Vulnerability of Biodiversity to Land Use Change and Climate Change in Mexico

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Own Work Declaration

I declare that the work contained in this thesis is my own, unless indicated otherwise. No part of this thesis has been previously submitted or accepted for a degree or professional qualification. Alma Virgen Mendoza Ponce

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Abbreviations

AC	Adaptive Capacity
AI	Aridity Index
AICAs	Important Birds Areas in Mexico
AR4	Assessment Report 4th
ASFR	Age-Specific Fertility Rates for a single year
CA	Cellular automata
CBD	Convention on Biological Diversity
CC	Climate Change
CCA-UNAM	the Centre of Atmospheric Sciences
CGCM2	Canadian Center for Climate Modeling and Analysis, Coupled Global Climate Model 2
CICESE	Scientific Research and High Education Centre of Baja California
CIESIN	The Center for International Earth Science Information Network
CLUE	Conversion of Land Use and Its Effects
CLUE-S	Conversion of Land Use and its Effects at Small regional extent
COLMEX	College of Mexico (El Colegio de México)
CONABIO	The National Commission for Knowledge and Use of Biodiversity (Comisión Nacional para el Conocimiento y Uso de la Biodiversidad)
CONANP	The National Commission of Natural Protected Areas (Comisión Nacional de Áreas Naturales Protegidas)
CONAPO	National Population Council (Consejo Nacional de Población)
CPD	The Centres of Plant Diversity
CRI	Critical Risk Index
DINAMICA EGO	Dinamica -Environment for Geoprocessing Objects
Dyna-CLUE	Dynamic Conversion of Land Use and its Effects
EBAs	Endemic Bird Areas
FMCN	The Mexican Fund for the Conservation of Nature
FNPA	Federal Natural Protected Areas
G	Grasslands
GCMs	General Circulation Models
GDP	Gross Domestic Product
GEC	Global Environmental Change
GEF	Global Environmental Fund
GEnS	global environmental stratification
GIS	Geographic Information Systems
HadCM3	Hadley Center for Climate Prediction, Hadley Centre Coupled Model 3
HV	Hidrophillic vegetation
IA	Irrigated Agriculture
IIASA	International Institute for Applied Systems Analysis

IMF	International Monetary Fund
IMTA	Water Mexican Institute
INECC	National Institute of Ecology and Climate Change
INEGI	The National Institute of Statistics and Geography (Instituto Nacional de Estadística y geografía)
IPCC	Intergovernmental Panel on Climate Change
IUCN	The International Union for Conservation of Nature
Kfuzzy	Kappa Fuzzy
LCM	Land Change Modeller
LGEEPA	General Act on Ecological Balance and Environmental Protection
LUCC	Land Use Cover Change
MEA	Millennium Ecosystem Assessment
MK2	the Commonwealth Scientific and Industrial Research Organization, Atmospheric Research Mark2
NAFTA	North American Free Trade Agreement
Nies99	the Japanese National Institute for Environmental Studies
NPA	Natural protected Area
OC	Other Covers
OECD	Organisation for Economic Co-operation and Development
OV	Other Vegetation
PET	Potential Evapotranspiration
PHR	Priority Hydrological Regions
PI	Potential impact
PMR	Priority Marine Regions
PNUD	the Programme of the United Nations Development Programme
PSBC	Priority Sites of Biodiversity Conservation
PTR	Priority Terrestrial Regions
RCP	Reprecentative Concentration Pathways
REA	Reliability Ensemble Averaging
RfA	Rainfed Agriculture
SRES	Special Report on Emissions Scenarios
SSP	Shared Socioeconomic Pathways
TDF	Tropical Dry Forest
TEF	Tropical Evergreen Forest
TF	Temperate Forest
TFR	Total Fertility Rate
TMDG	Temperature of growing degree-days
TSD	Temperature Seasonality
UN	United Nations
UNAM	Universidad Nacional Autónoma de México
UNEP	The United Nations Environment Programme
US	United States of America

V	Vulnerability
VAR	vector autoregressive model
WofE	Weights of evidence
WWF	World Wide Fund for Nature

Abstract

Biodiversity in Mexico is threatened by Land Use/Cover Change (LUCC) and Climate Change (CC). Identifying what sites will be most vulnerable to these threats can help to prioritise conservation, mitigation and adaptation strategies and target limited resources. Therefore, the aims of this study are 1) to identify the most vulnerable sites to LUCCs under different socio-economic and CC scenarios, and 2) to assess the vulnerability of endemic and threatened vertebrate species to establish prioritization strategies for biodiversity conservation. Spatially explicit socio-economic scenarios were created at national and subnational level (Chapter 3). National LUCC models were then developed using the DINAMICA EGO software (Chapter 4). These models were run for three future time slices (2020s, 2050s and 2080s) and two contrasting future climate and socio-economic scenarios to determine biodiversity vulnerability (Chapter 5). Vulnerability was estimated by quantifying the exposure, sensitivity and adaptive capacity to LUCC and CC. This framework integrates national information about the priority sites of biodiversity conservation and their future extent of natural covers under future socio-economic and climate conditions. Finally, the vulnerability framework was also applied in a regional case-study in three municipalities of southern Mexico (Chapter 6). Results reveal that temperate forest is the most vulnerable ecosystem type in Mexico, followed by natural grasslands and tropical evergreen forests. Agriculture is the driver of this threat, which is projected to expand to feed an increasing population under dryer climatic conditions. More than 40% of endemic and endangered mammals are in places ranking from medium to extremely high vulnerability, followed by the 28% of the amphibians, 25% and 23% for reptiles and birds, respectively. These vertebrates are principally distributed on temperate forests and tropical dry forests. In the regional scale, rain-fed agriculture (RfA) and anthropogenic grasslands are the principal LUCC drivers, threatening 31 species of endangered vertebrates. A local strategy for creating corridors between patches close to rivers from the south to the north of one municipality is supported as conservation priority for the regional biodiversity. This research presents a novel approach for prioritising conservation strategies in highly biodiverse countries using readily available data sources, demonstrated at different spatial and temporal scales.

Chapter 1

1.1 Global change impacts on biodiversity

Biodiversity loss continues globally, driving major alterations to the Earth's ecosystems and the services they provide (Cardinale *et al.*, 2012; Hooper *et al.*, 2012; Newbold *et al.*, 2015). Humans have affected the atmosphere, hydrosphere and biosphere (Foley *et al.*, 2005; Steffen *et al.*, 2007; Ellis, 2011; Halpern *et al.*, 2015). Anthropic alterations include land use/cover change (LUCC), changes in biogeochemical cycles (Erisman *et al.*, 2013; Randerson *et al.*, 2015), and biotic perturbations such as invasion, extinctions and modification of ecosystems (Vitousek *et al.*, 2008; Barnosky *et al.*, 2012). Global processes such as CC or globalization impact at regional and local level affecting ecosystems and their management (Ellis and Ramankutty, 2007). To assess the effects of human populations and their use of land, spatially and temporarily explicit estimates of direct and indirect forces of change should be considered, quantitatively and qualitatively, as well as their interactions (Anastasopoulou *et al.*, 2009). Principal causes of biodiversity loss are LUCC and CC (Sala *et al.*, 2000; Oliver and Morecroft, 2014a). LUCC comprises changes in biophysical attributes of the Earth's surface (land cover) and land used for human purposes such as agriculture or pasture (Lambin *et al.*, 2001; Lambin and Meyfroidt, 2011). LUCC is one of the prime forces of changes in the Earth's system and climate in particular. The expansion of cropland and pasture at the cost of forests results in an increase of atmospheric CO_2, and in a decrease in the sink capacity of the global terrestrial biosphere, amplifying atmospheric CO_2 concentration (Verburg *et al.*, 2011).

