UNIVERSIDAD NACIONAL AUTÓNOMA DE MÉXICO

PROGRAMA DE MAESTRÍA Y DOCTORADO EN GEOGRAFÍA
Centro de Investigaciones en Geografía Ambiental

El uso de *Brahea dulcis*. Implicaciones del manejo en el paisaje del Valle de Tehuacán-Cuicatlán.

Tesis para optar por el grado de
DOCTORA EN GEOGRAFÍA

PRESENTA

CLOE XOCHITL PÉREZ VALLADARES

Directores de tesis

JOSÉ ALEJANDRO VELÁZQUEZ MONTES
Centro de Investigaciones en Geografía Ambiental

ANA ISABEL MORENO CALLES
Escuela Nacional de Estudios Superiores Unidad Morelia

Comité tutor

JEAN FRANCOIS MAS CAUSSEL
Centro de Investigaciones en Geografía Ambiental

Morelia, Michoacán, enero 2021

Venimos con flores en las manos,
venimos con guirnaldas,
trece sobre la estera
trece sobre el sitial de la ofrenda,
en la Casa de la lluvia grande,
en la Casa de la lluvia,
la que es recibida en vuestra estera,
la recibida en vuestro sitial de la ofrenda.
Aquí viene la resina de copal,
la que es aromática,
¡bebedla, comedla!

Oración para pedir la lluvia, tradición oral mixteca
Traducción de Leonhard Schultze-Jena 1938

Agradecimientos institucionales

Mis agradecimientos a la **Universidad Nacional Autónoma de México**, por brindarme el espacio para seguir formándome como investigadora. Agradezco el apoyo económico otorgado a través de los proyectos de investigación "Agricultura y agroforestería familiar y social en contextos de cambios locales y globales" (DGAPA-UNAM-PAPIIT IG200720) y "Dinámica multiescalar y temporal para evaluar el impacto de las funciones del paisaje" (DGAPA-UNAM IN105721), por medio de los cuales pude realizar las salidas a campo y apoyar el financiamiento de las publicaciones.

Agradezco al **Posgrado en Geografía** por darme la oportunidad de continuar mis estudios de doctorado, al personal de la coordinación, quienes amablemente atendieron mis dudas y apoyaron en los trámites necesarios, muy especialmente al maestro Macario Arrendondo, por su siempre presto apoyo. Un agradecimiento particular al **Programa de Apoyo a los Estudiantes de Posgrado** a través del cual pude financiar una parte de las salidas a campo, y cuyo apoyo económico me permitió compartir los resultados preliminares del proyecto fuera del país. De manera muy especial, agradezco a mi institución de adscripción como estudiante: el **Centro de Investigaciones en Geografía Ambiental**, en donde tanto en sus pasillos como en sus salones, fue creciendo mi interés por la investigación y fortaleciéndose la reflexión critica. Agradezco a lxs investigadorxs[1] que, a través de sus pláticas, fortalecieron mi formación academica. A todo el personal administrativo siempre atento a apoyar. Al **Centro de Documentación**, me refiero especialmente a Raquel González, siempre amable y accesible para apoyar en el préstamo de los materiales necesarios para el desarrollo de este proyecto.

Al **Consejo Nacional de Ciencia y Tecnologia** por la beca otorgada para la realización de mis estudios de grado, con la cual pude durante este tiempo dedicarme de tiempo completo al proyecto doctoral

Un agradecimiento especial al equipo de la **Reserva de la Biósfera Tehuacán-Cuicatlán**, de manera muy especial al biologo Fernando Reyes, por su continuo apoyo y disposición para apoyar las actividades de investigación del presente proyecto, así como a otras actividades llevadas a cabo dentro de la reserva y para las cuales siempre nos ha brindado su apoyo.

Al equipo de guías comunitarios de las comunidades de **Santa María Ixcatlán, Santiago Quiotepec** y **Zapotitlán Salinas**, por el cálido recibimiento y apoyos en campo, siempre atentos y amables. De manera muy especial a Maurino Reyes incansable conocedor de su territorio y aguerrido protector del patrimonio biocultural de su región, siempre abierto a aprender y siendo el mismo un libro abierto para quienes le conocemos.

[1] Como muchas personas, comparto la necesidad de hacer uso de un lenguaje inclusivo para nombrarnos, para reconocernos y visibilizarnos. Es por esa razón que he decidido usar aquí la letra x como comodín para saber que cuando se usa, me estoy refieriendo tanto a mujeres como a hombres que han aportado al desarrollo de este proyecto y a mi persona.

Agradecimientos personales

Inconmensurables gracias a mi madre Julieta Valladares y a mi padre Salvador Perez, por quienes estoy aquí, por su confianza y apoyo infinitos, por su gran ejemplo de trabajo y dedicación. A mis hermanas Mónica y Ximena, de las que siempre aprendo.

De manera especial agradezco a mis asesorxs, Alejandro Velázquez que con su apoyo me ayudo a reorientar mis inquietudes de investigación, y gracias a quien conocí una gran comunidad internacional de la que ahora soy parte. A Ana Isabel, por su presencia y apoyo constante, por su profundo compromiso por hacer de este mundo un lugar mejor para todxs, por su amoroso ejemplo de construir en colectivo. A Jean Francois, por su apoyo constante, su acertado consejo y su valiosa experiencia siempre dispuesta a mostrar el camino.

Este trabajo no hubiera sido posible de concretar sin la valiosa ayuda de una gran cantidad de investigadorxs, que en diferentes momentos, me brindaron su apoyo y su sabio consejo, a Alejandro Casas, Oswaldo Tellez, José Blancas, Nacho Torres, Selene Rangel, muchas gracias por todo. A Horacio Torres de Ita del Colectivo el Torito y Luis Valderrama Landeros, quienes sin conocerme, me apoyaron y brindaron información geográfica de la plama para los análisis de este proyecto. Un agradecimiento especial a Pedro Urquijo, de quien, a lo largo de este proceso, he recibido un gran apoyo a través de las charlas temáticas, de orientación y los libros prestados (siempre regresados).

A Ivan Franch, América Navarro, Valerio Castro, José Luis Caballero, Estefania Cano, Laura Chang y todxs lxs amigxs, colegas y compañerxs del CIGA y del LabETA-ENES, con quienes de alguna u otra manera nos apoyamos a través de la palabra de aliento, el intercambio de ideas, las conversaciones en los pasillos y seminarios, y mucho también, a través del ejemplo. A Carla Novoa por su continuo ánimo y consejo para lo que viene. A lxs amigxs de la música siempre presentes, las platicas y los fandangos ayudaron a no volverme loca en los momentos difíciles. A la música y sus grandes artífices, a las personas del gusto, que con su cariño instruyen el amor por el campo y las formas de vida rurales, que tanto me han enseñado.

A Juan por su apoyo siempre presente, por comprender en este tiempo juntos, las viscicitudes y dificultades de este proceso, por entender los tiempos y por su gran cariño.

A las comunidades de la Reserva de la Biósfera de Tehuacán-Cuicatlán, y todas las comunidades rurales del mundo que, con mucho esfuerzo, amor y tenacidad, mantienen profundas y estrechas relaciones con el entorno, de las cuales podemos aprender mejores formas de vida.

A lxs manejadorxs de palma, a lxs tejedorxs, quienes con su esfuerzo y amor han mantenido este legado del tejido desde tiempos ancestrales. Por conservar para sí y para todxs, esta identidad tan cercana a la naturaleza, por su continuo y arduo trabajo, por su arte y su resistencia.

Resumen

Esta investigación tuvo como fin estudiar las interacciones entre los grupos humanos y la palma *Brahea dulcis* en la Reserva de la Biósfera de Tehuacán-Cuicatlán, con la finalidad de reconocer las implicaciones ecológicas y espaciales asociadas al manejo de la especie, así como indagar en los procesos que subyacen a la presencia de palmares en la región. Para lo anterior se partió de un enfoque multiescalar para identificar los distintos niveles de organización en los que influye el manejo tradicional de la palma. El análisis de caracterización del manejo permitió identificar que éste tiene influencia a nivel de especie, de población y de comunidad, y dado que en la práctica el manejo se realiza sobre territorios extensos, tiene implicaciones a nivel de paisaje. A través del uso de técnicas de modelación de distribución de especies incorporando variables ecológicas y sociales vinculadas al manejo, se determinó la distribución potencial de palmares. La coincidencia entre la distribución real de palmares y la modelada, develó los factores asociados a su presencia, mientras que la perspectiva histórica en el manejo de la biodiversidad, permitió indagar en los procesos asociados que determinaron la presencia y distribución actual de los palmares en la región. Se propone aquí, que las comunidades de palmar son de origen antrópico y que su presencia tiene origen en el establecimiento de una relación temprana entre los grupos humanos con la palma.

Palabras clave

Manejo tradicional, domesticación del paisaje, bioculturalidad, etnoecología, modelación.

Abstract

The aim of the study was to acknowledge the interactions between human groups and the palm *Brahea dulcis* in the Biosphere Reserve of Tehuacan-Cuicatlan, in order to identify the ecological and spatial implications associated to the management of the species, as well as to inquire in the processes that underlay palm stands presence in the region. A multiscale approach was used to identify the different levels of organizations influenced by traditional palm management. The characterization of palm management allows recognizing its influence at species, populations, and community levels, and as in practice, management is performed in full territories it has implications at landscape level. By means of techniques of species distribution modelling and incorporating ecological, as well as social variables associated with management, the potential distribution of palm stands was modelled. The coincidence between real and potential distribution revealed the factors associated with palm stand presence, while the historical perspective in the management of the biodiversity allowed to inquire in the process associated to its presence and distribution. It is proposed that palm stands are of antropic origin, and that it establishment originated from the antique relationship between human groups and the palm.

Key words

Traditional management, landscape domestication, bioculturality, etnoecology, modelling.

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Capitulo I
Introducción general

El paisaje y la subsistencia

Se estima, que entre el 25-46% de la población en América Latina y el Caribe habita en ámbitos rurales (Chomitz et al., 2005). La agricultura es frecuentemente el eje rector de las economías rurales, pero estas sociedades generalmente se involucran en una gran cantidad de actividades, y por lo tanto, su economía se encuentra altamente diversificada (Alarcón-Chaires, 2006). Ello comprende un amplio espectro de actividades relacionadas con el aprovisionamiento de recursos, entre las que se incluyen la agricultura, la agroforestería y la silvicultura o manejo forestal (Blancas et al., 2010; Toledo, 1990). Estas actividades se diversifican en el espacio y en el tiempo, con la finalidad de disponer de recursos a lo largo del año (Alarcón-Chaires, 2006; Blancas et al., 2010; Farfán-Heredia et al., 2018; Pérez-Negrón y Casas, 2007; Solís, 2006); lo cual implica un conocimiento profundo de la naturaleza circundante y sus ciclos. Por esta razón, estas sociedades poseen un complejo vínculo con su entorno, que deriva del distinto grado de dependencia que estas poblaciones mantienen en relación con la diversidad biológica, de la cual obtienen recursos para el autoconsumo o la venta, lo que les permite satisfacer sus necesidades.

El entorno inmediato constituye para las sociedades rurales la fuente primordial de sustento. La constante interacción de los humanos con el ambiente, derivada de esta búsqueda, ha supuesto el establecimiento de relaciones humano-naturaleza profundas en el tiempo, que entendidas en el marco conceptual de la etnoecología se encuentran mediadas por un sistema de creencias (*cosmos*), conocimientos (*corpus*) y prácticas (*praxis*) (Toledo et al., 2001). El desarrollo de este sistema es el resultado de complejos procesos históricos y sociales, originados de la particular percepción que los grupos humanos construyen sobre su lugar en el mundo y sobre la naturaleza, estructurados en conocimiento que más tarde se traduce en acciones particulares de manejo. Este conocimiento es primordialmente trasmitido de manera oral entre generaciones subsecuentes, afinado gradualmente, y constantemente construido a partir de la práctica y experimentación en geografías específicas (Lepofsky, 2009). El paisaje circundante conforma el escenario en el cual se desarrollan estas interacciones. En términos escalares, su extensión es lo suficientemente amplia que permite encontrar discontinuidades ecológicas de las cuales se aprovechan la variedad de recursos, sin embargo, dicha extensión no es tan grande como para imposibilitar su recorrido de forma habitual en el transcurso de una vida humana. Constituye también el territorio (pues son espacios sujetos a relaciones de poder y a los mecanismos de apropiación) del cual se obtienen los bastimentos a partir de los cuales las culturas florecen, y al cual se encuentran vinculadas en el transcurso de su existencia (Splenger, 1922).

A pesar de que el término *paisaje* integra un concepto polisémico, que adquiere distintos significados dependiendo del contexto en el que se utilice (Santos y Ganges, 2002), existen diferentes nociones sobre el concepto que parten del enfoque teórico-metodológico con que se aborda, por su relevancia se pueden mencionar los siguientes. El enfoque físico-geográfico, que otorga un gran peso a las cuestiones genético-evolutivas de la conformación física de los paisajes y es ampliamente utilizado en la geoecología (Mateo, 2002; Priego Santander y Esteve Selma, 2017); El enfoque sistémico de la ecología del paisaje, que concibe el paisaje ponderando la interrelación existente entre sus componentes, para describir de forma corológica los patrones encontrados en la superficie terrestre (Troll, 1938; Velázquez y Bocco, 2001; Zonneveld, 1990); de este último se desprende el enfoque analítico-espacial de Forman y Godron (1981). Por último el enfoque de la geografía cultural, que considera al paisaje como una formación socio-histórica que deriva de la relación sociedad-naturaleza, concediéndole al espacio la cualidad del paisaje al presentarse en él la expresión humana (*paisaje cultural* en Sauer, 1941; Santos y Ganges, 2002; Urquijo y Barrera-Bassols, 2009). Para el abordaje de este estudio, se consideró necesario adoptar de manera integral estas últimas dos visiones, ya que la conformación de los paisajes acontece a partir de las dinámicas establecidas entre los subsistemas que integran la naturaleza (entre ellos el humano), las cuales ocurren a diferentes escalas de organización. Y puesto que el presente estudio tiene como objetivo el conocer los efectos del manejo humano de uno de sus componentes, es decir la vegetación, se plantea necesario abordar la perspectiva histórica para develar los resultados de esta interacción en la Reserva de la Biósfera de Tehuacán-Cuicatlán. En este trabajo, el paisaje es entendido en términos de Santos y Ganges (2002), como la configuración de un espacio geográfico humanizado, que presenta una evolución dinámica de elementos que "*…hace referencia a la percepción estética del espacio, al mismo tiempo que a una realidad ecológica y (...) a una realidad social con una condición cultural e histórica*".

Aproximaciones a la relación sociedad-naturaleza

El vínculo creado y mantenido por la constante interacción entre los seres humanos y la naturaleza, se ha señalado como la base material a partir de la cual florecieron las culturas de tradición mesoamericana (Caballero et al., 1998). Hoy en día, estas interacciones se mantienen a través de sistemas de vidas diversificados, los cuales se sustentan en el manejo de especies, comunidades, ecosistemas y paisajes (Blancas et al., 2010; Caballero, 1994; Casas et al., 2016. En México, las etnociencias se han encargado de la importante labor de estudiar estas experiencias por el alto valor cultural de este conocimiento; pero, más importante aún, porque representan valiosas alternativas para el aprovechamiento y conservación de la naturaleza (Blancas et al., 2010; Lepofsky, 2009; Lertzman, 2009; Toledo, 1990). Estos estudios han producido una vasta bibliografía en relación al conocimiento y manejo local/tradicional de elementos cognitivos del entorno, revelando importantes interacciones e información valiosa para la implementación de estrategias sustentables de desarrollo (Caballero et al., 1998; Casas et al., 1997; González-Insuasti et al., 2008; Illsley et al., 2001; Pulido y Coronel-Ortega, 2015; Torres-García et al., 2019). La relación sociedad-naturaleza expresada en las muy diversas formas en las que el ambiente influye y es influido por los seres humanos, ha conformado también uno de los más fructíferos campos de interés y una de las más antiguas tradiciones geográficas: los estudios de la relación humano-tierra (Pattison, 1964). En este sentido, desde la Geografía Cultural Tradicional, se han trabajado con un claro enfoque etnográfico para el abordaje de dinámicas vinculadas a la transformación del paisaje derivadas de estas interacciones (Denevan, 2001; Doolittle, 2000; Sauer y Brand, 1932; Whitmore y Turner, 2001).

Entre estos campos del conocimiento se expone una coincidencia de interés por el estudio de la integralidad entre las sociedades humanas y la naturaleza, reconociendo en palabras de Arias Maldonado (2011) que tanto sociedad como naturaleza "…*son conceptos mutuamente contingentes,* [por lo cual]…*su separación conceptual no oculta la imposibilidad de su completa separación práctica*". Ambos campos del conocimiento indagan en las dinámicas de aprovechamiento del entorno, confiriéndole un gran valor a lo que permanece en nuestros días desde épocas antiguas, abordando el estudio del manejo de la diversidad con perspectiva en el lazo de continuidad que mantienen con el pasado. Se otorga de esta manera, una particular atención a la cuestión histórica desde la geografía (Sauer, 1941), y a la memoria desde las etnociencias de la naturaleza (la *memoria biocultural*, Toledo y Barrera-Bassols, 2008), ópticas de largo plazo que son imprescindibles para la comprensión de las dinámicas asociadas a los procesos de trasformación del paisaje (Urquijo y Bocco, 2011).

El lugar común entre ambas áreas del conocimiento ha sido, por un lado, el estudio de las relaciones entre sociedades-naturalezas con una fuerte inclinación al análisis espacial de sus dinámicas desde la geografía; mientras que, desde la etnociencia, el análisis está mayormente encaminado al estudio del conocimiento del entorno, cimentado en el cercano y prolongado vínculo de las sociedades tradicionales con la naturaleza. En la década de los 1980's, con el fortalecimiento de la perspectiva ecológica de la etnobiologia, los estudios se orientaron a la expresión de ese conocimiento en el ejercicio práctico, revelando el contexto ecológico y espacial del mismo, así como su carácter profundamente relacional de los elementos de la naturaleza, dando origen al análisis etnoecológico (Hunn, 2007; Toledo y Alarcón-Chaires, 2012), estrechando aún más los intereses con la geografía. La amplitud de perspectiva que trajo consigo la incorporación del análisis ecológico vínculado al conocimiento tradicional de la biodiversidad (presente, pero hasta antes poco abordado), permitió dimensionar la complejidad del conocimiento tradicional, así como su interescalaridad, observadas a través del reconocimiento de las relaciones entre los diferentes subconjuntos de la naturaleza (clima, suelos, relieve, etc.) y la aplicación de formas de manejo prácticadas a diferentes niveles de organización biológica (individuos, poblaciones, comunidades, ecosistemas, paisajes), lo que manifiesta una clara relación de intereses con la geografía.

Aún más, la escala de trabajo de la etnoecología correspondería al *lugar* de la geografía; esto es, un territorio de extensión variable con identidad propia, que revela una serie de relaciones construidas históricamente entre la sociedad que lo habita y el entorno, manteniendo dinámicas únicas, que no obstante también se encuentran ceñidas espacio-temporalmente (Cresswell, 2008; Ramírez Velázquez y López Levi, 2015). En este sentido, podemos visualizar la convergencia entre la geografía y la etnoecología cuando se estudian los procesos tanto históricos como ecológicos, que determinan los rasgos particulares de un lugar. Un ejemplo sería el desarrollo de una zona destinada al cultivo de especies domesticadas, bajo ciertos condicionamientos ecológicos y con un bagaje particular de conocimientos del medio. Este tipo de dinámicas que presentan singularidad, tienen una manifestación rápida y una alta visibilidad. No obstante, en los últimos años la convergencia de intereses se ha dirigido a tratar de entender las implicaciones paisajísticas de dinámicas de aprovechamiento que presentan fenómenos espaciales poco perceptibles y paulatinos, buscando comprender e identificar la impronta humana en espacios considerados *naturales* o poco intervenidos (Levis et al., 2018; Maezumi et al., 2018; Terrell et al., 2003). Particularmente aquí me refiero al manejo *in situ* de especies silvestres y las implicaciones espaciales de estas actividades en los paisajes sujetos a manejo.

El enfoque etnoecológico y el geográfico en los estudios de la interacción sociedad-naturaleza

Reflexivos en el contexto geográfico, los estudios etnoecológicos desde sus inicios han buscando la integración de la multidimensionalidad asociada al conocimiento tradicional, reconociendo los componentes estructural, relacional y dinámico vinculados a los elementos y fenómenos naturales (Toledo, 1990). Si bien estas investigaciones se han enfocado al estudio integral de las cuestiones filosóficas, socioculturales y ecogeográficas de la diversidad biocultural, algunas cuestiones relativas a la transformación del espacio geográfico, particularmente a las implicaciones espaciales que el manejo *in situ* de la biodiversidad tienen sobre el paisaje, o la distinción de particulares patrones de distribución asociados a estos fenómenos etnoecológicos, han permanecido hasta muy recientemente poco abordadas.

Desde la geografía, los procesos por los cuales los grupos humanos se apropian de un espacio, y como gradualmente sus actividades van marcando su impronta en el paisaje, es una de las cuestiones que más nutrieron a la llamada Geografía Cultural Tradicional (GCT), de quien fuera fundador Carl Sauer (Urquijo et al., 2020). El trabajo académico e intelectual de Sauer, aunque originalmente gestado en la geomorfología, se inclinaba por integrar las visiones aparentemente contrastantes de la geografía física y la cultural desde un enfoque descriptivo-estructural (Sauer, 1941). Sus propuestas metodológicas fueron novedosas para su época, abordando los procesos ecológicos de cambio ambiental asociados al desarrollo cultural a través de una visión interdisciplinaria, desde una aproximación histórica y apoyándose en las ciencias sociales en busca de develar el desarrollo y la conformación de los paisajes (Price y Lewis, 1993; Urquijo et al., 2020).

La GCT exploró los procesos que subyacían la conformación de paisajes indagando en los dinámicas sociales y culturales que se manifestaban en cambios ecológicos en los territorios (Mathewson, 2010), su trabajo buscaba el reconocimiento de la integralidad entre lo humano y la naturaleza (Sauer, 1926). En esta búsqueda, se estudiaron las formas y los procesos visualmente más impactantes del desarrollo cultural, centrando la atención en las dinámicas de conformación de los paisajes que resultaban del uso intensivo del espacio geográfico, el cual deriva en evidentes transformaciones de las cubiertas naturales (Denevan, 2001; Doolittle, 2000; Whitmore y Turner, 2001). Estos usos, a los que aquí me refiero como usos intensivos del paisaje, son las actividades humanas de gran impacto ambiental, incontrovertiblemente antrópicas y claramente identificables en el paisaje: los asentamientos humanos, la urbanización, la minería, la agricultura y la ganadería. No obstante, otros procesos derivados de formas más sutiles de uso o la visión sistémica del paisaje como los que se mencionan a continuación permanecieron sin ser abordados.

El continuum de interacciones sociedad-naturaleza y la domesticación del paisaje

Aunque a la agricultura se le refiere con frecuencia como uno de los acontecimientos más importantes en la historia de la humanidad, este se ha reconocido como un proceso evolutivo que derivó en diferentes formas e intensidades de aprovisionamiento (Higss y Jarman, 1969; Rindos, 1984; Weisdorf, 2007). El proceso gradual que dio paso a la agricultura involucró distintos grados de interacción con los sistemas naturales para la procuración de recursos. Entre estos, la manipulación de la diversidad silvestre a través del manejo *in situ* ha jugado un importante papel en los procesos de domesticación por medio de la selección artificial, asi como influyendo en la composición y estructura de las comunidades vegetales a través de prácticas de manejo que favorecen la presencia de especies deseadas (p.e. tolerancia, promoción y protección) (Harris, 1989; Casas et al.2007). Se plantea que con el tiempo, algunos de estos procesos derivaron en el establecimiento de espacios designados a la agricultura, mientras que el manejo de la vegetación y de especies silvestres permanecio en alguna medida como una significativa parte de la dieta (Harris, 1989); así, las distintas formas en las que se manifestó esta interacción con el ambiente, fueron reconociendose como fases dentro de un gradiente continuo de inversión de energía y cambio ecológico, que era inducido y mantenido por actividades humanas (Fuller, 2010; Harris, 1989; Smith, 1965). Dependiendo del grupo humano y el contexto geográfico, esto podía implicar distintos periodos de tiempo, y tomar rutas alternas a la adopción de la agricultura, prescindiendo total (en el caso de los aborígenes australianos) (Hynes y Chase, 1982), o parcialmente de ella (el caso de Mesoamérica) (Caballero et al., 1998; Casas et al., 2014).

La facultad de los humanos para modificar sus ambientes a través de cualquiera de estas formas, de manera que generan las condiciones adecuadas para su aprovisionamiento y sobrevivencia se ha planteado como parte de un proceso evolutivo nombrado construcción de nicho (Smith, 2011; Fuller, 2010), que se refiere en términos muy generales, al proceso mediante el cual los organismos modifican su ambiente para sobrevivir (Odling-Smee et al. 2013). En este sentido, las sociedades humanas adecuan su entorno para proveerse de satisfactores, y los cambios generados permanecen en forma de herencia ecológica hacia las generaciones subsiguientes (Laland et al, 2000), las transformaciones permanecen en tanto se sigan applicando las dinámicas que los generaron. Smith (2007) ha señalado a la agricultura como un ejemplo evidente de este proceso. Los profundos contrastes que se evidencian entre los espacios utilizados por la agricultura, de aquellos en donde aún prevalecen las dinámicas naturales, fueron posiblemente lo que argumento a favor de la desarticulación sociedad-naturaleza. Fue quizás esto mismo, lo que dificultó la identificación de procesos de conformación de paisaje derivados de aprovechamiento mas sutiles, formas de subsistencia que, como se mencionó anteriormente, continuan siendo comunes (en el sentido de permanencia, pero también en el de coincidencia) entre sociedades tradicionales de América. Me referiré aquí a éstas, como formas no intensivas de uso de paisaje, es decir, al sostenimiento de estrategias de aprovechamiento que incorporan procesos de adecuación de los elementos paisajísticos para mejorar las condiciones de diversidad y disponibilidad de satisfactores, que por su menor impacto mantienen diferentes grados de similitud con espacios considerados naturales, y que incluyen el manejo *in situ* de especies silvestres (o en procesos de domesticación emergente) (Balée, 1988; Clement et al., 2015; Levis et al., 2018; Maezumi et al., 2018).

Estas prácticas son de impacto moderado, y sus efectos pueden incluso pasar desapercibidos; no obstante, al ser ejercidas de manera constante durante largos periodos van modificando de manera paulatina los paisajes sujetos a manejo. Como breves ejemplos se pueden citar los casos de *Stenocereus pruinosus* (pitayo) en el Valle de Tehuacán, Puebla, una cactácea columnar que se encuentra sujeta a manejo tradicional; entre las prácticas domentadas en esta especie se encuentran: su propagación por medio de partes no vegetativas, así como la protección y el cuidado de plántulas y juveniles de poblaciones silvestres (Parra et al., 2012). Otro ejemplo es el manejo de la zona estuarina en la Costa Nororiental por las Naciones originarias del actual territorio de Canadá, quienes a través de la remoción de plantas competidoras y el mejoramiento del substrato, incrementaron la zona de establecimiento de las especies *Potentilla egedii* y *Trifolium wormskioldii,* plantas con tuberculos de gran valor alimentario (Turner et al., 2013). Estas formas de manejo tienen claras implicaciones espaciales y con el tiempo devinieron en diferentes configuraciones de estos elementos en el paisaje a través de la propagación y el mejoramiento del hábitat de las especies de interés, lo que derivó en cambios en la estructura y composición de las comunidades vegetales a nivel de paisaje. Estas prácticas se reconocen por tener un amplio espectro de inversión energética y formas graduales de modificación del espacio geográfico (Harris, 1989), y son por ejemplo, las que se vinculan a la existencia de *bosques de palmas* dominados por *Attalea speciosa* (babasú) en la Amazonia brasileña. Especie muy relevante como fuente de carbohidratos y proteínas, y estrechamente asociada a substratos antrópicos y sitios arqueológicos de la región Amazónica (Balée, 1988).

A estos procesos alternos o paralelos por los cuales las sociedades humanas modifican el ambiente para hacerse de satisfactores se le ha denominado *Domesticación del Paisaje* (Deur, 2000; Erickson, 2006; Smith, 2011; Terrell et al., 2003). Este concepto se refiere a la forma en la que ciertos territorios son sujetos a prácticas de manejo específicas, las cuales se ejercen con la finalidad de mejorar la disponibilidad de especies silvestres, y se basan en el conocimiento acumulado de las sociedades para adecuar el ambiente en paisajes *culturales* con patrones definidos (Erickson, 2006; Smith, 2011b). Este concepto, se ha usado preferentemente para describir los procesos ocurridos en sitios que históricamente se han percibido como prístinos (Clement et al., 2015; Erickson, 2003; Franco-Moraes et al., 2019; Levis et al., 2018; Maezumi et al., 2018).

Al menos dos décadas antes a la definición del concepto, estos temas ya habían sido planteados. Los estudios etnobiológicos de William Baleé, y Arturo Gómez-Pompa, debatieron el mito de lo prístino en sus estudios sobre los territorios americanos, en los cuales abordaron el origen antrópico de los bosques de palma derivados de manejo en la Amazonia Brasileña (*indigenous adaptation to Amazonian palm forest,* Baleé, 1984), y los bosques manejados en la zona Maya (*the 'pet-kot': A man-made tropical forest of the Maya* Goméz-Pompa, 1987; *taming the wilderness myth,* Gómez-Pompa y Kauz, 1992); al igual que desde la geografía saureana William Denevan (*the pristine myth*, 1992), discutió sobre la huella humana en áreas consideradas poco manipuladas o incluso "vírgenes", una reflexión que dos décadas atrás iniciara el geógrafo James Parsons (y Sauer incluso antes. *Grassland climax, fire, and man*, 1950), destacando la influencia humana sobre la composición y estructura de los bosques tropicales de América y poniendo de manifiesto las importantes implicaciones espaciales del manejo histórico de especies no cultivadas en los paisajes americanos (*the changing nature of the New World,* Parsons, 1974). En sus palabras, los paisajes americanos considerados prístinos, presentaban una profunda influencia humana cuyo manejo, no obstante, en muchos casos presentaba poco impacto. Más recientemente se han reconocido los beneficios diversos que el manejo humano puede tener no solo para la conservación, sino para el incremento de la biodiversidad (a diferentes niveles: genes, especies, ecosistemas, paisajes) y su disponibilidad (McNeely, 2004).

La profundidad con la que los estudios geográficos abordaron la estrecha relación sociedad-naturaleza, develan la cercana relación con los estudios etnoecológicos. No obstante, trabajos encaminados a estimar los cambios en el espacio geográfico derivados de este tipo de aprovechamiento del paisaje no fueron emprendidos, temas que hasta el día de hoy han continuado poco abordados.

La integración de enfoques

La contribución esencial de la geografía a las ciencias ambientales, aparte de importantes conceptos y disciplinas como la ecología del paisaje (Forman y Godrom, 1981; Troll, 1939; Zonneveld 1990), reside en la integración de la variable espacial para explicar procesos que determinan la distribución de fenómenos ambientales, entre los que se encuentran la configuración de los paisajes resultante de las diversas y complejas relaciones entre los grupos sociales y la naturaleza. En este particular, la expresión espacial de formas no intensivas del uso de paisaje es un tema que ha quedado como una gran faltante, así también, la relación de estas formas de manejo con otros temas tan esenciales como sus implicaciones para la sostenibilidad y la conservación de ecosistemas. La integralidad del enfoque geográfico en general y del paisaje en particular, puede servir de apoyo para abordar las complejidades emergentes en la diversidad dialéctica entre sociedad-naturaleza, ayudando a integrar el conocimiento de otras disciplinas en el contexto espacial (Franch-Pardo et al., 2017).

De acuerdo con Urquijo y Bocco (2011), *"…paisaje es una categoría geográfica que ofrece una posición unificadora ante la dicotomía sociedad-naturaleza que dificulta cualquier comprensión social y ecológica, tanto en lo funcional como en lo histórico y espacial*". Una idea cercana se ha propuesto bajo el concepto de socioecosistema, en el cual se reconocen y enfatizan las interdependencias entre los subsistemas ecológico y social, planteando la necesidad de una visión integral para su estudio y análisis (Young et al., 2006). En este sentido, se entiende al socioecosistema como aquel que se integra mediante la interacción entre los grupos humanos y los ecosistemas, mediada a través de la tecnología, el conocimiento local y las instituciones establecidas (organización social), que se encuentran interactuando en un espacio definido (Berkes y Folkes, 1994). El paisaje aquí, correspondería al resultado de esta interacción, es decir es la transformación resultante del espacio habitado y manejado. Como el paisaje, el concepto de socioecosistema no tiene una dimensión definida o preestablecida; no obstante a diferencia de este, el socioecosistema puede adquirir dimensiones macro-escalares (p.e. globales *sensu* Young et al., 2006). La perspectiva de paisaje permite entonces, observar una realidad concreta de manera integral, considerando un conjunto de variables de distinto origen ontológico (físico, biológico, histórico, cultural), que se encuentran interactuando en un espacio geográfico situado. En México, el estudio del manejo tradicional ha tenido implícito el concepto de espacio y ha sido reflexivo en las dimensiones temporales y geográficas, abordando las implicaciones espaciales que derivan de la relación establecida a través del manejo histórico de las especies silvestres, así como de las acciones ejercidas sobre el paisaje para mejorar su disponibilidad (Illsley 2001; Parra et al. 2012; Moreno-Calles et al, 2013; Toledo y Barrera-Bassols, 2011). No obstante, aún hay campos de oportunidad que explorar en relación a los aportes metodológicos e intrumentales que puede ofrecer el uso de sistemas de información geográfica para indagar sobre estos procesos a escala regional.

Como se ha planteado anteriormente, el concepto de paisaje que se considera para este estudio es el mencionado por Santos y Ganges (2002), como la configuración de un espacio geográfico humanizado; no obstante, como este estudio busca ser transdisciplinar y parte del trabajo y las reflexiónes elaboradas en distintas disciplinas, se encuentran aquí distintas acepciones del concepto. Aquellas que emanan desde la antropología, la arqueológia y la biología, incluso el uso de paisajes adjetivisados desde la geografía. La noción de paisaje domesticado parte de la antropología y es propuesto por Douglas Yen en 1989 ("*The domestication of environment"*), y más tarde conceptualizado como Domesticación del Paisaje por Clements, como el proceso por el cual las sociedades transforman los paisajes (Clements, 1999; Clements y Casssino, 2018). Estos estudios no proporcionan una definición de lo que se concibe como paisaje, pero se puede entender que hay un paisaje que antecede a la influencia humana, y por tanto deber referirse alguna extensión del medio físco circundante y sus subsistemas biológicos no humanos. El concepto definido así, es muy amplio, pero como se mencionó anteriormente, ha sido preferentemente utilizado para definir procesos de adecuación de los territorios con la finalidad de mejorar las condiciones de aprovisionamiento de especies silvestres (Erickson, 2006; Smith, 2011), particularmente para describir los procesos ocurridos en sitios que históricamente han sido percibidos como prístinos (Clement et al., 2015; Erickson, 2003; Franco-Moraes et al., 2019; Levis et al., 2018; Maezumi et al., 2018). Utilizado de manera recurrente en estudios etnoecológicos (Clement et al., 2015; Levis et al., 2018) así como arqueológicos (Smith, 2007, 2011; Terrel, 2003). Aunque plantean una contrariedad las dos nociones de paisaje aquí descritas, el término Domesticación del Paisaje se utiliza haciendo esta aclaración, pues la conceptualización de estos procesos resultan útiles para entender la conformación de los paisajes; al mismo tiempo, estas contradiciones resultan de las distintas perspectivas que se tratan de integrar en este argumento, y dan cuenta de las dificultades transdisciplinarias que emergen y que necesariamente se afrontan al tratar de integrar perspectivas que confluyen de distintas disciplinas. Por ultimo, señalar, que se reconoce al manejo tradicional como el medio por el cual estos procesos de domesticación son llevados a cabo.

