and herbaceous perennials and annuals.

There is a proposal to transform the park into a biosphere reserve (Minnich et al., 1997) that is currently under consideration by the environmental authorities. The goal of this biosphere reserve is to protect the unique combination of biotic richness, cultural importance, and relative isolation of the sierra. However, this proposal has faced opposition from Ejido Bramadero (A. Melling, pers. comm.) and thus its future is now uncertain.

2.3. Ambiguity in the park boundaries

A 1947 presidential decree created the SSPM and established its boundaries through reference landmarks, distances, and bearings. Previous to this decree, the same area was declared a forest reserve in 1932 (Minnich et al., 1997).

The main reference point for setting the park's boundaries is Picacho del Diablo, the highest peak in the peninsula, also known as La Encantada (Minnich et al., 1997). Picacho del Diablo is located in the eastern portion of the sierra and *Polygon 2* in Fig. 1 results from this reference point.

However, the decree is bound to an ambiguous interpretation of the exact location of the reference landmarks. According to the account of the inhabitants of the ejidos surrounding the park, the boundaries of the park should be delineated using as the main reference point a lower peak, also called La Encantada, located at the northwestern section of the sierra. The ambiguity in the park boundaries has been aggravated by the actions of the Federal authorities, which have issued the respective boundary certificates to the ejidos. *Polygon 1* in Fig. 1 results from this interpretation of the decree, whereas *Polygon 2* results from the interpretation of the federal government agency responsible for mapping (INEGI, Instituto Nacional de Estadística, Geografía e Informática).

Thus, the ejidos advocate the implementation of *Polygon 1* because it excludes from the reserve about 3000 ha of mixed conifer stands of high commercial value. The Ejido Bramadero claims that these stands are within its boundaries and have requested logging permits to the forestry authorities. This position is also supported by the park administration as a political settlement to the land tenure conflicts of SSPM. On the other hand, conservationists and the academic community are in favor of *Polygon 2* because it would protect those forest stands.

Likewise, a potential for land-use conflicts exists between the park and the ejidos Tepi and Plan Nacional Agrario. In the eastern escarpment of the park, the land tenure maps extend over areas critical for either conservation, namely on mountain bighorn sheep habitats, or astronomical observation.

3. Method

We implemented the LSA through a raster-based GIS, following the procedures described in Bojórquez-Tapia et al. (2001) and, Malczewski (1999), Malczewsky et al. (1997), and Pereira and Duckstein, 1993). In general, an LSA consisted of the combination multivariate statistics, multicriteria modeling, and mathematical programming procedures.

It should be noted that the aim and scope of this research were focused on the following two issues: (1) the conflicts generated by the boundary ambiguities of the park and its neighbors, and (2) the goal of maximizing the conservation value of the new park in an area similar to that of the current park. Consequently, we excluded from consideration some important issues beyond the immediate vicinity of the park (e.g. the problems of the Kiliwa natives in the region). Many of these concerns were accounted for in the proposal for a biosphere reserve of Minnich et al. (1997).

3.1. Database

The cartographic database was compiled from thematic map layers available at the Centro de Investigaciones Científicas y Educación Superior de Ensenada (CICESE). The map layers included the two interpretations of the park boundaries, vegetation (generated from the map reported in Minnich, 2001; Minnich and Franco-Vizcaino, 1998; and Minnich et al., 2000), roads, streams, elevation (DEM). The pixel size for all map layers was 1 ha. We employed the program Geographic Resource Analysis Support System, GRASS v.4.2 (USA-CERL, 1998) for all the spatial analyses.

3.2. Expert and public consultation

Expert consultation was carried out in a series of group decision-making workshops with local stakeholders. The goal was to obtain the physical and biological attributes that had to be considered for the delimitation and zoning of the park. In preparation for the workshops, the relevant stakeholders were identified by consensus between the members of the park technical committee (see Background section) and included the park administration, ejidatarios, OAN, and conservationists (this represented by the faculty of local academic institutions). Independent workshops were carried out with representatives of academic institutions and stakeholders organizations in October 17th thru 18th, and November 24th, 2000 (see acknowledments).

During the workshops, the experts and stakeholder representatives were asked to declare their objectives and activities, and to identify the physical and biological attributes of the study area needed to carry out their activities. A facilitator guided the discussions during the workshops to assure that each specialist could propose his/her own list of criteria to be evaluated.

These attributes were translated to corresponding decision criteria and importance weights by means of the Analytical Hierarchy Process (AHP; Saaty, 1980). The AHP was implemented through the program Expert Choice (1995), which facilitated debates among experts until consensus was reached in each workshop. The AHP weighted each decision criterion by its importance in a [0–1] interval scale (see Malczewski et al., 1997; Smith and Theberge, 1987). At the lowest level of the hierarchy structure, each decision criterion was associated with specific land attributes that could be mapped.

Once the decision criteria and their weights were established, the land attributes were related to their worth for achieving a stakeholder activity. These attributes were obtained by the generation of the respective utility functions; these transferred the specific values of each land attribute to a utility score in a [0,1] scale of interval properties (Keeney and Raiffa 1976, Smith and Theberge 1987). As suggested by Pereira and Duckstein (1993), the utility functions for continuous decision criteria (for example, elevation) were generated using the bisection approach and elementary analytical geometry; for nominal decision criteria (for example, vegetation type), discrete values were derived for each category using the AHP.

3.3. Multicriteria modeling

The multicriteria model for SSPM valued the landscape attributes with respect to a specific land-use or sectoral activity. Each thematic layer represented an evaluation criterion and grid cells were valued according to their suitability for a particular activity.

Following Pereira and Duckstein (1993), each pixel in the GIS database was associated with a number of criteria or decision variables represented by map layers. The land suitability score for a sectoral activity j, in the kth pixel was obtained by a weighted linear combination (Bojórquez-Tapia et al., 2001; Eastman et al., 1993; Jankowski, 1995):

$$s_j^k = \sum_i^I w_{ij} Uf\left(x_{ij}^k\right), \qquad (1)$$

where: j is the sectoral index; w_{ij} is the importance weight of criterion i for the sector j;$Uf(\cdot)$ is the value function of criterion i for activity j.

Equation (2) implies the following conditions:

$$0 < w_{ij} \leqslant 1, \quad (2)$$

$$\sum_{i}^{I} w_{ij} = 1, \quad (3)$$

$$0 \leqslant Uf\left(x_{ij}^{k}\right) \leqslant 1, \quad (4)$$

$$0 \leqslant s_{j}^{k} \leqslant 1. \quad (5)$$

Equations (3) and (4) are conditions of the AHP; Eq. (5) alludes to the possible utility scores of a decision criterion; and Eq. (6) results from Eq. (2) when conditions (3) through (5) are met.

3.4. Delimiting the park

The limits of the SSPM that maximized the conservation value of the reserve were established by means of an optimization model applied to the results of the land suitability for biodiversity conservation. The landscape units (tracts of land to be examined during the optimization procedure) were delineated by means of overlay operations of the watersheds and elevation digital maps. To examine the sensitivity of the reserve boundaries demarcation to the definition of the landscape units, a total of ten optimization scenarios were examined. These resulted from using two different numbers of watersheds that produced by the GIS (e.g. 48 or 60 watersheds), and five different possible elevation intervals. Thus, the landscape units were established as watershed segments of different elevation intervals (e.g. 100, 200, 300, 400, and 500 m). For example, the landscape units for the 100 m interval were defined as follows: from 600 to 699 m, from 700 to 799 m, 800 to 899 m, etcetera.

The conservation value, b_{kl}, was obtained for each landscape unit as follows:

$$b_{kl} = \overline{S_{kl}} a_{kl}, \quad (6)$$

where: k is the watershed index; l is the elevation interval index of the landscape unit; $\overline{S_{kl}}$ is the average suitability score for conservation of the landscape unity l in watershed k; and a_{kl} is the area of that landscape unit.