LUCC not only affects CC, which in turn impacts biodiversity, but also forms of LUCC, themselves (Oliver and Morecroft, 2014b), are the main cause of extinction of many species (Brooks *et al.*, 2002). Deforestation is the single most measured process of LUCC on a global scale. Forests area loss has been cut in half and is now less than one-tenth the rate of human population growth (FAO, 2015). By 2015 there is 0.6 ha of forest *per capita*, while in 1990 was 0.8 ha per person these figures are differentially distributed considering that temperate zones keep increasing the forest area while the tropics augment the forest loss (FAO, 2015).

Impacts of LUCC on CC are studied as drivers of CC; however, in many cases the interrelations are more complex (Oliver and Morecroft, 2014a), and LUCC are also induced by CC as in the case of droughts that impact the suitability of land (Dale, 1997; Verburg *et al.*, 2011; IPCC, 2014b). Besides these direct drivers of LUCC such as climatic variables, other indirect influences are demographic and economic (Geist and Lambin, 2002; Lambin *et al.*, 2003; Houghton *et al.*, 2012; Elmhagen *et al.*, 2015), technological, or political and cultural factors (Geist and Lambin, 2002; Nelson *et al.*, 2006; IPCC, 2014b). Consequently, interactions of LUCC, climate and biodiversity should be thought as phenomena with multiple socio-ecological and socio-economic elements that interact on different spatial and temporal scales (Lambin and Meyfroidt, 2010; Elmhagen *et al.*, 2015).

CC has been the consequence of anthropogenic activities such as energy use, aerosols, and LUCC (IPCC, 2013). These activities have caused the increase of greenhouse gas (GHG) concentrations that have directly related to surface temperatures and changes in climate variability including precipitation (Raja *et al.*, 2005). CC, as with LUCC, has effects on different scales, modifying the phenology, physiology and distribution of many species (Gian-Reto *et al.*, 2002; Broennimann *et al.*, 2006). CC and LUCC are the major threats to biodiversity, and are consequently considered a major challenge for conservation practices (Pressey *et al.*, 2007; Kujala *et al.*, 2013). The majority of studies has examined effects of a single driver such as LUCC or CC but research that integrates effects among multiple drivers is needed (Tylianakis *et al.*, 2008). This applies especially in megadiverse, developing tropical countries where interactions between LUCC and CC will severely affect biodiversity (Lambin *et al.*, 2003). Accordingly, LUCC research that includes biological, climatic and socio-economic characteristics will allow a deeper understanding of the causes and consequences of the LUCC and CC phenomena, serving to point out places that are most vulnerable (Asner *et al.*, 2004).

1.1.1 Spatial Conservation Prioritisation

During the last decades some global and national efforts have been developed under the spatial conservation prioritisation framework. This prioritisation is understood as the process of quantitatively analysing data to identify locations for conservation purposes (Wilson *et* *al.*, 2009). Global and national efforts have been built on two key concepts: 1) irreplaceability and 2) vulnerability (Pressey *et al.*, 1994; Margules and Pressey, 2000).

Irreplaceability has been defined in two ways: 1) as the likelihood that a site will be required to meet a given set of conservation targets, and 2) as the extent to which these targets can be achieved if the area is lost (Pressey *et al.*, 1994; Ferrier *et al.*, 2000; Margules and Pressey, 2000). Irreplaceability cannot only be considered as the number of species alone because several areas can share the same number of species. In contrast, areas with high levels of endemism have been considered a better indicator for irreplaceability because of their uniqueness (Krupnick and Kress, 2003; Mittermeier *et al.*, 2011).

Vulnerability can be defined in qualitative terms as the capacity to be wounded (Kates, 1985). However, in quantitative terms, vulnerability is a function of exposure, sensitivity, and adaptive capacity (Turner *et al.*, 2003; Adger, 2006). Exposure is the possibility of entities being placed in areas that could be adversely affected when harmed (IPCC, 2014a). Sensitivity is the susceptibility of the entities to be harmed (IPCC, 2014b), and AC is the process of adjustment to actual or expected conditions (IPCC, 2014b).

Considering that vulnerability is not spatially and temporarily homogeneous there are approaches and tools that allow the prioritisation of areas depending on specific conservation or mitigation targets. In the context of biodiversity, spatial conservation prioritisation allows analysis of quantitative data for the purpose of identifying locations to lead resources not only to places vulnerable to LUCC or CC but also to places that are irreplaceable in terms of biodiversity (Pressey *et al.*, 1994; Margules and Pressey, 2000) such as megadiverse areas with high levels of endemism (Krupnick and Kress, 2003; Mittermeier *et al.*, 2011). In recent decades some global and national efforts about prioritising places to conserve biodiversity have been developed, such as the group of megadiverse countries or the Aichi targets (CBD, 2002, 2014). Mexico has been part of the countries that have been adopted the Strategic Plan for Biodiversity 2011-2020. Mexico, as the rest of signing countries, should develop national and regional targets, using the Strategic Plan and its Aichi Targets, as a flexible framework. Aichi Targets are focus on 5 key points: 1) address the underlying causes of biodiversity loss by mainstreaming biodiversity across government and society, 2) reduce the direct pressures on biodiversity and promote sustainable use, 3) improve the status of biodiversity by safeguarding ecosystems, species and genetic diversity, 4) enhance the benefits to all from biodiversity and ecosystem services, and 5)enhance implementation through participatory planning, knowledge management and capacity building (CBD, 2014).

Global and national efforts to prioritise biodiversity conservation have shown that a wide area (~33% to 65%, depending on the study) of Mexico should be protected, rendering these efforts useless due to difficulties in addressing economic and social resources to fulfil the enormity of the desired targets making more difficult to achieve the Aichi targets (chapter 5) because of the scarcity of resources for conservation management that Mexico faces (Salcido *et al.*, 2009). In this context, Mexico as a megadiverse country has a responsibility to apply strategies for biodiversity conservation by avoiding, minimizing or mitigating the effects of the most important threats, such as LUCC and CC. Consequently, prioritisation of irreplaceable and vulnerable places in terms of biodiversity might facilitate stakeholders to address the available resources in an efficient way making easier to fulfil the Aichi targets.

1.2 Objective and research questions

This thesis will address the need for methods to prioritise biodiversity conservation in Mexico. The main objective of the thesis is therefore:

To develop a methodology to spatially prioritise biodiverse areas in Mexico which are the most vulnerable to LUCC under different socio-economic and CC scenarios?

Specifically, the research will answer the following research questions:
- How many people pressuring the ecosystems would live in Mexico by 2020, 2050 and 2080 under different scenarios?
- What will be the effect of this increasing population on the Mexican LUCC?
- What places in Mexico are the most vulnerable to LUCC and CC?
- What ecosystems are the most vulnerable to LUCC and CC?
- What species of endemic and threatened vertebrates live in the most vulnerable areas?

1.3 Thesis Outline

To answer these questions the thesis is structured in six chapters which include an overview of Mexico’s diversity and its threats, followed by a chapter of socio-economic projections at different scales and time slices; then a chapter focus on modelling forms of LUCC and detecting the hotspots of change under different CC and socio-economic scenarios at national level. The following chapter depicts the national vulnerability approach at regional level by providing a case study (Figure 1). The last chapter summarises the general contributions and limitations of the work. The following paragraphs describe in more detail the structure of the chapters and their objectives.