El manejo tradicional como expresión geográfica en el espacio

El manejo tradicional de la biodiversidad se refiere al conjunto de prácticas ejercidas sobre los ecosistemas, comunidades, o poblaciones de especies, que puede incluir entre sus prácticas no solo acciones de aprovechamiento, sino también de protección y conservación. Estas son el resultado del desarrollo y evolución del conocimiento ecológico tradicional, que emana de las diversas formas en que las sociedades tradicionales se relacionan e interactúan con la naturaleza (Casas et al., 2014; Fowler y Lepofsky, 2011), y que en su conjunto, conforman la diversidad biocultural (Toledo y Barrera-Bassols, 2008). Las prácticas de manejo mencionadas, son realizadas a distintas escalas de organización biológica (individuos, poblaciones, comunidades, ecosistemas, etc.), y se encuentran supeditadas a diferentes escalas de organización social (unidad familiar, comunidad) (Casas et al., 2014). Este manejo de la naturaleza tiene como propósito la generación de condiciones apropiadas para satisfacer necesidades humanas básicas de alimentación, vivienda y sustento (Terrell et al., 2003), y en consecuencia, frecuentemente involucra acciones de conservación. El conjunto de estas acciones ejercidas en el tiempo sobre espacios específicos resulta en modificaciones progresivas al ambiente que mejoran la disponibilidad y suponen una ventaja para el aprovisionamiento de recursos. De manera que el manejo tradicional tiene una dimensión que se expresa geográficamente como el resultado de las decisiones deliberadas ejercidas sobre el espacio. Estas adecuaciones son heredadas dentro de los grupos humanos, a lo que se ha denominado herencia ecológica (Laland, Odling-Smee y Feldman, 2000) y la permanencia de estos espacios modificados se da por la continuidad transgeneracional de las acciones de manejo.

A este respecto, la caracterización del manejo a través del entendimiento y la sistematización de las dinámicas incorporadas, facilitan la comprensión de las implicaciones ecológicas y espaciales asociadas a estas prácticas. Tal caracterización en conjunto con una perspectiva geográfica y el análisis espacial, permiten abordar escalas regionales de análisis para rastrear su expresión espacial en el paisaje.

Brahea dulcis en la Reserva de la Biósfera de Tehuacán-Cuicatlán (RBTC)

El área protegida de la RBTC contiene uno de los registros de ocupación humana más antiguos de México. Entre los vestigios arqueológicos que resguarda esta región, se encuentra uno de los registros de uso y domesticación de especies más completos de Mesoamérica, el de la cueva de Coxcatlán del Proyecto Arqueológico-Botánico de Tehuacán a cargo del Dr. Richard Stockton MacNeish en los años sesenta (McClung, 1985). En esta cueva que se encuentra en lo que corresponde actualmente el centro de la RBTC, se encuentra el registro de palma más antiguo para Mesoamérica, que corresponde a unos fragmentos de hojas de *B. dulcis* que datan de alrededor de 12,000 aAP (Smith, 1967).

Estas palmas resultan de particular importancia por el contexto ecológico de la región, debido a las multiples funciones que desempeñan, ya que su uso es diversificado e incluye desde lo alimentario, hasta materiales para la construcción y elaboración de objetos domésticos (Blancas, 2000; Illsley, 2001; Rangel-Landa et al., 2014). En contextos secos y semiáridos como los de la RBTC, una especie multifuncional como *Brahea dulcis* puede presentar gran relevancia en términos económicos, ya que provee de fuente de alimento y fibra, representando una fuente de ingreso monetario a través de su comercialización. Estas características hacen de esta especie la palma de mayor uso en México (Quero y López-Toledo, 2014). Su particular relevancia deriva de su afinidad por regiones secas, lo que la convierte en un recurso muy importante para las poblaciones asentadas en estos ambientes complejos. En la Reserva de la Biósfera de Tehuacán-Cuicatlán, con su larga historia de ocupación por grupos humanos (más de 12,000 aAP, Smith, 1965), se encuentra el registro más antiguo de esta palma en contextos arqueológicos (Morcote-Ríos y Bernal, 2001), y por las particularidades del sitio se presume que este registro podría representar el vestigio más antiguo de uso de palmas en Norteamérica (Smith, 1965).

Esta relación temprana establecida entre los antiguos grupos humanos que habitaron la RBTC y *Brahea dulcis* puede representar un lazo de continuidad con el pasado. Se tiene registro de la presencia de esta palma en varios sitios arqueológicos de distinta antigüedad (Smith, 1967), y la mención constante de los productos elaborados con su fibra en distintos documentos prehispánicos e históricos de la región (Acuña, 2017b, 2017; Chadwick y MacNeish, 1967; Dalhgren, 1979; García Castro, 2013; Spores y Balkansky, 2013; Velázquez de Lara, 1984); así como en la historia reciente (Miramontes, 1949; Steffen, 2001). Actualmente, esta palma es ampliamente utilizada por los grupos culturales que habitan la reserva, ostentando una gran variedad de usos que van desde lo agrícola hasta lo ritual-ceremonial, siendo objeto de un relevante manejo. Dentro de la RBTC, *Brahea dulcis* se distribuye sobre una gran variedad de tipos de vegetación (Valiente-Banuet et al., 2009), entre los que se encuentran diversos tipos de matorrales, bosques de encino y táscate (Rangel-Landa, 2014). En algunos sitios es posible observar grandes extensiones de comunidades vegetales donde esta palma es dominante, los cuales son denominados localmente como *palmares* o *palmonares* (Rangel-Landa, 2014; Valiente-Banuet et al., 2009). Diversos autores han debatido sobre el origen de estas comunidades vegetales, que se cree derivado de actividad humana (Casas et al., 1994; Illsley et al., 2001; Rzedowski, 1978). En el presente trabajo se retoman estas propuestas para indagar en las cuestiones ecológicas asociadas a la distribución de *Brahea dulcis* en la RBTC, y las implicaciones ecológicas y espaciales de su manejo, para aproximarnos a los mecanismos de domesticación del paisaje que pueden subyacer en la presencia de estos palmares en la región.

Preguntas de investigación

En la indagación sobre el origen de las comunidades de palmar, se plantearon las siguientes preguntas:

¿Cuáles son las relaciones que se establecen a través del manejo entre las comunidades humanas y *Brahea dulcis*? ¿Que niveles de organización biológica se involucran?

¿Cuál es el contexto vegetal donde se distribuye *Brahea dulcis* dentro de la RBTC?

¿Cómo se expresan las relaciones ecológicas y geográficas del manejo de *Brahea dulcis* en la configuración del paisaje de la RBTC?

Objetivo general

Analizar las relaciones eco-geográficas del manejo tradicional de la palma *Brahea dulcis* (soyate) en el paisaje de la Reserva de la Biósfera Tehuacán-Cuicatlán, como procesos asociados a la presencia de palmares en la región

Objetivos particulares

i) caracterizar el manejo tradicional de *Brahea dulcis*, señalando la relevancia ecológica y cultural del recurso, así como identificar las implicaciones ecológicas y espaciales de las prácticas de manejo de las que es objeto; ii) analizar la distribución espacial de las comunidades vegetales al interior de la RBTC, a través de la elaboración de cartografía que permita relacionarla con la presencia de palmares; iii) comprender los procesos que subyacen la presencia de las comunidades de palmar en la región

Para dar respuesta a las preguntas de investigación, se abordaron los tres objetivos propuestos que se corresponden con los tres capítulos que integran la tesis doctoral. En el primer capítulo llamado "*Ecological, Cultural, and Geographical Implications of Brahea dulcis (Kunth) Mart. Insights for Sustainable Management in Mexico*" publicado en la revista *Sustainability,* se exploran las dimensiones asociadas al manejo de *Brahea dulcis,* para comprender su relevancia cultural, ambiental y económica. A través de una revisión bibliográfica extensa, se identifican y describen las prácticas de manejo desarrolladas en torno a la palma para construir una caracterización del manejo tradicional de la especie. A través de esto, se identifican los procesos asociados al manejo de *Brahea dulcis* y se describen las implicaciones ecológicas de las prácticas particulares en relación con los individuos y poblaciones de palma, así como las implicaciones espaciales que derivan en una expresión en el paisaje. En el segundo capítulo que lleva por nombre "*An expert knowledge approach for mapping vegetation cover based upon free access cartographic data: the Tehuacan-Cuicatlan Valley, Central Mexico*" publicado en la revista *Biodiversity and Conservation,* se realiza un análisis regional de las comunidades vegetales de la RBTC, indagando en los factores que subyacen su distribución espacial. El producto cartógráfico de este análisis permitió establecer el escenario vegetal en el cual se inscribe *Brahea dulcis*, así como la identificación de las zonas al interior de la RBTC en donde existen condiciones ecológicas para su presencia. Aunque la distribución de las comunidades de palmar no pudo lograrse a través de este análisis, la determinación de los patrones de distribución espacial de las comunidades vegetales de las cuales forma parte *Brahea dulcis* fue, en análisis ulteriores, determinante para establecer asociaciones entre los patrones ecológicos de la región y la presencia de palmar. El capítulo tercero, nombrado "*Species distribution modeling as a tool* *to approach processes of Landscape Domestication in Central Mexico"* es un capitulo integrador que indaga en el origen de la presencia de las comunidades de palmar en la RBTC. A través de metodologías de Nicho Ecológico y Modelado de Distribución de Especies se identificaron los factores ecológicos y de manejo asociados a la presencia de palmar, a partir de los cuales se hace una propuesta sobre los procesos que dieron origen a los palmares en la región desde una perspectiva histórica del manejo de recursos. De acuerdo con diferentes fuentes documentales (arqueológicas, códices prehispánicos y documentos históricos), el uso de *Brahea dulcis* comenzó desde tiempos antiguos que se remontan al inicio de la presencia humana en la región (~12,000 aAP); más tarde se registran en códices prehispánicos objetos hechos tradicionalmente con esta especie; registros que se continúan en fuentes coloniales y de manera más profusa en la historia reciente. Por lo anterior, se plantea que su uso se estableció desde tiempos tempranos y se ha sostenido a través del tiempo debido a la relevancia cultural y económica de la especie. Los palmares representan entonces, el resultado de procesos de adecuación de las poblaciones humanas dentro de la RBTC para la procuración y aprovisionamiento de fibra vegetal, que forma parte de un proceso de Domesticación del Paisaje que comenzó desde tiempos inmemoriales en la región.

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Capítulo II

Ecological, Cultural, and Geographical Implications of *Brahea dulcis* (Kunth) Mart.
Insights for Sustainable Management in Mexico.

Artículo publicado en:

Sustainability **2020**, 12, 412; **doi**:10.3390/su12010412 *sustainability*

Article

Ecological, Cultural, and Geographical Implications of *Brahea dulcis* (Kunth) Mart. Insights for Sustainable Management in Mexico

Cloe X. Pérez-Valladares [1], Ana I. Moreno-Calles [2,*], Alejandro Casas [3], Selene Rangel-Landa [3], José Blancas [4], Javier Caballero [5] and Alejandro Velazquez [1]

[1]Centro de Investigaciones en Geografía Ambiental (CIGA), Universidad Nacional Autónoma de México, Antigua Carretera a Pátzcuaro 8701, Morelia 58190, Michoacán, Mexico; cvalladares@pmip.unam.mx (C.X.P.-V.); alex@ciga.unam.mx (A.V.)
[2]Escuela Nacional de Estudios Superiores (ENES), Universidad Nacional Autónoma de México, Antigua Carretera a Pátzcuaro 8701, Morelia 58190, Michoacán, Mexico
[3]Instituto de Investigaciones en Ecosistemas y Sustentabilidad (IIES), Universidad Nacional Autónoma de México, Antigua Carretera a Pátzcuaro 8701, Morelia 58190, Michoacán, Mexico; acasas@cieco.unam.mx (A.C.); srangel@cieco.unam.mx (S.R.-L.)
[3]Centro de Investigación en Biodiversidad y Conservación (CIByC), Universidad Autónoma del Estado de Morelos, Av. Universidad 1001, Colonia Chamilpa, Cuernavaca 62209, Morelos, Mexico; jose.blancas@uaem.mx
[5]Instituto de Biología, Universidad Nacional Autónoma de México, Cto. Zona Deportiva, s/n, Ciudad Universitaria, Ciudad de Mexico 04510, Mexico; jcaballero@ib.unam.mx
* Correspondence: isabel_moreno@enesmorelia.unam.mx

Received: 5 December 2019; Accepted: 2 January 2020; Published: 5 January 2020

Abstract: Palm plants provide important benefits for rural communities around the world. Of the 95 native palm species in Mexico, *Brahea dulcis* (*Soyate* palm) has been tagged as an important resource for many Mesoamerican ethnical groups. Scientific and empirical knowledge concerning *Soyate* is thematically fragmented and disassociated, meaning that sound sustainable management is far from established. Research of over 20 years has permitted us to document ecological, cultural and geographical outcomes of *B. dulcis;* thus, the present paper aims at compiling all knowledge on *Soyate* to eventually guide its long-term management. It was conducted in two stages: firstly, it comprised a thorough review of previous studies on the management of *B. dulcis* in Mexico; secondly, we integrated unpublished outcomes obtained from fieldwork, including participatory ground-truth validation and semi-structured interviews obtained from local ethnic groups. Five factors guided our compilation effort: (i) biological and ecological information, (ii) cultural importance, (iii) economic triggers, (iv) traditional management, and (v) ecological and ecogeographical implications of *Soyate* palm management. The present paper confirms that *B. dulcis* is an important cultural resource whose utilization can be traced back over 10,000 years. The leaves of *Soyate* are the most useful part of the palm and were profusely used in the past for thatching roofs and weaving domestic and agricultural objects. Currently, however, palm-leaf weaving is primarily oriented toward satisfying economic needs. We depicted ten management practices aimed at favoring palm availability. Most of these management practices have enhanced sustainable palm leaf harvesting; however, these practices harbor spatial trends that turn highly diverse habitats into *Soyate*-dominated spaces. To conclude, we propose a framework to describe sound and sustainable *Soyate* management in the light of the current long-term *Soyate*–human relationship. It is here acknowledged that *Soyate* has played and continues to play a critical socioeconomic and cultural role for many ethnical groups in Central Mexico. Nonetheless, emerging challenges concerning the sustainability of the whole socioecological system at a landscape level are yet to be overcome.

Keywords: non-timber forest products; traditional palm management; palm ethnobotany; landscape domestication; fiber handcrafts; ecological inheritance

Introduction

Non-modern practices performed on individuals, populations, and ecosystems directed toward the use, maintenance or increase in the availability of resources are forms of traditional management [1–3]. Such actions are performed at different spatial and temporal scales and operate at different levels of social organization [4]. These practices and strategies are constructed from perceptions and knowledge of nature, as well as complex socio-historical processes influenced by the human–nature relationships of cultures [5]—a knowledge that is gradually improving and constantly built from experimenting in specific places [6,7]. Traditional management has the purpose of establishing appropriate conditions for obtaining natural resources or environmental benefits to satisfy human needs [1–4]. Five general types of management practices are commonly recognized, namely, gathering (which may include the selection of phenotypes, as well as the regulations or social organization required to carry this out), tolerance, promotion, protection, and cultivation [1,2]. These five actions may be performed in situ, in natural areas where the species occur, or may be extracted from the original distribution sites and manipulated ex situ, in areas such as home gardens and other agroforestry systems [4]. Although such practices are commonly directed to specific plant resources, with time, the continual practice of these actions results in progressive modifications of the environment that improve or reduce resource availability. Thus, management has ecological, cultural, and spatial dimensions [4,8,9].

Examples of the effect of traditional managing palms are the atypical presence and abundance of some species of *Astrocaryum*, *Acrocomia*, *Attalea* and *Bactris* related with ancient human settlements in Amazonia [10,11]. These species are used in searching for archaeological remains since they are considered indicators of ancient human settlements. The continuous selection of individuals with desirable characteristics has given way to the domestication of some species populations and to the consequent differentiation of varieties responding to different human needs. This has been the case for date palm (*Phoenix dactylifera*) [12], coconut palm (*Cocos nucifera*) [13], and pejibaye palm (*Bactris gasipaes*) [14]. The traditional management of palms as non-timber forest products (NTFPs) has been pointed out as a strategy that could allow ecosystem conservation, while generating economic benefits for communities [15–17]. For this reason, scientific surveys aimed at assessing management implications should holistically analyze the entire geographical context, addressing spatial, ecological, and cultural aspects. Such a landscape perspective has been poorly addressed in the global study of NTFPs.

Traditional palm management is performed by rural communities in tropical regions around the world [18,19] where these resources fulfill several necessities: they are a source of food, fiber, construction material and oil, as well as raw materials for handcrafts. This has made the Arecaceae family the third most important cultural and economic botanical group worldwide, after only grasses and legumes [19]. Records of human groups using palms in the Americas go back almost to 12,000 years before present (BP) [10]. Due to their remarkable ecological and cultural importance, Balick [11] considered palms to be as important as maize in the development of precolonial societies in the Americas and suggested that their prehistoric use is deeply related to the dispersion, selection, domestication, and extinction of species, which has important implications for explaining their current geographical distribution. Traditional palm management frequently occurs in arid and sub-humid ecosystems, where the selling of palm-derived products sometimes represents the only source of income; thus, this is regarded as critical for monetary compensation [11,20]. Furthermore, palms have been present in a diversity of aspects of the cultural life of indigenous, afrodescendant and mestizo communities in Latin America [10,11,21–24], playing an important role in their identities due to the large amount of resources they provide [10,11,23,25].

Mexico has not been an exception regarding the use of palms since ancient times. The earliest record of palms being used by humans in Mexico dates back nearly 11,950 years BP [10], and a large amount of archeological remains has been identified in caves and other sites [26]. These records suggest that palms were originally used for the confection of fiber strips [27]. The cultural importance of palms among Mexican people is reflected in the inclusion of these plants in daily life and ritual–ceremonial practices [3], as well as in the traditional knowledge of communities regarding their uses [28,29]. Several indigenous groups are recognized through their bond with palms: among the Maya people, the use of guano palm (*Sabal* spp.) and its leaves has been practiced since ancient times, mainly for thatching traditional houses [29]. The *Ñuu savi* (Mixtec), *Xwja* (Ixcatec), and *Ngiwa* (Popolocan) ethnic groups have been dubbed "the eternal palm weavers" due to the cultural importance of weaving hats, "petates" (a kind of palm woven mat), and "tenates" (a palm woven container), as well as other diverse handcrafts using *Brahea dulcis* palm leaves [30–34]. In addition, there are several cultural groups which are deeply bound with this palm, such as the *Nahua*, *Nduudu yu* (Cuicatec), *Binni zá a* (Zapotec), *Ayuukjä'äy* (Mixe), *Runixa ngiigua* (Chocho), *Ha shuta enima* (Mazatec), and *Hñä hñü* (Otomi). Thus, palm management has been culturally connected with the identity of the Mesoamerican people, through this acquiring its traditional representation [35].

Similarly, as in other countries of South America [23], palms in Mexico have mostly been used as material for construction, food, and the production of tools and utensils of domestic and agricultural use. The palm's leaves, fruits, and apical meristems are the most used parts [21,29,36–40]. The plant fiber which makes up the leaves is of primary importance in roof thatching and the production of household goods [29,41]. According to Belcher [16], plant fibers are the most important NTFPs, after medicinal and food plants. In Mexico, the *Brahea* and *Sabal* species stand out for their value as plant fiber sources [21,28,29,36–41]. *Brahea* is of primary importance since it is a predominantly Mexican endemic genus, primarily occurring in dry climates and semiarid environments [42]. In this context, *Brahea* plays an important role as a strategic resource in rural household economies [41]. Prior to this study, several local surveys documented the economical relevance of *B. dulcis* (*Soyate*) for rural communities [20,21,37,41,43,44]. The outreach of these surveys, however, did not permit the provision of a national perspective in order to assess implications for sustainability.

The present paper aims at compiling ecological, cultural, and geographical information relating to the traditional management of *Brahea dulcis* to feature insights regarding its sustainability. We argue that the *Soyate* palm socio-ecological system might be regarded as one of the most culturally outstanding examples in Mesoamerica. We further discuss *Brahea dulcis* as a model for exploring the implications of in situ traditional palm management for reshaping the region at a landscape level.

Methods

Our research was conducted in two phases: firstly, a bibliographic search was conducted from February to August 2018 using the Scopus, Web of Sciences, and Google Scholar databases using "*Brahea dulcis* México", "palm management Mexico", "palm traditional management", "manejo tradicional *Brahea dulcis*", and "manejo palmas *Mexico*" as keywords. We additionally performed a continuous review of new sources based on the literature referred to in the documents obtained from these databases. These results are presented in Supplementary File S1.

We secondly integrated unpublished outcomes obtained from fieldwork, including participatory ground-truth validation and semi-structured interviews obtained from Guerrero, Puebla, and Oaxaca local ethnical groups. Five factors guided our compilation effort: (i) general biological and ecological information; (ii) cultural importance; (iii) economic triggers; iv) traditional management; and (v) landscape implications of the *Soyate* palm management. By means of participative observation [45] and open and semi-structured interviews [46] held with weavers, harvesters, sellers, and local authorities, we documented detailed aspects of the management of *Brahea dulcis*. As part of the dialogues established with stakeholders, a technical report on palm stand management was also provided by the administration of the Tehuacán-Cuicatlán Biosphere Reserve.

An update was made of the palm species list reported for Mexico by Quero (1994) [38], and we reviewed the inventory and general information of the Mexican taxa of the Arecaceae family in order to be able to refer to this study within the context of palm cultural diversity in Mexico (Supplementary File S2).

A map of the known distribution of *Brahea dulcis* was created in a Geographical Information System (the open source Quantum Geographical Information System, QGIS www.qgis.org/es/site/; an official project of Open Source Geospatial Foundation) based on georeferenced records obtained from the Global International Biodiversity Facility (https://www.gbif.org/). The results of the bibliographic search were used to complement the map of *B. dulcis* studies in Mexico. On this map, the geographic location of the studies is indicated by the ID assigned in the table of bibliographic results (Supplementary File S1).
Integrated outcomes were further discussed in light of their implications for the sustainable management of *Soyate* and geographic implications at the landscape level.

Results

Brahea dulcis (Soyate Palm). Biological and Ecological Information

A total of 95 palm species belonging to 21 genera are listed for Mexico; of these, *Brahea* stands out as a predominantly Mexican genus. The *Brahea dulcis* species is that with the highest number of records of use among ethnic groups in Mexico (Supplementary File S2). Although the known distribution range of *B. dulcis* is from northern Mexico to Central America (Figure 1A), all results from the bibliographic search are studies conducted in Central–Southern Mexico (Figure 1B).

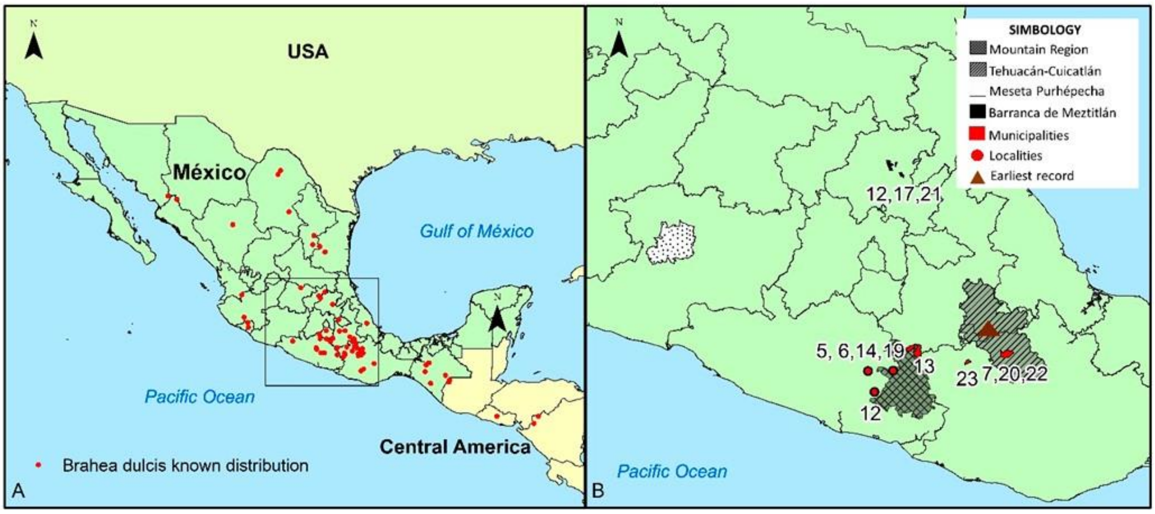

Figure 1. (**A**) Known *Brahea dulcis* distribution. (**B**) The geographic location of studies relating to *Brahea dulcis* management in Mexico. Numbers indicate the ID of studies referred to in Table 2.

Brahea is one of the least-known palm genera in the Americas [19], even though *Brahea dulcis* is the most abundant and widespread palm species in Mexico [43]. This species is mainly found in limestone soils, predominantly at elevations between 800 and 1600 m. It occurs in tropical dry forests, oak forests, and xerophytic scrubland from sub-humid to semidesert climates [20,28,38,47]. *Brahea dulcis* constitutes vegetation patches known as palm stands or *palmares*. According to several authors, *palmares* derive from management, through which the dominance of *B. dulcis* is favored by the selective removal of competing standing vegetation and man-made fires [20,37]. These management practices may increase palm abundance by up to 12-fold [48].

The phenotypic plasticity of *Soyate* palm has been reported [28,37]. Differences in the size of stems and leaves may depend on the developed life habits, which can be solitary or colonial (Figure 2).

This variable phenotype is malleable through management, where arboreal palm stands develop from solitary life habits with tall individuals or *Soyacahuite* (term derived from the Náhuatl meaning *soyatl* = palm and *cuahuitl* = tree; or, in other words, arboreal palms). Thus, arboreal palm-dominated stands are locally known as *Soyacahuiteras*, while the stands of shrubby colonial palms are called as *Manchoneras* (their nature and relation to management are discussed below).

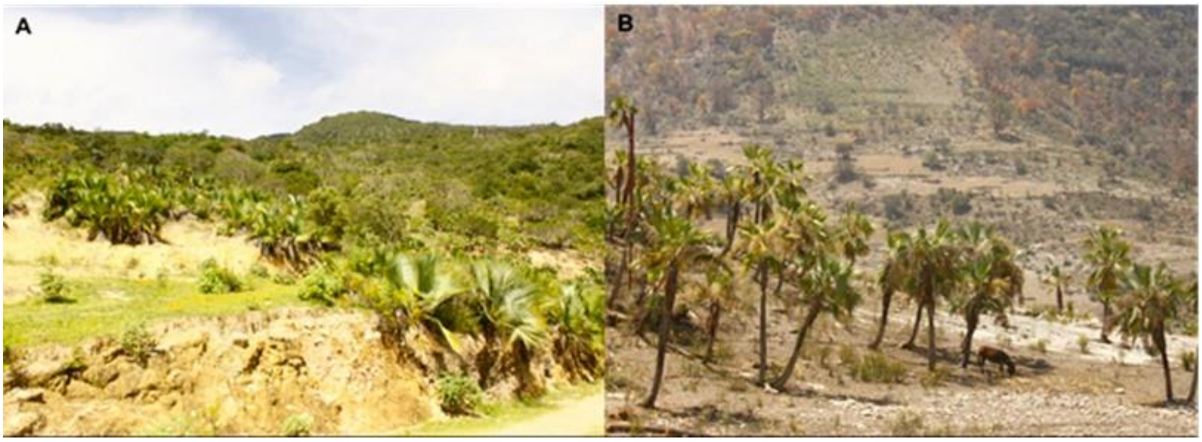

Figure 2. Morphotypes of *Brahea dulcis*. (**A**) Low-stature colonial life habit. Palm stands with a dominance of this phenotype are named *Manchoneras*. (**B**) High-stature individual life habit. Palm stands dominated by this phenotype are named *Soyacahuiteras*. Photo credit: Cloe Xochitl Pérez-Valladares.

Cultural Relevance

The earliest archaeological record of *Brahea dulcis* associated with human use dates back ca. 11,950 years BP in the caves of the Tehuacán Valley [26]. The discovered remains correspond to fragments of palm leaves that are assumed to have served as a fiber source since antiquity and were used to produce fiber strips by the earliest hunter–gatherer human groups in Central–Southern Mexico [26,27]. During pre-Hispanic times, Mesoamerican ethnical groups paid tribute to the Aztec Empire with objects made of *B. dulcis*. Products such as *tenates* and *petates* were used as tribute; the former were and still are useful and common containers, whereas the latter were regarded as valuable objects in wars, protecting armies from the sun during the day and used for rest at night [49,50]. The exchange of palm products for gold and other goods was documented in the 16th century and was carried out long before [49]. Dominican friars introduced the practice of hat weaving—a production that became an important industry during the 19th century and most of the 20th century [51,52].

Currently, *B. dulcis* has a wide variety of uses. Firstly, indirect food sources such as edible insects hosted by the palm are used as protein sources, such as for *soyacuilin* and *sochiahuatl*, insects from the genus *Rhynchophorus* (order Coleoptera) whose larvae are consumed after being cooked [28]. All the main parts of the palm are used, from roots to apical meristems (Supplementary File S3). Relevant uses are for handcraft fabrication (which provides economic incomes), utensils directly used by households (domestic use), construction, and important ritual/ceremonial practices (Table 1).

The most important aspect of using this palm is related to cultural engagement and identity (Figure 3). Knowledge of palm weaving can start from an early age (6 years): "They teach me [his grandparents], in the beginning there are *panalitos* [referring to the weave of objects that resemble small honeycombs, which are the first thing that is taught when beginning to weave] [. . .] those are the first steps [. . .], that is why people from before, at 20 years old, already know how to make *petates* and everything they want" (people from Zapotitlán Salinas Puebla). Among the *Xwja*, *B. dulcis* is considered a staple plant: "Palms are our life because with palm leaves, we make hats and we can get all we need to live" [53]. In different studies, interviews suggest that people remark not on the need of weaving, but their desire. As an elder *Ñuu savi* woman said, "My hands hurt, but I will not stop weaving because soon my little heart feels that it wants to weave" (San Pedro Jocotipac, Oaxaca).

Table 1. Palm part and uses of *Brahea dulcis*

Part Used	Product	Use
All plant	Palmo	Ritual
	Palm	Ornamental
Inflorescense	Crown for dances	Ritual
	Dried floral adornments	Ornamental
Fruits	Capulín/*Soyacapolli* *	Food
Apical meristem	*Palmito*	Food
	Infusion	Medicinal
Tomento	Cataplasm	Medicinal
Mature leaves	*Fuel*	Domestic
	Fumigant	Domestic
	Patchole *	Domestic
	Tlatepatchole *	Construction
	Tlatepatchos *	Food
	Palm toy whistles	Domestic
	Green leaves	Ornamental
Leaf buds	*Acachiquehutle* * Tenate	Domestic
	Aventador	Domestic
	Beehive	Domestic
	Strips	Handcraft
	Cachache **	Domestic
	Capote	Domestic
	Crosses and *Ramos*	Ritual
	Hats	Handcraft
	Mecapales *	Domestic
	Petate	Domestic
	Pixcalon **	Domestic
	Soyacatle *	Ritual
	Soyate	Domestic
	Strainer	Domestic
	Tenates	Domestic
	Tecolpetes *	Domestic
	Tentematlat */*Temposha* **	Domestic
	Tehiotzibtke *	Domestic
	Thumnails	Handcraft
	Tlachpahuastle *	Domestic
	Tlaistechicone *	Domestic
	Xoxolochtli *	Domestic
	Zazca **	Domestic
	Jewelry	Handcraft
	Wrap	Domestic
Foliar bracts	*Coaxtli* * or pads	Domestic
Roots	Roots	Domestic
	Roots	Medicinal
Stem	Poles	construction

* Word of Nahuatl origin. ** Word of Popolaca origin.

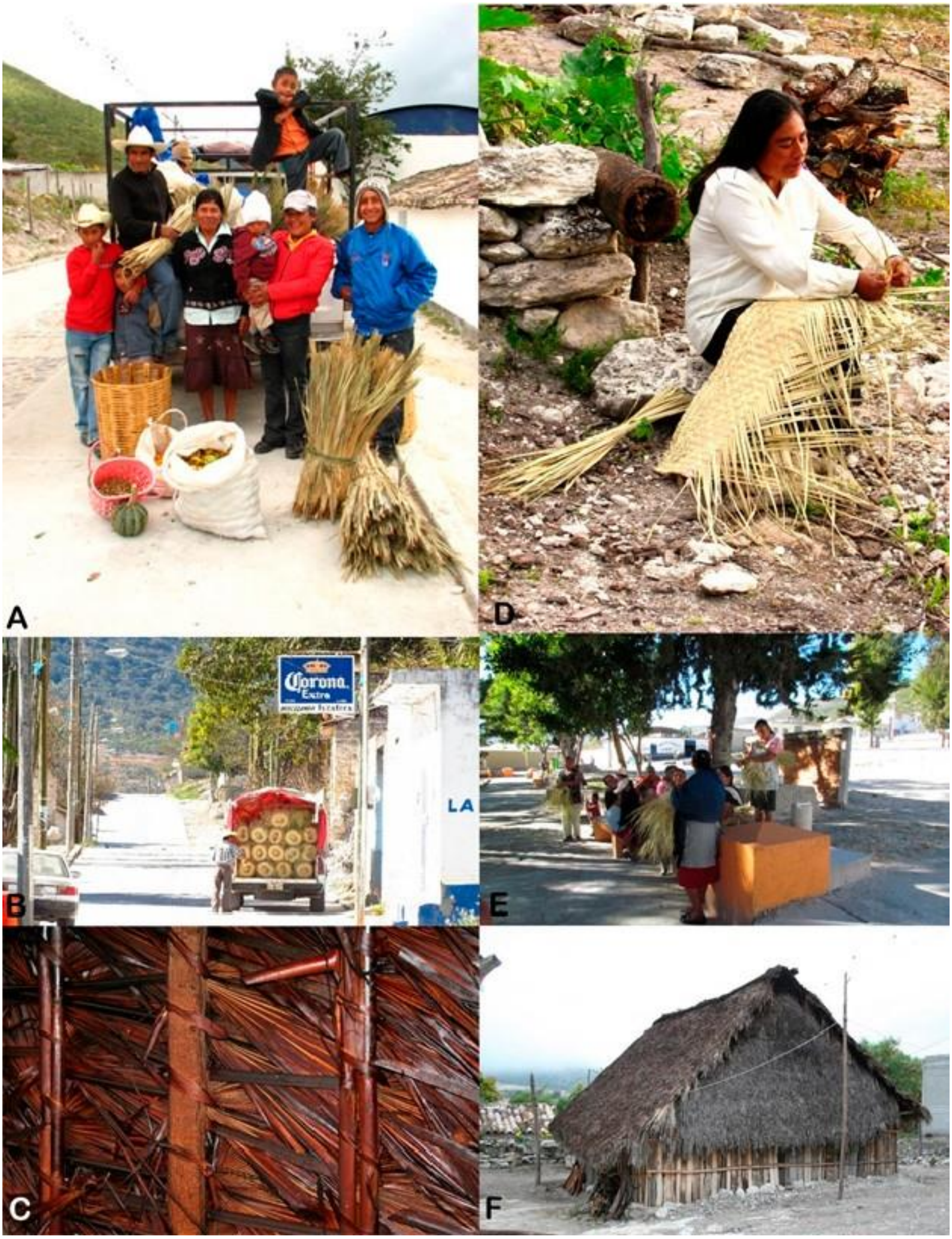

Figure 3. Cultural aspects of palm importance. (**A**) Interchange (trueque) of palm leaves for merchandise. (**B**) Hats ready to be transported to Tehuacán, Puebla. (**C**) Detail of a palm roof made with *Brahea dulcis* leaves. (**D**) Weaving of a *petate*. (**E**) Weaving as a form of social and intergenerational bonding. (**F**) Traditional house with palm roof at Santa María Ixcatlán. Photo credit for A, B, and E: Selene Rangel-Landa; C and F: Ignacio Torres-García; D: Erandi Rivera Lozoya.