The computation of b_{kl} was carried out by means of the GRASS software. The procedure required the coding of each landscape unit, and then the of the *r.average* command to obtain $\overline{S_{kl}}$. Next the command *r.stats*, linked to a Unix shell, was employed to multiply the average conservation value by the area of the landscape unit.

The optimal combination of landscape units for delimiting de reserve was addressed as 0–1 mathematical programming (Dykstra, 1984). The program *IBM-OSL* (Ming et al., 1994; Minkoff, 1992) was used for all the computational procedures; this program was loosely linked to the GIS. The objective function selected the landscape units that maximized the total conservation value of the reserve, given a total area constraint; formally:

$$\text{Maximize} \quad Z = \sum_{k}^{K} \sum_{l}^{L} b_{kl} X_{kl}, \quad (7)$$

subject to:

$$\sum_{k}^{K} \sum_{l}^{L} a_{kl} X_{kl} \leqslant A, \quad (8)$$

$$X_{kl} \leqslant X_{kl-1}, \quad (9)$$

$$X_{kl} = 1, 0, \quad (10)$$

where: k is the watershed index; l is the selection units index; b_{kl} is the conservation quality; a_{kl} is the area of the landscape unit; A is the total area for the scenario; and X_{kl} is the decision variable that equals 1, if landscape unit is selected, or 0 otherwise.

Eq. 8 ensures that the combined area of the selected landscape unit is equal or smaller than the maximum established by the total area scenario; Eq. 9 assures that the sequence of selection of landscape unit in watershed ith is from higher elevations (j–1) to lower elevations (j); and Eq. 10 is the binary restriction for the decision variable.

Four different total area constraints were examined. Two were based on the original estimates by the environmental authorities about the size of a new SSPM (either 60,000 or 80,000 ha). The others were based on the sizes of the two alternative interpretations of the presidential decree (e.g. *Polygon 1* of 67,200 ha, and *Polygon 2* of 69,290 ha).

3.5. Zoning

Zoning of SSPM was carried out following the land suitability assessment approach described by Bojórquez-Tapia et al. (2001). Accordingly, the map layers that resulted from the sectoral land suitability assessments (by applying Eq. 2) were subjected to a numerical classification to identify homogeneous land parcels or land suitability groups. These aggregated pixels that presented similar land suitability scores for the considered sectoral activities.

In summary, the computational procedure required a numerical classification of the suitability map layers of the stakeholders by means of a divisive polythetic partitioning (Noy-Meir, 1973; Pielou, 1984). This partitioning technique was implemented in the GIS by a sequential application of principal component analyses using the command *i.pca* of GRASS. The resulting land suitability groups were transferred to a nominal map. Next, a matrix was prepared to depict the average land suitability (in the cells) of each sectoral activity (in the rows) in each suitability group (in the columns). This matrix was adjusted following the Gower's residuals by a double centering procedure (Bojórquez-Tapia et al., 1994; Digby and Kempton, 1987; Gower, 1966).

The identification of land uses or activities for land suitability group was achieved by examining which activities presented positive values of Gower's residuals. Conflicts at each land suitability group were avoided by restricting the selection of sectoral activities to those that were compatible to each other, and that such combination of activities maximized the total suitability value of the study area. This procedure was achieved by means a 0–1 mathematical programming procedure (Malczewski et al., 1997; Bojórquez-Tapia et al., 2001)

4. Results

The hierarchy structure included five levels (Fig. 2). The first level or goal was defined as "Designing a park that protects the most valuable biodiversity attributes of the North American Mediterranean region and avoids conflicts among competing activities in the Sierra San Pedro Mártir." The second level included the three relevant stakeholders for the study area: *Cattle Grazing*, *OAN* and the *Park Administration*. The stakeholders were weighted equally with respect to their importance to achieve the goal and for determining the suitable land-uses in a pixel.

In the third level, one land attribute was associated to *OAN*: a "dark" area defined as a circle of 10 km of diameter centered on the main telescope. This criterion was implemented through a viewshed analysis by means of the GRASS command *r.los*; this land-use was referred as *Dark Area*. For *Cattle Grazing*, the third level included three decision criteria: *Enclosures*, *Springs*, and *Grasslands* and *Meadows*. For *Park Administration*, the third level included the criteria *Restricted Use* and *Biodiversity Protection*, which corresponded to the main objective of the park and hence the latter received the highest weight.

The fourth hierarchical level included three criteria for *Restricted Use* and two for *Biodiversity Protection* (it should be noted however that one criterion, *Traditional Use*, was eliminated from *Restricted Use*, to avoid repetition with *Cattle Grazing*).

The land attributes for Scenic Quality, were slope, elevation and mixed forests; for Environmental Education, vegetation type; and for Access, distance to major roads.

With respect to Biodiversity Protection, the fourth hierarchical level included the decision criteria Flora and Fauna. The fifth hierarchical level corresponded to the vegetation types, and the critical terrestrial vertebrates of SSPM.

The value functions used in Eq. 1 (see Appendix A), which described the state of a decision criterion in a pixel, included continuous variables (slope, elevation), discrete variables (vegetation, habitat), and binary variables (distance to roads, slope, habitat, vegetation, corrals, distance to water holes, grazing areas, and distance to OAN).

The analysis for delimiting the SSPM boundaries was not sensitive to the size of the landscape units (which were determined by different altitude intervals and number of watersheds). In general, all the scenarios showed a similar spatial pattern of selected landscape units (Figs. 3a,b) and conservation values (Table 1). Hence, the scenario chosen for delimiting the park was that of 60 watersheds and altitude interval of 500 m because presented the fewest number of landscape units and higher conservation value.

The comparison of the alternative designs (Table 2) revealed that the boundaries of *Polygon 1* presented the lowest efficiency in terms of conservation value. In contrast, the efficiency value of *Polygon 2* was closer to the one obtained by the optimization model for 60,000 ha. This alternative obtained the highest average conservation value.

The zoning procedure required the application of four iterations of PCA to generate five land suitability groups, which presented a zoning pattern of concentric areas (Fig. 4a–d). Except for Group 4, the extent of the suitability groups was similar among the alternative park designs (Table 3).

Group 1 was located at the center of the study area and. It encompassed mixed conifer forests, Jeffrey pine forests, and meadows (Fig. 4a–d), and, depending on the scenario, occupied an area of 11 to 12% of the reserve (Table 3).

The suitability scores were comparatively high for all the land-uses with respect to the other groups, especially *Dark Area* (Table 4). According to the Gower residuals (Fig. 5a), the primary land use was *Dark Area*, and the secondary one was *Biodiversity Protection*, because the latter is compatible with the primary use, in spite of its negative residual values. By excluding *Dark Area* from the calculation of the Gower residuals, *Biodiversity Protection* was the only activity that resulted with a positive value (Fig. 5b), confirming the land-use assignment for Group 1.

Group 2 surrounded the first one and extended over an area of 16–21% of the reserve, depending on the reserve delimitation scenario (Table 3, Fig. 3a–d). It included mixed conifer forests, Jeffrey pine forests, and the meadows known as La Encantada and La Grulla. It presented a high suitability for *Biodiversity Protection* and *Restricted Use* (Table 4, Fig. 5a), however, since these two uses were incompatible with each other, the latter was discarded. As in the previous Group, excluding *Dark Area* from the computations corroborated the assigned land-uses (Fig. 5b).

Group 3 was located mainly in the southwestern section of the study area. It was also found as small patches neighboring Group 1, at the central portion of the park, and Group 2, at the western and southeastern sections o the park (Fig. 4a–d). It occupied an area equivalent to 15 or 19% of the park, depending on the delimitation scenario. Although *Biodiversity Protection* and *Cattle Grazing* presented similar land suitability scores (Table 4), the Gower residuals revealed that the land-use of this Group should be as *Cattle Grazing* (Fig. 5).