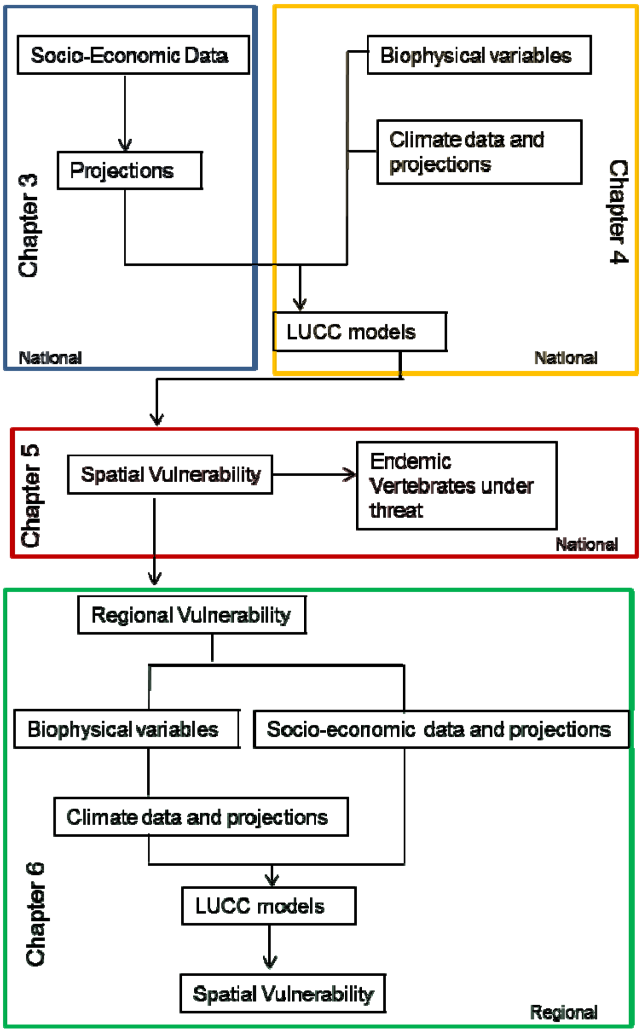

Figure 1. Research methodology flow chart.

Chapter 2 contextualises Mexico as a country megadiverse in cultural and biological characteristics. This richness is the result of biophysical and social features. The chapter gives a general overview of the Mexican context to facilitate a general understanding of the chapters that follow. It gives information about Mexican geography, administrative divisions, cultural and biological diversity and the importance of this diversity for landscape history related to LUCC and CC.

Chapter 3 contextualises socio-economic variables through projections under different scenario assumptions, at sub-national level and in fine grid resolution for Mexico. The chapter consists of three parts: 1) Development of demographic projections following a deterministic bottom-up method, and a downscaling probabilistic approach under different scenarios on different scales. 2) Development of economic projections by using a downscaling probabilistic approach under different scenarios on different scales. 3) Spatial contextualization of the socio-economic projections at 1km x 1km resolution showing the real inhabited area by different time slices and scenarios at country level.

Chapter 4 focuses on determining the hotspots of LUCC under different CC and socioeconomic scenarios for Mexico. The LUCC models were developed in the Dinamica EGO platform by using maps (1:250,000). The LUCC models were projected for three-time slices: 2020s, 2050s and 2080s, under A2 and B2 assumptions of the Special Report on Emissions Scenarios (*SRES*) by the Intergovernmental Panel on Climate Change (IPCC). The chapter provides first a general description of the different LUCC models and approaches. Secondly, it gives a summary of the inputs and the steps involved in the model. Thirdly, the principal results highlight the natural land covers that have been more affected by LUCC under different socio-economic and CC scenarios, and the principal socio-economic and biophysical variables for these changes. Finally, the strengths, the limitations and the implications of this approach are discussed.

Chapter 5 describes a general framework for spatial conservation prioritisation and its concepts and tools by taking the national example of Mexico. This chapter links the spatial information about LUCC and CC hotspots identified in Chapter 4 to biodiversity. The concepts of ‘irreplaceability’ and ‘vulnerability’ are used to build a model framework to prioritise regions for biodiversity conservation in Mexico. The vulnerability of the biodiversity is quantified in terms of exposure, sensitivity and adaptive capacity (AC). The outputs of this chapter are the hotspots of vulnerability at national level by integrating biodiversity indicator and their threats (LUCC and CC). The chapter concludes by identifying endemic and threatened species of vertebrates which are present in the vulnerable places of the country.

Chapter 6 applies the vulnerability framework at a regional level by focusing on three of the most vulnerable municipalities determined in Chapter 4 in a tropical dry forest (TDF) region, in southern Mexico. The LUCC models were developed in the Dinamica EGO and projections were developed by the same three-time slices and scenarios as the national model. This chapter first provides a general overview of TDF, its importance and threats. A section therefore follows in which the inputs and the steps involved in modelling the LUCC and especially the Rain-fed Agriculture (RFA) is developed. The results then show the past and future dynamics of TDF in the region and the differences between municipalities based on the socio-economic and biophysical variables of change. Moreover, it is determined what endemic and endangered species of vertebrates there are in the region. Finally, the challenges and limitations of applying a vulnerability framework at regional scale and further work are discussed**.**

Chapter 7 focuses on summarising and analysing the principal findings, the strengths and the weaknesses of the methodology and the approach applied. It analyses the possible practical application of the vulnerability framework on different scales in the Mexican context. Finally, it critically discusses the relevance of this work to the field of spatial conservation prioritisation and suggests some challenges of integration in further and future work.

Chapter 2. General Context of Mexico

Mexico is a megadiverse country in cultural and biological features. This richness has been the result of biophysical and social historical and geographical processes. This chapter will give a general overview about the Mexican context to facilitate a general understanding of the chapters that follow it.

2.1 Geography

Mexico is located in North America between 14^{o} and 33^{o} North and - 86^{o} and - 119^{o} West; it is bordered to the North by the United States of America, in the South by Guatemala and Belize. Mexican physiography is complex, resulting from the interaction of five tectonic plates (Ortega *et al.*, 2000): 1) North American, 2) Pacific, 3) Rivera, 4) Cocos and 5) Caribbean. Two mountain chains were generated by the convergence of these plates: La Sierra Madre Occidental and La Sierra Madre del Sur; whilst volcanism created La Sierra Madre Oriental, the Trans-Mexican Volcanic Belt (or Central Volcanic Belt), and the plains and depressions (Espinosa *et al.*, 2008) (Figure 2).

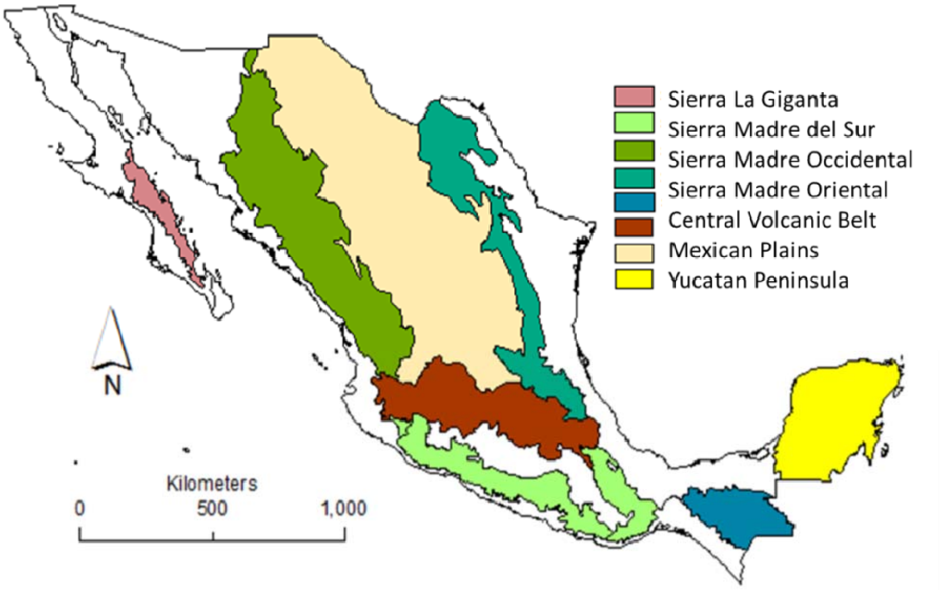

Figure 2. Mexico’s physiographic divisions, modified from Rzedowski and Trujillo-Reyna (2001) .