Some renowned uses are those related with ritual and religious practices. When a person dies, the Nahua from Guerrero and the *Xwja* from Oaxaca weave *huaraches* (a kind of sandal) which the deceased person wears [20,28]. They believe that these sandals help the person to overcome the obstacles on their way to the afterlife [28]. The *Hñä hñü* people from Hidalgo weave a headpiece with palm in the form of a crown that bears a small cross; a story of the village tradition says that when a deceased man reached heaven, San Pedro asked him why he arrived in heaven with his head uncovered. The man then returned to earth to tell people that they must be buried with a headpiece [41]. Religious practices also include palm-woven pieces related to dances and *ramo*, a floral arrangement used during Easter which is blessed in a religious ceremony and provides protection. This is placed behind the front door of the house for protection by driving away bad spirits, and it is believed that when there is a storm or other strong atmospheric event, the burning of the *ramo* will bring calm (Zapotitlán Salinas, Puebla). In Santa María Ixcatlán, Oaxaca, the elders say that the ceremony of blessing the palm represents the sacrifices and the life of Christ. It is also a ritual praying for the palm and the woods, so that there is rain and they do not lose what nature gives. Palm leaves are also used with other plants in rituals known as *limpias* (healing ritual). This is because the palm is considered a purified plant and is used to heal people suffering from cultural diseases. It is also used in pre-Hispanic dances to summon rain or when asking for a good harvest season [28]; the entire palm is used as religious ornament in Zapotitlán Salinas, Puebla, and Huitziltepec, Guerrero during Holy Week (Semana Santa in Mexico) to decorate churches.

The weaving of objects for self-consumption, sale, or exchange also plays an important cultural role (Figure 3). For those weavers who have the possibility to move to commercial centers, the market is used to exchange products and obtain money [54]. *Brahea dulcis* is strongly traded in traditional markets across Central Mexico, such as Chilapa, Tulcingo and Tlapa, Guerrero) [55–57], Sahuayo, Michoacán [41], Ajalpan, Coxcatlán, Tehuacán, and Zinacantepec, Puebla and Cuicatlán, Huajuapan and Teotitlán del Camino, Oaxaca. Permanent transportation of palm leaves takes place via trucks, and therefore leaf pickers, handlers, handcrafters, and sellers are involved in commercial activities [20,58,59].

Hat production persists as an important economic activity [20,28,37], whereas other palm products are falling into disuse, likely as a result of precarious market conditions and decreasing demand. A decrease in the use of *B. dulcis* for thatching houses has been reported for the region of La Montaña de Guerrero [28,56]. In other places, roofing is already in disuse, such as in the region of La Huasteca [41]. In the region called La Meseta Purhépecha in the state of Michoacán, as well as in La Huasteca, the production of raincoats made of *B. dulcis* leaves, named *capote*, fell into disuse due to the introduction of plastic raincoats [41,60]. In the latter region, only older people are dedicated to palm weaving; young people have shown an increasing disinterest in learning palm weaving given that it is undervalued and poorly paid work [41]. According to people from Zapotitlán Salinas, Puebla, many domestic and agricultural uses of palm have been lost due to the introduction of plastic objects, which have replaced many utensils and tools previously obtained through palm weaving. The *zazca* (a large woven palm basket case for storing maize) and the *pishcalon* (a woven palm tool for cutting cobs) were utensils used in agriculture, as were the *cachache* for containing beans during their harvesting, and the *temposha*, a woven mask for preventing bulls from eating the green leaves of the milpa during agricultural labor (Table 1). As plastic objects started becoming available, they replaced palm utensils and progressively displaced them. Today, most agricultural needs are covered by plastic objects, and palm weaving persists as an activity which is mainly related to handcraft manufacture and commercialization.

The replacement of *B. dulcis* fiber by plastic strips for weaving is notorious in some regions. In the

Tehuacán-Cuicatlán Biosphere Reserve, people recognize that *fibra* (as they named the polypropylene strip) is preferred by consumers because it lasts longer and can get wet without becoming spoiled. Furthermore, locals mentioned that what they like to weave is palm. In this biosphere reserve, the replacement of palm crafts by such plastic materials has caused the gradual decrease of the traditional management of palms [36]. Nevertheless, it appears that palm weaving is far from disappearing. This activity remains relevant because of its economic importance. Income from the sale of woven objects is often the only monetary income, or woven items are bartered for food in local stores in numerous rural communities [20,28,37,61–63]. Weaving is done during spare time and while performing other activities, such as taking care of elders and children, and attending community assemblies. As it does not overlap with other productive activities, it is possible to maintain the activity despite its low economic return. Groups of people weave palm together in the early evening, when they have all concluded their day-labor. It is a kind of social activity, allowing conversation while working. There is renewed interest in making small handcrafts such as earrings and thumbnails.

These objects require less palm fiber but demand a greater investment of time for artisans, and their prices—in spite of being better than those received for the sale of traditional objects such as hats, *petates*, or *tenates*—are low considering the time invested, given that they require special labor time, since their elaboration requires more concentration than other traditional objects: in the artisans' words, they need to "sentarse a tejer" (sit down to weave), while traditional product weaving can be performed simultaneously with other activities, even while walking. Although the demands for earrings and thumbnails are low, there are organizational experiences in training and selling these products, such as the conformation of collective brands of palm products such as "Palmart's" [64] and "XULA Palma Artesanal" [65], which have reached national and even international markets by way of the Internet

Economic Triggers

During the first half of the 20th century, the palm weavers of the region of La Mixteca received a daily income that did not exceed US$0.06 [66] ($0.16 Mexican pesos, based on an exchange rate of $3.60 Mexican pesos per US dollar). For the elaboration of a palm hat, the most highly demanded woven article, an adult weaver could require 12 h of work to weave 3–4 hats, for which they received US$0.08, from which they still had to subtract the cost of raw material. One hundred young palm leaves were priced at US$0.24 on average, which was enough to produce 12–18 hats. Therefore, *Ñuu savi* weavers had a net income of about US$0.02 for 12 hours of work [67]. Hat production was concentrated in regional markets and then distributed to companies that selected, bleached, and finished the hats for their later sale either in the country or abroad [52].

In recent years, one dozen ordinary palm hats or "en greña" (in the rough) cost US$0.8 (based on a modern exchange rate of $20.00 Mexican pesos per US dollar) [66]. From 2011 to 2015, the price paid for one hat was US$0.16 (US$1.92 per dozen), and they were then moved to industrial plants where they are cut, dried, bleached, sewn, and ironed, increasing their price value by up to 1000% [58]. Although this low return has not changed for decades, the weaving and selling of palm objects continues since it is the most important or the only source of monetary income for numerous rural households—income that pays off food and other products not produced by the families [20,28,57,61,68]. In 2001, it was estimated that palm was an essential economic source complement for more than 50,000 peasant families of Mexico [51]. During this year, in the locality of Santa María Ixcatlán, Oaxaca, the price for one hat—that takes around three hours of work—was US$0.33 (based on an exchange rate of $12.00 Mexican pesos per US dollar). Despite monetary compensation for this activity being inequitable, the sale of these objects has provided crucial economic income for sustaining families since early colonial times [69].

The trading of palm leaves between localities is important for sustaining palm weaving at the regional level. *B. dulcis* is not equally available in all palm weaving-dependent rural communities. These communities—for instance, San Luis Atolotitlán in Puebla—are supplied by regional hoarders who periodically visit the rural localities [62]. One way in which these hoarders obtain the leaves is by exchanging products such as wheat, maize, or fruits, for palm leaves with harvesters in towns where *B. dulcis* is abundant, as is the case in Santa María Ixcatlán, Oaxaca [20].

Brahea dulcis Traditional Management

Traditional management refers to several non-modern man-made practices conducted at several scales of social organization to enhance the availability of natural resources. The following practices are regarded as traditional—each is related to one category of management (gathering, toleration, protection, promotion, cultivation) [2], and holds a particular purpose—these practices also entail ecological implications that have spatial outcomes (Table 2 and Figure 4).

Gathering

Gathering involves the harvesting of fruits, stems, foliar bracts, and leaves. Here, we refer to the harvesting of young and mature leaves, given that this is the most economically relevant palm product and the best-documented activity. In the case of young leaves or *cogollos*, the annual frequency of harvesting events can range from one to eight, or even every week. The gathering can be conducted by people that both harvest and weave the palm leaves, but there are people that only harvest leaves to sell them [44,61]. This is usually carried out by family leaders, frequently men, as the main activity of a journey, or practiced opportunistically during other activities, such as firewood gathering or pastoralism practices [20]. Although harvesting is possible throughout the whole year [61,62], people in some communities prefer to harvest palm during the wet season because young palm leaves, which are softer and easier to handle, are more abundant than compared to during the dry season [57]. Harvesting and weaving are also related with patterns of production, occupation, and necessities. During the dry season, agricultural activities are less demanding, and people can spend more time gathering palm and weaving [20]; people can also dedicate more time to these activities when there is a special need for monetary income, as is the case when there are bad years for agriculture and production is low.

Decisions and even regulations about when to carry out the gathering of palm leaves are based on moon cycles, which are related to leaf quality and duration, as similarly reported for other palm species [9,12]. There is a consensus in preferring the crescent moon until a few days after the full moon for harvesting; it is believed that, in this way, the palm and production of leaves is not negatively affected, and otherwise leaves are prone to being eaten by insects, becoming fragile and rotting because of excessive water [5]. In some communities, if this criterion is not respected, people can be penalized [62].

Palm leaf extraction is mainly practiced in agricultural areas where palms have been left standing and in palm stands—most probably a secondary vegetation derived from management [37,62]. Harvesting can occur at distant sites from human settlements where *B. dulcis* is found in natural vegetation, secondary forests, and pasture lands [41,44,62,70]. Harvesting on low-stature individual palms is oriented toward larger and immature leaves, while in arboreal palms, this is oriented to mature leaves, foliar bracts and fruits. There is little information related to the time invested in transfers to harvesting sites. In the documented records, transfer times can range from 15 min to 14 h [44], which translates to a ~400 m to 21 km round trip. The harvesting of young and mature leaves is conducted without felling the palm, and it is socially agreed that felling should not be practiced unless planning to use the entire palm or stem; it is frowned upon to do otherwise [70]. The harvesting of small individuals is conducted with a machete (bowie knife), and taller ones are harvested with a purpose-made cutting tool, which is a stick (that can be from *Arundo donax* L.) with a blade on its tip; people also use this tool to make incisions on the stem like steps of a staircase, making it easier to climb the palm and reach the leaves. Harvesting consists of cutting mature or young leaves that have not yet unfolded and cutting is done with care to avoid harming the new leaf buds [20]. Valderrama et al. [44] recorded average harvest intensities of 471 leaves per harvest event, with a range of 200–600 leaves, and Casas et al. [58] estimated gathering ranges between 300–400 *cogollos* per day of labor.

Constant Harvesting

This practice is related to the maintenance of low-stature individuals, growth retardation of the stem, and an increase in vegetative propagation. Continuous pruning stimulates the increasing availability of stem and leaf buds for harvest from *manchoneras* [37]. A *Hñä hñü* harvester from Guerrero mentioned that "it is necessary to harvest constantly the leaves in order to avoid stiffness so that leaves can be used for selling" [44]. Nevertheless, peasants associate constant harvesting with a reduction in leaf size [37,55], which is an unwanted consequence given that the availability of larger leaves is reduced. In the case of *soyacahuiteras*, the harvesting of leaf buds is never practiced in some localities for these reasons (Restrained harvesting on Figure 4) [37]; this is a topic that demands further research due to the lack of conclusive information [55,63]. On these palm stands, harvesting is oriented toward extracting primarily dry leaves and foliar bracts, and practices that could risk the permanence of these resources are avoided [28,37].

Table 2. *Brahea dulcis* management implications.

			Purposes	Ecological Implications	Spatial Implications	Spatial Outcome
Management practices	**Harvest**	*Intensive*	Promotion of small stature individuals and increase vegetative propagation	Promotion of colonial life habits with same genetic information (ramets), small stature and short leaves	Promotion of palm stands with accelerated vegetative propagation of colonial life habit, which can cover areas of different sizes	***Manchonera***
		Restrained	Maintain high stature individuals and sexual propagation	Maintain individual life habits and promotes genetic diversity	Promotion of palm stands of high stature individuals, which can cover areas of different sizes	***Soyacahuitera***
	Tolerance	*Selective felling*	Leave useful palm individuals standing	Palm individuals can benefit from elimination of competition	When lands left under rest or abandoned, palm individuals can easily propagate and cover cleared areas	**Propagation** of palms to abandoned areas
	Promotion	*Burning*	If incidental, reduces plant competition by non-fire resistant species	Palm propagation by regrowth of resistant individuals	Burned areas prone to be covered by palm stands resulting of palm fire resistance and elimination of competition	**Propagation** of palms to burned areas
		Cleaning	Stimulate growth and increase productivity	Improves individual's fitness	-	-
		Weeding	Eliminate competition and promote nutrients reassignment	Improves individual's fitness	May prevent the growth of palm stands by removing seedlings	**Deceleration** of palm stand growth
		Grounding	Improve substrate conditions	Improves individual's conditions	-	-
	Protection	*Harvest restriction*	Control harvesting	Prevention of over-harvesting	May prevent the expansion of palm stands by controlling harvest intensity	**Preservation** of certain areas or places
		Prohibitions	Regulate periods and places of extraction	Prevention of over-harvesting and protection of particular places	Some places may be under protection regulations in order to conserve them	
		Nature observation	Respect natural cycles	Collective benefit by understanding of management impacts	-	-
	Cultivation	*Transplanting or sowing*	Ornamental purposes	Palms presence beyond its natural dispersion limits	It could conform large areas under cultivation if were intensively sowing or transplanted	**Conversion** of natural places to crops *

* Not seen. Bold: emphasize.

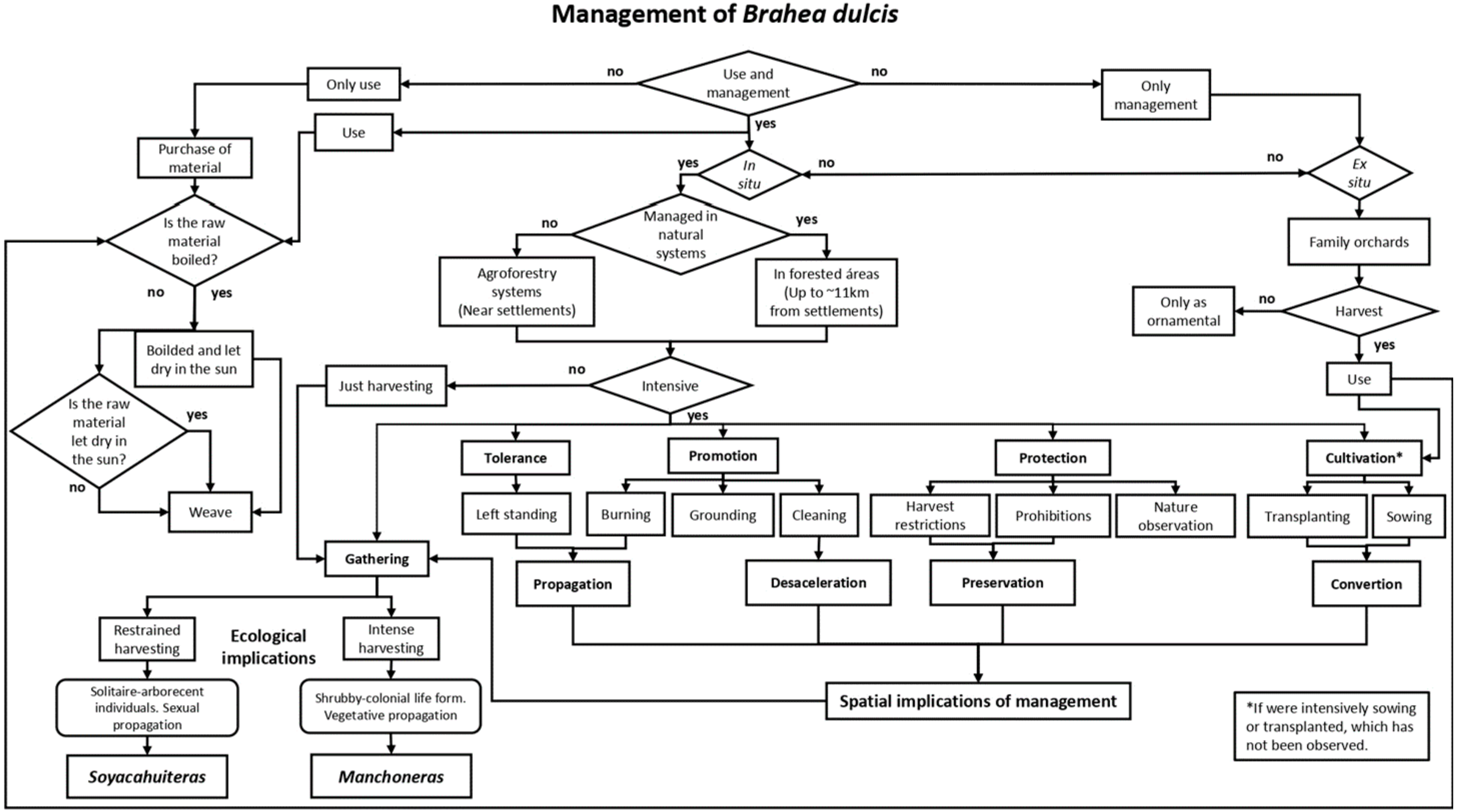

Figure 4. *Brahea dulcis* management flowchart.

Selective Felling

This activity refers to the act of letting certain valued plants stand when clearing a vegetation area and removing plants that are not useful. When land is cleared for farming in agroforestry systems in numerous regions of Mexico, the usual practice is that useful trees are kept standing [71–74]. This practice has been reported for palm species in northern and southern Mexico, as is the case for several species of *Sabal* and *B. dulcis* [20,22,29]. On plots cleared for cultivation where *B. dulcis* individuals are maintained, these benefit from management practices dedicated to the care of the *milpa* (traditional Mesoamerican polyculture of maize, beans, squashes and other species) [28,37]. The main reason for leaving the palm standing is because of its use and the strength of the roots affixed to the soil [37]. Letting palms stand can allow the initiation of a new palm stand; the elimination of shading and competition with other plants allows the palm to spread on the farmland during fallow periods [28].

Burning Practices

The practice of burning an area is related to agricultural activities. Fire events may not be incidentally used for the benefit of palms but may involuntarily promote palm dominance given the fire resistance of *B. dulcis* [28]. It also has been proposed that palm stands of this species in La Mixteca are a product of deliberate fire and extensive livestock [1,58,75,76]. Involuntary promotion of this palm can derive from burning as a common practice in slash-and-burn agriculture. These induced fires damage most herbs, shrubs, and trees and are the reason why a Nahua user from Guerrero said "when the mountain burns, the other season is full of palm" [28], as palm leaves burnt by fires fall out and sprout anew. Fire use is avoided in the *soyacahuiteras* from La Montaña de Guerrero region, since these can easily be affected or destroyed [20,55]; also, fire was recorded to accidentally benefit *manchoneras* palm groves in this region [37,55]. Uncommonly, some people rely upon burning areas within their plots to eliminate dry leaves and herbs around palms.

Practices of Special Care

There are some management practices targeted towards improving palm development. Cleaning consists of removing dry leaves from the stem. According to Illsley et al. [37], this will prevent leaves from becoming a shadow for the scarce rain on these regions, allowing humidity to reach the root area. The dry material is then minced and left at the base of the stems, helping the plant to conserve moisture and returning nutrients to the soil, which favors stem growth. Tiller thinning or *deshije* consists of removing vegetative shoots in order to reduce competition for resources. This also promotes nutrient reassignment and results in increased stem growth and foliar production. This practice also includes weeding for maintaining monospecific stands [55]. Another important management practice consists of improving soil conditions for palms by bringing soil from other places, which is named "arrime de tierra", or grounding. This practice, as well as sowing, is only carried out in orchards, home gardens, or on newly open farming lands [37].

Social Organization and Regulations related to Palm Use

In indigenous localities, where land is conceived and legally sustained as social property, it is common that all community members have equal rights to access resources in the communitarian territory, but decisions related to land use rights are discussed and defined in communitarian assemblies; thus, management is carried out based upon customs and traditions (uses and practices are regulated by communities as traditional forms of appropriating resources). In Santa María Ixcatlán, Oaxaca, all members of the community have the right to harvest leaves for their own use; commercialization of palm leaves is allowed between community members. In this way, palm can be purchased by people who cannot harvest palm themselves, such as the elderly and sick people who need to weave the palm to survive. People who arrive from other places offering products or merchandise—such as fruit, maize, wheat, clothing, and home utensils—can receive payment through barter with palm leaves [20]. In some communities, the harvesting of palm leaves to sell outside the community is prohibited as a precautionary regulation [61]. In localities where there is a regime of land tenure for small landowners, the owner of the plot and their family are the only ones allowed to access the resources, but can establish selling or interchange agreements, or even freely allow people to make use of resources inside their property [37].

Rules may vary among communities but are oriented to avoid contested situations. If there is a decrease in arborescent palms from which dry leaves are harvested, rules and actions are agreed upon to favor the presence of these palms, such as not allowing the cutting of stem and leaf buds or extracting foliar bracts. There are also implicit rules that are transmitted intergenerationally and are respected because not doing so is socially frowned upon. These include not cutting the palm stem, careful harvesting to avoid damaging the apical meristem and compromising palm welfare, and not harvesting more leaves than necessary [20]. Issues related to respecting moon cycles for harvesting are sometimes implicitly followed, but if these are not respected in some localities, may result in economic sanctions [62]. In Hidalgo, some *Hñä hñü* communities believe that palms do not need special care, given that they grow on their own, and it is only necessary to harvest them so they do not become "stiff" and can keep producing good-quality leaves.

Ecological and Ecogeographical Implications of Management

The constant palm management has impacted ecological aspects such as species phenotypes, abundance, distribution and sympatric biodiversity. As these processes are derived from dynamic interactions with other species and may be related to the plant response to environmental factors, which affects their abundance and distribution, they can be defined as ecological [77]; however, since management practices are performed in a geographical space, there is also a spatial dimension of the ecological implications (Figure 4), which have their clearest imprint at the landscape level.

Ecological Implications at Population and Community Levels

According to Quero [38], the *Brahea* genus population has increased in abundance despite its intensive management. The phenotypic plasticity of this species allows it to respond to intense harvesting by developing a colonial life habit that can hold up to 22 stems covering areas of 24 m^2 [78]. This clonal spreading appears to facilitate resource uptake in modified ecosystems and the rapid clonal propagation of seedlings [79]. The hybridization of *B. dulcis* with other species of this genus, such as *B. calcarea,* is another factor that increases morphological variability [80]. Extensive palm stands of *soyate* have been documented for several regions of Central Mexico [37,58,59].

Leaf production varies widely and is apparently little affected by harvesting [41,55,56]. The annual leaf production per individual is in the range of 5–20 leaves [36,37,61]. Pulido et al. [41] compared leaf production amongst the different arborescent palms of the Americas and showed that *B. dulcis* had the highest leaf-production rate. According to previous studies of the authors, *B. dulcis* produces numerous leaves within a relatively short lifespan, making it ideal for management and harvesting. During one-year studies [36,41], the harvesting of *B. dulcis* did not show significant effects on individuals and the population death rate. In most studied cases, leaf harvest has not been shown to have a significant impact on palm leaf production or the demographic parameters of *B. dulcis.* This is a similar pattern as that found for other palm species used in Mexico, such as *Sabal mexicana* and *S. yapa* [40]; although for *B. dulcis,* peasants had observed a decrease in the height of individuals which is associated with leaf size reduction [37,56,57]. The leaf harvest and management practices of *B. dulcis* have an important influence on plant morphology and in maintaining a reservoir of genetic diversity. Management has derived stands of secondary origin with a high abundance of palm known as *palmares*. In several locations, people reported the recognition of two types of palm groves; given the sharp difference between the two phenotypes, it was first believed that they corresponded to two variants of *B. dulcis* [73], when in fact they are two morphs of the species [81], apparently derived from the manipulation of phenotypic plasticity by centuries of management [28,37]. This is supported by recent studies that found a significant and negative effect on adult palm height derived from leaf harvesting [79], and have been registered in several places of central-southern Mexico [37,41,44,55,56,61,70].

These two palm groves are distinguished by differences in height, propagation, and developed life habits (Figure 2). Low-growing palms stands of about 1.5 m tall, reproduce predominantly by vegetative propagation and are characterized by caespitose growth-forming colonies known as *manchoneras* [37]. Leaf buds are intensively harvested from this kind of palm stand and elaborated into hats and diverse utensils (Table 1). The constant cutting of leaf buds maintains the low size of these palms and promotes the growth of several stems of small size, which facilitates harvesting and confers a shrubby appearance (*manchoneras* on Figure 4).

Stands dominated by palms of more than 6 m in height are known as *soyacahuiteras*. These are characterized by vigorous sexual reproduction and solitary growth habits. This kind of palm grove is maintained mainly for harvesting foliar bracts, fruits, and mature leaves. These leaves are used for thatching traditional roofs of houses. Foliar bracts are used for the manufacture of a special cushion for loading donkeys in different parts of La Montaña and the Tehuacán-Cuicatlán Biosphere Reserve. Fruits are eaten as candy [20]. Palm groves made by these two *B. dulcis* morphs are subjected to different management practices according to what is needed to maintain their characteristics and, through management, a *manchonera* can grow into a *soyacahuitera* [37]—a process recently documented in San Francisco Cotahuixtla, Oaxaca [47].

Other effects of palm management on ecosystems have been little studied or described, such as the effects of the management of palm groves on biodiversity. Although the promotion of *B. dulcis* on natural vegetation derives from biodiversity loss, there is a substantial proportion of plant diversity maintained within palm groves, which is not retained in conventional crops. In Santa María Ixcatlán, the surrounding natural vegetation in which the palm is naturally distributed has recorded diversity values of H = 1.516 for the *Mexical* [3], a kind of *Quercus* scrubland; H = 1.47 for a *Quercus* forest; and H = 1.28 in a *Juniperus flaccida* forest, while palm groves retained a diversity of H = 0.827 [20].

Ecogeographical Implications

The management of palms occurs in forest, agroforestry or agricultural areas. It is common to find palm individuals used as living fences, terrace borders, or deliberately left standing in agroforestry systems of Mexico, given that they are appreciated for their fruits and leaves [71]. Palm management is also carried out in forest areas, where management practices have the potential to influence and transform plant communities, resulting in important modifications to plant distribution, population, and diversity parameters at the landscape level [81]. These plant formations in which *B. dulcis* is the dominant floristic element are believed to be deliberate human-made stands derived from management or disturbance, particularly from induced fires and the clearing of vegetation for agriculture. This is supported by recent studies that found that management has a significant and positive e*ff*ect on palm density on managed stands where fire routines are performed, which is associated with slash-and-burn agriculture [79]. The *B. dulcis* management flowchart (Figure 4) indicates those management practices associated to spatial outcomes. The action of palms left standing on cleared or abandoned lands can set the mark for palm individuals to facilitate their propagation [28].

Erosion also plays a part in palm grove establishment. *Brahea dulcis* is highly tolerant to soil erosion and degraded environmental conditions, so it can be easily established and can endure on abandoned farmlands and deteriorated terrain [61,62]. The people from the La Montaña de Guerrero region who manage the palm commented that *soyate* is resilient to the cutting o*ff* of leaves, sprouts and stalk. Even then, the plants produce shoots for up to ten years. It sprouts very well after fire: "it endures the trampling and browse of animals, and endure[s] the drought" [38]. As a plant that is left standing when clearing for agriculture, when the land is fallow, *B. dulcis* freely propagates on these open lands [5]. On forested areas some people promote the propagation of the species by deliberate fires such as in the case of La Montaña [55,56] and La Mixteca regions [58]. As a fire-resistant species, slash-and-burn practices and the deliberate burning of natural vegetation can promote *soyate* palm distribution and density by increasing areas for colonization, reducing competition, and fostering an increase of recruitment through sexual and asexual mechanisms [79]. Quero [38] states that *Brahea dulcis* stands are favored by anthropic disturbance and increased populations of this species. On the other hand, there are certain practices that avoid palm stand expansion. The cleaning of tillers and harvesting restriction and prohibition acts as decelerators of palm stand growth by regulating the presence and development of o*ff*shoots, as well as by regulating places, periods and intensities of extraction. All the management practices have spatial implications that differ in their outcomes (Figure 4). Palm stands of *Brahea dulcis* are commonly found in the upper Papaloapan Basin, Central Chiapas, and the state of Oaxaca State (at southern Mexico), Barranca de Metztitlán, Hidalgo, the Tehuacán-Cuicatlán region, the Balsas river basin (central Mexico) and from the mountain range Sierra Madre Oriental to the southern Tamaulipas State (northeastern Mexico) [3,41,75,76].

Discussion and Concluding Remarks

Traditional Management: Insights for Sustainability

Brahea dulcis ought to be regarded as the palm species with most widespread cultural relevance in arid to sub-humid regions in Mexico. The cultural and economic importance of *soyate* palm, as other traditionally managed resources, has been developed through generations of interactions [82]. Since management is place-based, it has triggered an intermingling of ecological and cultural landscape configurations. Currently, management practices reported for *Brahea dulcis* in the country include all forms reported by Gonzalez-Insuasti et al. [2], such as gathering (selective harvesting), toleration (leaving standing), propagation (the promotion of vegetative reproduction through pruning and burning), protection (cleaning, grounding, weeding, social conventions), and cultivation (ex situ planting on family gardens). This is a gradient of management intensity that does not resemble steps of a sequence and does not exclude them from each other [1]. They conform to a broad spectrum of management that is implemented at different intensities, which varies regarding the degree of sophistication, number of people involved, and number of management practices performed, which relates to its ecological and cultural importance [2]. Based upon the ecological adaptations, it is here stated that *soyate* palm might be harvested sustainably as a profitable resource [53]. Nevertheless, over-harvesting must be carefully avoided since it could result in a decreased leaf size, which has implications for its use, given that certain leaf sizes are needed for specific resource uses [37,55]. Studies must be oriented to define thresholds of harvest, in order to define harvesting dynamics that can ensure the maintenance of an optimal leaf size [45]. *Soyate*'s traditional management promotes sufficiently frequent seedling recruitment of different genotypes, thus maintaining high genetic diversity. The renewal of palm individuals by slash-and-burn events may even enhance genetic diversity, which indicates that current traditional management practices on these sites may not only preserve the resource, but also its capacity to cope with environmental changes [79].

The high number and effective management practices relating to *Brahea dulcis* use (Table 2) are particularly outstanding when compared to other palms of South America. According to a recent review by Bernal et al. [83], at least 22% of used palm species have no record of management, 55% are subject to one or two, and only 7% of palm species are subject to five to eight management practices. *Brahea dulcis* management involves sophisticated practices that integrate social organization and nature observation; unsustainable practices have been avoided by respecting natural cycles and precluding unnecessary damage, such as the felling of the tree palms, which has been reported in South America for the harvesting of palm leaves and fruits of *Astrocaryum chambira*, *A. standleyanum*, *Aphandra natalia*, *Mauritia flexuosa,* and *Oenocarpus bataua* [83]. Furthermore, practices benefit *B. dulcis* by promoting resource availability and competition elimination, which results in increased palm density [28,37] and also the permanence of palm stands [36,72]; however, information relating to the impact of palm stand promotion on loss of biodiversity must still be assessed, since the dynamics of accumulation of organic matter, nutrient cycling, and soil maintenance are drastically altered in palm stands with respect to primary vegetation. Effects on soil and hydric dynamics in palm groves that are still poorly known need to be assessed. Despite the relevance of *Soyate*, a further assessment of other palm species in Mexico is needed, such as for the *Sabal* species which represents an outstanding resource in the warm and humid regions of southeastern Mexico [29,39,40].

From the ten recorded management practices, at least six imprint landscape configurations (Figure 4). Selective felling and burning is related with the propagation of palms stands, resulting in the opening of new palm areas or the expansion of established palm stands; weeding is related to the deceleration of palm stand expansion due to the control of vegetative growth; preservation of certain areas due to protection is carried out by social organization of users who have constructed harvesting restrictions or prohibitions in particular places; and although these are not yet seen, the massive transplanting of palms or sowing in certain areas could lead to the total conversion of natural places to croplands. Thus, use and management may have a profound influence on palm attributes and distribution. Selective felling, slash-and-burning, weeding, protection of certain areas, and the massive transplanting of palms are distinguished as the most relevant ways to transform the region into a cultural–natural mosaic landscape. We state that the recognition of spatial implications of these practices is necessary to assess the impacts and benefits of management, given that socio-economic and environmental pressures can trigger palm stand expansion [1,29,84]. Long-term trends are yet to be ascertained, and so far, they have been difficult to unravel since socio-economic drivers are changing constantly [38]. The authors strongly argue that land use planning must be oriented towards regulating and preventing the expansion of *soyate* palm stands. This is especially important to reduce the impact upon other native—and highly biodiverse—vegetation types, which are often diminished and disturbed to favor *palmares*. If the creation of new palms stands is necessary, this could be promoted on degraded sites and under situations of degraded soil, where the palm could play an important role in preventing increased soil erosion [55,56]. According to managers of this species, the *soyate* palm plays an important role as a pioneer plant in successional processes, and its (fascicular) roots favor its ability for trapping soil and prevents its erosion [41,55]; it also favors the formation of organic matter and help in microclimate improvement for the establishment of other plant species [79].