Group 4 occupied the smallest area and was distributed as patches within Group 5 (Table 3; Fig. 4a–d). It encompassed chaparral, Jeffrey pine forests, and pinyon pine forests. According to the Gower residuals, its primary land-use was as *Restricted Use* (Table 4, Fig. 5a–b); a secondary land-use could not be assigned because they were considered incompatibilities with the primary one.

<table>
<tr><th colspan="5">Hierarchical Level</th></tr>
<tr><th>1st</th><th>2nd</th><th>3rd</th><th>4th</th><th>5th</th></tr>
<tr><td rowspan="20">Goal (1.000)</td><td>OAN (0.333)</td><td colspan="3">Not applicable</td></tr>
<tr><td rowspan="15">Park administration (0.333)</td><td rowspan="3">Restricted Use (0.055)</td><td>Scenic Quality (0.024)</td><td rowspan="3">Not applicable</td></tr>
<tr><td>Environmetal Education (0.024)</td></tr>
<tr><td>Access (0.008)</td></tr>
<tr><td rowspan="12">Biodiversity Protection (0.279)</td><td rowspan="6">Fauna (0.139)</td><td>Black tail deer (0.023)</td></tr>
<tr><td>Cougar (0.023)</td></tr>
<tr><td>Small mammals (0.023)</td></tr>
<tr><td>Condor (0.023)</td></tr>
<tr><td>Trout (0.023)</td></tr>
<tr><td>Herps (0.023)</td></tr>
<tr><td rowspan="6">Flora (0.139)</td><td>Mixed conifer (0.045)</td></tr>
<tr><td>Meadows (0.040)</td></tr>
<tr><td>Jeffrey pine (0.023)</td></tr>
<tr><td>Pinyon (0.013)</td></tr>
<tr><td>Oak (0.013)</td></tr>
<tr><td>Chaparral (0.005)</td></tr>
<tr><td rowspan="4">Cattle grazing (0.333)</td><td>Springs (0.148)</td><td rowspan="4">Not applicable</td><td rowspan="4">Not applicable</td></tr>
<tr><td>Meadows (0.119)</td></tr>
<tr><td>Enclosures (0.037)</td></tr>
<tr><td>Grasslands (0.030)</td></tr>
</table>

Fig. 2. Results of the hierachichal structure for the Land Suitability Assessment of Sierra San Pedro Mártir National Park, Baja California, México (importance weights in parenthesis; OAN = National Astronomic Observatory; and na = not applicable).

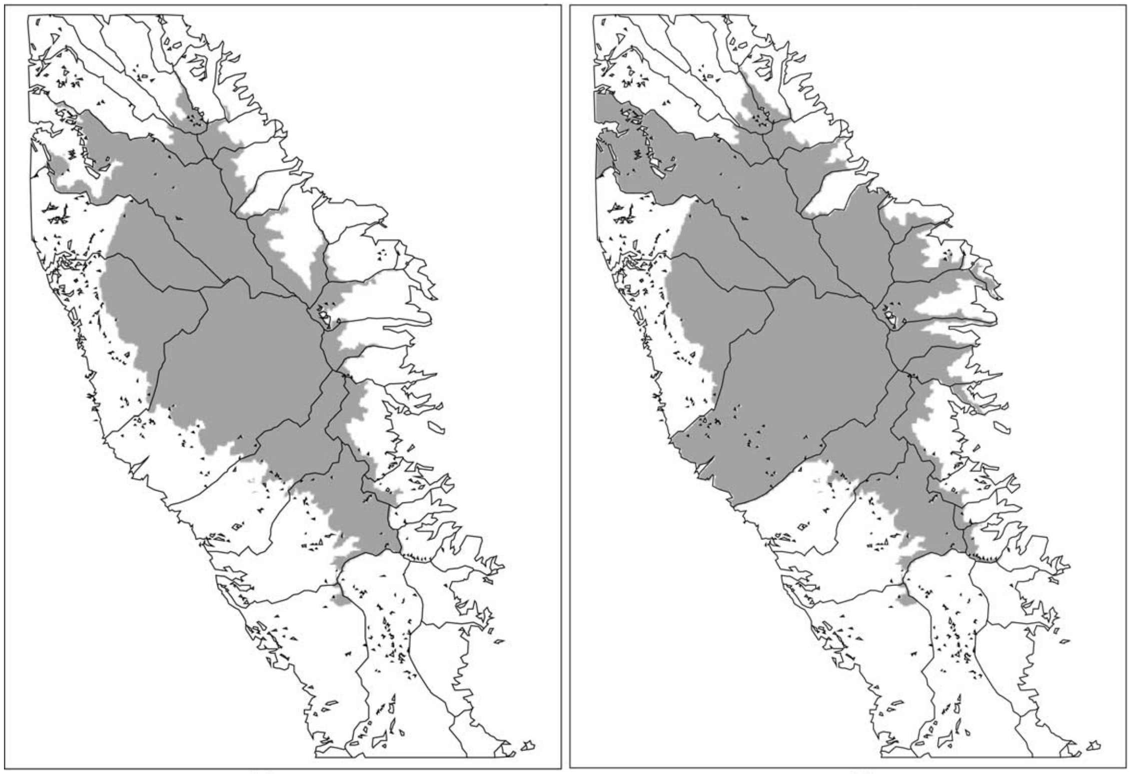


Fig. 3. Results of the optimal delimitation procedure for Sierra San Pedro Mártir National Park, Baja California, México; a = total area restriction of 60,000 ha; and b = total area restriction of 80,000 ha; gray indicate the area to be included within the reserve bounsaries, and dark lines indicate the watershed boundaries.

Table 1
Results of the optimization scenarios for delimiting the Sierra San Pedro Mártir National Park, Mexico

Elevation Interval (m)	Area Restriction of 60,000 ha			Area Restriction of 80,000 ha		
	Number of Landscape units	Average conservation value ($\times 10^3$)	Total conservation value ($\times 10^3$)	Number of Landscape units	Average conservation value ($\times 10^3$)	Total conservation value ($\times 10^3$)
48 Watersheds						
100	108	3.6	2.15	168	3.0	2.41
200	57	3.5	2.12	99	3.0	2.40
300	49	3.6	2.14	72	3.0	2.41
400	47	3.5	2.08	52	3.0	2.37
500	38	3.5	2.13	49	3.0	2.40
60 Watersheds						
100	130	3.6	2.15	207	3.0	2.44
200	73	3.6	2.13	111	3.0	2.42
300	49	3.6	2.14	75	3.0	2.43
400	48	3.5	2.10	66	3.0	2.41
500	37	3.6	2.14	55	3.0	2.42

Group 5 was the largest one and surrounded the other four suitability groups (Table 3, Fig. 4a–d). It extended over chaparral, pinyon pine forests, Jeffrey pine forests, and oak woodlands. Its suitability scores were rather low amongst the land-uses (Table 4), although the Gower residuals revealed that a high suitability for *Cattle Grazing* (Fig. 5a–b).