Mexico has a funnel shape that impacts the effect of the trade winds which, with the seasonal oscillation of the subtropical belt, creates a very diverse climatic pattern in the country (García, 2004; Vidal-Zepeda, 2005). For instance, Mexico has 15 out of the 18 Global Environmental Zones and 73 out of the 125 Global Environmental Strata identified by Metzger et al. (2013) based on bioclimate characteristics. Mexico shows very hot and dry climes in the north, while the south is warm, temperate and mesic, until becoming hot and moist. From west to east the pattern is hot and dry on the Pacific coast until very moist on the Gulf Coast. However, on the tops of the mountains of the Trans-Mexican Belt, the clime is temperate, from cool to cold (García, 2004) (Figure 3).

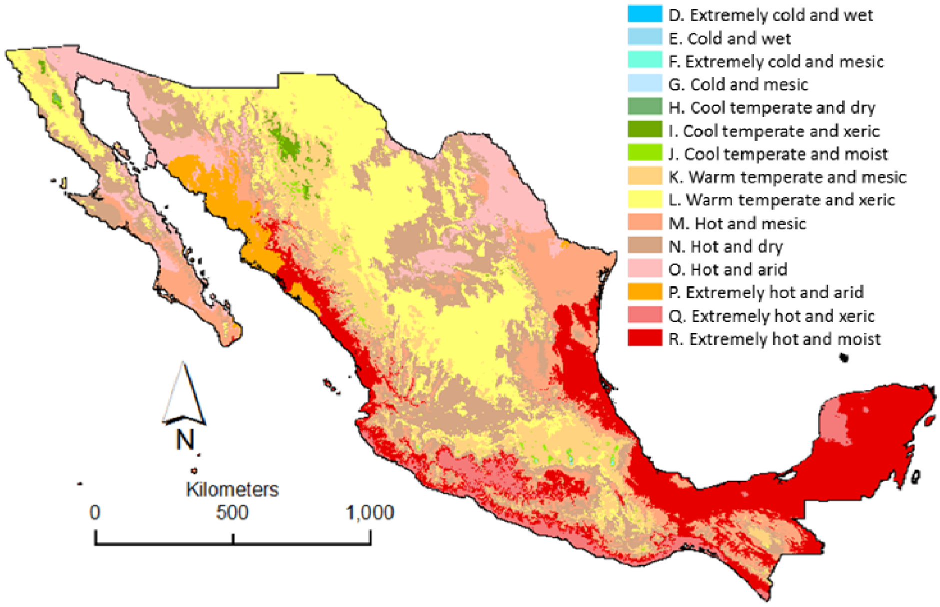

Figure 3. Mexico's Environmental Strata according to Metzger (2013).

2.2 Administrative divisions

Mexico has 32 states divided into 2,456 municipalities with high heterogeneity in area, population, and economic development. For instance, although Mexico's average population density is ~57 persons per km^2, there are some municipalities showing ~6,000 inhabitants per km^2 and others reporting ~9 inhabitants per km^2 (Figure 4).

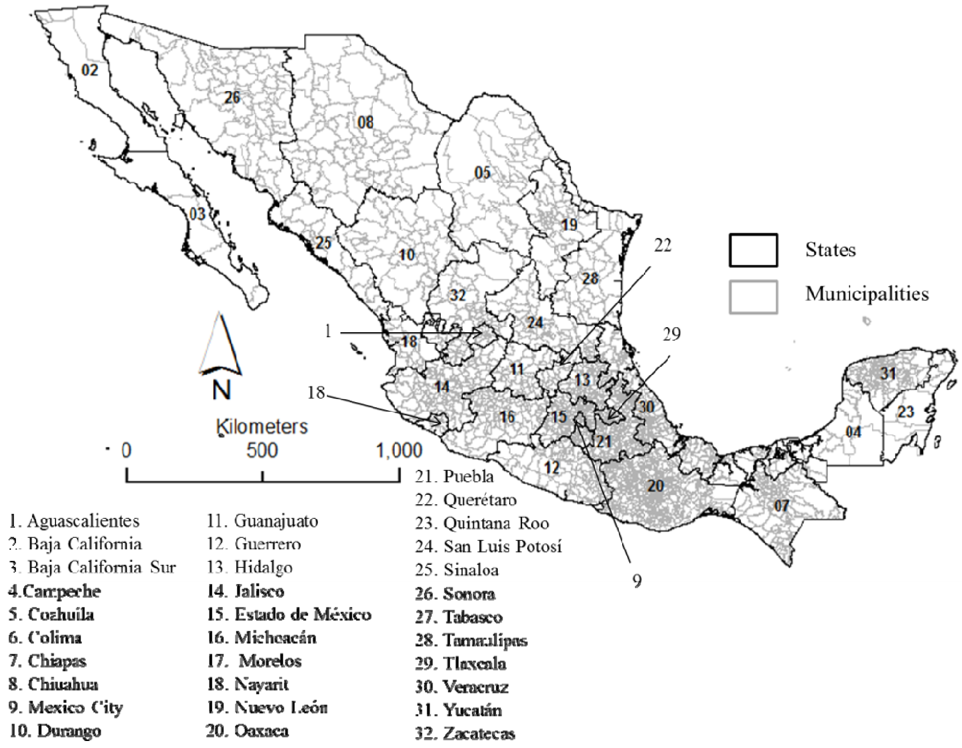

Figure 4. Mexican States (n=32) and municipalities (n= 2,456), modified from INEGI (2010d).

2.3 Biological diversity

Mexico is one of the richest countries in biological diversity worldwide. Biologically, Mexico is in fourth place in the group of 17 megadiverse countries, whose biodiversity represents around 70% of the known species (Mittermeier *et al.*, 1997; Sarukhán and Dirzo, 2001).

In terms of fauna, Mexico ranks third in species of mammals (Ceballos and Brown, 1995; Ceballos *et al.*, 1998; Ceballos *et al.*, 2002; CONABIO, 2009). It possesses more species of mammals than Western Europe, the United States, Canada, or Australia. The uniqueness of its mammalian fauna is based on its species' richness and endemicity (Ceballos and Navarro, 1991). Mexico is the second and eighth ranked country for richness of, respectively, reptiles and birds (Llorente-Bousquets and Ocegueda, 2008b).

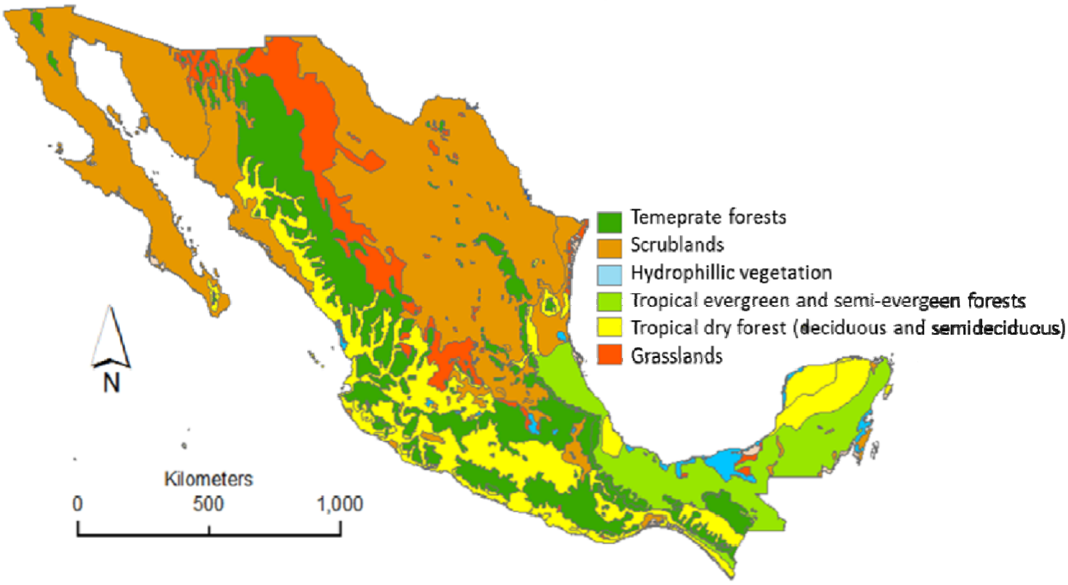

Figure 5. Mexican types of potential vegetation, modified from Rzedowski (1990).