Although the concept of space is implicit in traditional management, the way this interacts has been largely overseen despite the broad-scale implications of historical human behavior patterns relating to in situ resource management [85,86]. In Mesoamerican ethnical groups, as in most other ancient cultural regions, people integrally manage their territories. In our study, a special focus on the landscape level proved to be useful to understand the man–nature relationship as a baseline for setting sustainable management [85,87,88]. Hence, precise traditional management practices, performed at local scales, (dis)favor the occurrence of certain phenotypes or species with important implications at the landscape level [89]. Wide-ranging practices, in order to increase the relative abundance of certain species at the expense of others, may result in large-scale patterns of transformation, which have been termed cultural niche construction [90] and landscape domestication [85,91]. These transformations of natural spaces are inherited among human groups in the form of ecological-and hence geographic- inheritance [92], and the permanence of transformed spaces is accomplished by the continuity of management practices through time.

Understanding the dynamics of the traditional management of non-timber forest products is complex because several factors are involved. In Figure 4, we propose a general view of the management of *B. dulcis*. The flowchart shows the set of decisions that are made relating to this resource, displaying actions that are translated to specific outcomes. The degree of participation and intensity of management depends on the involvement or not of managing actions. Some people only use the resources; thus, they do not actively participate in actions that benefit or drawback the resource or the natural context of it, so they may be unaware of harvesting actions that are detrimental. On the other hand, people that are actively involved in management make deliberate decisions to derive certain resources (e.g., the managing of a *soyacahuitera*) or to reach certain purposes (e.g., promotion), and some of these actions have explicit spatial outcomes (e.g., propagation of palm stands) while others do not. These management actions also occur in different contexts (agroforestry systems and forest areas), and consequences of management will differ among them. For the case of *soyate* palm, attention should be paid to practices that involve spatial outcomes on forest areas, given that natural vegetation may be eliminated as a consequence of palm stand propagation. A balance of the benefits and harms of this should be estimated before any actions are taken.

(Un)weaving a Sustainable Future

Despite the multidimensional relevance of *B. dulcis*, the trend of disuse of activities and products has been driven by the introduction of plastic and tools that replaced palm-woven objects [28,33,41]. In addition, this trend of disuse grows due to the low remuneration that weavers can expect from their work. As a result, young indigenous people become disengaged from learning this activity and focus on searching for better life opportunities outside their communities [36]. This, in many cases, implies permanent migration and family fragmentation, and the abandonment of agricultural activities with important repercussions for basic and sensitive subjects, such as the endangerment of self-supported food systems and community disarticulation [93,94]. Another discouraging issue concerns palm harvesting regulation established in the NOM-007-RECNAT-1997 (Mexican normativity that regulates the extraction of plant parts). Regional authorities regulate palm leaf harvesting through extraction licenses that are expensive and difficult to obtain, which prevents the accessibility of many people to legal extraction. Some authors state that regulations are enforced in an excessive way given that demographic studies have demonstrated that palm leaf production can endure harvesting [36,63], and through management, the genotypic diversity is maintained [79]. The revision of the current normativity on palm use is necessary in order that the imposed regulations are founded upon scientific studies and oriented toward protecting resources and the involved human groups.

Further Research

Ecological features are insufficient to depict the sustainable management implications of the *soyate* palm. Socio-economic, cultural, ecological and geographical factors need to be regarded holistically to eventually develop a sound sustainable management scenario for the *B. dulcis* socioecological system. On the socio-economic side, this represents an essential part for thousands of rural families—in some cases, as the only way to gain monetary income and as a currency in communities where income is limited [20,28,68]. On the cultural side, it participates as an important part of ceremonial and religious events of spiritual significance; moreover, it is considered as a substance that sustains day by day: it strengthens the cultural identity of people by the continual practice of shared activities and knowledge,which bonds people with their ancestors and roots people to their territory [95]. It serves as a means of family integration, promoting intergenerational links through the process of teaching and weaving, and of intercultural recognition and social articulation through commercialization as a process that unites and reinforces "community identity" [95,96]. Ecological and geographical aspects have been thoroughly explained before. We regard our contribution as an effort to set a baseline for further practice which may eventually drive traditional *soyate* management into a sustainable program.

Five research lines have been considered as critical for favoring the sustainable management of *B dulcis* and its habitat. Participatory communication should be encouraged to engage stakeholders into constructive packs and agreements to set and implement regulations and rules for sustainable management. Attention may be focused on the spatial implications of management and disturbing actions as well as on soil erosion, soil fertility, sympatric biodiversity and hydrological dynamics. Also, the geographical determination of current palm groves and the evaluation of factors linked to their presence can support estimations of future conditions, as well as the extent and distribution of palm stands. A holistic socio-economic, cultural, ecological and geographical scientific approach for *B. dulcis* management and its habitat should be encouraged to understand its role as an umbrella species for the sustainable management of non-timber forest products. Actions must depart from comprising economic benefits to peasant communities while promoting ecosystem conservation. A fair appreciation of palm weaving should be fostered, in which products must be regarded as social and environmentally sound products. Palm products, contrary to plastic ones, have a low carbon footprint, enhance cultural identity and reinforce the long-term conservation of environmental services. It is important to acknowledge that palm-weaving techniques represent knowledge built through generations, beginning in antiquity; technique innovation and product diversification have permitted their continual use until the present. For that reason, palm objects are a repository of knowledge and of cultural value. Regional-scale studies in order to understand the heterogeneity of management across ethnical groups and landscapes should be conducted. Proximal and underlying triggers and drivers of management must be identified in order to favor sound regional sustainable management, so that one human settlement does not jeopardize the neighbor's activity. This is especially relevant to gain insight into the different management strategies and to avoid contested situations within the cultural mosaic comprised in the region, including Central America. Finally, researchers should review and document the historical importance and ecogeographic inheritance of *Brahea dulcis* management based upon codices and archives. Oral and empirical sources of information suggest the long-standing tradition of *soyate* management in precolonial times [97]. This information is needed to reveal the historical and cultural importance of non-timber products in large parts of Mesoamerica and other regions worldwide.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/12/1/412/s1. Supplementary File S1: Bibliographic query results. Supplementary File S2: Mexican palm species and their uses; updated list of *Arecaceae* species native to Mexico categories and parts used of Mexican palms. Supplementary File S3: Palm parts used and weave objects.

Author Contributions: C.X.P.-V. was the leading author who conducted all of the research as part of her PhD studies; she further contributed to the systematization, data analysis, and writing of this paper. A.I.M.-C. suggested the elaboration and structure of the present manuscript; jointly with A.V. they are PhD advisors, and constantly guided the research and reviewed the manuscript. S.R.-L., J.B., J.C. and A.C. have been working with Brahea dulcis in ethnobiological, ecological, cultural and conservations initiatives for over 20 years; they also revised, commented on, and improved the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: The first author acknowledges CONACYT for their support with a PhD scholarship, the PAEP program for the economic support for fieldwork received through the Centro de Investigaciones en Geografía Ambiental, UNAM. To the DGAPA-UNAM for supporting the PAPIIT IN200417 project and CONACyT for financial support of the project A1-S-14306. This study is part of ongoing research of the thematic network of the Non-timber Forest Product Network (Spanish acronym, RPFNM) of CONACyT.

Acknowledgments: The author thanks Biol. Fernando Reyes, director of the Tehuacán-Cuicatlán Biosphere Reserve for all the support granted for the ongoing research in the reserve relating to *Brahea dulcis* management. Thanks go to all the people who kindly shared their knowledge, and especially Maurino Reyes from Zapotitlán Salinas Puebla for his tireless work as a promoter of the natural and cultural heritage of his region, and to Ignacio García-Torres and L.C.A. Erandi Rivera-Lozoya for sharing their photographic work for this document. We finally thank Base de Datos Etnobotánicos de Plantas Mexicanas, Jardín Botánico, Instituto de Biología, UNAM (BADEPLAM) and the biologist Laura Cortés Zárraga, for sharing information regarding palm use in Mexico. Final English editing was conducted under the guidance of the service provided by the present journal support system and the Academic Writing Office (Susana Kolb) of UNAM.

Conflicts of Interest: The authors declare no conflict of interest.

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Suplementary Material S1

Bibliographic Query

A total of 23 documents were found referring to the management of *B. dulcis* (Table 1); they cover a time span of 25 years (from 1994 to the present). From these, 11 documents were the result of the first bibliographic search, the rest were accessed by consulting bachelor thesis databases, author specific search and direct request of technical reports.

Table 1. Result of bibliographic query relating Brahea dulcis management.

ID	Authors	Study Region	Topic	Common Name
(Casas et al., 1994)	Casas et al. 1994	La Mixteca region	Ethnobotany importance, use, commercialization	Palma
(Sánchez-Díaz, 1998)	Sanchez-Díaz 1994	La Meseta Purhépecha, Michoacán	Use, weave objects and economic aspects	Palma abanico, palma dulce, palma sombrero
(J. G. Aguilar, 1996)	Aguilar et al. 1996	La Montaña region, Guerrero	Population parameters, traditional knowledge and management	Palma soyate
(J. G. Aguilar, 1998)	Aguilar et al. 1998	La Montaña region, Guerrero	Population parameters, traditional knowledge and management	Palma soyate
(Catherine Illsley et al., 2001)	Illsley et al. 2001	Chilapa, Guerrero	Social organization, traditional knowledge and management	Palma soyate
(Blancas, 2001)	Blancas 2001	Huitziltepec, Guerrero	Economic importance, traditional knowledge and management	Soyatl (Nahuatl)
(Rangel-Landa y Lemus, 2002)	Rangel-Landa y Lemus 2002	Sta. María Ixcatlán, Oaxaca	Population parameters, ecology, use and traditional management	Palma criolla

(Torres-García, 2003)	Torres-García 2004	San Luis Atolotitlán, Puebla	Traditional management	Palma verde
(J. Aguilar et al., 2005)	Aguilar et al. 2005		Management, use and commercialization	Palma soyate
(Echeverria, 2003)	Echeverria-Ayala	Nodón y Jocotipac, Oaxaca (VTC)	Populations parameters, ecology, use and traditional management	Palma criolla
(Catarina Illsley et al., 2006)	Illsley et al. 2006	La Montaña region, Guerrero	Management and commercialization	Soyate
(Pavón et al., 2006)	Pavón et al. 2006	Barranca de Meztitlan Biosphere Reserve	Leaves harvest and population parameters	Palma
(Valderrama, 2006)	Valderrama et al. 2006	Xochihuehuetlan, Guerrero	Palm availability, use and commercialization	Palma
(Catarina Illsley et al., 2007)	Illsley et al. 2007	Topiltepec, Guerrero	Traditional management, social organization and commercialization	Palma soyate
(Aponte y Sarria, 2010)	Aponte y Sarria 2010	Tehuacán-Cuicatlán Biosphere Reserve	Traditional management	Palma
(Ortega y Pulido, 2010)	Coronel-Ortega y Pulido 2010	Barranca de Meztitlan Biosphere Reserve	Artisan use, phenology and optimal harvest	Soyate
(Coronel y Pulido, 2011)	Pulido y Coronel-Ortega 2011	Hidalgo	Use and conservation	Soyate
(SEMARNAT, 2011)	SEMARNAT 2013	Tehuacán-Cuicatlán Biosphere Reserve	Use	Palma de sombrero
(Ramírez-Rodríguez et al., 2012)	Ramírez-Rodríguez et al. 2012	Huitziltepec, Guerrero	Traditional management and genetic structure of populations	

(Rangel-Landa, 2014)	Rangel-Landa et al. 2014	Sta María Ixcatlán, Oaxaca	Traditional management and commercialization	Palma criolla *yatjen chjanha* (Ixcateco)
(Pulido y Coronel-Ortega, 2015)	Pulido y Coronel-Ortega 2015	Barranca de Meztitlan Biosphere Reserve	Population dynamics, harvesting and potential for exploitation	Palma sombrero, soyate
(Rangel-Landa et al., 2016)	Rangel-Landa et al. 2016	Sta María Ixcatlán, Oaxaca	Ethnoecological importance	Palma criolla
(Martínez-Gonzalez, 2017)	Martínez-González 2017	Santiago Cacaloxtepec, Oaxaca	History and symbolism in the palm weaving	

Suplementary Material S2

Mexican palm species and their uses

Checklist of palm species reported for Mexico. This table was obtained through bibliographic query, reported species names were verify for synonymy in the Plant List database (www.theplantlist.org). Only data with the highest level of reliability were included, and subspecies were not considered. In order to obtain and list the reported uses, a search was performed for taxonomic genera reported for Mexico on Google Scholar ("genus" + "Mexico"), and by requesting support from the Ethnobotanical Database of Mexican Plants (BADEPLAM, a Spanish acronym).

Table 1. Palm species of Mexico.

Genus	Number of species			Especies	Uses	Cultural group	References
	World	America	Mexico				
Acoelorrhaphe	1	1	1	*A. wrightii*	Food, construction, handcrafts	Maya, Chontal	[2] [3]
Acrocomia	8	8	1	*A. aculeata*	Food, construction, handcrafts, domestic, fodder, medicinal.	Chontal, Maya, Mestizo	[3] [4][5] [6] [7]
Astrocaryum	38	38	1	*A. mexicanum**	Food, ornamental, construction, medicinal, ritual-ceremonial	Maya, Mestizo, Popolaca, Tojolobal, Zoque	[7] [8] [9]

Attalea	72	50	4	*A butyracea* *A. cohune*	*A. guacuyule** *A. rostrata*	Food, construction, handcrafts, fodder, domestic, medicinal, ornamental, ritual-ceremonial	Chontal, Maya, Mestizo	[3] [4] [10]
Bactris	81	64	2	*B. major*	*B. mexicana**	Food, construction, domestic, fodder, handcrafts, medicinal, ritual-ceremonial	Chontal, Mestizo	[3] [7] [8] [11]
Brahea	11	11	11	*B. aculeata** *B. armata** *B. brandegeei** *B. calcarea** *B. decumbens** *B. sarukhanii**	*B. dulcis* *B. edulis** *B. moorei** *B. pimo** *B. salvadorensis†*	Food, construction, medicinal, handcrafts, fodder, domestic, ritual-ceremonial	Cuicateco, Ixcateco, Guarihio, Mixteco, Mestizo,Nahua, Pima, Pame, Popolaca, Purhépecha, Ópata, Otomi, Seri	[10][12] [13] [14] [15] [16] [17]

Calyptrogyne	18	9	1	*C. ghiesbreghtiana*		Construction, ornamental		[18]
Chamaedorea	107	98	47	*C. adscendens* *C. alternans** *C. arenbergiana* *C. atrovirens** *C. carchensis* *C. cataractarum* *C. costaricana* *C. elatior* *C. elegans** *C. ernesti-augusti* *C. fractiflexa* *C. geonoformis* *C. glaucifolia* *C. graminifolia* *C. hooperiana** *C. ibarrae* *C. keelerorum* *C. klotzschiana** *C. liebmannii* *C. metallica** *C. microspadix** *C. monostachys** *C. neurochlamys*	*C. oblongata* *C. oreophila** *C. parvisecta* *C. pinnatifrons* *C. plumosa* *C. pochutlensis** *C. queroana** *C. radicalis** *C. rhizomatosa** *C. rigida** *C. rojasiana* *C. sartorii* *C. schiedeana** *C. seifrizii** *C. simplex* *C. stolonifera* *C. stricta* *C. tenerrima* *C. tepejilote* *C. tuerckheimii* *C. vulgata* *C. whitelockiana* *C. woodsoniana*	Food, ornamental, ritual-ceremonial	Chinanteco, Chol, Maya, Mestizo, Nahua, Popolaca	[4] [8] [9] [19] [20] [21] [22]

				C. nubium				
Coccothrinax	54	51	1	*C. readii**		Construction, domestic, ornamental	Maya	[23]
Cryosophila	10	8	2	*C. stauracantha**	*C. nana**	Construction, domestic, fodder, food, ornamental, ritual-ceremonial		[4] [7] [8]
Desmoncus**	11 (15)	9 (13)	2	*D. chinantlensis**	*D. orthacanthos*	Domestic Handcrafts,	Chontal, Maya, Mestizo	[3] [8] [21] [24]
Gaussia	5	5	2	*G. gomez-pompae**	*G. maya**	Unknown		
Geonoma	69	63	2	*G. interrupta*	*G. pinnatifrons*	Food, construction, ornamental		[18] [25]
Pseudophoenix	4	4	1	*P. sargentii*		Food, ceremonial ornamental	Maya	[26] [27]
Reinhardtia	6	6	3	*R. elegans* *R. gracilis*	*R. simplex*	Ornamental	Mestizo, Popolaca	[21]
Roystonea	10	10	2	*R. dunlapiana*	*R. regia*	Construction, medicinal, ornamental	Chol, Chontal, Mestizo	[3] [4] [7] [10] [28]
Sabal	16	14	7	*S. gretherae**	*S. rosei**			

				S. mauritiiformis *S. mexicana* *S. pumos**	*S. uresana** *S. yapa*	Food, construction, medicinal, domestic handcrafts	Chol, Guarihio, Chontal, Maya, Mestizo, Pima, Ópata Seri	[2] [3] [4] [12] [29] [30]
Schippia	1	1	1	*S. concolor*		Unknown		
Synechanthus	2	2	1	*S. fibrosus*		Unknown		
Thrinax	3	3	1	*T. radiata*		Construction, domestic	Maya	[2] [31] [32]
Washingtonia	5	2	2	*W. filifera*	*W. robusta**	Food, construction, ornamental	Mestizo, Seri	[13]
21	532	456	95	37			**TOTAL**	

† Not mentioned on Ulloa et al. (2017), but Quero (1994) mentioned its presence in Chiapas.
*Endemic to Mexico
** Genera with species whose taxonomic identity is not yet resolved to include them as species, subspecies or synonymous.

Three out of 21 genera reported for México are outstanding providers of NTFP: *Brahea*, *Chamaedorea* and *Sabal* (Table 2). These also contribute with an important proportion of endemic species: 52 per cent for *Brahea*, 32 per cent for *Chamaedorea* and 25 per cent for *Sabal*. The three genera include species under different types of management and are among the ones with the greatest number of use categories and with the highest record of use by ethnic groups.

Table 2. Palm species used in Mexico, categories and palm part use

Categories of Use	Food	Construction	Medicinal	Fodder	Ornamental	Domestic y Handcrafts	Ritual/Ceremonial

Palm Part Used		Fr, In, Am, Lv	St, Lv	St, Lv, Fr	Lv	All, Lv	Lbd, Ro, Se	St, Lbd
Acoleorhaphe	*wrightii*		■					
Acrocomia	*aculeata*	■		■				
Astrocaryum	*mexicanum*	■	■			■		■
Attalea	*butyracea*	■	■	■	■	■		■
	cohune					■		
	guacuyule	■	■		■		■	
	rostrata	■	■	■	■	■	■	
Bactris	*major*	■	■	■	■		■	
	mexicana	■	■	■				■
Brahea	*aculeata*		■			■	■	
	armata		■				■	
	berlandieri		■			■	■	
	calcarea		■			■	■	
	dulcis	■	■	■	■	■	■	■
	edulis					■		
	moorei	■						
Caloyptrogyne	*ghiesbreghtiana*					■		
Chamaedorea	*alternans*	■				■		

	arenbergiana							
	cataractarum							
	costaricana							
	elegans							
	elator							
	elegans							
	ernesti-augustii							
	graminifolia							
	liebmannii							
	metallica							
	oblongata							
	pinnatifrons							
	pochutlensis							
	radicalis							
	schiedeana							
	seifrizii							
	tepejilote							
	woodsoniana							
Coccothrinax	*readii*							
Cryosophila	*stauracantha*							

	nana	■						
Desmoncus	*orthacanthos*		■				■	
	chinantlensis					■		
Geonoma	*pinnatifrons*	■	■			■		
Pseudophoenix	*sargentii*	■				■		■
Reinhardtia	*gracilis*	■				■		
Roystonea	*dunlapiana*	■	■			■		
	regia	■	■	■	■	■		
Sabal	*mauritiiformis*		■	■			■	
	mexicana	■	■	■	■	■	■	■
	pumos	■						
	uresana	■	■	■			■	
	yapa	■	■	■			■	
Thrinax	*radiata*	■	■			■	■	
Washingtonia	*filifera*					■		
	robusta	■	■			■		
Species used in each category		28	25	16	8	37	20	12
Total species used:						54		

Code to labels in second row: Fr: fruit, In: inflorescence, Am: apical meristem, Lv: leaves, St: stem, All: all plant, Ro: roots, Lbd: leaf buds, Se: seeds.

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Suplementary Material S3

Palm parts used and weave objects.

After the harvesting of palm leafs, which is the most important resource retrieve from palms, a laborious process to create palm objects and handcrafts take place. After harvesting the palm buds or *cogollos*, there are different types of pre-treatments before using them for weaving, and these treatments vary among cultures and regions. For instance, for the *Hñä hñü* people from the state of Hidalgo, palm leaves are cut and directly woven while still green. This gives the material a dark color, and makes the objects more prone to getting torn or broken, but for making hats people prefer to boil the material and let it dry to the sun before weaving; in this way, leaves are more flexible, easier to work, and more durable [1]. For the Ixcatec and the Mixtec from La Mixteca region, leaves buds are let lying in the sun and later stored in a cave made explicitly for weaving the palm (Figure 2). These caves are commonly located near the kitchen or other rooms or in homegardens. It is a ground excavation commonly of about 10 m^2 or even smaller, a hole is let open as entrance and people descend to the cave through a carved staircase. Inside, the dried palm buds are stored and woven, since cave conditions maintain the fiber in good state and flexible for work [2]. In the region of Chilapa, Guerrero palm leaves are boiled to soften them and then are plaited into strips called "cinta", which are sewn or woven to make handcrafts [3]. After the treatments, objects are weave and then sold on regional markets (Figure 3).

Figure 3. Processing of *Brahea dulcis* from palm to weaving. (**A**) Cutting of leaf buds. (**B**) Leaf bud or cogollo. (**C**) Load transportation. (**D**) Sundrying. (**E**) Rajando, palm before weaving. (**F**) Weaving inside a cave in Santa María Ixcatlán, Oaxaca. Photo credit

for A, B, E, and F: Selene Rangel-Landa; C: Ignacio Torres-García; D: Erandi Rivera Lozoya

Figure 2. Traditional and novel objects weave with *Brahea dulcis* fiber. (**A**) Woman selling *tenates* (objects of traditional use to contain tortillas) at Cuicatlán, Oaxaca. (**B**) Woman weaving *petates* (prehispanic kind of mat) at San Luis Atolotitlán, Puebla. (**C**) *Tenate* with figures from Santa María Ixcatlán, Oaxaca. (**D**) Jewelry made of palm sell at Chilapa, Guerrero. (**E**) Thumnails. (**F**) Shoes, bags and toys sell at Chilapa, Guerrero.

Authorship of photos: A, Cloe Xochitl Pérez-Valladares; B, C and E, Selene Rangel-Landa; D and F, Ana Isabel Moreno-Calles.

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Capítulo III

An expert knowledge approach for mapping vegetation cover based upon free access cartographic data: The Tehuacan-Cuicatlan Valley, Central Mexico

Artículo publicado en:

Biodiversity and Conservation **2019**, 28:1361-1388; **doi**: 0.1007/s1053
1-019-01723 -w

Biodiversity and Conservation
https://doi.org/10.1007/s10531-019-01723-w

ORIGINAL PAPER

An expert knowledge approach for mapping vegetation cover based upon free access cartographic data: The Tehuacan-Cuicatlan Valley, Central Mexico

Cloe Xochitl Pérez-Valladares, et al. ***[full author details at the end of the article]***
Received: 14 June 2018 / Revised: 13 February 2019 / Accepted: 19 February 2019

Abstract

Vegetation maps have been key tools for synthesizing large amounts of information and supporting geographical location of biodiversity. Traditional vegetation map development demands acquisition and processing of expensive supplies, expertise of qualified interpret- ers and extensive fieldwork; nevertheless vegetation maps are crucial in areas where con- servation policies ought to be rapidly produced, as it is the case of the Tehuacán-Cuicatlán Valley which was recently declared a hotspot of biocultural heritage of highly important conservation. Currently, mapping approaches that integrate plant diversity outcomes, expert knowledge and land cover information are still scarce. In this study we combined free access cartographic data and expert knowledge to develop a vegetation map, in order to provide basic criteria for decisions on conservation of regional biocultural diversity. Biocli- matic regionalization, georeferenced fieldwork, over 30 years of vegetation outcomes and expert knowledge enabled us to develop a novel method for vegetation mapping. Climatic, lithologic and topographic affinities were used as main criteria for map class reassign- ment. Field verification allowed quantifying an acceptable certainty of class assignation. Our comprehensive approach proved fundamental for developing a detailed vegetation map elucidating complex vegetation diversity patterns. The classification scheme here proposed increased almost twofold that of the original land cover map. Regarding the outstanding plant diversity harbored, the extent of the study area (~ 12 000 km^2) and the scale of the vegetation map obtained, we regarded the map certainty as meaningful. To conclude, the present vegetation map proved to be a powerful communication tool to facilitate sound conservation policy making.

Keywords Vegetation mapping · Plant community · Free-access data · Bioclimatic regionalization · Tehuacán-Cuicatlan Biosphere · World heritage

Published online: 27 February 2019

Introduction

Sound vegetation mapping has been pointed as a bridge to close the gap between scientists and environmental policy makers (Velázquez et al. 2016). Vegetation maps can graphi- cally support comprehension of large amounts of information and geographically locate scientific knowledge, eventually helping to prioritize actions in environmental management (Olson et al. 2001). This is especially relevant for regions where effective conservation of natural heritage is urgent due to their outstanding biodiversity and the speed of undergoing disturbance. Under this paradigm, efforts of turning existing scientific botanical knowledge into tools for supporting decision making in protected areas are yet scanty (Velázquez et al. 2016).

Land cover mapping has been extensively conducted since the seventies using as main input remote sensing techniques. The significant progress in remote sensing sources, tech- niques and tools for spatial data analysis has been well documented (Alexander and Mil- lington 2000; Chuvieco 2002), nonetheless, site-based botanical information has been largely overseen in most land cover mapping efforts (Pedrotti 2013). Although free access cartographic data are very practical, sometimes it has been overly generalized, and in many cases spatial resolution or information detail of biodiversity thematic maps must be improve to adjust the needs of ecological research (Araújo et al. 2005). Downscaling of natural variables such as precipitation and temperature has been possible through statisti- cal methods (Timbal et al. 2009; Liu and Zuo 2012). Nevertheless, methods to improve detail of vegetation maps are yet scarce, despite of the great utility they may represent for addressing practical implementation at different spatial scales (Vaca et al. 2011). This is particularly true for highly geo-ecologically diverse regions, where the elaboration of new products may involve acquisition of expensive satellite images and extensive field work, which imply large amounts of time and financial resources that are not always avail- able (Austin 1987; Zonneveld 1988). In many cases such activities are unaffordable and resources at hand are underestimated. Given the outstanding importance of such places, these are frequently the focus of several research groups which have accumulated a large amount of fieldwork information and expert knowledge, which can be used for improving cartographic material available to provide more informative and detailed maps.

Protected areas are inherently spatial entities (Cumming and Allen 2017), for which vegetation mapping is critical so that information relating spatial disposition, distribution patterns, cover extent and geographic localization of natural elements is available. Proper distribution patterns of natural objects and cultural subjects are critical for guide decision making relating management and conservation practices. Informed decision making is particularly critical on sites designated to protect natural and cultural heritage, such as Bio- sphere Reserve Protected Areas, since these places sustain unique socio-ecological systems (Gallopín 2006). Contrary to popular belief, at least 50% of world protected areas are not effectively managed, undergoing decline in threatened species populations, ecological deg- radation and vegetation loss (Watson et al. 2014). In fact, some have experienced increased ecological degradation after the protected figures were established, mainly by land use and cover change (LUCC) (Liu et al. 2001). In Mexico 96% of natural protected areas undergo LUCC and 46% of them are pointed as weak or non-effective (Figueroa and Sánchez-Cor- dero 2008). The improvement of this situation is critical, not only for safeguarding natural heritage, but also to warrant livelihoods of socio-ecological systems associated with ser- vices provided by these sites (Cumming and Allen 2017).

Research studies conducted on protected areas contribute to a better understanding of local ecosystems; therefore, accumulated knowledge should be used to improve land man- agement. The Tehuacán Cuicatlán Valley (TCV) is a large floristic province (Rzedowski 1978), that due to its vast biological and cultural diversity, was decreed as natural pro- tected area in 1998. Four years later it was incorporated as part of the World Network of Biosphere Reserves of Man and the Biosphere Program of UNESCO, and later on pro- claimed as mixed (biological and cultural) World Heritage Site in 2018. With only 0.65% of Mexican national territory, the region host ~ 13% of the estimated Mexican flora (Ulloa et al. 2017), with more than 3 000 plant species in nearly 10 000 km^2 of land. The TCV represents the most diverse arid region in Mexico and the North American's arid -semiarid region with the greatest biological diversity (Dávila et al. 2002; Casas et al. 2016a). Despite its great importance as host of a high number of endemic species (365 plant species), the
reason why the region earned the denomination of floristic province by Rzedowski (1978), the TCV stills lacks a proper spatial representation of its vegetation cover diversity, which is currently recognized to harbor at least 36 different types of plant communities (Valiente- Banuet et al.

2009). These communities are well differentiated physiognomic and floristic types of vegetation cover, most of which conform sufficiently extended areas to be dis- played cartographically on a 1:250,000 scale. Most of the recognized plant communities are dominated by endemic species and genera, as are several types of columnar cactus for- ests (*sensu* Valiente-Banuet et al. 2000, 2009).

In addition, the TCV is a region harboring a remarkable biocultural heritage. Archaeo- logical research conducted during the sixties identified the region as one of the areas with the earliest records of agriculture for the New World (MacNeish 1967). During the 1990s and until present, ethnobotanical and ethnoecological research conducted in the TCV iden- tified an extraordinary mosaic of interactions between humans and nature, with nearly 2000 plant species used by eight indigenous ethnic groups, hundreds of them under a great diversity of managed forms (Casas et al. 1997, 2016a, b; Blancas et al. 2013). These stud- ies have documented numerous species of plants under incipient domestication in a high variety of agroforestry systems (Moreno-Calles et al. 2010, 2013; Vallejo et al. 2015, 2016; Campos et al. 2016). All these aspects are considered extraordinary valuable expressions of biocultural heritage, which are crucial for understanding the civilizations and the origins of agriculture on Mesoamerica (Casas et al. 2016a, b). Protecting such valuable heritage is highly important and generating tools and criteria for decision making is a priority.

Botanical, faunal, and socio-ecological research has been conducted in the TVC with- out other cartographic material related to vegetation cover than the one generated by the National Institute of Statistics and Geography (INEGI, by its acronym in spanish), which due its national scale, fails in properly display the vegetation diversity of the region. The studies conducted in the region so far could have benefited from a detailed vegetation cover map, which would have allowed to explore spatial context of research such as: geographic location of valuable resources (Casas et al. 1997, 2001, 2015, 2016a, b; Torres et al. 2013), visualization of plant communities' distribution (Valiente-Banuet et al. 2000, 2009), identi- fication of priority areas for species conservation (Cardel et al. 1997; Méndez-Larios et al. 2005; Angel and Mandujano 2017), assessment of spatial relations among agroforestry systems and natural vegetation (Moreno-Calles et al. 2010, 2012; Vallejo et al. 2015) and estimate faunal species distribution (Rojas-Martínez and Valiente-Banuet 1996; Ornelas et al. 2002; González-García et al. 2012; Farías et al. 2016). The purpose of this contribution was targeted at developing a methodological approach to combine: free available cartographic data, bioclimatic and botanical outcomes, and sup- ported by expert knowledge to generate a vegetation cover map. The results were further discussed in the light of their relevance for ongoing research in the region and supporting decision making for the effective conservation of the biodiversity in the protected area. In addition, this contribution aims at supporting planning actions for conservation of the important biocultural heritage of the region.

Methods

Study area

The study region comprises the Biosphere Reserve of Tehuacan-Cuicatlán and its influ- ence zone (RBVTC). It has a total area of 11 897 km^2 (about the size of Jamaica) located in southeast Mexico City, at the border between the states of Puebla and Oaxaca, within parallels of 17°32′24.00″ and 18°52′55.20″ north latitude and meridians 96°59′24.00″ y 97°48′ 43.20″ west longitude (Fig. 1).

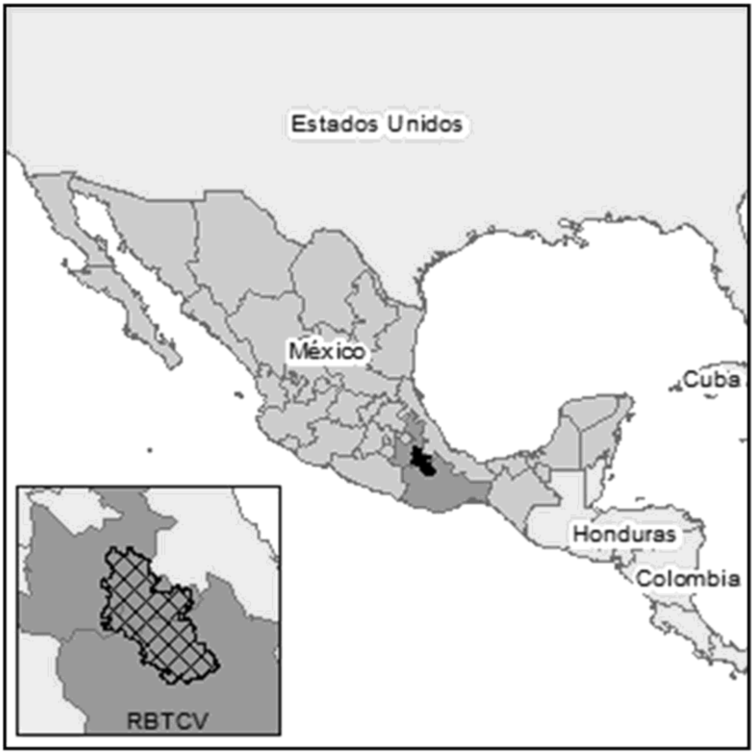

Fig. 1 Study area, biological reservation Tehuacan-Cuicatlan Valley, Mexico

The Tehuacan-Cuicatlan Valley is a topographic depression formed by the late Creta- ceous orogenic events that shaped the highlands of Sierra Madre del Sur, and the sinking of a structural block event related to the northern sector of the Oaxaca fault (Dávalos-Álvarez et al. 2007). The base layer of this formation consists of metamorphic rock from Proterozoic to Cretaceous, which currently outcrops in Zapotitlan, Miahuatepec and Atzingo mountain ranges. According to Valiente-Banuet et al. (2009) and based on Brunet (1967), Fuentes-Aguilar (1971) and López-Ramos (1981), before the orog- eny at early Cretaceous, the region was under marine conditions, which resulted in the sedimentation of a thick sequence of marine deposits. The lower part of the valley and nearby hills are composed of limestones, flint and marls. By the end of the Mesozoic era, marine regression and the onset of orogeny of Sierra Madre del Sur gave form to the basin, forming a lake. This lake derived in chemical and continental deposits forming plaster, travertine, conglomerate, limolite, limestone, tuff and sandstone. Part of these deposits are present in the lowlands of the valley and outcrops in the Cerro Colorado and Cerro de la Mesa mountain ranges. In the beginning of the Quaternary, tectonic events opened the basin which drained into the Papaloapan River and the TVC acquired the current geomorphological configuration.