5. Discussion and conclusions

Conflicts like the ones found in SSPM are characteristic of nature reserves in Mexico. In general, these kinds of conflicts can be related to reserve designs lacking a comprehensive and systematic evaluation of the conservation priorities and the inherent environmental

Table 2
Comparison of the efficiency of different reserve design scenarios for the Sierra San Pedro Mártir National Park, Mexico

Land cover	Reserve scenario					
	Boundaries according to decree interpretations		Boundaries according to the results of the selected optimization models (area restriction scenario in ha)			
	Polygon 1 (ha)	*Polygon 2* (ha)	(60,000) (ha)	(80,000) (ha)	(67,200) (ha)	(69,300) (ha)
Mixed forest	18,283	20,527	20,543	20,645	20,638	20,638
Meadows	2429	1,672	2408	2,425	2415	2,415
Jeffrey pine forest	16,013	14,095	16,215	16,609	16,339	16,339
Pinyon woodlands	1176	8,874	2591	10,670	5140	6,397
Oak woodlands	1675	2,959	2711	3,549	3165	3,392
Chaparral	23,507	19,919	14,982	25,547	18,951	19,567
Barren soils	494	542	530	535	531	531
Total area	67,195	69,293	59,980	79,980	67,179	69,279
Conservation value index (dimensionless)						
Total conservation value ($\times 10^7$)	1.99	2.17	2.14	2.42	2.25	2.28
Average conservation value ($\times 10^3$)	3.0	3.1	3.6	3.0	3.3	3.3

Table 3
Distribution of the land suitability groups for different reserve design scenarios of the Sierra San Pedro Mártir National Park, México

Land Suitability Group	Reserve Scenario					
	Boundaries According to Decree Interpretations		Boundaries According to the Optimization Models (area restriction scenario in ha)			
	Polygon 1 (ha)	*Polygon 2* (ha)	(60,000) (ha)	(80,000) (ha)	(67,200) (ha)	(69,300) (ha)
1	8575	8882	8901	8902	8901	8901
2	11,872	12,235	13.002	13,070	13,064	13,064
3	10,884	9210	11,586	11,828	11,710	11,710
4	5433	6671	7043	8479	8217	8234
5	27,737	32,295	19,468	37,720	25,306	27,389

conflicts. We then may assert that a revision of the design of nature reserves is not a futile exercise, but an opportunity for those parties concerned to re-evaluate and negotiate conservation areas and priorities.

We agree in principle with the generalized opinion that public participation is a critical element for attaining a more sensible conservation approach (see Christiansen et al., 1996; Grumbine, 1994; Scott et al., 1995). The idea is that a collaborative decision-making process results in partnership and commitment among the stakeholders, and that provides a means for gaining insight of the relevant biological and socioeconomic issues. As the case of SSPM demonstrates, however, incorporating public participation into conservation planning is challenging because of the stakeholders' different perspectives on the value of biotic and abiotic resources.

Primary among the considerations for a legitimate public consultation process are the requirements of explicit descriptions of the interest and objectives of the stakeholders (Wondelleck, 1985), and transparent assessments of different planning scenarios (Webler et al., 2001). From an analytical viewpoint, we affirm that an efficient way to fulfill such requirements is through a decision theory framework (see Keeney and Raiffa, 1976; Malczewski, 1999; Szidarovszky et al., 1986), as the one used in the case of SSPM.

Perhaps, the most important contribution of a decision theory framework in conservation planning is providing a means for handling what Shrader-Frechette and McCoy (1993) called "the value judgments". In SSPM, both the bias and the methodological value judgments (e.g. the omission or misinterpretation of data, and the use of assessment methods to support preconceived notions, respectively) were avoided through the application of the AHP in the consultation stage. The AHP resulted in a minimum set of decision criteria pertinent to the activities of each stakeholder. Although we acknowledge that there may be a number of different hierarchical structures for the design of SSPM, we regarded the one in Fig. 2 as valid because it satisfied Keeney and Raiffa's (1976) requirement of direct correspondence to the stakeholders' preferences.

Additionally, the LSA proved to be effective for preventing "contextual value judgments" (that is, interpretations influenced by personal, social, ethical or philosophical predilections). That is, the results

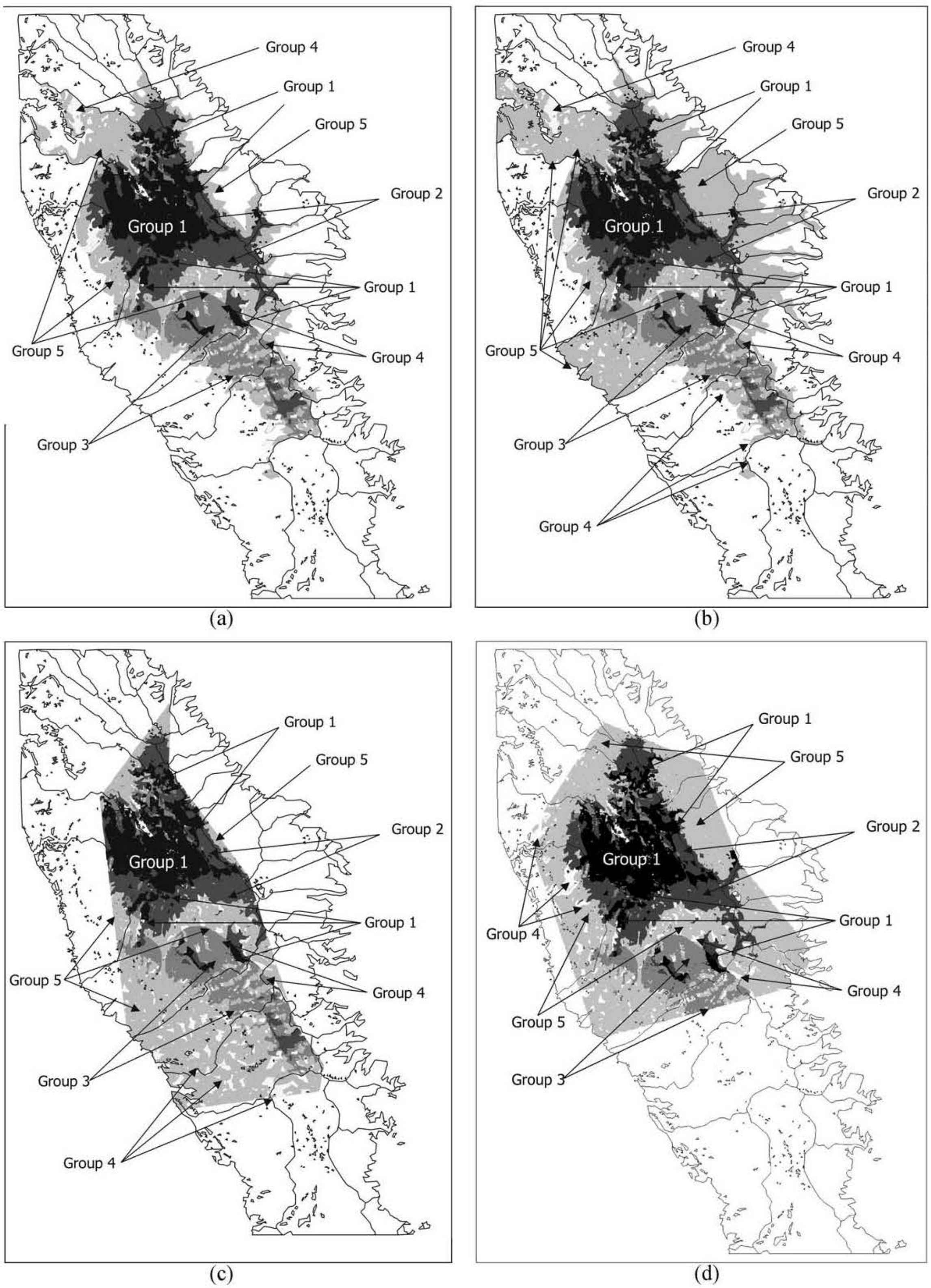


Fig. 4. Results of the zoning procedure for Sierra San Pedro Mártir National Park, Baja California, México according to four potential delimitations (a = optimal delimitation, total area restriction of 60,000 ha; b = optimal delimitation total area restriction of 80,000 ha; c = *Polygon 1*; d = *Polygon 2*).