Mexico has 32 major types of vegetation (Table 3) which follow a moisture gradient from tropical evergreen forests in the south to extreme aridity vegetation in the north (Miranda and Hernández, 1963; Robles and Dirzo, 1996). The most used and detailed system in Mexico is the INEGI's system, which proposes more than 50 types of land uses and covers. This dynamic classification system is continuously corroborated by field work through the national forestry inventory (INEGI, 2001, 2005, 2008). The different classes are clustered for this study into eight groups, six natural covers (Figure 5) and two anthropogenic covers (Figure 6): 1) temperate forests (conifers, deciduous forests); 2) scrublands; 3) hydrophilic vegetation (including mangroves and riparian tropical forests; 4) tropical dry forests (comprising tropical semi-deciduous forests and thorny forests); 5) tropical evergreen forests (including different types of semi-evergreen forest); 6) natural grasslands (including high altitude grasslands, lowland grasses and halophilic grasslands); 7) other kinds of vegetation and 8) other covers that include agriculture, urban and rural settlements.

Temperate forests (TF) are distributed along the mountain chains through the Sierra Madre Occidental, the Sierra Madre Oriental, Sierra de Oaxaca and the Trans-Mexican Volcanic Belt. These forests are related to humid and sub-humid conditions. They are characterized by different species of conifers (pines and firs) and broadleaves (oaks). These ecosystems present not only boreal affinities but also neo-tropical ones because of their underwood. TF reports more than 7,000 species (~25% of the Mexican phanerogamic flora) (Rzedowski, 1998). It is important to notice that 27% out of the genera of conifers is endemic (Rzedowski, 1998). Mexico is the richest country in species of *Pinus*, having 69 taxa, including subspecies and varieties of 29 species (Mirov, 1967; Eguiluz-Piedra, 1985). Temperate forests are spread on 439,600 km^2 (INEGI, 2003), and according to official and recent reports they nowadays represent 16.45% (323,200km^2) (INEGI, 2005).

Cloud forests were considered as TF because they occupy ~0.45% of the natural vegetation of Mexico and because of their climate similitudes (INEGI, 2005). Cloud forests are the highest altitudinal border of the warm and humid vegetation, and they are present in mountain landscapes between 800 to 2,200 m.a.s.l. (Rzedowski, 2006), presenting a high level of endemism (~3,000 species) (Rzedowski, 1998). Originally cloud forests occupied ~31,000 km^2 (INEGI, 2003); however, their distribution has been diminished ~50% (INEGI, 2005).

The scrublands-ecosystem is the most spread natural cover of the country. It includes a range of vegetation of dry, semi-arid and arid conditions. Scrublands are distributed especially in the north of the country (in the states of Tamaulipas, Sonora, Baja California), some parts of the centre (Puebla), and to a lesser extent in southern regions (Oaxaca). The endemism of this vegetation is 37% for the genera which contributes 44% of endemic flora (Rzedowski, 1998). The original extension of scrublands was ~710,000 km^2 (INEGI 2003); nowadays they occupy 29.7% of the country (~540,000 km^2) (INEGI, 2005).

Hydrophilic vegetation (HV) is spread on all types of climate. It is distributed in hot places with high precipitation, until meeting temperate conditions with low precipitation (Rzedowski, 2006). This category includes a great variety of ecosystems, such as mangroves, popal and riparian forests. Mangroves are principally represented in the Gulf of Mexico from the northern states of Tamaulipas through Veracruz, Tabasco and Yucatán. This vegetation can be found in shrubby or tree shapes on muddy soils (Rzedowski, 2006). Finally, riparian forests are associated with rivers showing themselves from 0-2,800 m.a.s.l. through the borders of Tropical Dry Forest (TDF), Tropical Evergreen Forests (TEF) and TF (Rzedowski, 2006). HV covers only 0.66% of Mexico; that means 12,400 km^2 that are not mangroves and 7,700 km^2 which are mangroves (INEGI, 2005). Although this kind of vegetation has been significantly damaged by LUCC there is a lack of studies at national level to determine the status of these ecosystems (Ruiz-Luna *et al.*, 2008; Berlanga-Robles *et al.*, 2011).

Tropical Dry Forests (TDF) include deciduous, semi-deciduous and thorny tropical forests. They are representative of tropical weather with strong differences during rain and drought seasons (5-7 months) showing flooding and dry soils (Rzedowski, 2006). This vegetation borders the TEF (Pennington and Sarukhán, 1998). TDF is distributed on the Pacific coast and lowlands in the south-east of the country (Yucatán Peninsula, Tabasco and south of Veracruz) (Rzedowski, 1998). TDF has 25% of endemic genera and 40% of endemic species (~6,000 species) (Rzedowski, 1998). Potential distribution of TDF amounts to 335,000 km^2 of Mexico (INEGI, 2003). However, by 2003, TDFs occupied 11.26% that is ~220,000 km^2 (INEGI, 2005).

TEFs include tropical evergreen and sub-evergreen forests which are distributed by the Atlantic Ocean (Challenger and Soberón, 2008). They are distributed in small parts of the centre of Veracruz and the Yucatan Peninsula bordering with TDF (Rzedowski, 1990). Precipitation of TEF is over 2,000 mm annually (Challenger and Soberón, 2008) while mean temperature is between 20-26^{o}C (Rzedowski, 2006). The biodiversity richness of TEF is very high, reporting more than 5,000 species (17% of Mexican flora) (Challenger and Soberón, 2008), but endemicity is low (around 5% of species) (Rzedowski, 2006). Potential distribution of TEF was ~9.1% of the country (178,200 km^2) (INEGI, 2003) but TEF has been reduced and by 2003 these forests occupied only 4.82% of the country (31,600 km^2) (INEGI, 2005).

Grasslands (G) are grouped in different varieties of natural grasses. Highland grasslands grow on the borders of temperate forests on the mountains (~4,300 m.a.s.l); they are distributed on the trans-Mexican volcanic belt. A different kind of grassland is found in the lowlands; they are spread in the north of Mexico between the chain mountains of the country (Miranda and Hernández, 1963) through the Sierra Madre Occidental from Chihuahua to Jalisco, and some places in the centre of the country (state of Guanajuato) (INEGI, 2009b). Lowland grasslands show high endemicity although the biodiversity richness in terms of number of species is not very high (Rzedowski, 2006). Natural grasslands have occupied 186,800 km^2 (INEGI, 2003); however, by 2003 they only covered 6.38% of the country, or 84,200 km^2 (INEGI, 2005).

Other vegetation (OV) includes many different communities that, because of their origin (kind of soil, fires, etc.), show special ecological characteristics different to the big groups such as TF and TDF (INEGI, 2009b). This category includes: palms, halophilic, gypsophila and dune vegetation that are related to saline soils, rich in gypsum, located on coastal lagoons, marshes and littoral borders, showing a variety of shapes (scrubs, trees and herbaceous types) (Rzedowski, 2006).

Other covers (OC) include anthropogenic uses such as agriculture (rain-fed, slash-burn and irrigated agriculture), grasslands for cattle production, rural and urban areas, and places with no vegetation (INEGI, 2009b).