The complex geological history of the TCV resulted in an intricate physiography and wide elevation gradient, ranging from 70 to nearly 3300 masl. This condition favors environmental heterogeneity with several climatic types throughout the region. The southwestern part of the TCV has warm to temperate xeric conditions, resulting from low rainfall derived from the pluviometric shadow that de eastern mountains draws over the territory and the low water retention of limestones. Climate is predominantly dry in the lower zones, with an annual precipitation range between 400 and 500 mm and temperatures averaging 22–24 °C, while higher altitudes in the eastern mountain ranges yield warm to temperate sub-humid climates on western slopes and temperate humid conditions in higher altitudes and eastern hillsides (García 1998).

Environmental heterogeneity favors high vegetation diversity. Different communities of tropical deciduous forest occur contiguous to oak scrubland on lower slopes. Oak, mixed and pine forest develops in higher altitudes. Patches of tropical evergreen forest are found in warm humid zones on the eastern slopes receiving humidity from the Gulf of Mexico. Xerophytic vegetation is found at the western side of the valley and at lower altitudes of the study region, comprising several types of scrublands, some composed of clearly differen- tiated dominant columnar cactus (Valiente-Banuet et al. 2009). These plant communities constitute well differentiated vegetation covers which provide diverse resources according to its plant composition, and are of high economic and cultural importance for the social life of cultural groups within the reserve (Blancas et al. 2010, 2013; Pérez-Negrón and Casas 2007; Arellanes et al. 2013, Vallejo et al. 2016). According to Casas et al. (2016b), among the activities that threaten the extent and composition of these natural communities, are agricultural encroachment, livestock grazing, firewood extraction and intensive extrac- tion of non-timber forest product for commercialization. All these activities have important implications on current distribution range and extent of plant communities.

Mapping method

The research method consisted of three phases, beginning with the bioclimatic region- alization of the study area to produce a regional climate map, followed by the acquisition of free cartographic information, reviewing of previous botanical studies and finally incorporation of previous studies georeferenced vegetation sample points. These alto- gether supported class reassignment based on equivalences among vegetation classifica- tory systems and the elaboration of a preliminary map of vegetation. Subsequently we presented this first product to experts for assessment and incorporate their contributions. Finally, we assess map certainty by ground truthing (Fig. 2).

Bioclimatic regionalization

The bioclimatic regionalization was made with continual surfaces of meteorological data obtained from the Digital Climatic Atlas of Mexico (http://uniatmos.atmosfera.unam.mx/ ACDM/). The Digital Climatic Atlas was built from data obtained from the National Meteorological System. Monthly precipita- tion and average temperatures from 1902 through 2011 of 5227 meteorological stations, were compared with the surface climatic data from WorldClim (http://www.worldclim. org) (Hijmans et al. 2005), to assess differences. Stations with values outside two stand- ard deviations below or above the mean were eliminated. Remaining stations where used to develop climatic surfaces by performing spatial interpolation using Inverse Distance Weighted Interpolation (Shepard 1968). The raster layers developed include average, mini- mum, and maximum monthly temperature and average monthly precipitation, with a spa- tial resolution of 926 m^2.

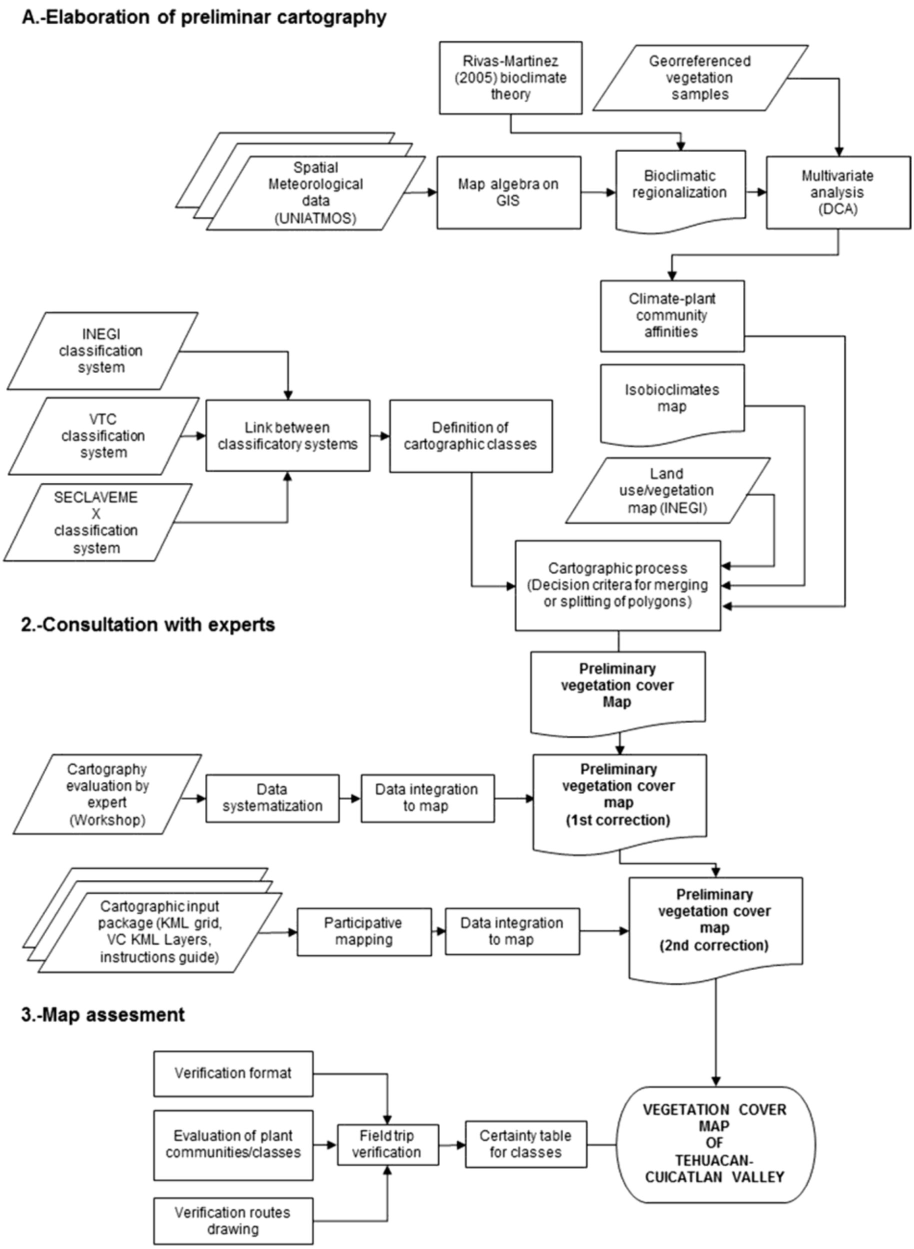

Fig. 2 Methodology flowchart for mapping vegetation communities based on free access cartographic data and expert knowledge

Bioclimatic regionalization

The bioclimatic regionalization was made with continual surfaces of meteorological data obtained from the Digital Climatic Atlas of Mexico (http://uniatmos.atmosfera.unam.mx/ ACDM/; consult Fernández-Eguiarte et al. 2014 for details). The Digital Climatic Atlas was built from data obtained from the National Meteorological System. Monthly precipita- tion and average temperatures from 1902 through 2011 of 5227 meteorological stations, were compared with the surface climatic data from WorldClim (http://www.worldclim. org) (Hijmans et al. 2005), to assess differences. Stations with values outside two stand- ard deviations below or above the mean were eliminated. Remaining stations where used to develop climatic surfaces by performing spatial interpolation using Inverse Distance Weighted Interpolation (Shepard 1968). The raster layers developed include average, mini- mum, and maximum monthly temperature and average monthly precipitation, with a spa- tial resolution of 926 m^2.

Bioclimatic map was developed using the methodology proposed by Rivas-Martínez (2005). This system attempts to establish clear and quantitative climate-vegetation rela- tionships by relating values of meteorological variables with presence and absence of plant species and communities to set distributional thresholds. In accordance with Rivas-Martínez (2005), Mexico holds a tropical macro-bioclimate, this greater range typology is defined by Mexico's latitudinal position and to summer rainfall regime in most part of the territory (the northwestern side of the country is an exception).

To define the subsequent bioclimatic hierarchical levels (bioclimate, ombrotype and thermotype), calculations of ombrothermic index (*Io*), ombrothermic index of the two driest months (Io_2) and thermicity index (*It*) were performed. These correspond to bio- climatic indices derived of meteorological parameters such as: mean annual temperature and precipitation, monthly minimum and maximum temperatures, annual positive tempera- ture and precipitation (Online resource 1. For further information on this approach and explanation and calculation of all parameters please refer to http://www.globalbioclimatics. org/book/bioc/global_bioclimatics_0.htm). For each bioclimatic level, bioclimatic indexes and parameters were calculated using map algebra, so values were calculated for each pixel of the entire spatial surface under study, and then reclassified using the classifica- tion scheme developed by

Rivas-Martínez et al. (2011). Bioclimate, a typological unit of higher rank defined by climatic singularities and moisture-related values, is determined by the amount and seasonality of precipitation. For instance, a pixel with a value of $Io > 3.6$, $Iod_2 >= 2.5$ and without three consecutive months with average monthly precipitation lower than 10 mm, will reflect rainfall throughout the year, which in this climatic approach corresponds to a *pluvial* bioclimate. In the same manner variations in seasonal rhythms of temperature (thermotypes, which have correspondence with altitudinal-temperature belts) and humidity (ombrotypes, related with humidity gradients) were estimated, and the pixels classified in these two climatic levels. Each bioclimatic layer is overlaid to define the isobi- oclimates, which are the more detailed units in Rivas-Martinez's bioclimatic classification scheme. Thus, the previously mentioned pixel has an *It* value of 210, which corresponds to a *supra-tropical* thermotype, and the same pixel with an *Io* value of 18 corresponds to a *hyper-humid* ombrotype, hence the iso-bioclimate will be *tropical pluvial supra-tropical hyper-humid.*

Bioclimate affinities of sampled plant communities

To explore affinities between plant communities and isobioclimates, 135 vegetation sur- veys (provided by the laboratory of Management and Evolution of Genetic Resources Laboratory, MARGEN, UNAM) were overlap to the bioclimatic regionalization map. A qualitative diagram of affinities was elaborated based on presence of plant communities on isobioclimates and fieldwork observation. The bioclimatic formulas are displayed with bioclimates in the upper horizontal axis, ombrotypes in lower horizontal axis showing a humidity gradient from left to right, and termotypes in vertical axis, showing a top to bot- tom thermic gradient.

Vegetation cover layers and link between different vegetation classifications systems

We obtained the national land use and vegetation map provided by INEGI (Vector data set. Scale 1:250 000. Series V). This map uses a vegetation classificatory system based on two of the most widely accepted vegetation nomenclatures in Mexico (Miranda and Hernandez- Xolocotzi 1963; Rzedowski 1978; INEGI 2015). To transfer information to other classificatory systems we established a link between INEGI's classification system and the latest and more detailed vegetation classification of the Tehuacán-Cuicatlán Valley proposed by Valiente-Banuet et al. (2009). In order to recognize class equivalences between them, we identified the categories of vegetation cover assigned by INEGI for the region and their corresponding plant communities defined by Valiente-Banuet et al. (2009), in obedience to structural and physiognomic criteria (Rzedowski 1978; Mueller-Dombois 1984; Velázquez et al. 2016): dominant life forms, phenology, relative height of the canopy, succulence and in some cases floristic detail were regarded as attribute to differentiate among vegetation units (e.g. tropical deciduous forest by INEGI, may correspond to at least three different tropical deciduous forest *sensu* Valiente-Banuet et al. (2009): "*cuajiotal*", "*fouquerial*" and "*selva baja caducifolia*").

Due to the high diversity and complexity of the Mexican vegetation, current classifica- tion systems are unable to be practically adapted to the cartographical needs of displaying information at different scales of analysis. To achieve this goal without losing congruence and precision, we translated vegetation classes to the hierarchical vegetation classification system of SECLAVEMEX. This system has proven to be a practical method to elaborate vegetation cartography (see Velázquez et al. 2016). SECLAVEMEX seeks to improve the practice of vegetation analysis and classification at different scales explicitly for vegetation mapping, through standardized and hierarchical organization of vegetation information.

Other thematic cartography of support

Lithology map (INEGI. Vector data set. Scale 1:250 000) and a digital elevation model (ASTER GDEM, v2, 30 m resolution) were used to improve the interpretation of vegeta- tion distribution, given the important ecological relationship between vegetation and envi- ronmental factors such as topography, lithology and climate (Mueller-Dombois 1984; Web 1986; Zonneveld 1988; Austin 2002; Pedrotti 2013), specifically denoted for the region by Valiente-Banuet et al. (2009).

Table 1 Linking among vegetation classificatory systems

Link between vegetation classificatory systems								
INEGI	Tehuacan-Cuicatlan Valley Vegetation Guide		Seclavemex					Legend
Miranda, Hernandez and Rzedowski	Valiente-Banuet et al.		Velazquez et al.					
Vegetation types	Series of associations	Associations	Biome	Grand formation	Formation	Sub-formation	Series of associations	
Succulent dominated scrub	Columnar cactus forest	Tetechera de *Neobuxbaumia tetetzo*	Sensu lato Scrub	Tropical dry	Deciduous	Armed succulent	*Neobuxbaumia*	"Tetechera de *Neobuxbaumia*"
		Tetechera de *N. mezcalaensis* y *N. macrocephala*						
		Jiotillal de *Escontria chiotilla*	Sensu lato Scrub	Tropical subhumid Tropical dry	Deciduous	Armed succulent	*Escontria*	"Jiotillal de *Escontria*"
		Chichipera de *Polaskia chichipe*	Sensu lato Scrub	Tropical dry	Deciduous	Armed succulent	*Polaskia*	"Chichipera de *Polaskia*"
		Cardonal de *Pachycereus grandis*	Sensu lato Scrub	Tropical dry	Deciduous	Armed succulent	*Pachycereus*	"Cardonal de *Pachycereus*"
		Cardonal de *Pachycereus weberi*						
		Cardonal de *Pseudomitrocereus fulviceps*	Sensu lato Scrub	Tropical dry	Deciduos	Armed succulent	*Pseudomitrocereus*	"Cardonal de *Pseudomitrocereus fulviceps*"
		Cardonal de *Cephalocereus columna-trajani*	Sensu lato Scrub	Tropical dry	Deciduous	Armed succulent	*Cephalocereus*	"Cardonal de *Cephalocereus columna-trajani*"

Table 1 (continued)

Link between vegetation classificatory systems

INEGI	Tehuacan-Cuicatlan Valley Vegetation Guide		Seclavemex					Legend
Miranda, Hernandez and Rzedowski	Valiente-Banuet et al.		Velazquez et al.					
Vegetation types	Series of associations	Associations	Biome	Grand formation	Formation	Sub-formation	Series of associations	
	Thornbushes dominated scrub	*Echinocactus platyacanthus* scrub	Sensu stricto Scrub	Tropical dry	Deciduous	Armed succulent	*Echynocactus*	"Matorral de *Echinocactus platyacanthus*"
Rosetophyllous desert scrub		Rosetophyllous *Dasylirion-Agave* scrub	Sensu stricto Scrub	Tropical subhumid Tropical dry	Sub-deciduous	Armed rosetophyllous	*Dasylirion-Agave*	"Matorral crasi-rosulifolio"
	Upland wooded vegetation	Izotal de *Nolina longifolia*	Sensu lato Scrub	Temperated subhumid Tropical dry	Semievergreen	Unarmed rosetophyllous	*Nolina*	"Izotal de *Nolina longifolia*"
	Lowland wooded vegetation	Izotal de *Yucca periculosa*	Sensu lato Scrub	Tropical dry	Deciduous	Armed rosetophyllous	*Yucca*	"Izotal de *Yucca periculosa*"
		Izotal de *Beaucarnea gracilis* Izotal de *Beaucarnea purpusii*	Sensu lato Scrub	Tropical dry	Deciduous	Sub-armed rosetophyllous	*Beaucarnea*	"Izotal de *Beaucarnea*"
Tropical deciduos forest		Izotal de *Beaucarnea stricta*	Forest	Temperated subhumid	Evergreen	Unarmed broadleaved		
		Tropical deciduos forest	Forest	Tropical subhumid Tropical dry	Deciduous	Armed microphyllous	Fabaceae-Cactaceae	"Selva baja caducifolia"
		Tropical deciduos forest (Cuajiotal)	Forest	Tropical subhumid Tropical dry	Deciduous	Unarmed microphyll	Burseraceae	"Cuajiotal"
		Tropical deciduos forest (Fouquerial)	Forest	Tropical dry	Deciduous	Armed microphyll	Fouquieriaceae	"Fouquerial"

Table 1 (continued)

Link between vegetation classificatory systems								
INEGI	Tehuacan-Cuicatlan Valley Vegetation Guide		Seclavemex					Legend
Miranda, Hernandez and Rzedowski	Valiente-Banuet et al.		Velazquez et al.					
Vegetation types	Series of associations	Associations	Biome	Grand formation	Formation	Sub-formation	Series of associations	
Mezquital		Tropical thorny forest (mezquital)	Forest	Tropical dry	Evergreen	Armed microphyll	*Prosopis*	"Mezquital"
Chaparral	Evergreen unarmed shrubby vegetation	evergreen sclerophyll unarmed scrub	Sensu *stricto* Scrub	Temperated subhumid Tropical dry	Evergreen	Unarmed Sclerophyllous broadleaf	*Quercus*	"Mexical"
Oak forest	Upland wooded vegetation	*Quercus*Forest	Forest	Temperated subhumid	Evergreen	Unarmed broadleaf	*Quercus*	"Bosque de *Quercus*"
			Forest	Tropical subhumid	Evergreen			
			Forest	Tropical dry	Deciduous			
Pine forest		*Pinus* Forest	Forest	Temperated wet Temperated subhumid Tropical subhumid Tropical dry	Evergreen	Unarmed needleleaf	*Pinus*	"Bosque de *Pinus*"

Table 1 (continued)

Link between vegetation classificatory systems								
INEGI	Tehuacan-Cuicatlan Valley Vegetation Guide		Seclavemex					Legend
Miranda, Hernandez and Rzedowski	Valiente-Banuet et al.		Velazquez et al.					
Vegetation types	Series of associations	Associations	Biome	Grand formation	Formation	Sub-formation	Series of associations	
Pine oak forest		*Pinus-Quercus* Forest	Forest	Temperated wet Temperated subhumid Tropical subhumid Tropical dry	Evergreen	Unarmed needle-broadleaf	*Pinus-Quercus*	"Bosque de *Pinus* y *Quercus*"
Juniper forest		*Juniperus* Forest	Forest	Temperated subhumid Tropical dry	Evergreen	Unarmed scale-leaf	Cupressaceae	"Bosque de *Juniperus*"
Cloud forest	–	–	Forest	Temperated wet Tropical subhumid	Evergreen	Unarmed broadleaf		"Bosque mesófilo de montaña"
Tropical evergreen forest			Forest	Temperated subhumid Tropical wet	Evergreen	Unarmed broadleaf		"Selva mediana perennifolia"

Names of classificatory systems are given in second row, authors on third row. Fourth row indicate level of aggregation of vegetation information for each classificatory system. The column "Legend" indicate cartographic classes on the final plant communities' map

Plant communities map

Exploration of affinities between plant communities and isobioclimates supported class re- assignation of plant community classes, this activity was reinforced with information of environmental affinities of vegetation provided by Valiente-Banuet et al. (2009). Topog- raphy and lithology were used as secondary criteria to readjust classes. Class reassign- ment was performed upon results from the linkage among vegetation classificatory systems (Table 1); shape and dimension of initial polygons were readjusted and named accordingly. We strengthened the plant community reclassification by using 148 georeferenced survey points holding floristic composition and vegetation structure information.

Expertise input. Expert botanist scholars were invited to evaluate reclassification in pre- liminary maps, collect information regarding general vegetation distribution patterns in the region and to integrate georeferenced information of vegetation. The expert group which was comprised by eight members of the laboratory MARGEN, has been working in the reserve for more than 20 years and harbors an outstanding knowledge of plant communi- ties and factors underlying their distribution. The activity was developed in three phases. First, the cartographic method was presented to the expert group. The classificatory output and final vegetation classes to be included in the legend was evaluated and discussed with experts. Further, general impressions on reclassification scheme and preliminary map was gathered through surveys, inquiring about vegetation distribution presented on preliminary map, types of vegetation on specific places and the adjacencies between types of vegetation on the altitudinal gradient. Finally workshops attendees were provided with a cartographic package with layers of vegetation distribution proposals and a series of georeferenced grids of 1 km^2 gap on KML format to be displayed on Google Maps. In this manner, they could integrate information in an organized and independent way. A total of 139 georeferenced sites with information about location of plan communities were obtained. This information was integrated to the preliminary map to correct miss-assignment of classes.

Map assessment. An attempt was made to assess the accuracy of the cartography. How- ever, at this stage of the study, it was not possible to conduct a statistically robust assess- ment as recommended by Stehman and Czaplewski (1998) or Olofsson et al. (2014) based on a probabilistic sampling due to the fact that i) ground-truth data should be collected by field inspection because vegetation classes cannot be determined accurately even with very high resolution images and ii) many parts of the large mapped area are inaccessible. Therefore, a qualitative approach was used to assess map reliability: efforts were guided to places lacking expert information and polygons with dubious assignation were specifically revised. A total of 82 verification points were georeferenced and visited to determine the plant community. Miss-assignments were calculated to elaborate a certainty table of carto- graphic classes.

The final digital map is linked to a database that includes the information of each clas- sificatory system for every polygon on the map; therefore, vegetation information can be displayed in any of these systems. Man made land cover types were generalized as cultural. Given that the level of detail is defined by the minimum mapping unit (MMU) (0.86 km^2 for the base map and 1 km^2 for the climatic regionalization map of 1 km^2), we defined 1:250,000 scale with a MMU of 1 km^2 (Priego-Santander et al. 2010), in order to reduce at maximum the level of detail lost with scale (Knight and Lunetta 2003), and also adjusting to information resolution of base layers. This corresponds to an MMU of 4x4 mm on the map.

Results and discussion

The expert-knowledge based approach developed in this contribution, allowed the construction of the final map obtained, which depicts the core purpose of this paper. The out- comes of the different methodological steps are further explained in the following para- graphs so that replicable scientific exercises may be conducted.

Bioclimatic regionalization and climatic affinities of plant communities. A total of 14 isobioclimates were identified in the region (Fig. 3). The outcome from merging the biocli- matic regionalization map with the land use national map, showed some conflicts between climate and vegetation relationships, these correspond solely to the assignation of tropical dry forest to humid mesotropical isobioclimate. Review and evaluation of vegetation sam- pling points from the database and field work, indicated that these polygons correspond in fact to tropical dry forest occurring in a sub-humid mesotropical climate. The ground truthing showed misclassification of pluvial isobioclimates in mountains southeastern of the reserve and of humid ombrotypes in the western orientation of the eastern slopes at the south of the region. These inconsistencies may be the result of a reduce number of mete- orological stations in the western side of the Montañas Orientales, which imply that inter- polation performed on these sites may be less robust. This apparently was the reason for a poor representation of the pluviometric shadow draw in the western side of this mountain range, where limited entrance of humid winds translates in a subhumid climate.

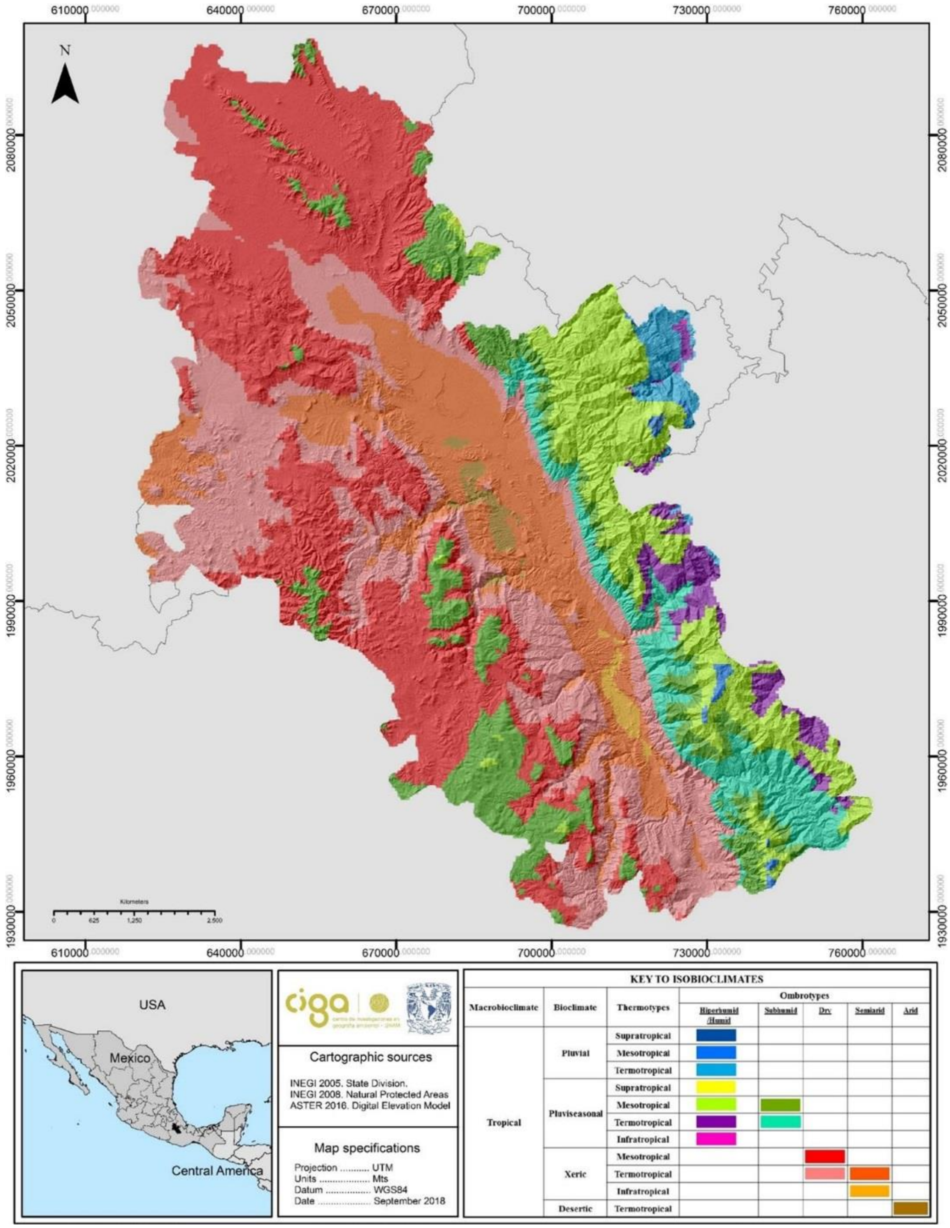

Fig. 3 Bioclimatic regionalization of the Tehuacán-Cuicatlán Valley

Plant community-isobioclimate relationship diagram displays general patterns of vegetation distribution on isobioclimates on the reserve (Fig. 4). This diagram was based on georeferenced vegetation surveys and fieldwork and is consistent with information pro- vided by Valiente-Banuet et al. (2009) relating environmental gradients associated with plant communities' distribution. On the horizontal axis, ombrotypes shows a left to right humidity gradient, from the driest arid climates to the left and wettest climates to the right; on vertical axis thermotypes describe variations in temperature, from the lowest tempera- ture at the top to the warmest at the bottom, these have close correspondence with altitudi- nal belts given the vertical thermal gradient associated with altitude (Rivas-Martínez et al. 2011).

Established notions of climate-vegetation relationships (Rivas-Martínez 2005; Pedrotti 2013) played an important part in supporting class reassignments performed in this study. The relationship between plant communities and isobioclimates showed that pluvial mes- otropical isobioclimates relate to plant communities from temperate humid to subhumid climates such as *Pinus* and *Pinus-Quercus* mixed forest. *Quercus* forests outstands for its presence in an ample gradient of temperature and humidity, which derive from the ecologi- cal plasticity of this genus (Zavala 1998), which favors the presence of this plant commu- nity along broad environmental gradients (Arizaga et al. 2009). Evergreen formations of *Quercus* forest relate to wet conditions on pluviseasonal meso-supratropical humid-sub- humid isobioclimates and deciduous *Quercus* forest is associate to xeric mesotropical to termotropical isobioclimates. This decidous plant community are also in vicinity to roseto- phyllous desert scrub with species like *Dasylirion* and *Agave* (*matorral crasi-rosulifolio*), and shrubby *Quercus* species that conforms evergreen sclerophyllous unarmed scrub vege- tation (*mexical*). This *mexical* is also establish in transition between semi-humid vegetation of higher altitudes and drier-conditions of lower altitudes (Valiente-Banuet et al. 2000).

Presence of other forms of rosetophyllous desert scrub like *izotales* with *Yucca* and *Beaucarnea* species as dominant, and tropical deciduous forest (*selva baja caducifolia*) with genera such as *Ceiba* and *Bursera* occurs on warmer and drier conditions (thermotro- pical thermotypes and subhumid to semiarid ombrotypes). Columnar cactus forest distrib- utes on driest and warmest isobioclimates (left and lower part of diagram. Figure 4). From higher to lower altitude in termotropical dry to arid isobioclimates dominates *Pseudom- itrocereus fulviceps* and the giant cylindrical cactus

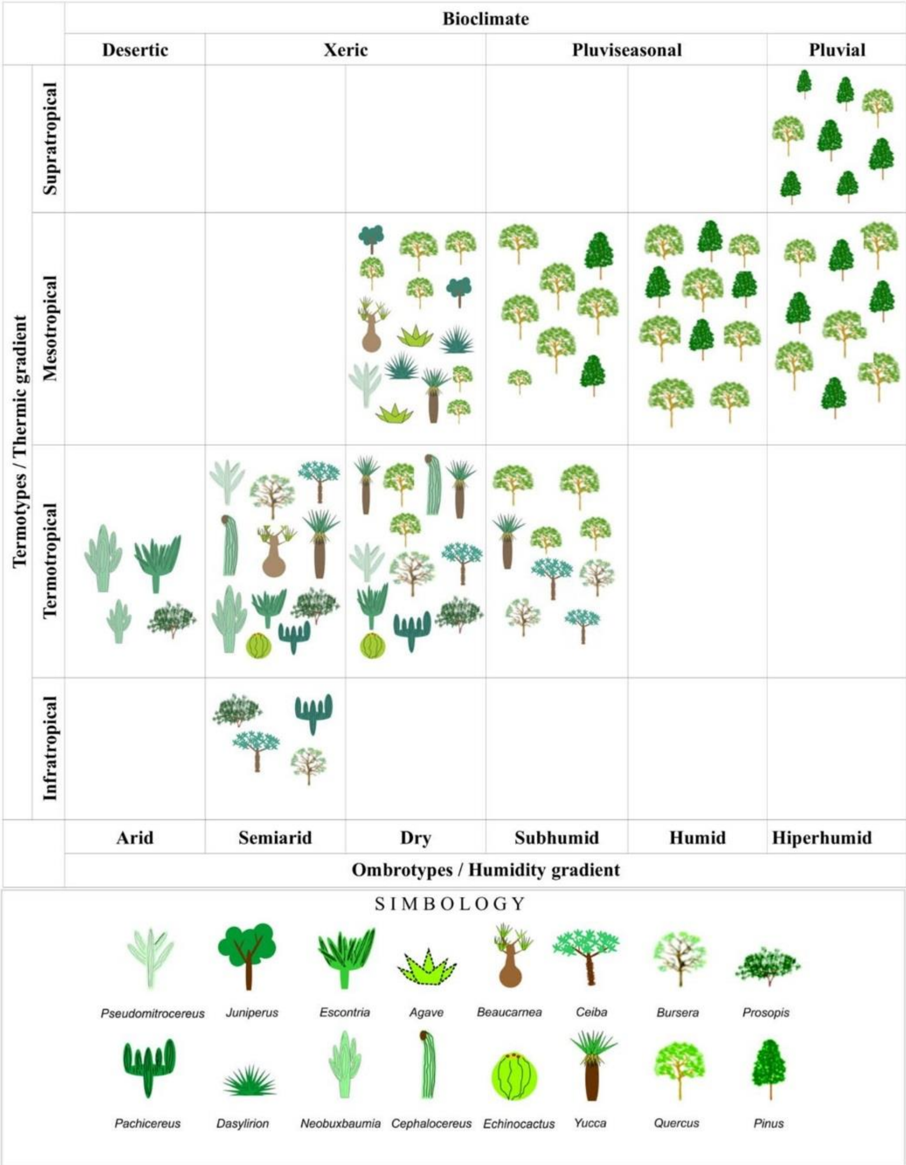

Fig. 4 Distribution of plant communities on isobioclimates from Tehuacán-Cuicaltlán Valley. Plant com- munities are indicated by its most representative arboreal/arborescent elements in each isobioclimate. Bio- climatic formulas are displayed with bioclimates in the upper horizontal axis. Ombrotypes in lower hori- zontal axis represent a humidity gradient from left to right and termotypes in vertical axis, describes a top to bottom thermic gradient

Echinocactus platyacanthus species; in addition to columnar cactus forest dominated by *Cephalocereus* and *Escontria*. The species *Prosopis laevigata* conforms a low stature perennial tropical forest (*mezquital*) associated to presence of perennial and seasonal water courses on termotropical dry and infratropical semiarid isobioclimates, along with tropical deciduous forest and columnar cacti forest of *Pachycereus* and *Neobuxbaumia* genera on lower altitudes.

The link between classificatory systems and plant community classes. We identified 21 plant communities with enough extension to be displayed cartographically (Table 1). The reduction in this number compared with categories from Valiente-Banuet et al. (2009) cor- responds to the exclusion of communities whose coverage is not large enough to meet the required minimum mapping unit (e.g. *gallery forest*), and the inclusion in the same cat- egory of communities dominated by different species of the same genera (e.g. tetechera of *Neobuxbaumia tetetzo* and tetechera of *N. mezcalaensis* were grouped in tetechera of *Neobuxbaumia*). This was also the case for oak and pine forests of different isobioclimatic affinity, where different species of *Quercus* and *Pinus* were dominant. Although the communities were assigned to the same class, information related to their isobioclimate affin- ity were maintained in the database, because they exhibit clearly differentiated phenology and physiognomy. Classes like mountain cloud forest (*bosque mesófilo de montaña*) and tropical evergreen forest (*selva alta perennifolia*) were added since these were absent from the plant community's classification reference. A total of 22 classes (cultural cover class included) compose the legend on the final map.

Participatory mapping workshops. The participatory mapping workshops showed dif- ferent perceptions among expertise. Based only on vegetation-environmental factor rela- tionships, a preliminary map showed misrepresentation of *mexical* in the southwestern part of the region, in the vicinity of Santa Maria Ixcatlán, where this community is distributed in altitudinal gradient prior to *Quercus* forests; this was also the case for *mezquital* and *matorral crasi-rosulifolio* in the northern VTC, where the extent of these communities was not properly represented. The presence of *mezquital* along the valley was also underesti- mated, giving more importance to columnar cactus forests on sites where experts knew *mezquital* occurs, near El Salado River. Other areas such as the surroundings of San Luis Atolotitlán, Los Pápalos, Santa Maria Coyomeapan, Zapotitlán Salinas and Santiago Qui- otepec were particularly well reviewed since plenty of information was shared by experts working on these sites.