Table 4
Average land suitability scores for land-uses in the Sierra San Pedro Mártir National Park

Land suitability group	Average Land Suitability Score			
	Restricted use	Biodiversity protection	Cattle grazing	Dark area
1	7.34	8.26	5.10	10.00
2	7.30	8.55	4.54	1.00
3	4.81	5.35	5.10	1.02
4	3.51	1.64	1.56	1.15
5	2.19	1.56	1.30	1.09

corresponded to the optimal solution of the park configuration based on the issues and weighted criteria expressed by all stakeholders that participated in the workshops, rather than an obscure interpretation of the issues from the planners or the authorities. In this process, there are three points worth mentioning: Firstly, the multicriteria modeling exercise (Eq. 1) generated a set of land suitability maps that represented the interests of each individual stakeholder, and did not assume any trade-off among the alternative land-uses. For this same reason, these models did not violate the necessary condition of independency of decision criteria in the additive value function (Keeney and Raiffa, 1976; Lahdelma et al., 2000; Smith and Theberge, 1987).

Secondly, the zoning and delimitation procedures did not assume any particular land-use as "right" or "wrong." Instead, the numerical classification of the land suitability map layers divided the park in homogeneous areas with respect to the land suitability scores of each pixel.

And thirdly, the use of mathematical programming techniques provided a systematic mechanism for comparing alternative reserve designs, confirming the claims of Chuvieco (1993) on the worth integrating of linear programming algorithms and GIS in land-use planning. This assertion is based on the fact that the objective function and the restrictions (as indicated in Eqs. (7)–(10) and in the description of the zoning procedure) were established considering the fundamental goals of both conservation biology and conflict resolution. Thus, the optimization models were useful in determining which alternative delimitation maximized the conservation value of the park (Table 2, Fig. 3), and to derive an arrangement of land-uses within the park and neighboring areas that minimized conflict among the stakeholders (Fig. 4).

Wondolleck (1985) affirms that the key elements in participatory planning are how issues are framed, what information is bought to bear, and how the alternatives are evaluated. Although we concur with this opinion in general, the fact of the matter is that any planning effort based on public participation is limited by the information that the stakeholders are willing to state publicly. One aspect in our study proves this point: because the ejido's representatives neglected to state that logging of the above-mentioned forest stands was one of their objectives, we did not consider forestry in the zoning assessment. At the present time, it is unclear whether this omission will intensify the environmental conflicts among the local inhabitants and conservationists.

The lack of complete and unambiguous information from the stakeholders does not invalidate the assessment for SSPM. We acknowledge that the LSA limits us to the issues and criteria expressed by the participants. Thus the failure of a stakeholder to express any of his/her interests resulted in the exclusion of that issue from the model. One lesson from this experience is the importance of undertaking a comprehensive examination of the range of possible issues and activities in the region before working directly with the stakeholders. Certainly, additional planning exercises will be needed to resolve conflicts that our assessment overlooked. For example, the issues outside our mandate, such as the interests of the Kiliwa natives, the role of wildfire, the forestry practices in the Ejido Bramadero, or the proposal for the creation of a biosphere reserve, could be evaluated using the techniques shown here.

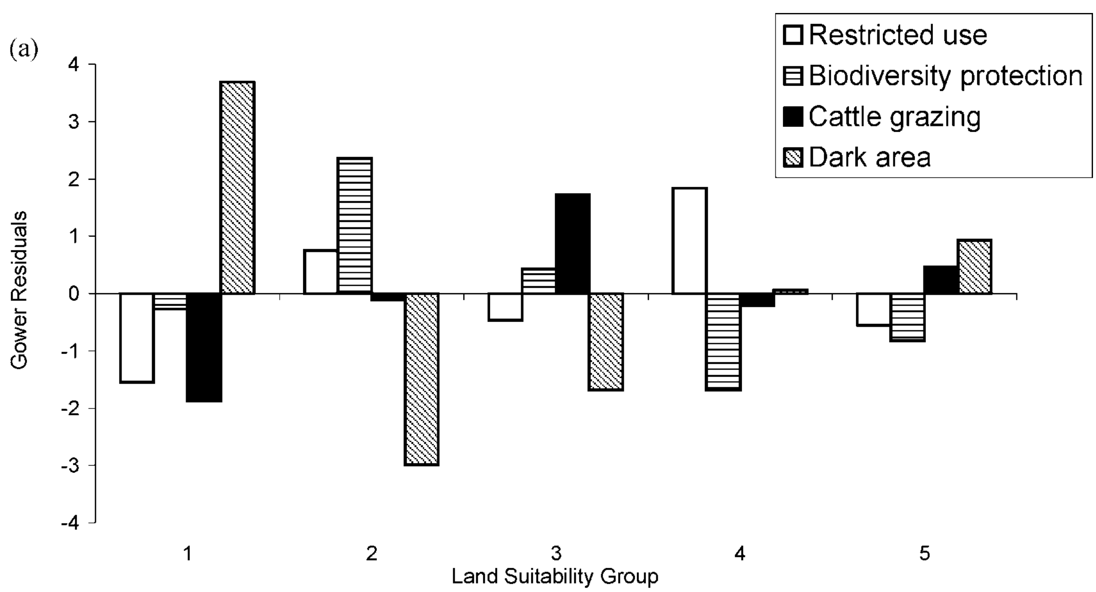
Hence, we maintain that the issue is not whether or not an analytical tool can be used to resolve all the problems in a single planning exercise, but whether such a tool can help park planners and managers to deal with the environmental conflicts within an adaptive planning setting (see Holling, 1978). This position is also congruent with the concept of ecosystem management (Christiansen et al., 1996; Grumbine, 1994).

Following the ideas of Holling (1978), we are in favor of the idea that, rather than delaying decisions until unambiguous information can be available, conflicts should be managed and resolved along a continuous and permanent process. In practical terms, the results of our study can be incorporated in the management plan of the park, as required by law. In general, the following recommendations emanate from the assessment of SSPM:

1. The implementation of either of the two alternative interpretations of the presidential decree (polygons 1 and 2 in Fig. 1) would lead to a less-than-optimal reserve design with respect to

biological conservation. Therefore, if the protection of critical biological entities is to be maximized, the optimal delimitation should be adopted as the new park boundaries (Fig. 2a–b).

2. If for some reason the optimal design would not be possible to achieve so one of the two polygons has to be chosen as the official reserve boundaries, then *Polygon 2* should be preferred. This polygon has a higher conservation value and its shape provides better protection to land suitability group 1, the one with that should be allocated to biological protection and astronomical research (Table 2, Figs. 4 and 5).
3. Regardless of the final boundaries, the zoning of SSPM should resemble a biosphere reserve, in which a "core zone" is surrounded by a "buffer area" (Fig. 4). Since land suitability Group 1 contains the most valuable land for conservation and is located at the center of the park (Fig. 5), it should be dedicated to biological conservation analogous to a core area. The other activities (namely, ranching and recreation) should be allocated following a gradient of higher intensity up to the boundaries of the park, with lower intensity activities towards at the boundaries of Group 1 (Fig. 5). In addition, the results of this study complement the plan for the biosphere reserve proposed by Minnich et al. (1997) by explicitly addressing zoning and conflict resolution.