2.4 Land Use History

Mexico's landscape is the result of complex interactions between social and ecological systems. Mexican cultural diversity (54 indigenous groups and ~291 languages) (Gordon, 2005) is distributed in all of its ecosystems (Alcorn and Toledo, 1998). These socio-ecological systems have shaped different communal and private uses of land and property throughout the country (Alcorn and Toledo, 1998). The Mexican case is unique due to the large number of communities that are managing as common-property forests, for commercial and personal purposes (Bray *et al.*, 2003). Consequently, it is possible to trace a long and complex history of policy reforms leading to diverse land property rights which, in turn, have affected land tenure and, directly, the LUCC (Bonilla-Moheno *et al.*, 2013).

Traces of the historic complexity link back to the precolonial period when common-use and access to resources were established (Zúñiga and Castillo, 2010). However, the Spanish conquerors introduced the kind of private property where very large extensions of land were distributed among relatively few people (SRA, 2010). These inequalities in land distribution associated with the poverty work conditions of peasants have been pointed out as the principal triggers for the Mexican Revolution in 1910 (Bonilla-Moheno *et al.*, 2013). This phenomenon impacted in terms of LUCC, because just after the revolution successive Mexican Presidents, from the 1930s to the 1990s redistributed > 50% of the territory to communities. During that period, 950,000 km^2 were redistributed to ~2,200 people (Bizberg and Meyer, 2003), especially between 1964-1970 when contemporary land property rights were established (Botey, 1996).

Agrarian reform led, in some relevant aspects, to Article 27 of the National Constitution (1917) which established the supremacy of public property over private institutions. The redistribution of land led to a common use tenure of land called "ejido" which is a form of property right based on common-use. Ejidos are divided as follows: 1) common land (forest management and/or agriculture), where the rules regarding access and use are collective; 2) farm parcels for individual exploitation; and 3) village centre for houses plots (Haenn, 2006). By the 1980s agrarian reform had resulted in the creation of ~28,000 ejidos and the recognition of ~2,300 communities (Assies, 2008). That means that more than 50% of the farmlands were common lands, the average size of ejidos being 20 km^2 (Assies, 2008). The typical ejidatario possessed around nine hectares and had access to 28 hectares of the commons. Common property produced > 50% of agriculture and forestry products, so more than the private parcels (Assies, 2008). Consequently, the production of private parcels largely led to self-consumption which in turn caused those smallholders to need complementary activities (Bartra, 2004).

2.5 Current Land Use

After 1992 the Mexican government modified the National Constitution (article 27) establishing that no more land would be redistributed, and that intensification of agriculture would be promoted to improve productivity (Brown, 1997; Cornelius and Myhre, 1998; Assies, 2008). After this reform, and the neoliberal economic strategies followed by the Mexican government within the North American Free Trade Agreement (NAFTA), subsidies were cut or sharply reduced, affecting small and medium farmlands (Brown, 1997). One of the points enshrined by this reform was the certification of communal lands in which the commons or ejidatarios could obtain individual certificates of their land rights if their parcels had clear boundaries (Assies, 2008). Subsequently, having the certificates, ejidatarios had the legal right to sell, rent or sharecrop their lands. However, the decision to sell to outsiders had to be approved by a 2/3 vote of an assembly set up by the ejido itself. The same situation applied to common lands to be sold (Assies, 2008). Other points were integrated into this reform such as that owners were no longer required to work their land personally in order to retain it, so people could migrate to the cities or the US without losing their rights and continue receiving profits from their lands at the same time (Assies, 2008). After the reforms and the application of NAFTA, the state started dismantling support for the social sector, and promoted private investment (Appendini, 1998), causing an increase in migration from rural to urban areas and to the US (Levy and van Wijnbergen, 1992). Moreover, joined to these reforms in land tenure, Mexico suffered a profound transformation by promoting industrialization in cities. Consequently, whereas in the 1940s ~20% of the Mexican population lived in urban areas, by the mid-1990s, 73% of people lived in cities (Assies, 2008). Nowadays it is reported that ~11% of Mexico's population (10 million people) lives on communal lands (Brandon *et al.*, 2005); however, they own, according to different sources, between 60% (Bray, 1995; Castillo and Toledo, 2000) and 90% of Mexican productive areas (~1,000,000 km^2) (Klooster and Masera, 2000; Segura, 2000; SRA, 2010). Other data report that less than 25% is owned by individuals, and 5% to 9% by indigenous communities (Bonilla-Moheno *et al.*, 2013).

This community management has been studied in different areas through the country showing contrasting results related to conservation targets (Ellis and Porter-Bolland, 2008) based on the promotion of policies such as subsidies affecting LUCC and the biodiversity of the lands (Chowdhury, 2007). For instance, the tragedy of the commons does not neccesarily apply for the Mexican ejidos (Deininger and Minten, 1999; Sarukhan and Larson, 2001). However, ejidos are an example of dependence on governmental subsides, ignorance, and apathy toward most government-dictated initiatives, all leading to biodiversity loss (Weber *et al.*, 2006) and deforestation (Bonilla-Moheno *et al.*, 2013).

Nevertheless biophysical forces of change have a pivotal role in the LUCC process in Mexico (Kolb *et al.*, 2013) along with socioeconomic or demographic factors (Ellis and Porter-Bolland, 2008). It is important to keep in mind this complex dynamic of land tenure in

Mexico, which has had an important role in the LUCC throughout the country with different effects (see Chapter 4) (Figure 6) (Bonilla-Moheno *et al.*, 2013).

In terms of environmental policies regarding biodiversity conservation, the most important law in Mexico is The General Law of Ecological Balance and Environmental Protection established in 1998 and continuously modified and discussed. This Law is divided into six general topics: 1) pollution and hazardous waste, 2) water quality, 3) soil use and conservation, 4) biodiversity conservation and natural protected areas, 5) sustainable management, and 6) public participation regarding the right to get environmental information related to environmental impact assessments, the ordinance of the territory and planning (LGEEPA, 1998). This law provides all the legal framework for the Official Mexican Standards (NOMs) related to the environment. The articles that include the establishments, maintenance and management of the natural protected areas (NPAs) are linked in turn to the 27 article of the National Constitution. In these Acts, federal jurisdiction in the territory is privileged, followed by the common rights of land and finally the private areas.

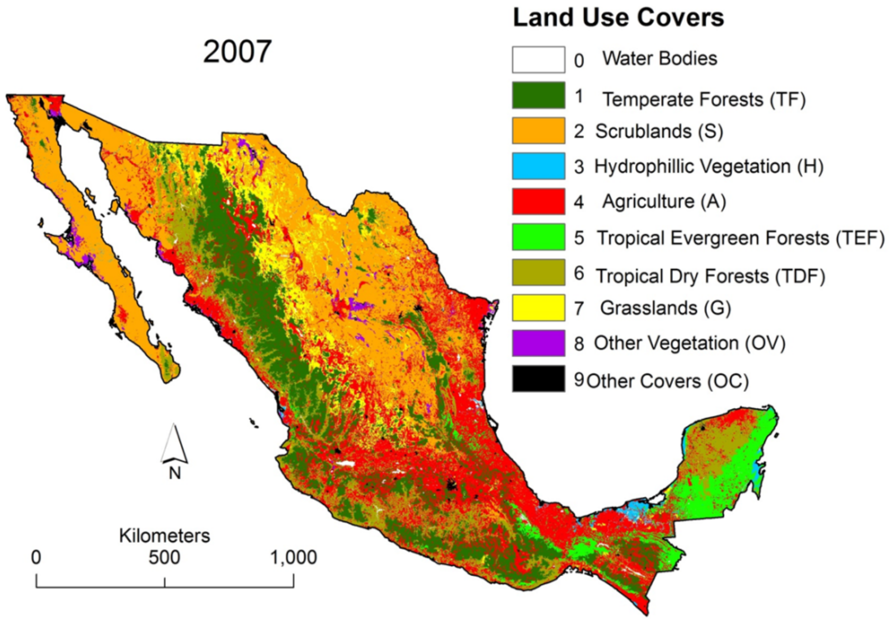

Figure 6. Land Use Cover map 2007. These categories are the result of gathering different ecosystems and anthropogenic uses, modified from INEGI (2005). For more details see chapter 4.