Most differences among workshop attendees was restricted to specific locations that are the focus of study at a site-specific scale. Up-scaling turn to be an issue since it was com- plicated to move from the local scale typical of plant studies performed in the reserve, to a regional perspective. To help getting their knowledge in place, their sampling sites were plotted along with vegetation unit class and label. In this way they learn to validate the label of the class based upon dominant plant communities they observed surrounding their site. Integration of expert knowledge and previous research data during the cartographic process helped to improve class reassignment, which confirms the relevance of drawing upon this frequently overlooked information source, and the scopes and products that can be obtained from spatialize information (Fabrikant 2001; Skupin and Fabrikant 2003).

Map assessment and final vegetation map. Map assessment showed differences in cer- tainty values depending on classes, ranging from 33% to 100% (Table 2). The global cer- tainty obtained (61%) was regarded as acceptable considering the extent and complexity of study area. The values of certainty are indicative because assessment was not based on a probabilistic sampling. Moreover, figures of certainty may eventually be pessimistic because verification sites were biased toward areas with dubious classification and lacking expert information. Also, low map certainty is very likely related to the extension of the study area and its geo-ecological complexity (Priego-Santander and Selma 2017). Accu- racy assessments on highly complex environments can derive on pessimistic accuracy values that may not reflect real map quality (Mas et al. 2016).

Study region has an extension of a small country (~ 12,000 km^2) and an intricate geological history, within its area converge five physiographic sub provinces (Lagos y Volcanes del Anahuac, Mixteca Alta, Sierras Centrales de Oaxaca, Sierras Sur de Puebla and Sierras Orientales), situation that confers to the region a high environmental heterogeneity. This poses challenges for research due to the difficulty of covering a large and environmentally complex region, where many sites remain poorly known due to accessibility restrictions. The highest parts of Sierras Orientales where bosque mesófilo de montaña and selva alta perennifolia development are among the most inaccessible areas of the region, and these classes could not be observed on fieldwork and were kept as provided by INEGI. Ongoing research aims at incorporating expert knowledge of several research groups to benefit from localized knowledge and to improve map reliability. It is important to recognize that initial efforts from mappingwill continue to be nurtured and improve in scale and certainty as more information is generated.

Table 2 Vegetation community class certainty

Plant community/cartographic class	Area (km^2)	Expert knowledge	Certainty analysis			
		Control points	Records	True	False	Certainty %
Tetechera de *Neobuxbaumia*	503	15	7	3	5	43
Jiotillal de *Escontria*	58	9	9	7	2	78
Chichipera de *Polaskia*	174	8	2	2	0	100
Cardonal de *Pachycereus*	249	6	4	4	0	100
Cardonal de *Pseudomitrocereus fulviceps*	138	10	4	2	2	50
Cardonal de *Cephalocereus columna-trajani*	250	9	7	6	1	86
Matorral crasi-rosulifolio	482	11	7	4	3	57
Matorral de *Echinocactus platyacanthus*	56	1	2	1	1	50
Izotal de *Nolina longifolia*	170	3	–	–	–	–
zotal de *Yucca periculosa*	147	6	2	1	1	50
Izotal de *Beaucarnea*	193	13	3	3	0	100
Selva baja caducifolia	1280	15	10	4	6	40
Cuajiotal	134	6	4	4	0	100
Mezquital	246	3	6	3	3	50
Mexical	404	31	2	1	1	50
Bosque de *Quercus*	1139	107	9	8	1	89
Bosque de *Pinus*	204	4	–	–	–	–
Bosque de *Pinus-Quercus*	878	26	3	1	2	33
Bosque de *Juniperus*	282	4	1	1	0	100
Bosque mesófilo de montaña	295		Average certainty			61%
Selva mediana perennifolia	77					
Cultural cover	4538	Total cover	11897 km^2			

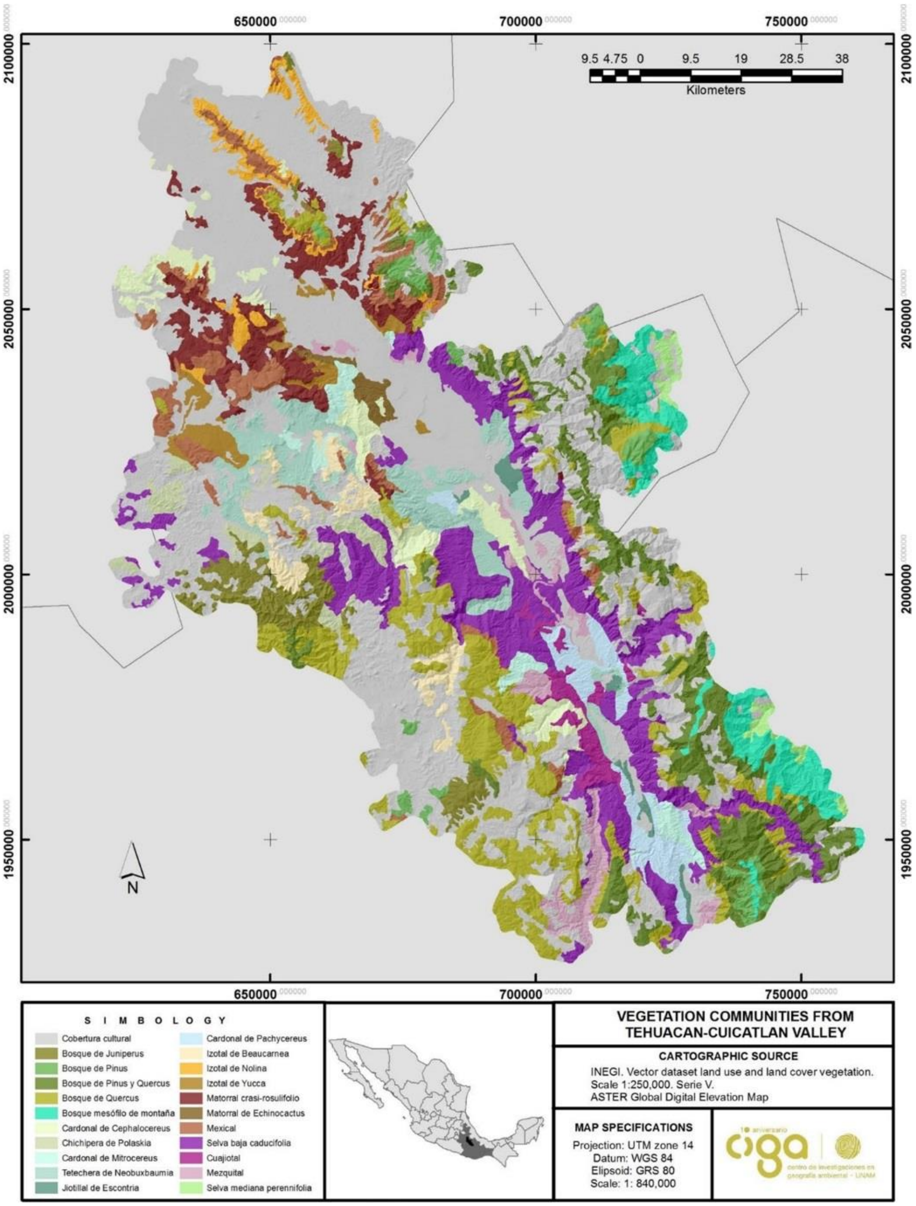

Fig. 5 Map of vegetation communities of the biosphere reserve of Tehuacan-Cuicatlan

This is the first attempt to draw upon pre-existing botanical and ecological information for the TCV to elaborate a vegetation cover map, aimed at assisting conservation strate- gies of natural resources and ecosystems.

The map provides valuable information on extent and distribution of plant communities' diversity in the region (Fig. 5) (For description of vegetation map please refer to Online Resource 2). The cartographic classes resulting from this study increased by 91% to those proposed by INEGI when accounting for the several columnar cactus forests, heterogeneity of tropical dry forest and of rosetophyllous desert scrub (Table 1). This was primarily due to the overrepresentation by INEGI of tropical deciduous forest on lower parts of the study area, a sub-region known as "La Cañada", where in fact large areas of columnar cactus forest are present. Recent distributional stud- ies have shown that this area and the Zapotitlán valley present the highest concentration of members of the Cactaceae family (Miguel-Talonia et al. 2014). Recognition of extent and distribution patterns of columnar cactus forests are of priority importance: they are habitat of several species sharing strong ecological interactions, and are significant resources for human groups inhabiting the reservation. In face of changing global patterns arid-semiarid lands portray as vulnerable systems (Ribot et al. 1996) and recent studies have revealed the high sensibility of Cactaceae family to climatic trends (Goettsch et al. 2015).

Tropical forest and rosetophyllous desert scrub show botanical variants not accounted for on previous map, although many of their floristic elements are endemic and/or endan- gered taxa (See online resource 2). According to Valiente-Banuet et al. (2009) four vari- ants of tropical forest and five variants of rosetophyllous desert scrub are found in TCV (Table 1), which depending on their floristic composition have different potential for pro- viding subsistence resources for the diversity of livelihoods developed in the region (Pérez- Negrón and Casas 2007; Blancas et al. 2010). These communities were not mapped before, and no graphical tool was available to identify their distribution and extent in the region, which is a matter of priority for designing management and protection actions. The main outcome of this research is the vegetation map linked to plant communities and sampling sites all conducted over 20 years of continuous floristic and botanical research.

Core contribution. The present vegetation map differs significantly from a tradi- tional land cover map. The former comprises detailed floristic and botanical information as main input for defining labels of vegetation classes. The latter, in contrast, comprises remote sensing data as main input and labels of land cover classes are therefore related to responses of vegetation to sensor capabilities. This contribution is, therefore, twofold rele- vant, one for the vegetation map and other for the methodological and practical value of the outcome. Locally this is the first cartographic reference for plant community diversity for the highly complex and diverse region of Tehuacán-Cuicatlán. The present method appears to have a better performance than conventional supervised classification of satellite images. An ongoing research aim at comparing methods for vegetation cartography, showed the present methodology improve by 23% the accuracy of the map compared to that of tra- ditional classification methods of remote sensing inputs. This has been also reported by Schmidt et al. (2004), who has compared vegetation maps obtained by field work, spectral classification of satellite images and aerial photography interpretation.

Capelo et al. (2007) have aimed at producing a similar mapping method by integrating bioclimatic regionalization and expert knowledge to derive a natural potential vegetation map with a certainty of 44%. Gebhardt et al. (2014) proposed an entirely automatic clas- sification approach using Landsat images and slope information for mapping land cover for Mexico, they reach overall map accuracies of 62–64%. The poor number of land cover classes (12 cartographic classes) explains the high certainty and depicts the relevance of developing hybrid methodologies to increase certainty and vegetation classes related to field data. Our vegetation map comprises 21 natural vegetation classes with an average certainty of 61%; this last could be increased if target-oriented sampling is conducted at the vegetation classes with less certainty.

Global outreach. The present vegetation map can be used to guide policy making and research projects. According to Lira et al. (2009), 61% (1,605) of the total species richness of vascular flora from TVC is used by people inhabiting the region, which represents the highest absolute richness of useful plant species in Mexico. Geographic representation of plant communities' distribution may enable localization of sites where valuable resources can be found and to define spatial, ecological and management strategies to set sustainable management actions. Aspects related to domestication processes may be geographically analyzed, to seek possible routes of management and domestication through current dis- tributional patterns of plant communities (Arellano and Casas 2003; Rodríguez-Arévalo et al. 2006; Parra et al. 2014). Also, faunal studies can be guided using plant community distribution to asses habitat and species distribution, identify potential biological corridors, spatial segregation of foraging derived from resource availability, search for new records, among others (Ornelas et al. 2002; González-García et al. 2012; Farías et al. 2016; Vasquez et al. 2016). In short, the present map is regarded as a primarily tool to guide research, define conservation and management policies and to monitor land use changes and losses of natural heritage (Mueller-Dombois 1984; Zonneveld 1988). Mapping the variability of natural resources through practical and feasible methods are needed to support spatial plan- ning and management (Bocco et al. 2001). This is crucial on fragile environmental condi- tions where scientific efforts should be conducted to provide useful tools to support deci- sion making. Highly diverse geo-ecological regions such as protected areas are frequently focus of study of several research groups, which have gathered information and field knowledge across time. Joining this expertise is beneficial if synergies among research groups are cre- ated to benefit from accumulated data. Furthermore, in recent years freely available infor- mation in the web from official cartographic and geospatial repositories and biodiversity information facilities has been increasing, e.g. GBIF (www.gbif.org), Copernicus (www. scihub.copernicus.eu), NCALM (www.ncalm.cive.uh.edu), INEGI (www.inegi.org.mx), UNIATMOS (www.atlasclimatico.unam.mx). Geographic information systems are power- ful tools to integrate information from these different sources, and are useful to systematize data, and more importantly, to make spatial synthesis of information. The present method- ological approach goes much further, since it promotes the integration of different sources of information and scientific approaches, such as bioclimatic regionalization and a land- scape approach. The latter being conceived as an integrated entity, spatially and temporally constricted, derived of interactions between biotic and abiotic components of a given geo- graphical space (Zonneveld, 1988); as such, vegetation can be conceived as an indicator of landscape properties, which through mapping delineate relatively homogeneous ecological management units (Schmidt et al. 2004).

Relevance for the study region. The Tehuacan-Cuicatlan Valley is recognized as the most biologically diverse semi-arid region of North America (Dávila et al. 2002), but also represents a fragile region considering climate change and human impact. In fact, arid zones are among the most vulnerable ecological regions of the world in the face of current global changes (Steinkamp and Hickler 2015; Greenwood et al. 2017). Rather scarce fertile soils, wildlife and vegetation are prone to anthropogenic and climate-related environmental deterioration due to changes in precipitation regimes, diurnal oscillation temperatures and patterns of resources use (Ribot et al. 2005). Cul- turally important plant communities as cactus forest are among the most fragile com- munities. Latest research depicts Cactaceae family as one of the most threatened with extinction (Goettsch et al. 2015), which means that endemic and endangered species that are currently the dominant element of several plant communities in TCV reserve will experience drastic contraction of their distribution, most likely endangering the viability of their populations and compromising availability of important cultural and economic resources (Tellez-Valdez and Davila 2003). High rates of LUCC on pro- tected areas also pose challenges to conservation efforts (Figueroa and Sánchez-Cor- dero 2008). In highly vulnerable biocultural regions, the mapping of natural resources among others, plant communities and populations, can contribute to the prevention of environmental and social deterioration. Improving land use planning and conservation strategies by means of providing a baseline to identify current conditions, recognize and monitor land cover changes through time, locate valuable places for resources and identify plant communities of restricted distribution and/or that harbors threatened taxa are necessary. This information, together with integral management proposals derived from assertive communication between reservation authorities and communi- ties, should take into consideration local and traditional knowledge as well as scientific contributions to approach conservation objectives (Casas et al. 2008, 2015, 2016a, b).

Limitations of the method. Some important landscape features could not be approached by this methodology. This region has been subjected to harvesting, propa- gation and domestication of plants recorded at least by 9 000 BP (MacNeish 1967; Smith 1967). Through constant interaction and accumulated knowledge, humans as species have intervened in constructing its own environment so that resource avail- ability has been enhanced (Odling-Smee et al. 1996; Smith 2012). People managed its landscape shaping the physical appearance of their surroundings (Terrel et al. 2003), making thoughtful decisions on which plant species should be left standing or removed, and by adapting components and functions of ecosystems, following as criteria aspects related to subsistence strategies, economic and cultural values (Casas et al. 2015, 2016b). Evidences remains from these interactions, some have derived in specific secondary vegetation types like *palmares* (Blancas et al. 2010), a plant com- munity dominated by the palm *Brahea dulcis*. This is a plant species of economic and cultural relevance in the region (Rangel-Landa et al. 2014), and evidences of their pro- motion can be found throughout the reserve. Also agroforestry systems are clear exam- ples of these dynamics in the TCV (Moreno-Calles et al. 2010, 2012, 2013; Vallejo et al. 2016). These land covers could not be

represented in the present map, as they fall in the "cultural cover" class, so special efforts should be adress to identify them and map their extent and distribuition, as they represent important cultural resources. A line research worth to explore will be the implications of ancient resource management on plant communities' distribution, which brings attention to subjects like landscape domestication and niche construction theory (Odling-Smee et al. 1996; Erickson 2006; Smith 2012).
Questions relating values of predictability of vegetation and environmental factors for a more automated mapping method cannot be answered so far. Modelling of this kind of relationships needs a far more sophisticated procedure that although interest- ing and useful, is beyond the scope of this study. This is the case of performing multi- variate analyses for exploring cultural and physical attributes driving present distribu- tion of plant communities. These types of complementary analyses can be consulted in Capelo et al. (2007) and Vaca et al. (2011). Current knowledge and field base infor- mation relating detailed plant community-bioclimatic-lithological relationships is still insufficient to address a vegetation modelling analysis. Ongoing research may help to enrich our data base, perform appropriate multivariate analyses and eventually to develop predictable scenarios. The future goal then may focus on designing of a semi- automated expert-oriented approach for mapping vegetation as a key tool for sustain- able management.

Conclusions

Vegetation maps are powerful spatially explicit communication tools that synthesize large amounts of information and allow locating scientific knowledge. This graphical representa- tion of information may serve as media to inform and locate current processes and guide initial steps of actions. Presentation of results and methodologies to local and regional authorities will enable the identification of strengths and weaknesses of the work, as well as the integration of new information to improve results. Guidance in the use and improve- ment of digital mapping will promote utility, while tracking of the use of information will allow the identification of pending actions and may promote cooperative work. A schedule of special meetings with this purpose will give the opportunity to identify stakeholders, evaluate the needs and gaps of information, and more importantly show commitment of the scientific community for collaboration in common goals.

High quality botanical data bases coupled with high resolution remote sensing data bases and bioclimatological regionalization turned out to be critical to integrate the present outcome. The mapping approach here presented may serve for improving spared inputs into one integrated geographically-explicit geodatabase.
Conservation of biocultural heritage is currently an important challenge. The Tehuacan- Cuicatlan Valley is a valuable source of past and present information for understanding processes that led to the origins of agriculture and civilizations through the diversifica- tion of plant and animal management systems. The extraordinary diversity of cultures and ecosystems make necessary to adopt strategies for a mosaic of local conditions. Our effort seeks at contributing with spatial criteria for defining local actions for conserving the bio- logical and biocultural heritage.

Acknowledgements The first author acknowledges the support received through a PhD scholarship granted by the Consejo Nacional de Ciencia y Tecnología. The Management and Evolution of Genetic Resources Laboratory (IIES, UNAM) provided georeferenced sites of vegetation samples and assess the prelimi- nary maps. The research was supported by the projects IN209214 and IN206217, granted by the DGAPA, UNAM. I. Franch and P. Urquijo made recommendations on an earlier version. The Academic Writing Office of UNAM helped editing the final version.

Funding Universidad Nacional Autónoma de México via its PAEP PhD program provided financial support for field work. CONACyT provided a scholarship program to the first author.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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Affiliations

Cloe Xochitl Pérez-Valladares[1]
Alejandro Velázquez[1]
Ana Isabel Moreno-Calles[2]
Jean-François Mas[1] ·
Ignacio Torres-García[3]
Alejandro Casas[3]
Selene Rangel-Landa[3] ·
José Blancas[4]
Mariana Vallejo[3]
Oswaldo Téllez-Valdés[5]

1 Centro de Investigaciones en Geografía Ambiental (CIGA), Universidad Nacional Autónoma de México, Antigua carretera a Pátzcuaro, 8701 Morelia, Michoacán, Mexico

[2] Escuela Nacional de Estudios Superiores (ENES), Universidad Nacional Autónoma de México, Antigua carretera a Pátzcuaro, 8701 Morelia, Michoacán, Mexico

[3] Instituto de Investigación en Ecosistemas y Sustentabilidad (IIES), Universidad Nacional Autónoma de México, Antigua carretera a Pátzcuaro, 8701 Morelia, Michoacán, Mexico

[4] Centro de Investigación en Biodiversidad y Conservación (CIByC), Universidad Autónoma del Estado de Morelos, Av Universidad 1001, Colonia Chamilpa, Cuernavaca, Morelos, Mexico

[5] Unidad de Biotecnología y Prototipos (UBIPRO), Facultad de Estudios Superiores, Iztacala, Avenida de los Barrios # 1, Los Reyes Iztacala, Tlalnepantla, Estado de México, Mexico

Capítulo IV

Species distribution modelling approach as a tool to approximate processes of Landscape Domestication in Central Mexico

Artículo sometido a *Landscape Ecology*

Species distribution modeling as a tool to approach processes of Landscape Domestication in Central Mexico

Cloe X. Pérez-Valladares[1*] (ORCID: 0000-0001-7013-1071)

Ana I. Moreno-Calles[2] (ORCID: 0000-0003-2526-2739)

Jean F. Mas[1] (ORCID: 0000-0002-6138-9879)

Alejandro Velázquez[1] (ORCID: 0000-0002-6353-2894).

[1]Centro de Investigaciones en Geografía Ambiental (CIGA), Universidad Nacional Autónoma de México, Antigua Carretera a Pátzcuaro 8701, Morelia 58190, Michoacán, Mexico;
[2] Escuela Nacional de Estudios Superiores (ENES), Universidad Nacional Autónoma de México, Antigua Carretera a Pátzcuaro 8701, Morelia 58190, Michoacán, Mexico

*Corresponding author: cvalladares@pmip.unam.mx

Abstract

Context

Mesoamerica was densely inhabited before European contact, and the profound adaptations made to the environment by the Native American societies remains imprinted in their landscapes. Nevertheless, most of them have gone unnoticed until recently, and most of the continent remains understudied.

Objectives

Our objective was twofold, (1) we focused on assessing the effectiveness of Species Distribution Modeling for addressing processes of landscape domestication, and we (2) aimed at revealing the origin of palm stands in Central Mexico.

Methods

If palm stands are the result of man-made action thus, their actual spatial distribution should be modeled by both ecological and management variables. We used ecological and social as covariates to build SDM on Maxent. Models performance were evaluated with statistical methods (AUC, OR, AICc). The best model was chosen, and the agreement between modeled and observed distribution was assess by visual inspection and ground-truth assessment to estimate the prevalence of actual palm stand presence on localities with high prediction values.

Results

The statistics indicate consistency and adequate model performance. Ethnic identity was the social covariate most strongly associated with palm presence. Visual inspection of the predicted distribution surface resulted coherent with known palm stand distribution, and ground truth assessment showed the prevalence of high-predicted values on nearly 80% of areas with palm stands.

Conclusions

Our model proved to predict accurately the actual spatial distribution of palms stands. Social covariates showed to be strong explanatory covariates, suggesting that palm stands are in a large extent the result of man-made actions.

Introduction

Neglectable environmental impact and minimal human influence on nature were thought to be the rule in America before European contact (Bakeless, 1961). Environmental footprint of native American societies have proven otherwise (Balée, 1988; Denevan, 1992a; Gómez-Pompa and Kaus, 1992; McNeely, 2004; Parsons, 1974), and human influence is recognized in terms of variations on composition and species abundance (Balée, 1988; Clement et al., 2015; Levis et al., 2018; Maezumi et al., 2018), soil quality (Deur, 2000; Erickson, 2003; Franco-Moraes et al., 2019), fire-derived patterns (Piperno, 2011; Terrell et al., 2003), landscape engraving (Clement et al., 2015; Denevan, 2001; Erickson, 2006); and exotic animal spreading (Terrell et al., 2003), among others. All these human made processes have been classified as landscape domestication (Erickson, 2006; B. D. Smith, 2011). Such processes have been initially described by Chase y Hynes (1982), and Chase (1989) in aboriginal societies in Australia (they named it *domiculture*), as that by which certain territories are subjected to human practices that are space-time specific, deliberately performed and based on traditional knowledge in order to sustain a livelihood. Later, Erickson (2006) further developed this idea by referring to "*cultural activities that transform land or environment into landscape, a form of built environment (…) that encompasses all non-genetic, intentional and unintentional practices and activities of humans that transform local and regional environments into productive, physically patterned cultural landscapes"*. Beside the polysemy of the word landscape (Urquijo Torres and Barrera Bassols, 2009; Zonneveld, 1990), here we understand it as an integrated system that accounts for all the ecological relationships between its components (the human included), so the patterns found on the surface can be described (Velázquez et al., 2003; Velázquez and Bocco, 2001; Zonneveld, 1990). As it integrates the human activity, and this has become one the mayor ecological drivers (Crutzen, 2002; Ellis, 2013; Ruddiman, 2013), landscape describes a humanized geographic space, that presents a dynamic evolution of elements with an ecological, cultural and historical identity (Santos y Ganges, 2002).

Although by 1492, most of America was densely inhabited as the case of Mesoamerica and the Andean region (Borah and Cook, 1962; Denevan, 1992b), detailed studies on landscape domestication have been mostly restricted to the Amazonian region (Van der Hammen 1992). Some of the more evident forms of landscape domestication refers to dynamics by which, the presence of patches of vegetation dominated by one or few useful species are promoted and maintained by long-term human activities (Levis et al., 2018). Although in Mexico these landscape dynamics of changes in wild plant species composition and abundance have been studied profusely in Mayan territory (Anderson, 2012; Ford and Nigh, 2009; Gómez-Pompa, 1987; Gómez-Pompa et al., 1987), other regions with evidence of long-term inhabiting and peculiar landscape features, have remained out of focus of this type of studies. One of these regions is the Tehuacan-Cuicatlan Biosphere Reserve, a territory inhabited by several ethnical groups that embraces a complex mosaic of plant communities (Valiente-Banuet et al., 2009, 2000). The history of human occupation in the region is long, as it is long the human-nature relationship, and is manifested by the several and sophisticated forms of traditional resource management developed through time (Blancas et al., 2013; Casas et al., 2014; Moreno-Calles et al., 2012; Rangel-Landa et al., 2016; Vallejo et al., 2015). One of the most relevant resources strongly managed in the region, is the wild palm *Brahea dulcis,* a palm species that holds the most biocultural importance from arid and semi-arid ecosystems of Mexico (Pérez-Valladares et al., 2020).

Traditional management refers to deliberated practices based on knowledge gain through intergenerational experiences on a particular geography; this is conducted at different scales of social organization to enhance the availability of natural resources (Casas et al., 2014). Through management and time, people have improved availability and fostered the expression of two morphs of *Brahea dulcis* (Castillo and Flores, 1993) from which harvest different resources (Blancas, 2001; Illsley et al., 2001). These have been accomplished through several practices performed in order to tolerate, protect and promote the palm such as: left standing palm individuals when clearing land for cultivation, constant harvesting which promotes its vegetative propagation, and burning of land which favors the palm as it is a fire resistant species, among others. Given its historical, economic and cultural relevance, management may also promote the establishment of nearly monospecific palm stands (locally known as *palmonares*) on landscapes under management. Nowadays, this type of plant communities, frequently associated to agricultural areas, is commonly observed conforming complex mosaics of agroforestry systems at landscape level (Vallejo et al., 2014, Moreno-Calles et al. *in press*). *Palmonares* are also present at distant sites from human settlements conforming patches of vegetation that intermingle with other plant communities (Valiente-Banuet et al., 2009). Although it has been proposed that these plant communities are the results of centuries of persistent human management (Illsley et al., 2001; Rangel-Landa, 2014; Rzedowski, 1978), there is still uncertainty about the palm stands origin and distribution. We argue that palm stands are the result of man-made actions, so that their actual spatial distribution should be modeled by a joint set of ecological and management variables.

We aimed at revealing the triggers of palm stands by means of a Species Distribution Modeling, as a surrogate approach for understanding landscape domestication processes.

Correlative species niche modeling relates georeferenced records of presence of the species (or phenomena), with explanatory environmental layers to approximate ecological conditions that favors the presence of the species (Cuervo Robayo et al., 2017). Further, this information can be projected to estimate the species potential distribution in the geographic space (Guisan and Zimmermann, 2000; Soberón et al., 2017). Following this logic, we assume that the potential distribution of a palm-dominated socio-ecological system can be approximated, using the pertinent ecological and social covariates associated to its presence. In this way, knowing the factors underlying its presence and distribution allows to inquire in the processes associated to those factors and propose hypothesis related to its presence and distribution. In this study, we test the effectiveness of a Species Distribution Modelling to approach the process of landscape domestication.

Methodology

Study area

The Tehuacan-Cuicatlan Biosphere Reserve (TCBR) is a natural protected area that encompasses ~12,000km^2, located in the states of Oaxaca and Puebla in Central-Southeast Mexico (Figure 1). Geo-ological complexity of the region has derived in a high environmental heterogeneity (this has been described elsewhere, Pérez-Valladares et al., 2019). This has favored a high plant diversity, used by ten different cultural groups that inhabit the region to derive a livelihood from the environment through differentiated management strategies (Casas et al., 2014). Among the more than 3000 plant species reported for the region (Dávila et al., 2002; Méndez-Larios et al., 2005), at least 61% (1605) are currently used species, which makes it the region with the highest richness of useful plants of Mexico (Lira et al., 2009). The multiple ways in which humans have historically interacted with their environment, and the widespread of human settlements, even on remote areas, have derived in complex mosaics of land uses, such as large conventional agricultural areas on the most densely populated localities in the valley of Tehuacan, traditional subsistence productive systems as agroforestry (Moreno-Calles et al., 2012; Vallejo et al., 2015, 2014), and intervened spaces where wild species are managed; all of which are surrounded or intermingled with natural vegetation (Moreno-Calles et al, *in press*) in such forms that it is often difficult to recognize one from another.

Characterization of the biological species

Brahea dulcis is a widespread palm species of the semiarid environments in Mexico. It is a palm up to 8 m high with petiolate fan-shaped leaves of 50-70 cm long; stems can be erect or decumbent. Individuals can be solitary, but given the species' phenotypic plasticity, it can also develop colonial habits where vegetative reproduction is enhanced, which ease its spread. The radicular system is a homorrize, of strong secondary fasciculate roots which fix it firmly to the ground (Quero, 2000). For this reason (among others), this species is usually left standing in agricultural areas. It is also a fire-resistant species due to the absence of meristematic tissue in the stem, which is vulnerable to fire and it presents vascular bundles where the xylem tissue performs a protection function (McPherson and Williams, 1998).

This palm distributes predominantly at elevations between 800-1600 masl. It is a common floristic element of several plant communities from *Juniperus* evergreen and deciduous oak forest, to xerophytic scrublands (Rangel-Landa, 2014). Given its distribution over a wide altitudinal gradient, it is also found on a broad climatic gradient, from warm and temperate dry to sub-humid temperate climates. It has a wide geographic distribution strongly associated with limestone soils of hills and low mountain environments from northern Mexico to Guatemala (Quero, 1994a).

Characterization of the socio-ecological system

The palm-human relationship in the region is antique and complex. The earliest record of use dates from nearly 12,000 yBP in a rock shelter near Coxcatlán, Puebla at the center of the TCBR (Smith, 1965), and has been reported on several historical documents since the colonial era (Acuña, 2017, 2017b; Velázquez de Lara, 1984). As a species of semi-arid environments, it plays an important role as a non-timber forest product. Nowadays it is recognized as the more abundant and the most used palm species in the country (Quero y López-Toledo, 2014), fulfilling important cultural and economic roles which project it as one of the most bioculturally relevant palm species of Mexico. Beside of being part of several vegetation types, *Brahea dulcis* also structures plant communities where it is the dominant species, these palm stands (*palmonares*) (Figure 2) can reach densities of 15,000 individuals per hectare (Valiente-Banuet et al., 2009).

Although management strategies are oriented toward individual palms, given that in practice people manage full territories, they have the faculty of modifying large areas. Management of *Brahea dulcis* involves several practices devoted to tolerate, protect and promote the palm in their natural distribution areas, this can happens in anthropogenic spaces, such agricultural sites or agroforestry systems (Vallejo et al., 2014), but also on natural vegetation. Management is performed at different levels of intensity, which are associated with the number of activities involved (González-Insuasti et al., 2008). Among the documented practices are: harvesting, selective felling, burning, cleaning, weeding, grounding; and also sophisticated arrangements of management in the form of social organization, in which are included: practices of nature observation and collectively agreed restrictions to harvesting. These practices have particular spatial outcomes, as either the propagation of palm in space, or the deceleration of palm growth and the preservation of particular places (Figure 3). In addition, the performance of particular practices and consequently, their outcomes, are related to ethnic affiliation, geographic distance of the resources to user communities, and type of land tenure (Pérez-Valladares et al., 2020).

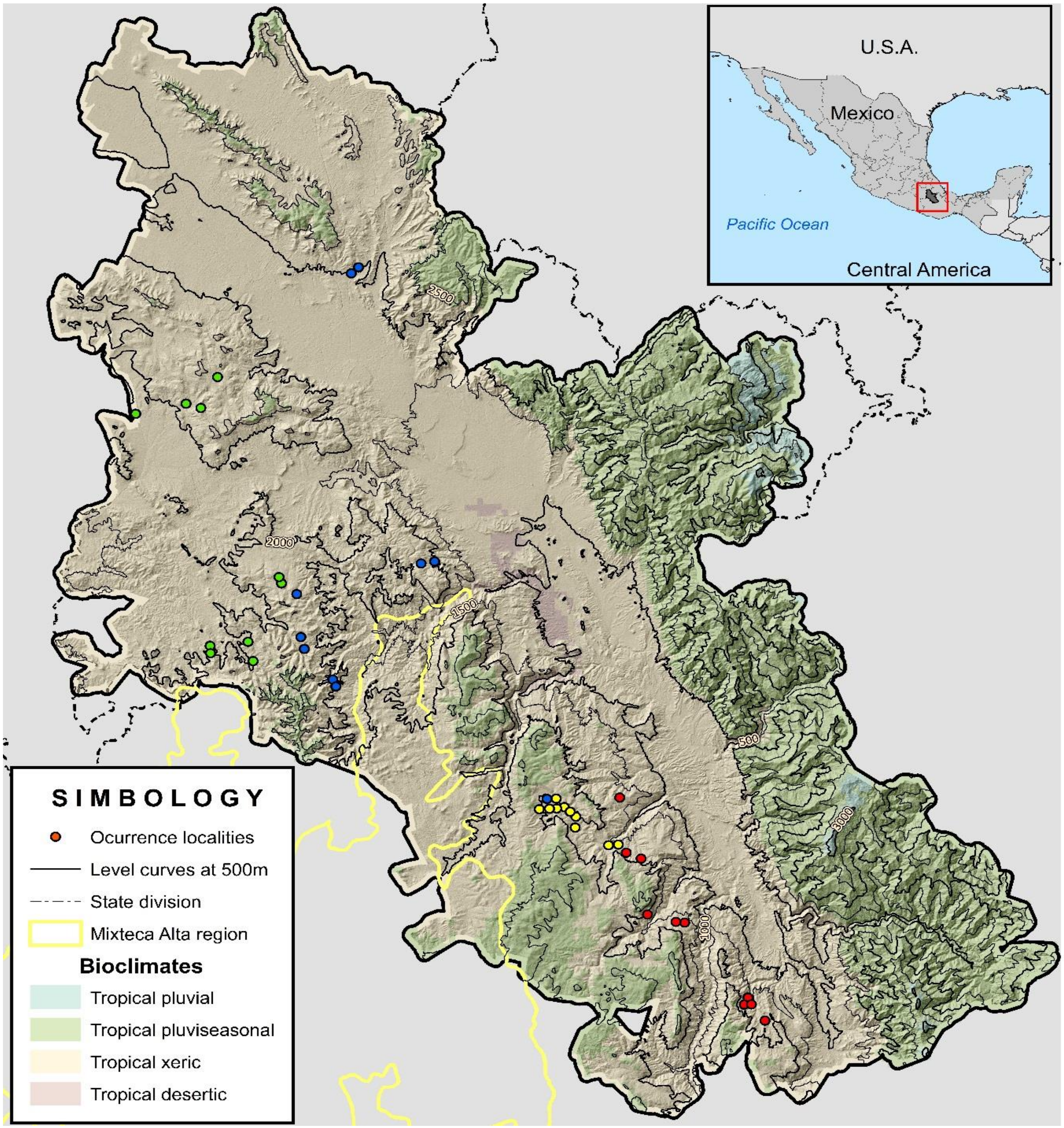

Figure 1. Occurrence localities of Brahea dulcis palm stands in the Tehuacan-Cuicatlán Biosphere Reserve, central-southern Mexico. Colors show the four geographically structured bins, which are spatially independent block partition method. Each of those bins is later used as an independent test dataset to assess model performance. Level lines are provided every 500m. Climatic description is provided at gross level following Rivas-Martinez (2008). Note physiographic relief variations.