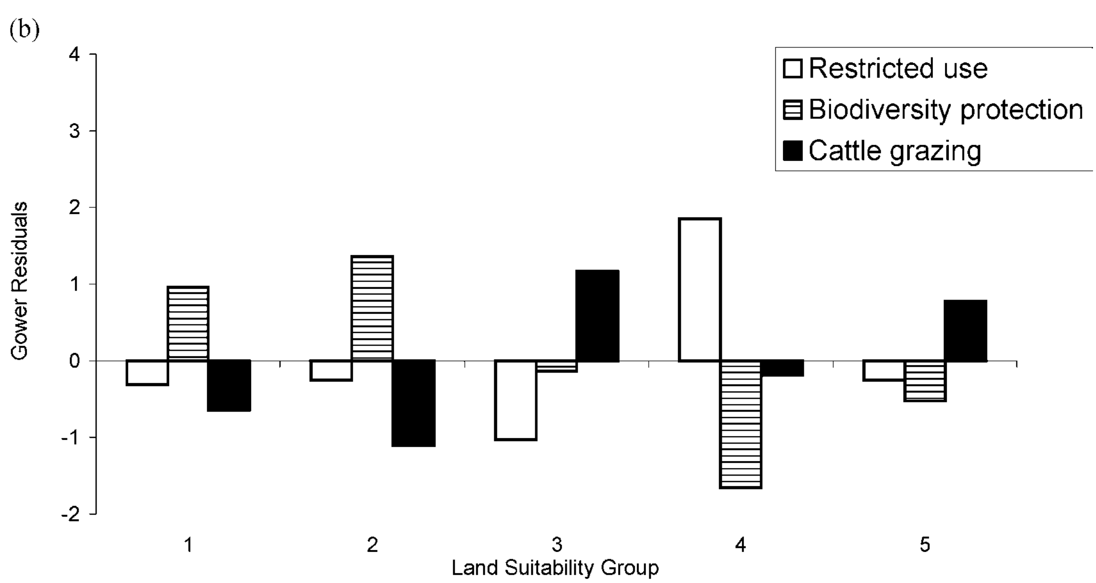


Fig. 5. Gower's residuals of the Land Suitability Assessment for Sierra San Pedro Mártir National Park, Baja California, México; a = computation using data from Table 4; b = computations using data from Table 4 but excluding *Dark Area*.

By expressly addressing environmental conflict resolution in the reserve design the resulting park boundaries and zoning will undoubtedly be different from a reserve in which biological factors alone were considered. However, to paraphrase Scott et al. (1995), only in the clear discussion of biological and economic factors together can one be assured that the conservation decision-making process will be transparent and effective.

Obviously, our results and recommendations reflect the limitations of the information readily available for our study. Overall, the LSA for SSPM corresponds to what Groves et al. (2002) identifies as a coarse filter approach to conservation planning, with a spatial resolution of hundreds to tens of thousands of hectares. Accordingly, the decision criteria derived from the vegetation and abiotic factors map layers served as surrogates for finer levels of biological organization, such as ecological processes or populations of keystone, endemic and endangered species. Additional research should be implemented to determine better management practices for the traditional livestock-grazing sector and to maintain the natural forest fire regime. These two issues are critical for the persistence of the grazing economy of for the preservation of natural ponderosa pine and mixed conifer stands (Minnich et al., 1997; Minnich et al., 2000).

Also, more research will be needed to determine if the design proposed here had compromised the long-term protection of population sizes of critical species and key ecological processes in SSPM. In that case, research should provide the information to modify the delimitation and zoning of the park and to implement better management practices. Under current environmental law, a regional land suitability analysis will be necessary to determine the compatible land uses in the areas neighboring the park, so that border effects are minimized. It is of particular importance to assess in this context the ecological impacts of the proposed forest practices in Ejido Bramadero.

Although we acknowledge that this study does not address all the important issues for conservation, we claim that our results are an improvement over the current configuration of SSPM. We conclude that a LSA is practical decision-making tool for: (1) making the best use of the available knowledge of experts and the stakeholders; (2) reducing the problem to a manageable format; and (3) generating solutions that, while mathematically valid, are congruent with both conservation biology and conflict resolution theories. After Davis and Johnson (1987), we also generalize that the LSA presented in this article can help park planners to identify the relevant goals, issues, and limitations, and produce realistic solutions. In that respect, we claim that the results presented in this article provided the necessary information for negotiating conflicts among the interests at stake in SSPM, as articulated by the relevant stakeholders.

Acknowledgements

We would like to acknowledge the experts that participated in the planning workshops for this project: E. Mellink and C. Montes, from Centro de Investigación Científica y Educación Superior de Ensenada; A. Meling Pompa, E. Meling Pompa, A. Meling Zaragoza, M. Montes Gelber, and H. Montes Gilbert, from Ejido Bramadero; M. Alvarez, A. López, and S. Torres, from Observatorio Astronómico Nacional, UNAM; F. Godínez, from Parque Nacional Sierra San Pedro Mártir.

Appendix A. Value functions used in Eq. (1) that describe the state of a variable in each pixel in the map layers examined in the LSA for Sierra San Pedro Mártir National Park

A.1. Value functions for Restricted Use

Criterion	Map	Function	Units of the independent variable
Scenic quality			
Slope	Interval	$y = \begin{cases} 0.0411x + 0.2877 & \text{if} \quad 0 > x \leqslant 11 \\ 0.0074x + 0.0667 & \text{if} \quad 11 > x \leqslant 45 \end{cases}$	degrees
Elevation	Interval	$y = 0.0009833x - 1.8692 \quad 1900 \geqslant x < 3000$	m asl
Environmental education			
Vegetation	Interval	$y = \begin{cases} 1 & \text{if} \quad x = \text{Mixed conifer forest} \\ 0.9 & \text{if} \quad x = \text{Meadows} \\ 0.5 & \text{if} \quad x = \text{Jeffrey pine forest} \\ 0.3 & \text{if} \quad x = \text{Oak woodlands} \\ 0.3 & \text{if} \quad x = \text{Bosque de pino piñonero} \\ 0.1 & \text{if} \quad x = \text{Chaparral} \end{cases}$	dimensionless

Appendix continued

Criterion	Map	Function	Units of the independent variable
Access			
Distance	Binary	$y = \begin{cases} 1 & \text{if} \quad x \leqslant 300 \text{ to main roads} \\ 0 & \text{if} \quad x > 300 \text{ to main roads} \end{cases}$	m
Traditional use			
Slope	Binary	$y = \begin{cases} 1 & \text{if} \quad x \leqslant 2 \\ 0 & \text{if} \quad x > 2 \end{cases}$	degrees

A.2. Value functions for Biodiversity Protection

Criterion	Map	Function	Units of the independent variable
Plants			
Vegetation	Interval	$y = \begin{cases} 1 & \text{if} \quad x = \text{Mixed conifer forest} \\ 0.9 & \text{if} \quad x = \text{Meadows} \\ 0.5 & \text{if} \quad x = \text{Jeffrey pine forest} \\ 0.3 & \text{if} \quad x = \text{Oak woodlands} \\ 0.3 & \text{if} \quad x = \text{Bosque de pino piñonero} \\ 0.1 & \text{if} \quad x = \text{Chaparral} \end{cases}$	dimensionless
Big horn sheep			
Habitat	Binary	$y = \begin{cases} 1 & \text{if} \quad 1500 \leqslant x \leqslant 2800 \quad \text{y} \ z \leqslant 31 \\ 0 & \text{other} \end{cases}$	x = m asl z = ° (slope)
Mule deer			
Habitat	Interval	$y = \begin{cases} 1 & \text{if} \quad x = \text{Meadows La Encantada} \\ 0.6 & \text{if} \quad x = \text{Meadows de Vallecitos} \\ 0.3 & \text{if} \quad x = \text{Meadows La Grulla} \\ 0 & \text{other} \end{cases}$	dimensionless
Condor			
Habitat	Binary	$y = \begin{cases} 1 & \text{if} \quad x \geqslant 30 \\ 0 & \text{other} \end{cases}$	(slope)
Trout			
Hábitat	Binary	$y = \begin{cases} 1 & \text{if} \quad x = \text{perennial stream} \\ 0 & \text{other} \end{cases}$	presence

A.3. Value functions for Cattle Ranching

Criterion	Map	Function	Units of the independent variable
Cattle ranching			
Corrals	Binary	$y = \begin{cases} 1 & \text{if} \quad x = \text{corrals} \\ 0 & \text{other} \end{cases}$	presence
Water holes	Binary	$y = \begin{cases} 1 & \text{if} \quad x \leqslant 3 \text{ km from a water hole} \\ 0 & \text{other} \end{cases}$	presence
Grazing areas	Binary	$y = \begin{cases} 1 & \text{if} \quad x = \text{meadows} \\ 0.3 & \text{other} \end{cases}$	vegetation type

A.4. Value functions for Dark Area

Criterion	Map	Function	Units of the independent variable
Distance	Binary	$y = \begin{cases} 1 & \text{if} \quad x < 10 \text{ km from a OAN} \\ 0 & \text{other} \end{cases}$	presence

References

Bojórquez-Tapia, L., Ongay-Delhumeau, E., Ezcurra, E., 1994. Multivariate approach for suitability assessment and environmental conflict resolution. Journal of Environmental Management 41, 187–198.