2.6 Natural Protected Areas (NPAs)

One of the most important strategies to face and reduce the impacts of GEC on biodiversity is the establishment of Natural Protected Areas. Mexico's conservation strategies rely on NPAs (Figueroa and Sánchez-Cordero, 2008). Natural Protected Areas (NPAs) are divided into: 1) federal, 2) state, and 3) private.

2.6.1 Federal Natural Protected Areas (FNPAs)

There are 176 FNPAs occupying ~253,498 km^2 (~12.7% of the country) oscillating from 8.4 km^2 (Chamela Bay Island Sanctuary, in Jalisco) to 2,493km^2 (Vizcaino Biosphere Reserve, in Baja California Sur) (Figure 7). FNPAs are divided in turn into six classes, depending on their restrictions of management. The classes are: 1) Biosphere Reserves (n=41; 127,751 km^2); 2) National Parks (n=66; 14,113 km^2); 3) Natural Monuments (n=6; 163 km^2); 4) Areas of Natural Resources Protection (n=8; 45,033 km^2): 5) Areas of Flora and Fauna Protection (n=38; 67,864 km^2); and 6) Sanctuaries (n=18; 1,481 km^2) (CONANP, 2014). A brief description of the FNPAs is given following the text of the General Act on Ecological Balance and Environmental Protection (LGEEPA) established in 1988, which has subsequently had modifications to some sections.

1) Biosphere Reserves. This category integrates ecosystems without human alterations or areas that because of their biodiversity, endemicity or vulnerability should be restored. These reserves are regionalized into one or more core areas and different buffer zones. Core areas are divided in two: 1) a protection area which can be only used for monitoring using non-invasive techniques and where other kinds of management are prohibited; 2) an area for restrained used is allowed for scientific and educational purposes and tourism of very low impact. Buffer areas can be managed by local people following eight different lineaments under sustainable structures.
2) National Parks are divided into zones as well. However, restrictions of management are less strict, and there are permits given for sustainable extraction in the buffer areas, and access for management for traditional purposes or public demand such as tourism or education.

3) Natural Monuments are areas which do not have the biodiversity richness or the extent to be considered as National Parks or Biosphere Reserves. However, Natural Monuments allow scientific, educational or procreative activities, but extraction or a different kind of management is prohibited.
4) Areas of Natural Resources Protection are aimed at preserving soils and hydrological basins. In these areas sustainable forestry is allowed, as well as scientific, educational and touristic purposes.
5) Areas of Flora and Fauna Protection are related, to preserve the ecosystem of some species. Those areas are established when it is known that modification of their ecosystems could directly affect one or more species. In these areas there are activities related to propagation, demographic monitoring, and sustainable management; even extraction is allowed. Tourism and education purposes are practised as well.
6) Sanctuaries are places where there are species of a small range of distribution. These areas are generally glens, creeks, cenotes or caverns. In the sanctuaries only scientific and educational activities are allowed.

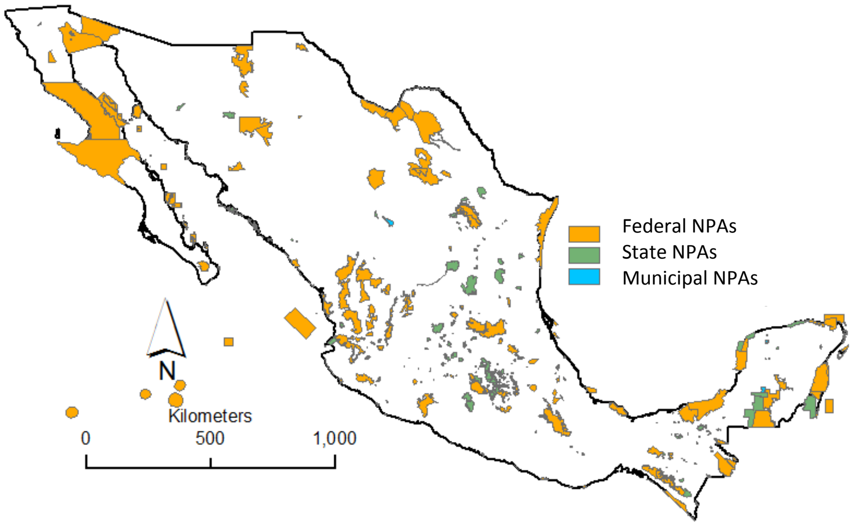

Figure 7. Different Natural Protected Areas according to the political division in Mexico modified from CONANP (2014).

The Biosphere Reserves have been shown to be the most effective FNPAs, preventing the loss of natural vegetation even if they are managed by local communities in their buffer zones (Figueroa and Sánchez-Cordero, 2008). However, other NPAs have been weakly effective, showing that deforestation is as high in buffer areas as outside the NPAs. This is not because of the permitted management but because of accessibility to nucleus zones, making the status of the management protection less relevant than other factors such as accessibility or distance to roads (Mas, 2005).

2.7 Global Environmental Change in Mexico

Mexico's richness is threatened by indirect and direct factors as a part of Global Environmental Change (GEC). Indirect factors are population growth, inadequate public policies and inappropriate technological developments. Direct factors are forms of LUCC, overexploitation and pollution, invasive species and climate change (CC) (Challenger and Dirzo, 2009). Habitat destruction and over-exploitation related to LUCC and CC are the most important threats to ecosystems in Mexico (Figure 8).

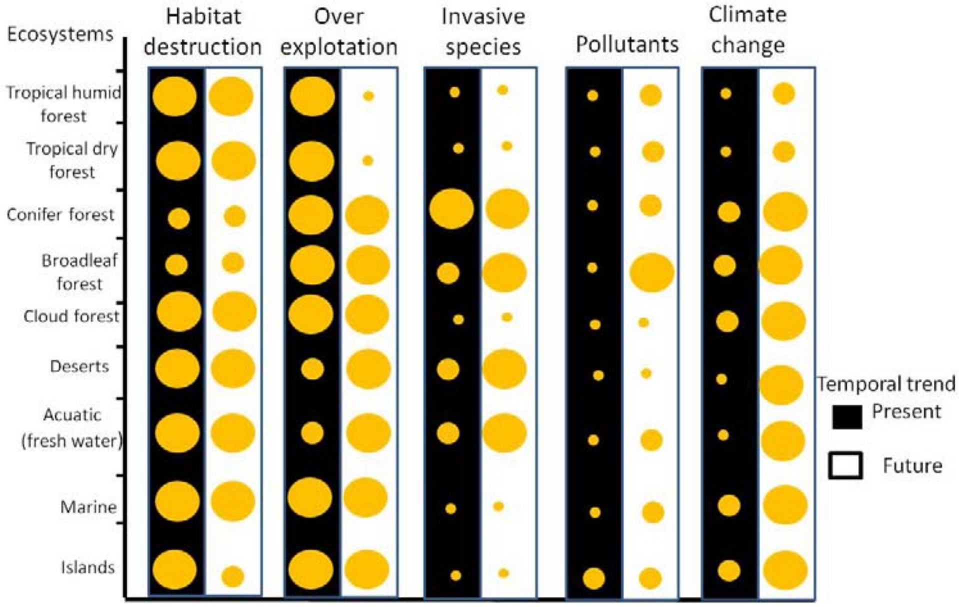

Figure 8. Impact of human activity on Mexico's biodiversity: magnitude of change and temporal trend, modified from Challenger and Dirzo (2009).