Figure 2. Palmares of Brahea dulcis at San Juan Sosola, Oaxaca. Solitary and tall individuals correspond to palm morphotypes known as soyacahuite; colonial and shrubby individuals are known as manchoneras.

Potential Distribution Modeling

We choose the algorithm of maximum entropy (MaxEnt) to carry out distribution modeling. MaxEnt (Phillips et al., 2017, 2006) is currently the most used algorithm for estimating potential distributions, and has been applied to diverse ecological research questions (Elith et al., 2011; Elith and Leathwick, 2009; Kalinski, 2019; Merow et al., 2013). A database of occurrence records of *Brahea dulcis* palms stands was built from the databases of technical reports about the species in the region, academic dissertations and complemented with our own field records. The data were processed in order to reduce spatial-autocorrelation and sampling bias (Phillips et al., 2017). First, duplicate data and outliers were removed. Then thinning of the database was performed at a fixed distance for reducing density in oversampled areas (Aiello-Lammens et al., 2015). Given the geocomplexity of the study region (Priego Santander and Esteve Selma, 2017), and the fact that *B. dulcis* is a non-vagile species, a distance of one kilometer was considered adequate.

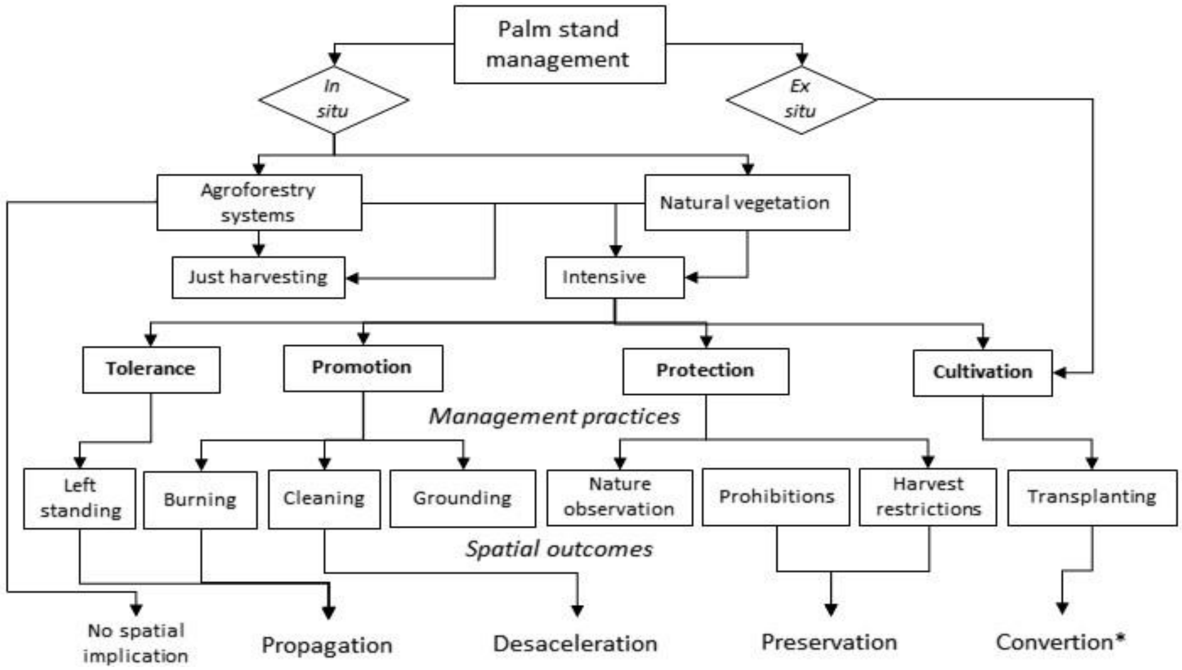

Figure 3. Management of Brahea dulcis palm stands. Practices performed on individual of this species have the faculty of modify large areas through propagations of palms. This can derive from the continual performance of practices for tolerate, protect and promote them. Although not observed, the conversion of areas could become, if the palm were extensively sowed or transplanted. Based on Pérez-Valladares et al. (2020).

The bioclimatic covariates used for modeling were obtained from Bioclim version 6.1 database and corresponds to 19 spatially interpolated bioclimatic parameters of WorldClim from over 5,000 meteorological stations in Mexico (Cuervo-Robayo et al., 2014). These climate variables were supplemented with a digital elevation model (www.asterweb.jpl.nasa.gov) for upgrading resolution. All variables have a 30m spatial resolution.

Exploratory analysis and model evaluations were executed in R-software version 3.6.2 (R Core Team, 2019). Pre-selection of bioclimatic covariates was performed using ecological criteria in order to select proximate variables that have a direct influence on the species distribution (Fourcade et al., 2017) (Table 1). Being *B. dulcis* of neotropical affinity and an arid zone species, selected climatic variables were related with temperature variability and water availability. Principal Component Analysis (PCA), was performed to assess the predictive capability of selected variables, eigenvalues were used to evaluate the contribution of each variable to data ordination. Correlation analysis of covariates was performed in order to identify highly correlated variables. These were identified by the non-parametric Spearman correlation coefficient (**rho** $>\pm 0.8$) and removed.

In order to integrate the social dimension of *Brahea dulcis* palm stand, variables associated to management were also selected. These variables are related with land tenure and ethnic identity of population entities, because not all inhabitants of the region manage and use the palm (there are certain cultural groups who are historically bound to the palm), and also, palm activities are more associated with communities where land tenure is of social property (common goods) (Pérez-Valladares et al., 2020). A spatial layer of ethnic identity was built from information obtained by municipality from the National Geoestatistic Framework (INEGI. Vector data set. 2019; https://www.inegi.org.mx/temas/mg/) and the catalogue of indigenous regulatory systems (SNI by its acronym in Spanish, http://www.ieepco.org.mx/sistemas-normativos). For the land tenure layer, information was obtained from the National Agrarian Registry (http://datos.ran.gob.mx). Both layers were converted to raster format before analysis. A model of cost distance was integrated, in order to represent the average effort to reach a palm stand in terms of invested time (Pérez-Valladares et al., 2020). This information was used to elaborate maps of cost surfaces using a digital elevation model to integrate relief information and to calculate the distance from communities and communication routes to open field. All the geographic information was processed in QGIS (https://qgis.org/es/site/).

Models and evaluations were computed using the **ENMeval** R package (Muscarella et al., 2018), which calls the **Maxent** package, which uses MaxEnt 3.4.1 algorithm (Phillips et al., 2017).

Model's settings

As default parameters lead to model overfitting and inflated estimates of performance, hiding real suitability areas for species distribution (Radosavljevic and Anderson, 2014), we compared tuned models derived from different sets of features classes (L, LQ and LQH) and regularization values (from 0.5 to 4.0, with 0.5 steps), and evaluated using three different methods for data partitioning (discussed later). After assessment, the predictive surface was built on the java interface of MaxEnt (https://biodiversityinformatics.amnh.org/open_source/maxent/), using the best setting configuration and the entire presence dataset, and is provided as an complementary log-log transformed data (cloglog) output that ranges from 0-1, where higher values represent higher predicted probability of presence according to Phillips et al. (2017).

We applied three forms of data partitioning for splitting occurrence records into training and testing datasets, in order to execute cross-validation. The k-fold cross-validation is the most popular method, in which the data is split into k subsets, the model is then trained using k-1 subsets and evaluated with the k^{th} subset (Merow et al., 2013); for this study we defined k= 5. The jackknife method represents a special case of k-fold sub-sampling, where the number of folds (k) equals the number of occurrence localities in the dataset (n-1) (Muscarella et al., 2018), then the performance of the model is evaluated based on the ability to predict the one locality excluded (Anderson and Raza, 2010). Finally, we applied a relatively novel form of this kind of techniques that incorporate geographic structure of the data to provide spatially independent sub-datasets. This is done by spatial partition of the data into four subsets or bins, which are dissected according to the longitude and latitude defined by the extent of the occurrence records area, so that each of the bins has equal sample size (Radosavljevic and Anderson, 2014); then the modeling surface is calculated with three out of the four bins, and evaluated with the 4^{th} bin, which is similar to transferring the model to regions without records of occurrence (Fourcade et al., 2017).

Evaluation metrics of the models

The built models were evaluated on output raw data using non-thresholding methodologies as suggested by Merow et al. (2013). Discriminatory ability was assessed computing the area under the curve (AUC) of the receiver operating characteristic on the testing data (AUC_{TEST}). This evaluation measures the ability of the model to discern from locations where the phenomena is present (palm-stands), from those where it is absent. AUC ranges from 0, indicating discriminatory ability worse than random; 0.5 when prediction ability is not better than random, and 1, which indicates perfect discriminatory ability. In general models with AUC values greater than 0.75 are considered sufficiently useful (Ellit et al. 2006). In order to quantify overfitting, the difference between training and testing data was calculated (AUC_{DIFF}), this metric is expected to hold high values on overfitted models (Warren and Seifert, 2011). Thresholding methods were also used. We performed the evaluation of the omission rate (OR) using as threshold the minimum training presence value (MTP), which indicates the proportion of test presences with probability values lower than the MTP (OR_{MTP}); and also by defining a threshold that indicates the proportion of test presences with probability values below than the 90% of training presences (OR_{10}). In both cases omission rates greater than expected (zero for OR_{MTP} and 10% for OR_{10}) indicate model overfitting (Muscarella et al., 2014). Akaike Information Criterion corrected for small sample sizes (AICc) was also determined in order to approach optimal model complexity, estimating information lost when a model is chosen for explaining data patterns. This metric has been proven to exhibit the best average performance on model selection for estimating true model complexity when the samples size is small; also on preferring models where the suitability of habitat is accurately estimated in both training and transferred regions (Warren and Seifert, 2011). Models with lowest values of ΔAICc, are assumed the best out of a suite of models, and values of $\Delta AICc < 2$ are considered to have substantial support (Muscarella et al., 2014).

Ground-truth assessment

The model with the best performance was selected for further assessment. Firstly, we assessed potential distribution by visual inspection of prediction surface based on field-ground experience, by observing: i) Coincidence between predicted distribution with field-knowledge of general pattern distribution of *palmonares*; ii) coincidence of particularly well known sub-regions with high prevalence of palm use and iii) evidence of overfitting to training presences. Additionally we compared predictions with ground-truth information of georeferenced areas of palm stands from the geodatabases derived of technical studies of *palmonares* of *Brahea dulcis* in the region (Aponte and Sarria, 2010). Prediction surface values from areas of georeferenced palm stands were extracted and assessed in order to evaluate the prevalence of actual palm stand distribution on localities with high prediction values.

Results and discussion

The final database consisted of 40 records. The selected ecological covariates included in the model were altitude, isothermality, temperature annual range, total annual precipitation and precipitations of the driest trimester. A total of 72 models were constructed and evaluated. Total annual precipitation showed the highest explicative value of covariates, and it is as well the one that holds the more unique information. This variable indicates total input of water to the region, a subject of main relevance in arid ecosystems; it was followed in importance by temperature annual range which indicates temperature variation along the year and may be crucial for species affected by extreme temperature conditions (O'Donnell and Ignizio, 2012). Ethnic identity was the most important social covariate, which is an indication of the relevance of historical relationship of certain cultural groups with the palm. Covariates of cost distance showed a lower informative capacity, this may be due to the fact that the models are simple and do not take into account the presence of footpaths or variation of land cover, improvement on these areas may provide more explicative covariates (Figure 4). Models that integrate linear, quadratic and hinge features (LQH), which corresponds to the default of MaxEnt, obtained better evaluation metrics; nevertheless, in all the cases, models with best performance exhibited regularization multiplier values that differed from default (RM=1) (Figure 4). Despite the wide use of MaxEnt, it has been pointed that less than optimal models are obtaining when using default settings, and further tune settings is needed in order to achieve reliable models (Kalinski, 2019; Merow et al., 2013; Muscarella et al., 2014; Radosavljevic and Anderson, 2014; Warren and Seifert, 2011).

	Explanatory covariates	ID
Ecological	Altitude	mde
	Isothermality	clima3
	Temperature annual range	clima7
	Total annual precipitation	clima12
	Precipitation of the driest trimester	clima17
Social	Ethnic identity	cult
	Land tenure	prop
	Distance to communities	costpend
	Distance to roads	costvias

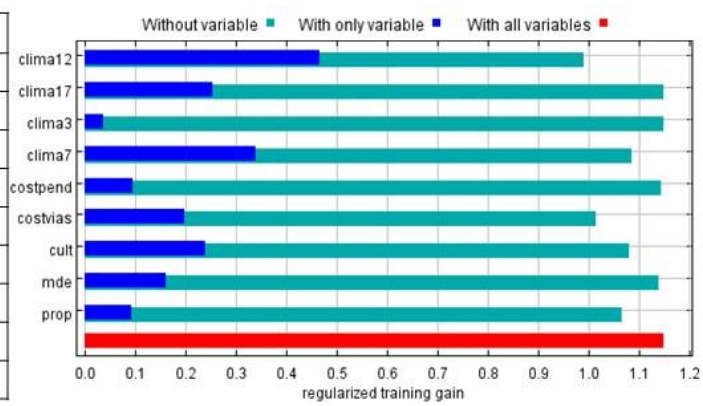

Figure 4. On the left, explanatory covariates used for modeling *Brahea dulcis* palm stands. On the right. Jackknife test of variable importance for modelling. Ethnic identity was the most important social covariate.

Statistical evaluation

Higher ΔAICc values, which are indicative of better model performance were achieved using LQH features, and a RM value of 2.5. Evaluation metrics reported for cross-validation techniques of the three methods, hold comparable results in discriminatory ability (Table 1), which is assumed to be an indication of the strength of the model. Despite of Jackknife and K-fold partition methods provide higher values of model performance (Figure 5), random partitioning has been criticized due to the lack of spatial independence of testing data derived from randomly withheld techniques (Merow et al., 2013). Often, calibration and test localities are close to each other in the geographic space, so even using random partition they are not truly independent due to spatial autocorrelation (Radosavljevic and Anderson, 2014). This is particularly relevant, given that non-independence leads to overestimate models performance (Anderson and Raza, 2010; Fourcade et al., 2017). Results from evaluation metrics of block partition method on the other hand, are more reliable. This masked geographically structured data partitioning, delivers the best spatial independence between calibration and evaluation test by sorting occurrence records in binds geographically defined, so that the test dataset and the geographic extent in which it is embedded is not used for the prediction. In this sense, this type of evaluation constitutes a test of transferability where the model is projected to an evaluation region not included in the calibration process (Radosavljevic and Anderson, 2014); hence spatially independent.

Partition method	**FC**	**RM**	**ΔAICc**	**AUC_{TEST}**	**AUC_{DIFF}**	**OR_{MTP}**	**OR_{10}**
Jackknife	LQH	2.5	0	0.92	0.05	0.05	0.10
K-fold 5 (*random partitioning*)	LQH	2.5	0	0.91	0.04	0.075	0.12
Block	LQH	2.5	0	0.87	0.06	0.15	0.27

Table 1 **AUCdiff**: difference between **AUC** of the training and the testing datasets; **ORmtp**: omission rate for minimum training presence; **OR10**: omission rate for the 10^{th} percentile

The results from the block data partition were further assessed (Table 1). Although the AUC metrics, have been severely questioned due to the lack of independence between training and testing data (Fourcade et al., 2017), in this case the use of masked geographically structured data partitioning guarantee the spatial independence, and hence the reliability of this metric. A value of AUC_{TEST}= 0.87, indicates that a randomly presence locality will be correctly rated with greater probability value than an absence locality, in virtually nine out of ten times (Hanley and McNeil, 1982). Low values of AUC_{DIFF} (0.06), indicate minimal difference between the values of AUC of the training and testing datasets, which is an indication of low overfitting of the model to the training data (Warren and Seifert, 2011).

Nevertheless, the thresholding evaluation metrics, the omission rate evaluation for the minimum training presence (OR_{MTP}) and for the 10th percentile (OR_{10}), hold values greater than expected (0 and 0.1 respectively), indicating less than optimal rates of omissions (Table 1). About 1.5 out of 10 test localities were omitted using as threshold the minimum predictive value at training presence; while nearly three out of ten are omitted for the 10th percentile of training presences that harbors the lowest predictive values, two more than expected. Although this could suggest model overfitting (Radosavljevic and Anderson, 2014), it could also be interpreted as an indicative of missing explanatory variables, which preclude the integration of relevant information associated with palms stand presence into the model, leaving out probable presence sites.

Palmonares are complex socio-ecosystems, which encompasses several social and cultural variables that relates with human management; these variables interact in several ways with those properly ecological that relate to *Brahea dulcis* as a biological species. Such interactions reflects in the way certain cultural groups are deeply related with the palm for historical reasons (Hironymous, 2007; Pulido and Coronel-Ortega, 2015), or that management is predisposed to occur on certain types of land tenure and is subjected to social organization and regulation (Pavón et al., 2006; Pérez-Valladares et al., 2020; Rangel-Landa, 2014), so that the presence of the palm in such territories may translate in a higher probability of being subjected to management. But also, other kinds of interactions are the result of environmental complexity and economic needs, or even the predisposition of some places adjacent to palm stands, to be converted. Due to system complexity, some relevant variables shaping this management relationship may not be considered because of difficulties in measuring them or because they are difficult to perceive or even remain unknown. Nevertheless, it is still possible that through the integration of other relevant variables, the processes underlying palm stand distribution can be approximated with enough reliability.

Visual inspection

General pattern of potential distribution of palm stands follows the well know distribution of *palmonares* on the west side of the study area (Figure 4). *Brahea dulcis* and palm stands of this species are strongly associated to limestone soils and semi-arid climates (Quero, 2000). These conditions are particularly prevalent at the west of the Sierras Orientales, from the central valley to the low mountain hills of the physiographic sub-provinces of Sierras Centrales de Oaxaca, Sierras del Sur de Puebla and the Mixteca Alta region (INEGI, 2001). The prevalence of limestone soils, along with low rainfall regimes derive in particularly complex environmental conditions in this part of the Reserve that promotes the prevalence of deciduous vegetation, like oak and dry tropical forests, as well as several forms of scrubland (Valiente-Banuet et al., 2009). The scarcity of precipitation is a consequence of the rain shadow that the eastern mountains draw over the entire valley and western mountains. The complex environmental conditions in this part of the Reserve, predisposes the use of the palm. *Brahea dulcis* has fulfilled since ancient times relevant roles as a source of fiber in the region (Smith, 1965, 1967), used since pre-Hispanic times for the thatching of roofs, elaboration of agricultural tools and domestic goods (Dalhgren, 1979; Hironymous, 2007); and is particularly relevant as a resource in those places where productivity of agricultural systems is low and erratic, in which the selling of palm weave objects palliate economic needs (Hironymous, 2007; Rangel-Landa et al., 2016; Torres-García,2003).

The eastern side of the TCBR exhibits a different environmental context. The eastern

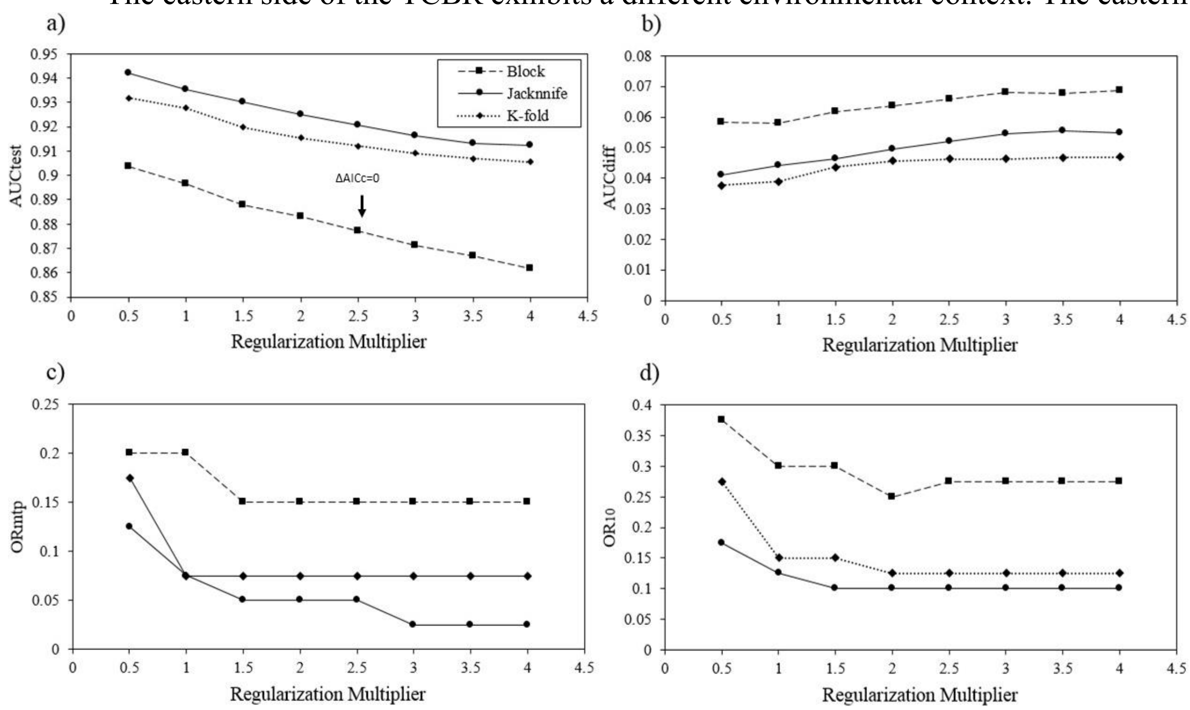

Figure 5. Evaluation metrics of MaxEnt models of palm stands of Brahea dulcis in Tehucan-Cuicatlan Biosphere Reserve. Results for LQH models using three partition method for evaluation are presented, metrics are: a) evaluation of AUC for the testing dataset; b) difference between AUC of calibration vs. training datasets; c) omission rate for the minimum training presence; and d) omission rate for the 10th percentile presence threshold. Discriminatory ability of models are described by AUCtest values, where higher numbers indicate better performance; while the rest of the metrics indicate model fit, where lower values indicate better performance (Radosavljevic and Anderson, 2014). Compare results for RM ≠ 1, which is the default value of MaxEnt. Arrows indicate value of RM where ΔAICc = 0 for block partition method.

mountains are part of the physiographic sub-province of Sierras Orientales, which holds a strong altitudinal gradient that ranges from 800 to more than 3000 masl. On low to mid-altitudes climate conditions are like the west of the region, holding semiarid conditions and showing an increase in humidity as the altitudinal gradient rises. This is evidenced by the replacement of vegetation on the altitudinal gradient, from xeric scrubland dominated by columnar cacti up to 1400 masl, adjacent to tropical dry forests (800-1800masl) and Mexical, a kind of evergreen shrubby oak vegetation, from which *B. dulcis* form part (1900-2200 masl), up to temperate forest above 2,000 masl (Valiente-Banuet et al., 2009). Despite model predicts presence of *palmares* in this area, not only palm stands are absent, but there are no records of presence of *B. dulcis* on this side of the reserve. The absence of *B. dulcis* may be due to some essential ecological requirements that needs further study.

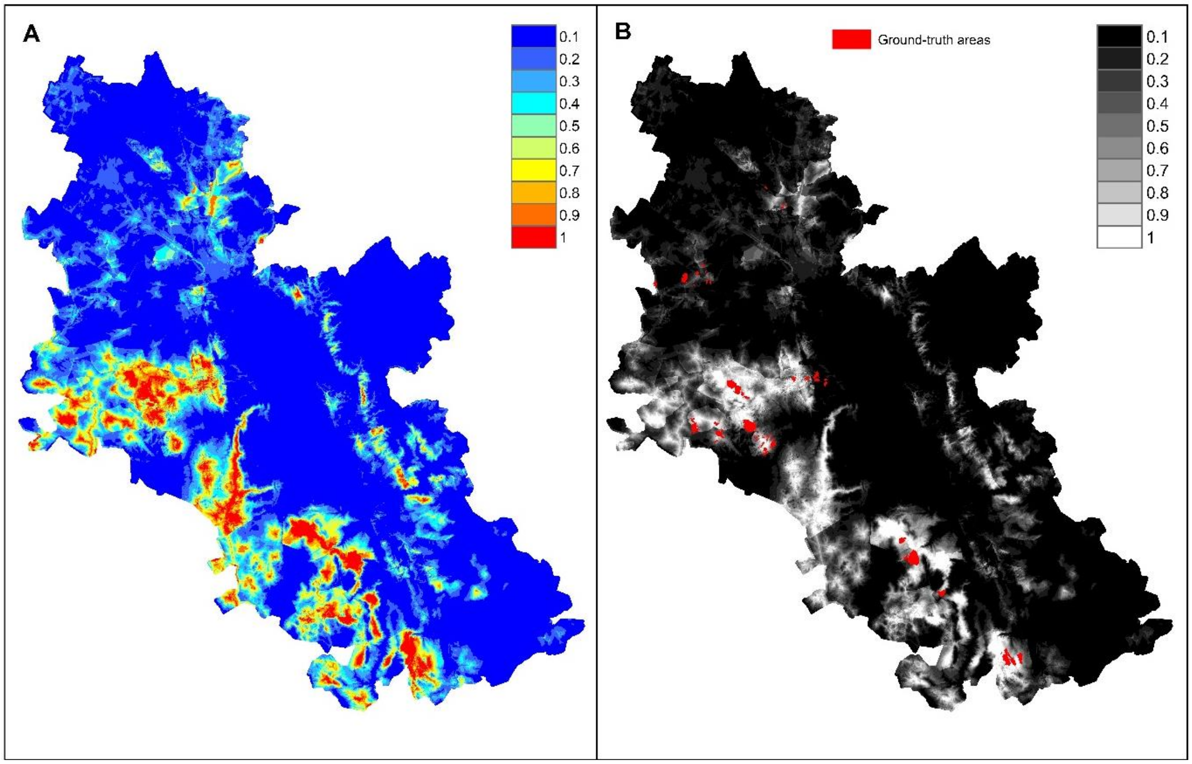

Figure 4. Potential distribution of palm stands of Brahea dulcis in the Tehuacan-Cuicatlan reserve, central Mexico. A) Predicted surface in which warmer colors indicates higher probabilities of palm stand presence, mainly at the western side of the reserve, the known distribution of this socio-ecosystem. B) Predicted surface of potential distribution displayed with a grayscale to improve the contrast with ground-truth validation areas (in red). Prevalence of palmonares on surfaces with high probability values is indicative of the satisfactory model performance.

Visual inspection of prediction surface area showed a strong agreement between potential distribution on surfaces modeled and field knowledge of *palmonares* distribution. Particularly prominent palm user communities as Santiago Nopala and San Luis Atolotitlán in Puebla (Aponte and Sarria, 2010); Santa María Ixcatlán, San Miguel Huautla, San Juan Sosola, San Pedro Nodón, and San Pedro Jocotipac in Oaxaca (Aponte and Sarria, 2010; Echeverria, 2003; Rangel-Landa, 2014) are well classified among sites with highest probability values. The model also correctly predicted localities far from the usually known distribution area, and correctly classified areas on northeast of the reserve where palm stands have been documented (Aponte and Sarria, 2010). Visual inspection to assess model overfitting showed consistency for likely distribution sites that are absent from the training dataset. La Mixteca Alta, a renowned region for its historical bond with the palm, and their crafted objects (Casas et al., 1994; Dalhgren, 1979), is projected with high probability values, especially in places from nearly 800 up to 2000 masl, the altitudinal range of the greatest distribution of *Brahea dulcis* (Quero, 1994b). Likewise, western mid-slopes of Sierras Orientales are classified with high probability values. As mentioned above, this region in fact bears some of the environmental characteristic required for the establishment of *Brahea* *dulcis* palm stands, but lacks the presence of limestone derived soils, known to be particularly associated with its distribution (Quero, 2000). The prevalence of other geologic materials in this side of the reserve such as metamorphic or non-calcareous sedimentary parent material, could be a condition that prevents *B. dulcis* establishment. Although useful, edaphic and geological information could not be integrated into the model construction, due to the low spatial resolution of this information layer (~ 1km^2, INEGI, 2014), which are far more coarser than the 30m resolution of the layers used in this study. Nevertheless, this information must be considered in future studies relating *Brahea dulcis* palm stands distribution, or of any other resource or socio-ecosystem that presents such a clear association with substrate. This will be of invaluable importance in discriminating among suitable and not suitable areas for the phenomena.

Another relevant subject is that the eastern mountains bears more developed and fertile soils than those on the western side; prevailing in the latter mostly regosols and rendzinas. These are poorly developed soils unsuitable for agricultural purposes given their restricted capacity to store and supply water (SEMARNAT, 2011). Due to geographical location, eastern mountains bear higher rainfalls due to the moisture-laden clouds coming from the Gulf of Mexico from the east. Most of the water is precipitated on the eastern slopes, but some clouds reach across the mountain range to drop their water at the upper leeward slopes. Better humidity conditions allow more developed soils and better conditions for agriculture. This is the reason why this part of the reserve holds more productive subsistence agricultural systems. Also, given the presence of rivers from which water is channeled for crops, part of its agriculture is irrigated (Solís, 2006) and sometimes allows two harvests per year (Pérez-Negrón, 2002). Although agricultural production is insufficient to satisfy local demands, the alternative economic activities in this part of the reserve, rather involve fruit orchards and extraction of non-timber forest products for self-consumption (Pérez-Negrón and Casas, 2007; Solís, 2006; Solís and Casas, 2019).

Ground-truth validation

Prediction surface values from areas of georeferenced palm stands showed a strong prevalence of palm areas on high probability values (Table 2). A total of 111631 pixels were revised, representing nearly 100 km^2 of palm stand area. With respect to the entire study area, only 16% of the surface displays probability values higher than 0.5. Those are the places where the 79% of the ground-truth areas distributes, showing a high prevalence of *palmonares* on surface that have high probability values, which is indicative of the good performance of the model for predicting potential distribution of *Brahea dulcis* palm stands. Nearly 50% of the entire ground-truth areas hold probability values higher than 0.8, and 79% displays values higher than 0.5; nevertheless, the remaining 21% of the localities holds values below 0.4 of predicted probability, which are in accordance with result values from the omission rate analysis (ORmtp= 0.2). This could be indication of model overfitting, but as mentioned before, we see as a more plausible explanation the lack of prediction variables that may hold socio-economic information relevant for understanding palm stand distribution, and that their absence may prevent the model to correctly predict those areas.

Entity	Area in km^2	Area in pixels	Area %
Tehuacan-Cuicatlan Biosphere Reserve	12,048	13708152	100
*Palmonares g*round-truth areas	98	111631	0.81

Tehuacan-Cuicatlan Biosphere Reserve				***Palmonares* ground-truth areas**			
Surface probability value	**# pixels**	**%**	**Accumulated %**	**Surface probability value**	**# pixels**	**%**	**Accumulated %**
1	291693	2.1	2.2	1	17720	15.5	15.5
0.9	293857	2.1	4.3	0.9	21105	17.8	33.2
0.8	309647	2.3	6.5	0.8	14432	13.9	47.2
0.7	349603	2.6	9.1	0.7	12365	11.2	58.4
0.6	416615	3.0	12.1	0.6	11874	9.8	68.1
0.5	509819	3.7	15.8	0.5	9758	10.6	78.7
0.4	714879	5.2	21.1	0.4	9352	7.8	86.5
0.3	1025989	7.5	28.5	0.3	4744	3.8	90.3
0.2	2088420	15.2	43.8	0.2	3277	3.4	93.8
0.1	7707630	56.2	100.0	0.1	7628	6.2	100.0

Table 2. Summary of predicted surface area and ground-truth validation of the socio-ecological model for estimating potential distribution of *Brahea dulcis* palm stands. On top, total area of the study zone and ground-truth areas assessed for validation, provided in square kilometers and pixel units. At the bottom, total pixel number and percentage, of ranges of probability predicted by the model for the entire study area (left) and the results of the ground-truth validation (right).

Ground truth sites that present low values of prediction are located on geographical areas that are particularly unsuited for productive activities. Under this condition, the palm weaving activity may acquire a more relevant economic role, providing stronger incentives for its promotion. The contrasting of ground-truth distribution areas with the map of plant communities for the region (Pérez-Valladares et al., 2019) shows a relevant pattern. Palm stands are mostly associated to oak (*Quercus* spp.) and juniper (*Juniperus spp.*) forest, plant communities which distribute predominantly at the southern part of the study area and are associated to less severe climate conditions (mostly temperate dry to sub-humid environments). At the northern side of the study areas *palmonares* also associated to scrublands such as rosetophyllous desert scrub and *Beaucarnea* dominated vegetation, which is a forest-like (scrubland *sensu stricto*, given the density of the arboreal component) plant community call *izotal*, which is associated with drier conditions, mostly temperate to warm dry-semiarid environments. Although plant communities map has a coarser resolution (one km^2), and therefore this information must be taken with caution, it is well known that given the complex environment characteristics in these regions agricultural systems display low yields. Local people alleviate this situation with the selling of items of household production, as the case of the communities of Santa Maria Ixcatlán, Oaxaca and San Luis Atolotitlán, Puebla, that improve the family economy through the selling of palm weave objects and mescal (a distilled beverage of *Agave* species) (Rangel-Landa et al., 2016; Torres-García, 2003). In these sites palm weaving and hence *palmonares*, may acquire more relevant roles as an economic input to family income. For future studies that attempt to inquire the potential distribution of socio-ecosystems, approaching this kind of socio-economic information through more intuitive ecological variables may play as a plausible alternative to integrate this kind of information into models.

Landscape domestication interpretation

Covariates selected for modeling showed the capacity to accurately predict observed *Brahea dulcis* palm stand distribution, thus allowing the identification of the processes underlying its presence. Social factors mainly associated with its presence were cultural identity and distance to roads (Figure 4); the former signaled as a highly relevant issue relating historical documentation of use and management of the palm (Dalhgren, 1979; García, 1940; Pérez-Valladares et al., 2019; Velázquez de Lara, 1984), and the later in coherence with minimizing effort and time invested in harvesting palm leaves.