Bojórquez-Tapia, L., Díaz-Mondragón, S., Ezcurra, E., 2001. GIS-based approach for participatory decision making and land suitability assessment. Journal of Geographical Information Science 15, 129–151.

Brooks, K.N., Ffolliott, P.F., Gregersen, H.M., Thames, J.L., 1992. Hydrology and the Management of Watersheds. Iowa State University Press, Ames.

Christiansen, N.L., Bartuska, A.M., Brown, J.H., Carpenter, S., D'Antonio, C., Francis, R., Franklin, J.F., MacMahon, J.A., Noss, R.F., Parsons, D.J., Paterson, C.H., Turner, M.G., Woodmansee, R., 1996. The report of the Ecological Society of America committee on the scientific basis for ecosystem management. Ecological Applications 6, 655–691.

Chuvieco, E., 1993. Integration of linear programming and GIS for land-use modeling. International Journal of Geographical Information Systems 7, 71–83.

Crowfoot, J.E., Wondolleck, J.M., 1990. Environmental Disputes, Community Involvement in Conflict Resolution. Island Press, Washington, DC.

Davis, L.S., Johnson, K.N., 1987. Forest Management. McGraw-Hill, Inc.

Digby, P., Kempton, R., 1987. Multivariate Analysis of Ecological Communities. Chapman and Hall, London.

Dykstra, D.P., 1984. Mathematical Programming for Natural Resource Management. McGraw-Hill Book Company, New York.

Eastman, J.R., Kyem, P.A.K., Toledano, J., Jin, W., 1993. GIS and Decision Making. UNITAR, Genova.

Expert Choice™ for Windows version 9.0 user manual. 1995. Decision Support Sofware, Mc Lean.

Gower, J., 1966. Some distance properties of latent root and vector methods used in multivariate analysis. Biometrika 53, 325–338.

Groves, C.R., Jensen, D.B., Valutis, L.L., Redford, K., Shaffer, M.L., Scott, J.M., Baumgartner, J.V., Higgins, J.V., Beck, M.W., Anderson, M.G., 2002. Planning for biodiversity conservation: putting conservation science into practice. BioScience 52, 499–512.

Grumbine, R.E., 1994. What is ecosystem management? Conservation Biology 8, 27–38.

Holling, C.S. (Ed.), 1978. Adaptive Environmental Impact Assessment and Management. Wiley, Chichester.

Jankowski, P., 1995. Integrating geographic information systems and multiple criteria decision-making methods. Journal of Geographical Information Systems 9, 252–273.

Keeney, R.L., Raiffa, H., 1976. Decisions with Multiple Objectives: Preferences and Value Tradeoffs. John Wiley & Sons, New York.

Lahdelma, R., Salminen, P., Hokkanen, J., 2000. Using multicriteria methods in environmental planning and management. Environmental Management 26, 595–605.

Maddock, A.H., Samways, M.J., 2000. Planning for biodiversity conservation based on the knolwdge of biologists. Biodiversity and Conservation 9, 1153–1169.

Malczewski, J., 1999. Spatial multicriteria decision analysis. In: Thill, J.C. (Ed.), Spatial Multicriteria Decision Making and Analysis, A Geographic Information Sciences Approach. Ashgate Publishing Ltd, Gower House, pp. 11–48.

Malczewski, J., Moreno-Sánchez, R., Bojórquez-Tapia, L.A., Ongay-Delhumeau, E., 1997. Multicriteria group decision-making model for environmental conflict analysis in the Cape Region, Mexico. Journal of Environmental Planning and Management 40, 349–374.

Margules, C.R., Usher, M.B., 1981. Criteria used in wildlife conservation potential, a review. Biological Conservation 21, 79–109.

Ming, S.H., Rom, W.O., Waren, A.D., 1994. Optimization with IBM® OSL. Boyd & Fraser Publishing Company, New York.

Minkoff, A.S., 1992. A systematic approach to OSL application programming. IBM Systems Journal 31 (1), 49–61.

Minnich, R.A., 2001. Fire and elevational zonation of chaparral and conifer forests in the Peninsular Ranges of La Frontera. In: Webster, G.L., Bahre, C.J. (Eds.), Changing Plant Life of La Frontera: Observations on vegetation in the United States/Mexico Borderlands. University of New Mexico Press, Mexico, pp. 120–142.

Minnich, R.A., Franco-Vizcaíno, E., Sosa-Ramírez, J., Burk, J.H., Barry, W.J., Barbour, M.G., de la Cueva, H., 1997. A land above: protecting Baja California's Sierra San Pedro Mártir within a biosphere reserve. Journal of the Southwest 39, 613–695.

Minnich, R.A., Franco-Vizcaíno, E., 1998. Land of chamise and pines: historical accounts and current status of the vegetation of Northern Baja California. University of California in Botany. Vol. 80.

Minnich, R.A., Barbour, M.G., Burk, J.H., Sosa Ramirez, J., 2000. California conifer forest under unmanaged fire regimes in the Sierra San Pedro Mártir, Baja California, Mexico. Journal of Biogeography 27, 105–130.

Noy-Meir, Y., 1973. Data transformations in ecological ordinations I. Some advantages of non-centring. Journal of Ecology 61, 753–760.

Pereira, J., Duckstein, L., 1993. A multiple criteria decision making approach to GIS-based land suitability evaluation. Journal of Geographical Information Systems 7, 407–424.

Pielou, E., 1984. The Interpretation of Ecological Data: A Primer on Classification and Ordenation. John Wiley & Sons, New York.

Saaty, T., 1980. The Analytical Hierarchy Process. McGraw Hill, New York, USA.

Scott, J.M., Tear, T.H., Mills, I.S., 1995. Socioeconomic and the recovery of endangered species: biological assessment in a political world. Conservation Biology 9, 214–216.

Shepherd, A., Bowler, C., 1997. Beyond the requirements: improving public participation in EIA. Journal of Environmental Planning and Management 40, 725–738.

Shrader-Frechette, K.S., McCoy, E.D., 1993. Method in Ecology: Strategies for Conservation. Cambridge University Press, New York, USA.

Smith, P.G., Theberge, J.B., 1987. Evaluating natural areas using multiple criteria: theory and practice. Environmental Management 11, 447–460.

Szidarovski, F., Gershom, M.E., Duckstein, L., 1986. Techniques for multiobjective decision making in system management. Elsevier, Amsterdam.

United States Army Construction Engineering Research Laboratories, 1998. Geographic Resources Analysis Support System (GRASS), version 4.2, User's Manual. United States Corps of Engineers, Champaign.

Webler, T., Tuler, S., Krueger, R., 2001. What is good public participation process? Five perspectives from the public. Environmental Management 27, 435–450.

Wondolleck, J., 1985. The importance of process in resolving environmental disputes. Environmental Impact Assessment Review 5, 341–356.

Discusión

En muchos casos, las áreas protegidas han sido diseñadas en función de su valor recreativo o estético y no por los hábitat que contienen o si su extensión asegura la protección de la biodiversidad. Sin embargo, con el desarrollo de nuevas técnicas y tecnologías, el interés por encontrar las herramientas que faciliten la decisión de dónde y qué extensión se debe proteger, va en aumento. En este sentido, el análisis de aptitud del suelo permite hacer una evaluación de la aptitud del hábitat donde es posible encontrar la especie a proteger.