As expected, *palmonares* do not occupy the entire suitable area; this has to do with a distinct rationale that underlies traditional forms of resource management (Toledo, 1990). In traditional forms of productive systems, profit is not necessarily privileged over other attributes of the system that may embrace greater benefits. Monospecific productive systems, although able to produce larger yields per unit area, imply the complete removal of biodiversity which is in fact, useful. The same applies for the intensification of land under use that tends to occupy the entire suitable area. On traditional forms, as the rationale is to guarantee a diversity of products for resource supply in space and time, a large number of product are profited from a territory along the year (Pérez-Negrón and Casas, 2007). This is part of a diversified subsistence strategy that depends to a large extent on wild and incipiently domesticated species under *in situ* management that are directly taken from the environment (Alarcón-Chaires, 2006; Blancas et al., 2013; Caballero, 1994). This has been recognized as characteristic of Mesoamerican cultures, and remains active in traditional and rural societies on ancient Mesoamerican territories (Caballero et al., 1998).

In these societies, the landscape constitutes the primary source of resources for making a livelihood. It has been said that cultural development departs from a natural landscape that nurtures it, and to which people are bonded throughout their existence (Splenger, 1922). This bond is established and maintained through constant interaction with the immediate nature for provisioning of food, shelter and clothing. This is the way how traditional knowledge is assembled, gradually improved and constantly built from practice and experimentation in specific geographies (Lepofsky, 2009; Toledo, 1990). This knowledge is in turn translated into management practices, which have been described as the purposefully actions deliberately performed on an object of interest (Blancas et al., 2010), which can be applied at different scales of biological and social organization (household units, community) (Casas et al., 2014). The object of management may be an individual or a populations of a species, but in practice people manage entire territories by gradually improving the environment to favor resource availability (Terrell et al., 2003). Human beings are biological entities and hence their interactions are ecological. If management actions are sustained during sufficient time, relevant ecological changes in the environment may occur, this have been termed niche construction (Odling-Smee et al., 1996). However, as humans are also a cultural species, these changes can be maintained over time through oral transmission of knowledge and transgenerational persistence of management actions, and the transformed landscape be bequeathed in the form of ecological inheritance (Laland et al., 2000) as a domesticated landscape (Deur, 2000; Terrell et al., 2003).

We argue that these are the processes underlying the establishment of *Brahea dulcis* palm stands in the TCBR. This species is known for its antique association to humans: the oldest archaeological record of palm use for North America (~11,500 yBP) belongs to this species and is located at the center of what is now the TCBR (Morcote-Ríos et al., 2011). According to Smith (1965), leaves of this palm were early used as a source of fiber for the elaboration of strips, and given its presence in low quantities it must have being scarcely available in the environs; so its presence in the archaeological record must indicate that it was an appreciated resource (Smith, 1967). The use of hard fibers should have continued, according to MacNeish (1964) the first evidence of basketry in the region dates from ~9200-7200 yBP when the first evidences of weaving are found as knotted nets and coiled baskets.

Early human semi-sedentary macro-bands inhabiting the Tehuacan Valley around 7,000-5000 yBP (MacNeish, 1964a), were plant collectors who were increasingly involved in agricultural activities due to the newly domesticated species (chili and squash and later corn, beans and gourd). According to maps (see *Ancient Mesoamerican Civilization,* MacNeish, 1964) some of these bands were dwelling between the valley and western low hills, about what currently corresponds to the territories of Zapotitlan Salinas and San Luis Atolotitlán, Puebla. With the advent of agriculture and the establishment of villages, *Brahea dulcis* leaves should have continued serving as a source of fiber for the roofing of houses, as it was frequently used in the recent past and is still seen on traditional houses at western side of the TCBR today (Byers, 1967; Rangel-Landa et al., 2016). Roofing must have implied a significant increment of fiber demand; according to Aguilar (1996) on La Montaña, a renowned and contiguous palm user region in the state of Guerrero, roofing a kitchen entails the use of nearly 5,100 palm leaves. Without doubt, this must have meant a strong pressure for the resource and a solid motivation to promote palm availability. This is outstandingly relevant, considering that the demographic density should have progressively increase with the gradual adoption of sedentary lifestyle, which may have happened at sometime between

5400-4300 yBP, when the first archaeological evidences of year round settlements have been found (MacNeish, 1992, 1964b). This implies a continued demand for fiber and the need for a constant production of leaves to meet that demand. It is in this period that incipient palm stands of *Brahea dulcis* could have been established at western side of the region, given the prevalence of limestone soils which are associated with palm presence (Byers, 1967; Quero, 2000).

Throughout the establishment of the first organized societies, *Brahea dulcis* would have continued to be used profusely for roofs and also for the manufacture of domestic and commercial objects. The representation of houses with vegetal fiber roofs are common on prehispanic codices of the region, such as Yuta Tnoho (Vidobonensis) and Borgia codex (Chadwick and MacNeish, 1967), as well as the profuse presence of *petates* (a kind of palm weave mat) and *icpalli* on Añute (Selden) and Yuta Tnoho codex, which have relevant ceremonial significance (Jansen and Pérez Jimenez, 2009). Objects such as baskets and containers were profusely used for domestic and commercial purposes, and also used as tribute to pre-Hispanic rulers (Dalhgren, 1979). These uses endured during the colony, as it is stated on historical documents as the *Relaciones Geográficas* of the region (Acuña, 2017, 2017b). These later uses should have been added to the previous ones, increasing palm leaves demand. If the establishment of *palmonares* did occur, by this time they must have been covered significant portion of land, perhaps visible at landscape level.

The use of common domestic objects seems to have been continuous, given the persistence to date of objects weave in antiquity such as *petates* and *tenates* (a kind of weave basket composed of two parts that fit together used for store *tortillas,* which is strongly associated to the region), and to a lesser extent thatching of houses (given the fallen in disuse of this activity). Nowadays palm use continues as an outstandingly relevant activity in economic and cultural terms. Palms are used as sources of food, raw material for elaboration of domestic objects and construction. It also involves in ritual and religious practices of cultural relevance as burial ceremonial practices and dances of pre-Hispanic origin to summon rain (Blancas, 2001). The weaving of palm objects is also a relevant economic activity, by the selling of objects in regional traditional markets or within communities, and also participates in old ways of commercialization that involves barter or *trueque* (Echeverria, 2003; Rangel-Landa et al., 2016). The palm weaving is an activity strongly associated to cultural identity of several cultural groups, as well as to the poorest communities in the region (Pérez-Valladares et al., 2020). The relevance considered to the palm, has derived in the establishment of (explicit and implicit) community norms to regulate its use, these are aimed at avoiding unjustified fell of individuals, regulating the harvest of leaves and, in general seeking for good practices to guarantee the availability of the resource (Rangel-Landa, 2014; Torres-García, 2003). These regulations appear to be effective, and currently palm stand are commonly seen in landscapes at the western side of the TCBR, which supply the demand for palm fiber at the regional level.

Conclusion

Palm stands management and establishment are closely related to economic needs of human populations, which depends of a variety of factors difficult to integrate fully into models. Factors associated to management of socioecological systems are numerous and complex, nevertheless, the substantial of ecological and socioeconomic interactions that underlies these dynamics can be approximated through current techniques for SDM.

This study provides a solid attempt to approach the spatial expression of long-term non-intense landscape management, as is the establishment of *Brahea dulcis* palm stands. Understanding their trigging source as a result of continual processes of human-nature interaction (that may have begun deep in time), allows to recognize them as a cultural heritage of landscape domestication (Bruce D. Smith, 2011). For this some indicators can be drawn: i) Longly-occupied territories. Sites with an ancient history of residence will be more likely to experience significant adaptations as a result of niche construction processes by human groups; ii) Time of human-resource interaction. Resources with a record of use in ancient times which currently maintain that same use(s) suggest a continued use over time, which requires a constant production of the resource; iii) economic relevance of resources. Societies on territories with complex environmental conditions may rely more on wild and incipiently domesticated resources than those with high agricultural production, so their natural spaces may be more prone to experiencing sustained interventions; iv) resource involvement in cultural aspects. The extent to which a resource and the activities related to it are involved in the cultural life of a human group, indicates its cultural relevance, which defines specific actions related with regulations on the use and access to resources; v) social organization for resource use. The establishment of specifics norms and regulations informs of the importance of a particular resource; this may involve particular actions to guarantee resource permanence which may imply deliberated actions for protection and/or propagation.

At this point it is considered relevant, to reveal the environmental history behind *palmonares*, their time and rhythm of establishment. This not only as a fair recognition of its cultural importance, its uses, products and derivatives, but as essential knowledge for the implementation of more sustainable productive systems. These forms of long-term non-intensive landscape management confirm the fact that other forms of use of nature are possible. Some that can be sustainable, as have proven to provide sustained ecological services to human societies since ancient times (Wu, 2013), without the disruptive consequences that intensive agricultural uses have had in many parts of Mexico and the world (Slaymaker, 2001; Turner et al., 1994; Velázquez et al., 2010, 2002). This is not only useful to know, but such stories need to be told in order to unveil other forms of nature interactions; forms that bring us closer to nature, instead of recede us from it, and which had allowed different societies of the world to remain and transcend for thousands of years. Current inhabitants of the region, and more precisely, palm weavers and managers are the direct inheritors of this cultural heritage imprint on landscapes, but *palmonares* and palm weave objects should be recognized as to be placed at the origins of the Mesoamerican societies.

Our model proved to predict accurately actual spatial distribution of palms stands. Social covariates showed to be strong explanatory covariates, suggesting that palm stands are in a large extent the result of man-made actions. There are still many processes that remain to be known relating palm stands, such as the time of establishment and the evolution of this anthropized spaces; paleoecological approaches, as well as detailed historical studies on the relationship between humans and *Brahea dulcis* can shed light on these subjects.

Acknowledgments

The authors thanks Biol. Fernando Reyes Flores, director of the Tehuacan-Cuicatlan Biosphere Reserve, for all the support granted for ongoing research in the reserve relating *Brahea dulcis* palm stands and several other resources and socioecological systems. Thanks to Dr. Oswaldo Téllez-Valdés, from UBIPRO FES-Iztacala, UNAM, for providing high resolution climatic layers for feeding the model and to Horacio Torres de Ita, from El Torito A.C. for sharing relevant information of ground-truth areas. The first author thanks the CONACyT for the scholarship granted for her PhD studies.

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Capitulo V

Discusión general y conclusiones

DISCUSIÓN GENERAL

Importancia biocultural de la palma

Brahea dulcis, conocida como soyate o palma de monte, ha constituido desde tiempos inmemoriales un relevante recurso como fuente de alimento y fibra para diversos grupos humanos de México. Las evidencias de su uso se remontan a algunos de los registros más antiguos de ocupación humana dentro del territorio (12,000 aAP, Smith, 1967). Desde tiempos remotos ha fungido como materia prima para la realización de correas, cordeles y enseres utilitarios (Smith, 1965), que más tarde se transformarían, a la par de las actividades y las sociedades humanas, en utensilios cada vez más complejos, con funciones domésticas, agrícolas o ceremoniales específicas (Chadwick y MacNeish, 1967; Dalhgren, 1979; Jansen y Pérez Jimenez, 2009). En la actualidad los usos de esta palma son muy diversos, pues se pueden obtener alimentos, medicinas, materiales para la construcción, entre otros; no obstante, el uso más relevante continúa siendo el de sus hojas como fuente de fibra para el tejido de distintos objetos de utilidad tanto práctica como suntuaria. La permanencia hasta la actualidad de muchos de estos objetos y formas de uso, sugiere el uso continuo a través del tiempo de esta especie. Hoy en día, *Brahea dulcis* es la especie de palma más utilizada en México (Quero y López-Toledo, 2014). Cuestión muy relevante si se pone en perspectiva que es la palma de zonas áridas mejor distribuida en el territorio mexicano, donde funge importantes roles económicos en estos ambientes complejos a través de la producción doméstica de enseres de uso cotidiano y también como fuente de ingreso monetario a través de la comercialización de los productos.

La relevancia del soyate no se limita solo a las importantes cuestiones económicas en las que se involucra, sino que deriva también, de las complejas relaciones establecidas entre los grupos humanos que la utilizan. Debido a la ancestralidad de la interacción entre los grupos humanos y la palma, esta ha llegado a formar parte de la vida social y cultural de muchos grupos étnicos del país, cumpliendo importantes roles de identidad y reafirmación étnica, integración comunitaria y arraigo, a través de las actividades asociadas a la palma. El manejo tradicional de la palma y el tejido de sus fibras, son actividades que no ocurren en solitario, sino que se práctican de manera colectiva, siendo la oralidad el medio de trasmisión de estos conocimientos. El aprendizaje se fomenta desde muy temprana edad, participando miembros de la familia de diferentes generaciones, lo que promueve la integración familiar a través de las actividades intergeneracionales; tejer es también momento de sociabilidad con otros miembros de la comunidad, lo que fortalece los lazos comunitarios y, a través del comercio en los mercados regionales, se reafirma la identidad de los grupos vinculados a la palma.

Complejidad de la relación

Se mencionó anteriormente la existencia de una dimensión económica, social y cultural fuertemente vinculada a la palma. Existe también, la dimensión ecológica y geográfica que deriva de la estrecha relación establecida a través del manejo tradicional. Las comunidades involucradas en el manejo de la palma a través de esta estrecha relación, han podido conformar un *corpus* de conocimiento tradicional sofisticado (Toledo et al., 2001), a través del cual, se han establecido prácticas de manejo que tienen como fin mejorar la disponibilidad de la palma para su aprovechamiento. En su conjunto, las formas de manejo desarrolladas conforman el cuerpo práctico (*praxis)* del conocimiento colectivo generado en torno a la palma. Este manejo es prácticado a distintas escalas y niveles de organización biológica, ya que, aunque está orientado a poblaciones y comunidades, en la práctica el manejo es ejercido sobre territorios completos a través de acciones específicas sobre el entorno para adaptarlo y fomentar la disponibilidad de recursos (Terrell et al., 2003), conformando así, una expresión geográfica del paisaje.

Contrario a otras formas de aprovechamiento de la naturaleza que se llevan a cabo ocasionando transformaciones contundentes al espacio geográfico, como son las actividades de agricultura y ganadería industrializada con su evidente cambio de uso de suelo, el manejo tradicional como el que se lleva a cabo con *Brahea dulcis* representa una forma de uso no intensivo del paisaje, que presenta manifestaciones ecológicas y espaciales que pueden pasar desapercibidas al conservar los espacios bajo manejo diversos grados de similitud (en términos de cobertura y composición vegetal) con espacios considerados naturales o poco intervenidos. El uso no intensivo del paisaje hace referencia a las adecuaciones realizadas sobre los territorios para el manejo tradicional de especies en un emergente proceso de domesticación o silvestres, que son manejadas *in situ* y que incluye actividades de recolección, selección, tolerancia, protección y cultivo (González-Insuasti y Caballero, 2007).

Implicaciones eco-geográficas

El manejo de *Brahea dulcis* ha tenido importantes implicaciones ecológicas a distintas escalas biológicas. A nivel de especie, los dos morfos reconocidos (la forma arbustiva y la forma arbórea) se han señalado como resultado del manejo diferenciado que se le da a las palmas. Esto ha dado lugar no solo a diferencias morfológicas entres estos, sino que han afectado directamente las formas de reproducción de cada uno. Dado que cada morfo provee de recursos singulares y deseables, ambos son promovidos, dando lugar al desarrollo de poblaciones diferenciadas (las manchoneras y las soyacahuiteras). Estas son mantenidas a través de prácticas de manejo particulares, orientadas a la preservación y fomento de la disponibilidad de los diversos recursos. Esto tiene como consecuencia el fomento de la reproducción vegetativa en las poblaciones arbustivas y la sexual en las arbóreas, lo que conlleva a importantes efectos en la genética de sus poblaciones.

Al ejercerse el manejo *in situ*, las palmas son promovidas en sus espacios naturales a costa de otras especies con las que coexisten. Las prácticas para fomentar la disponibilidad de la palma incluyen su promoción, al mismo tiempo que la eliminación de otras especies acompañantes. De esta manera el manejo, aunque orientado hacia las poblaciones de la especie, tiene resultados extendidos que repercuten directamente sobre las comunidades vegetales de las cuales la palma forma parte, modificando la composición y estructura de las mismas. Así, los palmares son promovidos a costa de la vegetación natural que va siendo necesariamente modificada. Dado que el ejercicio del manejo se da sobre territorios, éste tiene la facultad no solo de modificar comunidades vegetales, sino que, en la práctica, adquiere expresiones espaciales y ecológicas a escalas mayores.

En algunos territorios y bajo ciertas condiciones, el uso no intensivo del paisaje puede derivar con el tiempo en cambios en la conformación de grandes extensiones del espacio geográfico. Esto deviene por la conjugación de ciertos elementos: una alta relevancia económica y/o cultural del recurso, intensidades altas de manejo cuyas prácticas exhiben implicaciones ecológicas y espaciales, así como la continuidad del uso y manejo de las especies a través del tiempo. Estas condiciones actúan como detonadores de cambio, adaptando el entorno para cumplir funciones de abasto y sustento. La impronta humana perdura por la continuidad de estas acciones a través del tiempo y deriva en el proceso denominado Domesticación del Paisaje (Clement et al., 2015; Erickson, 2006; Terrell et al., 2003). Algunas de sus manifestaciones pueden ser cambios en la composición y abundancia de las especies (Balée, 1988; Clement et al., 2015; Levis et al., 2018; Maezumi et al., 2018), el mejoramiento de la fertilidad del suelo (Deur, 2000; Clark Erickson, 2003; Franco-Moraes et al., 2019), el establecimiento de zonas de caza a través del manejo periódico del fuego (Piperno, 2011; Terrell et al., 2003), movimientos de tierra que cumplen distintos propósitos agrícolas e hidrológicos, así como habitacionales (Clement et al., 2015; Denevan, 2001; Erickson, 2006), la introducción de especies (Terrell et al., 2003), entre otras. Una de las formas más comunes de este tipo de procesos es el progresivo desarrollo de parches de vegetación dominados por una o unas cuantas especies de plantas útiles, que son promovidas y mantenidas por actividades humanas de largo plazo (Levis et al., 2018).

Los palmares en la Reserva de la Biósfera de Tehuacán-Cuicatlán

La palma soyate constituye un importante recurso económico para los habitantes de la RBTC. Su uso representa uno de los más antiguos dentro de la región, y al día de hoy continúa siendo relevante como fuente de fibra para la elaboración de objetos comercializables que permiten un ingreso económico para las comunidades rurales más empobrecidas dentro de la Reserva (Echeverria, 2003; Rangel-Landa, 2014; Rangel-Landa et al., 2016; Torres-García, 2003). Quizás más relevante, su importancia biocultural se refleja en su antigüedad de uso y el lazo continuo con el pasado que tanto la palma, como la actividad del tejido, representan. La identificación temprana en el registro arqueológico (E. Smith, 1967), la presencia en códices prehispánicos de la región de objetos tradicionalmente elaborados con esta palma (Chadwick y MacNeish, 1967; Dalhgren, 1979; Jansen y Pérez Jimenez, 2009), la mención constante del uso de palma de monte en diversos documentos históricos del siglo XVI y XVIII (Acuña, 2017b, 2017; García Castro, 2013; Velázquez de Lara, 1984) y el registro de la permanencia de uso en la historia reciente (Dubranka, 2003; García, 1940; Hironymous, 2007; León et al., 1989; Miramontes, 1949; Nava y Romero, 2007; Rangel-Landa et al., 2016; Steffen, 2001), son indicio del uso continuo de esta palma desde tiempos remotos.

Dentro de la reserva, *Brahea dulcis* forma parte del diverso elenco florístico de especies y comunidades vegetales. Es posible encontrarla a lo largo de un amplio gradiente ecológico, formando parte tanto de los bosques templados de *Quercus* spp. y *Juniperus* y bosques de galería, como de una gran variedad de matorrales secos, entre los que se encuentran comunidades de arbustos esclerófilos perennifolios (mexicales), matorrales rosetófilos de *Beaucarnea purpusi* (izotales), entre otros (Rangel-Landa, 2014; Valiente-Banuet et al., 2009). Esta palma forma parte también de algunas comunidades vegetales en las que se presenta como la especie dominante, las cuales se pueden encontrar con cierta frecuencia en algunas zonas al oeste de la región, siempre asociadas a suelos calizos. Estos palmares se encuentran mayormente vinculados a regiones con presencia frecuente de matorrales, particularmente mexicales e izotales, así como a encinares caducifolios. Todas estas comunidades vegetales están fuertemente asociadas a climas secos (Valiente-Banuet et al., 2009). Estas condiciones ambientales desfavorables suponen para las poblaciones que las habitan, actividades agrícolas y pecuarias limitadas y de bajo rendimiento, que en muchos casos resultan insuficientes para el autosustento (Edgar Pérez-Negrón, 2002).

En estas partes de la reserva es frecuente que las poblaciones locales palíen esta situación a través de su integración al comercio, lo que les permite tener un ingreso económico con el cual complementan su economía familiar. En sitios como San Juan Sosola, Santa María Ixcatlán, San Luis Atolotitlán y San Pedro Nodón al Centro-Oeste de la RBTC, se practica el tejido de palma para la elaboración de objetos que son intercambiados por víveres en tiendas locales y/o vendidos en mercados tradicionales de la región (Echeverria, 2003; Rangel-Landa, 2014; Rangel-Landa et al., 2016; Torres-García, 2003). Se plantea aquí que la importancia económica y utilitaria, en conjunto con las muchas otras dimensiones culturales en las cuales la palma y su tejido se proyectan relevantes, debieron fungir desde la antigüedad, como incentivos para detonar el manejo *in situ* de la palma, lo que derivó más tarde en el establecimiento de palmares, razón por la cual estas comunidades vegetales se encuentran particularmente vinculadas a poblaciones asentadas en condiciones ecológicas secas.

Se argumenta aquí que el establecimiento de palmares conforma una de estas formas de domesticación del paisaje, y que, por tanto, si estas comunidades vegetales tienen su origen en el manejo humano, la distribución observada debería acercarse a una distribución potencial derivada de la modelación conjunta de variables ecológicas y de aquellas asociadas al manejo de la especie. Teniendo como base las tendencias observadas en los registros puntuales de presencia del palmar con relación a las covariables climáticas y de manejo, se modeló el nicho ecológico de los palmares en la RBTC, lo que permitió posteriormente proyectar en el espacio geográfico la distribución espacial probable de palmares en la región. La distribución modelada reveló que cerca del 80% del área conocida de palmares utilizada para la evaluación, presentó un valor de predicción por arriba de 0.5, que es un valor típico utilizado para la definición de umbrales de presencia/ausencia en este tipo de modelos (Freeman y Moisen, 2008; Hanberry y He, 2013; Liu et al., 2005). El restante 20% de los sitios que presentaron un valor de predicción por debajo de este número, muestra consistencia con la tasa de omisión estimada del modelo (0.2), que no se atribuye a un sobreajuste de éste, sino a la ausencia de variables explicativas que contribuirían a mejorar las estimaciones[2].

Se argumenta aquí, que dado que la modelación pudo predecir acertadamente ~80% de los sitios con palmar, las variables seleccionadas para la construicción del modelo informan de manera suficiente sobre sobre los factores asociados a la presencia del fenómeno. A partir de este conocimiento, es posible inferir los procesos que subyacen la distribución observada de los palmares. Así, se propone que la presencia de los palmares en la RBTC es el resultado del manejo humano de largo alcance de *Brahea dulcis*. Este manejo sostenido derivó en un proceso de domesticación del paisaje como resultado de años de interacción con la palma. Su sustancial papel como fuente de fibra debió fomentar el interés

[2] Las nuevas tecnologías probaron ser una herramienta útil e interesante para el abordaje de estos procesos. No obstante, los procesos que subyacen la distribución del socio-ecosistema de palmar son complejos, y muchas de las variables socioeconómicas son difíciles de integrar o incluso permanecen sin ser conocidas. Como una forma de mejorar el desempeño del modelo, se propone para futuras modelaciones, la inclusión de variables ecológicas que afinen la estimación del nicho ecológico de *Brahea dulcis,* como el tipo de suelo o la litología, el cálculo de superficies de costo o fricción que integren variaciones en el terreno, como por ejemplo la existencia de veredas o tipos de superficie, así como covariables asociadas al manejo que integren información sobre el rendimiento de las actividades agropecuarias y la relevancia económica y cultural de la palma.

en mejorar su disponibilidad, mientras que su relevancia económica cultural permitió que las prácticas de fomento tuvieran continuidad en el tiempo, llegando hasta nuestros días.

En el proceso de domesticación del paisaje asociado a la presencia de palmares de *Brahea dulcis* en la RBTC, se identificaron algunos indicadores que sugieren como estas relaciones se establecen a través del manejo entre grupos humanos y la biodiversidad de un territorio: i) la existencia de una larga historia de ocupación del territorio, ii) un tiempo prolongado de interacción de los grupos humanos con los recursos, iii) una alta importancia económica de los recursos iv) la integración de esta biodiversidad útil en aspectos culturales de relevancia y v) el desarrolló de la organización social en torno a su manejo. Los indicadores mencionados deberían probar ser en futuras investigaciones, lo suficientemente generalizables a otras formas de manejo tradicional aplicado a la diversidad biológica, lo que ayudaría a desentrañar otros procesos de domesticación del paisaje en Mesoamérica y otras partes del mundo.

Aspectos relevantes

La Reserva de la Biósfera del Valle de Tehuacán-Cuicatlán es uno de los territorios con mayor diversidad biológica y cultural de México. Constituye también el escenario de algunas de las relaciones más antiguas establecidas entre los primeros grupos humanos que habitaron la región y la naturaleza, resguardando registros arqueológicos entre los que se encuentran algunos de los más completos y antiguos de los procesos de domesticación de especies y el desarrollo de la agricultura en América (Mangelsdorf et al., 1967; E. Smith, 1967). Estos registros entre otros aspectos le han merecido su reciente designación como Patrimonio Mundial de la Humanidad por la UNESCO y son de indiscutible relevancia para el entendimiento del desarrollo agrícola en el mundo. No obstante, es necesario reconocer que la región resguarda también otras memorias de procesos antiguos que develan las múltiples formas en que las sociedades humanas interactúan y se vinculan con la naturaleza, cuyas expresiones materiales, aunque menos evidentes, ostentan una relevancia similar.

El entendimiento de estos procesos es de fundamental importancia, no solo como un justo reconocimiento a la notabilidad en este caso, del conocimiento gestado en torno a *Brahea dulcis* y su manejo como lazo de continuidad con el pasado que llega a tocar las raíces más profundas de los y las mexicanas; sino también como un conocimiento imprescindible sobre otras formas de relación y aprovechamiento de la naturaleza, y su utilidad para el establecimiento de sistemas productivos sustentables (Berkes y Folkes, 1994).

Los palmares como sistemas productivos tradicionales, conforman socio-ecosistemas que sostienen modelos de subsistencia muy diversificados, integrando múltiples formas de aprovisionamiento y una alta diversidad de especies (Casas et al., 2014; Moreno-Calles et al., 2013; Vallejo et al., 2014). Mientras que en los sistemas productivos convencionales el principal objetivo es conseguir el mayor rendimiento por unidad de área (lo que se obtiene a través de un uso intensivo del paisaje, promoviendo la expansión de los cultivos por lo regular monoespecíficos hacia toda el área disponible), las formas tradicionales de producción no privilegian la ganancia monetaria sobre otros atributos del sistema que son más beneficiosos, sino que buscan garantizar el flujo de recursos necesarios, por lo que una gran cantidad de productos son obtenidos de un territorio a lo largo del año (Berkes y Davidson-Hunt, 2006; Emperaire y Peroni, 2007; Farfán-Heredia et al., 2018; E. Pérez-Negrón y Casas, 2007). Esto permite liberarse de una alta dependencia sobre un mismo recurso, lo que marca una importante diferencia en contraste con tipos de manejo intensivos del paisaje, que derivan en cambios masivos en el uso de suelo (con las problemáticas asociadas de pérdida de hábitat, biodiversidad y alteraciones a los sistemas edáficos, hídricos y atmosféricos) (Slaymaker, 2001; Turner et al., 1994) y el desplazamiento de sistemas productivos integrales, promovido a través del fomento de grandes áreas de monocultivos, con las conocidas e indeseables consecuencias que esto acarrea (susceptibilidad a patógenos, vulneración de sistemas de subsistencia, alta dependencia en la economía de mercado) (Altieri y Toledo, 2011; Gebru, 2015).

Los socioecosistemas de palmar han mostrado ser efectivos para el sostenimiento de sociedades por largos periodos, integrándose en múltiples dimensiones de la vida humana. Estas formas de manejo derivan de la gran relevancia socio-económica y cultural asociada a los recursos y a los sistemas productivos tradicionales. En la parte económica, el sostenimiento de estos sistemas puede significar una parte substancial de las economías rurales, fungiendo en muchos casos como una de las pocas o la única fuente de ingreso económico, inscribiéndose en actividades de intercambio que les permiten a miles de familias rurales la adquisición de bienes de consumo no producidos por ellas (Aguilar et al., 2005; Echeverria, 2003; Rangel-Landa et al., 2016). Esto tiene una importante implicación socio-cultural, dado que a través de la comercialización se llevan a cabo importantes procesos de articulación social y de reconocimiento intercultural (Mintz, 1982), los cuales refuerzan la identidad cultural y comunitaria (Arellanes et al., 2013; Rojas Serrano et al., 2010). Asimismo, la continua puesta en práctica del conocimiento acumulado por generaciones, fortalece estos procesos, vinculando a las personas con sus ancestros y arraigándolas a los territorios (Rojas Serrano et al., 2010). Esto último tiene importantes implicaciones sobre temas sensibles como el sostenimiento y la continuidad de sistemas productivos de autosustento.

No obstante, la falta de apoyos gubernamentales, la economía de mercado y la baja remuneración y expectativa que plantea el trabajo en el campo, son factores que juegan en contra de la permanencia de estos sistemas, orillando a las generaciones más jóvenes a salir de sus comunidades en busca de mejores oportunidades de vida, lo que tiene importantes y negativas consecuencias en los sistemas productivos tradicionales, que son los primeros en resentir los efectos de la fragmentación familiar y la desarticulación comunitaria derivada de la migración (Barrios-Hernández y Hernández, 2003; Gómez, 2001). A esto se suma la existencia de subsidios gubernamentales que inducen al uso no sustentable de los recursos a través del fomento de actividades pecuarias, frutícolas o agrícolas que promueven la deforestación y/o degradación (CONAFOR, 2017), promoviendo la disrupción de estos procesos a través de la introducción de cambios en las formas de producción.

Por estas razones, para que este conocimiento pueda traducirse en sistemas socio-ecológicos auténticamente sustentables, se deben fomentar el justo reconocimiento al valor ecológico y socio-cultural que resguardan estas formas de producción, de manera que esto se traduzca en un mejoramiento de las condiciones de vida de las personas que resguardan la memoria de este conocimiento (los proyectos como REDD+ plantean un importante espacio para lograr que estas situaciones se hagan realidad a través de la gestión de políticas públicas que orienten subsidios a estas formas de producción y establecimieno de cadenas de valor para los productos provenientes de estos sistemas, no obstante, importantes obstáculos aún se deben salvar para gestionar la implementación de estos proyectos en ecosistemas secos y semiáridos). Estos sistemas productivos tradicionales son relevantes, no solo porque han probado ser capaces de sostener sociedades a largo plazo, sino que, además, se inscriben en las dimensiones más relevantes de la vida humana, teniendo mecanismo de retroalimentación que favorecen su permanencia y sostenibilidad.

CONCLUSIONES

Los estudios etnoecológicos y la perspectiva histórica en el manejo de recursos constituyen una invaluable fuente de información para reconocer interacciones sociedad-naturaleza de largo alcance y de esta manera inferir los procesos que subyacen la conformación del paisaje.

Esta información puede ser proyectada en el espacio a través de enfoques interdisciplinarios, que permitan espacializar los fenómenos. Los Sistemas de Información Geográfica y la Modelación Espacial, contribuyen al entendimiento de los procesos de domesticación del paisaje, abordados a través de la construcción de modelos ecológicos de distribución potencial y la incorporación de variables sociales asociadas al manejo de recursos. No obstante, existen limitaciones del método que es necesario reconocer, ya que no todas las variables sociales pueden ser integradas en estas metodologías, debido a que las interacciones y relaciones sociedad-naturaleza son complejas y difíciles de entender, e incluso percibir. Por tanto, es necesario un conocimiento profundo de las actividades y los territorios bajo estudio, de manera que se puedan reconocer las interacciones y dar una explicación plausible a la distribución espacial de los fenómenos asociados al manejo de recursos. La presente contribución es apenas una aproximación a la explicación de las implicaciones espaciales de estos procesos en el paisaje.

Los procesos que dieron origen a los palmares, así como otras formas de uso no intensivo del paisaje, conforman un testimonio vivo de otras formas de aprovechamiento y relación con la naturaleza, que es necesario conocer e investigar, cuyas historias vale la pena ser contadas a manera de una narrativa alterna sobre otras formas posibles de interacción. Esta otra narrativa nos muestra posturas distintas y formas diferentes de relacionarnos con el entorno, formas que nos acercan a la naturaleza, en vez de alejarnos de ella, y que han permitido a diferentes sociedades alrededor del mundo permanecer y trascender desde tiempos inmemoriales.

Por último, se considera que a pesar de las dificultades que juegan en contra de la permanencia de estas actividades en esta y otras regiones donde es común la baja retribución monetaria del trabajo, las actividades asociadas a la palma estan lejos de desaparecer. Esto se sustenta en la gran importancia biocultural de *Brahea dulcis*, su relevancia económica, así como a los multiples significados y funciones que se le otorgan en las comunidades de la RBCT. Por estas razones se considera que tanto la cestería y sus artífices, como el manejo tradicional y sus espacios construidos como herencia ecológica, representan acervos culturales que seguirán formando parte del paisaje regional. Ellos en su conjunto representan una herencia cultural que nos vinculan con las raíces más profundas de lxs mexicanxs por lo que es necesario incentivarse su justo reconocimiento y valoración.

Por otro lado, es necesario reconocer, que ante las crisis globales actuales, los objetos elaborados con fibras naturales representan también, una alternativa de bajo impacto ambiental para satisfacer la demanda de muchos productos que se elaboran con plástico. Voltear la mirada a estas formas de producción artesanal será beneficioso en al menos dos sentidos: sobre las economías familiares que dependen en alguna medida de estas actividades productivas, y en relación a los beneficios ambientales que significaría una reducción en los desechos plásticos. La producción y uso puede fomentarse a través de instrumentos económicos. Estos deben orientarse a establecer las condiciones que les permitan a las comunidades manejadoras organizarse para mejorar el manejo de la palma, la producción y la comercialización de los objetos, fomentando el diálogo horizontal con instituciones académicas y publicas. La educación fungirá un papel importante en estos procesos, como medio para estimular la valoración cultural de las formas tradicionales de producción, y para informar sobre los beneficios de la reducción en el uso de plásticos. Estas acciones contribuirán a la continuidad de esta actividad profundamente vinculada a la identidad mexicana.

Recomendaciones para investigaciones futuras

En este punto se considera relevante abordar temas aún faltantes que ayudarían a comprender integralmente los procesos de domesticación del paisaje en la RBTC. La investigación exhaustiva de la relación histórica de la palma con los grupos humanos de la región ayudará a dimensionar adecuadamente la importancia biocultural de los palmares y las poblaciones asociadas a ellos, así como a comprender su establecimiento y desarrollo en la región. El estudio de la historia ambiental asociada a los palmares, a través de la revisión de fuentes paleoecológicas, arqueológicas, códices y archivos históricos contribuirá a entender estos importantes procesos.

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