Los casos presentados en este trabajo ejemplifican la utilización del análisis de aptitud del suelo para determinar la aptitud del hábitat y establecer los límites de las áreas a proteger. En principio, la consulta a expertos, a través de la realización de varios talleres facilitó el reconocimiento de los criterios o variables ambientales que determinan el valor para la conservación de cada sitio. Este valor para la conservación fue determinado en función de diferentes criterios. Mientras que, en el caso de la Reserva de la Mariposa Monarca, fue definido con base en la presencia de la Monarca; en la Sierra San Pedro Mártir fue determinado a partir de considerar los intereses de los diversos sectores con actividades en la región, incluidos los de protección de la biodiversidad. En ambos, los métodos multicriterio-multiobjetivo permitieron el manejo de la información que resultó relevante para cumplir los objetivos.

En general, la utilización de métodos analíticos rigurosos asegura la reproducción de los resultados bajo los mismos criterios. Además, aseguran la transparencia de la selección final porque las conclusiones pueden ser ligadas directamente a los datos originales y a los juicios hechos durante el proceso. Por otro lado, los métodos de ponderación obligan a los expertos consultados a ser explícitos en sus juicios sobre las prioridades de conservación, con lo que se ganó claridad en la definición de lineamientos poco ambiguos. Por ello, en los casos aquí presentados es posible que con la misma información y métodos se consigan los mismos resultados, dándole confiabilidad y robustez a las delimitaciones propuestas. La ventaja principal de este tipo de métodos es que hace al proceso de toma de decisiones sistemático, repetible y coherente.

Sin embargo, como lo menciona Van Horne (2003), cualquier ejercicio de modelado para conocer la distribución de las especies incluye suposiciones biológicas poco realistas y más bien pragmáticas. Este pragmatismo está dado porque desafortunadamente se cuenta con poca información sobre las variables ambientales que determinan la presencia de una especie o incluso sobre la presencia de la propia. No obstante, esta falta de certidumbre sobre los sitios que son importantes de proteger provoca conflictos relacionados con la delimitación de las áreas. Por ello, este tipo de enfoques puede dar certeza sobre las predicciones obtenidas ante las presiones de desarrollo a las que se encuentra sometido casi cualquier parte del territorio.

La ambigua definición de los límites de las reservas, así como la propia designación como Reserva de la Biosfera en el caso de la Mariposa Monarca, origina conflictos entre los diferentes sectores que llevan a cabo sus actividades en la región. Así, por ejemplo, el personal del Observatorio Astronómico Nacional y de la administración del Parque Sierra San Pedro Mártir, a cargo de personal de la Comisión Nacional de Áreas Naturales Protegidas, está a favor de la conservación de los hábitats. Por otro lado, el sector ganadero representado en la zona por los ejidatarios, vecinos del parque, defienden límites de la reserva que les asegura contar con mayor cubierta forestal susceptible de ser aprovechada en sus ejidos.

Ante esta situación, en los casos presentados los métodos multicriterio-multiobjetivo facilitaron el trabajo hacia el consenso pues obligan a hacer explícitos las necesidades e intéreses de cada sector para la definición de los límites de las reservas. Sin embargo, aún falta camino por recorrer en términos de involucrar realmente a los diferentes sectores pues no sólo basta conocer sus intereses y necesidades dentro de las áreas protegidas, el siguiente paso es la inclusión real de prácticas de conservación y protección de la biodiversidad en sus actividades.

Finalmente, la revisión de los diseños de las reservas naturales no es un ejercicio espurio, sino una oportunidad para que los involucrados consideren la re-evaluación y negociación de las áreas y prioridades a conservar. Con el único objetivo de asegurar la conservación y protección de la biodiversidad que las define. Por ello, la utilización de mejor información técnica y cada vez mejores métodos de análisis aumenta la solidez de las propuestas de áreas protegidas.

Conclusiones

- Las herramientas analíticas aseguran la transparencia de la selección final en términos de sitios a proteger, pues los resultados pueden ligados a los datos de campo, así como a los juicios de clasificación y evaluación.

- El análisis de la aptitud del suelo mostrado en estos casos puede servir a los planeadores de los parques a identificar los asuntos, objetivos y limitaciones relevantes, así como producir soluciones realistas. Asimismo, los resultados presentados proveen de información importante para la negociación de los conflictos identificados en cada región, pues provee los medios para el manejo de los juicios de valor de los tomadores de decisiones.

- Con base en los casos aquí presentados, los modelos multicriterio son una valiosa herramienta para entender, identificar, estructurar y obtener la mejor delimitación de áreas de protección. La ventaja principal de estas herramientas es la obtención de elementos que permitirán construir una estrategia de negociación, a partir de las preferencias y actividades de los sectores en la región.

- La combinación de la opinión de los expertos y una selección objetiva del modelo resulto una buena aproximación en la determinación de las relaciones entre las especies y su hábitat; así como entre las actividades de los diferentes sectores en cada región.

Bibliografía

Bojórquez-Tapia, L.A., E. Ongay-Delhumeau y Exequiel Ezcurra. 1994. Multivariate approach for suitability assessment and environmental conflict resolution. *Journal of Environmental Management* 41:187-198

Steiner F. 1983. Resource suitability: methods for analysis. *Environmental Management.* 5: 401-420.

Fleishman E, Murphy D.D. y Per Sjögren-Gulve. 2003. Modeling species richness and habitat suitability for taxa of conservation interest. En: Scott J.M., Heglund P.J. Morrison M.L. (editors). *Predicting Species Occurrences: Issues of accuracy and scale*. Island Press. USA. 507-518.

Fitzsimons J.A. G. Wescott. 2004. The classification of lans managed for conservation: existing and proposed framework, with particular reference to Australia. *Environmental Science & Policy* 7: 477-486.

Malczewski J, R. Moreno-Sanchez, L.A. Bojórquez-Tapia y E. Ongay-Delhumeau. 1997. Multicriteria group decisión-making model for environmental conflict análisis in the Cape region, Mexico. *Journal of Environmental Planning and Management* 40 (3):349-374.

Malczwski J. 1999. *GIS and multicriteria decision analysis*. Jonh Wiley & Sons, New York. 392 pp.

Myers N., R. Mittermeier, C. G. Mittermeier, G.A.B da Fonseca y J. Kent. 2000. Biodiversity hotspots for conservation priorities. *Nature* 403: 853-85 8.

Larson B.D., Sengupta R.R. 2003. A spatial decision support system to identify species-specific critical habitats based on size and accessibility using US GAP data. Environmental Modelling & Software XX-XX

Larson M.A., W.D.Dijak, F.R. Thompson y J.J.Millspaugh. 2003. *Landscape-level Habitat Suitability Models for twelve wildlife species in southern Missouri*. North Central Research Station. Forest Service U.S. Department of Agriculture. 58 pp. www.ncrs.fs.fed.us

Cogan C.B. 2003. Biodiversity Conflict Analysis at Multiple Spatial Scales. En: Scott J.M., Heglund P.J. Morrison M.L. (editors). *Predicting Species Occurrences: Issues of accuracy and scale*. Island Press. USA. 229-239 pp.

Conroy M.J. y Moore C.T. 2003. Wildlife habitat modelins in a adaptative framewok: The role of alternative models En: Scott J.M., Heglund P.J. Morrison M.L. (editors). *Predicting Species Occurrences: Issues of accuracy and scale. Island Press*. USA. 205-218.

Van Horne B. 2003. Approaches to habitat modeling: The tensions between pattern and process and between specificity and generality. En: Scott J.M., Heglund P.J. Morrison M.L. (editors). *Predicting Species Occurrences: Issues of accuracy and scale*. Island Press. USA. 63-72.

Hale W.B. Steen-Adams M.M. Predick K. Fisher N. 2005. Ecological conservation through aesthetc landscape planning: A case study of the lower Wisconsin State riverway. *Environmental Management* 35 (4):381-395.

Peterson A.T. y D. A. Kluza. 2003. New distributional modelling approaches for gap analysis. *Animal Conservation* 6:47-54.