2.7.1 Land use/cover changes (LUCCs)

Humans have used Mexico's natural ecosystems for millennia, but the most remarkable degree of impact has occurred in the last 50 to 100 years. This particular period is characterized by a high rate of forms of LUCC (Challenger, 1998). Considering all kinds of vegetation and their original extent, by 1976 vegetation had been reduced by 38%; and by 1993 it had further reduced, covering only 54% of its original area (Challenger and Dirzo, 2009).

Most recent data report that during the period 1990-2010 Mexico was one of the countries with the largest rate of annual net loss of forest (a deforestation rate of -0.52% per year - 35,470km^{2}yr^{-1}) However Mexico is also one of the countries with the greatest extent of natural vegetation as well (FAO, 2010). That makes it important to develop continuous studies about the LUCC process, making hotspots of change especially explicit.

LUCC trends have impacted differently on Mexico's terrestrial ecosystems (Figure 9), affecting biodiversity unevenly. For instance, tropical rain forests have lost their major extent, but retain much more biodiversity richness in terms of number of species than temperate forest (Rzedowski, 2006). However, Mexican temperate forests contain the richest country in terms of diversity of pines (Styles, 1998) and endemicity (Rzedowski, 1998, 2006).

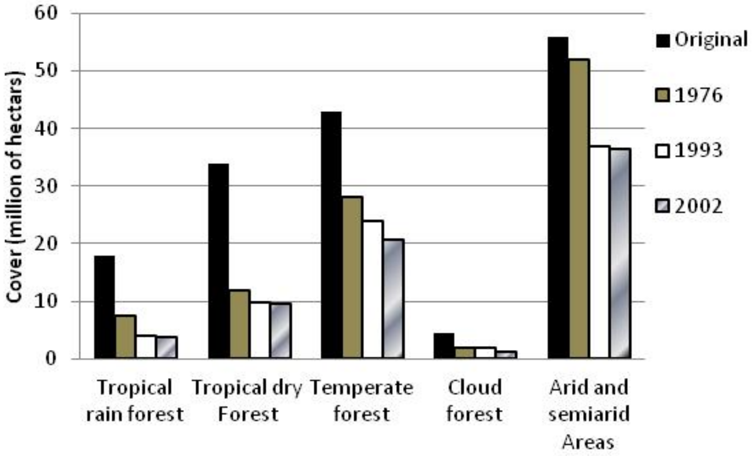

Figure 9. Trends of change in ecosystems contrasting the original vegetation cover. Bars represent remaining vegetation cover 1976, 1993 and 2002, modified from Challenger and Dirzo (2009).

In this context taking into account only the rates of deforestation and the extent of forest lost is not enough if the information is not spatially explicit or contextualizing hotspots of change. These elements are taken into account when studies of LUCC and biodiversity loss are developed, especially in megadiverse countries.

2.7.2 Climate Change (CC)

The fourth assessment report (AR4) of the IPCC were based on scenarios from SRES (Nakicenovic *et al.*, 2000) (see Chapter 3). After these scenarios, scientific community started to work on a set of new scenarios (the representative concentration pathways or RCPs and their associates Shared Socioeconomic Pathways SSPs) (Moss *et al.*, 2010) based on the IPCC's fifth assessment report (AR5). SRES scenarios considered as principal driving forces population, economic growth and technological advances which are combined emphasizing differences in political governance (from local to global) and "environmental awareness" or willingness of economic growth (Chapter 3). These combinations are the storylines and they constitute the families of scenarios called A1, A2, B1and B2 (Nakicenovic *et al.*, 2000). Differentially to the SRES, the new SSPs scenarios are not associated with a unique socio-economic or emission scenario that means that RCPs can result from different combinations of the assumptions (Kriegler *et al.*, 2012). The SSPs base their socio-economic drivers on the Shared Socio-economic Pathways (SSPs) which are quantitative projections focus on exploring the long-term consequences of anthropogenic climate change and the availability in response depending on the different ways that societies could unfold (Kriegler *et al.*, 2012). However because of the availability of information for modelling purposes at good resolution at national level, this study is focused on the SRES scenarios and their storylines. Nevertheless, it is important to keep in mind that the philosophy behind the scenarios is not to point out if the new scenarios are better than the previous, but rather to consider that SRES as well as the RCPs depict possible pathways of society in which the future could unfold under certain conditions.

In the mid-1990s the first regional scenarios of CC were produced for Mexico by The Centre of Atmospheric Sciences (UNAM) generating scenarios using ECHAM5, UKMO-HADGEM1 and GFDL-CM2.9 models (Gay *et al.*, 2006). These models were chosen to represent because they showed a higher probability of agreement, among the full range of possibilities, given by all the GCMs. They were able to provide a broad range of potential temperature increases (i.e. short term between 0.5 to 1.5°C and 1.5 to 4.5 °C long term for the B2 scenario) and, more importantly, they provided information about the reduction in precipitation in the north and an increase of it through the south of Mexico (Gay *et al.*, 2006; Conde *et al.*, 2008).

The results of these regional scenarios show that Mexico's temperature will be greater in higher latitudes and over continental regions. Between the decades 2010 and 2040 changes in most of the American Continent will not exceed 1° C, although the dispersion is about 0.75°C on the United States and about 0.5° C on Mexico. Between the decades 2040 and 2070 the average increase projected among models is 0.75° C. Finally, towards the end of this century, among the decades 2070 to 2099, increases in temperature occur between 4 and 5°C in northern Mexico, with a scatter between projections of up to 1.25° C (Gay *et al.*, 2006; Conde *et al.*, 2008).

According to the previous IPCC scenarios (AR4), the strongest magnitude of the annual average temperature anomaly in Mexico will amount to 5°C by the end of this century under the A2 scenario (Conde *et al.*, 2008). When the A1B emissions scenario is considered the magnitude of the increase in temperature is at least 1°C lower than in the A2 scenario. As in the case of A2, the assembly of the GCM shows that it is in the northwestern region where major temperature changes occur, reaching about 4.5°C (Conde *et al.*, 2008). Northern Mexico has faced recent drought (2010). This is because of global warming-associated CC becoming the new climatology of the American Southwest (Seager *et al.*, 2007; Wehner *et al.*, 2011). However, the same situation is projected to cause drying of the whole of Mexico. If the base climatology of Mexico is changing, the most vulnerable region may actually be the 13 states of Central Mexico that sit between the semi-arid region to the north and the wetter climate to the south (Seager *et al.*, 2009). Consequently, the potential convergence of natural and anthropogenic drought and changes in climate provides compelling motivation to improve efforts in Mexico to prioritise key factors and vulnerable systems throughout the country.

Mexico has been working on the new regional CC scenarios developed by the Scientific Research and High Education Centre of Baja California (CICESE), the Water Mexican

Institute (IMTA) and the Centre of Atmospheric Sciences (CCA-UNAM) in coordination with the National Institute of Ecology and Climate Change (INECC), under the finance of the Global Environmental Fund (GEF) and the Programme of the United Nations Development Programme (PNUD). They developed the “Update of CC Scenarios for Mexico”. This national study used 15 General Circulation Models (CGCMs) for one short-term period (2015-2039), and a long term period (2075-2099) for the RCP4.5, RCP6.0 and RCP8.5 scenarios. This information is part of the Fifth Assessment Report of the IPCC AR5 (IPCC, 2013) (Figure 10), and it is available in the webpages of the INECC (Cavazos *et al.*, 2013). The information available uses the “Reliability Ensemble Averaging” (REA) method developed by Giorgi and Mearns (2002), which gives more weight to the models with less uncertainty and bias.

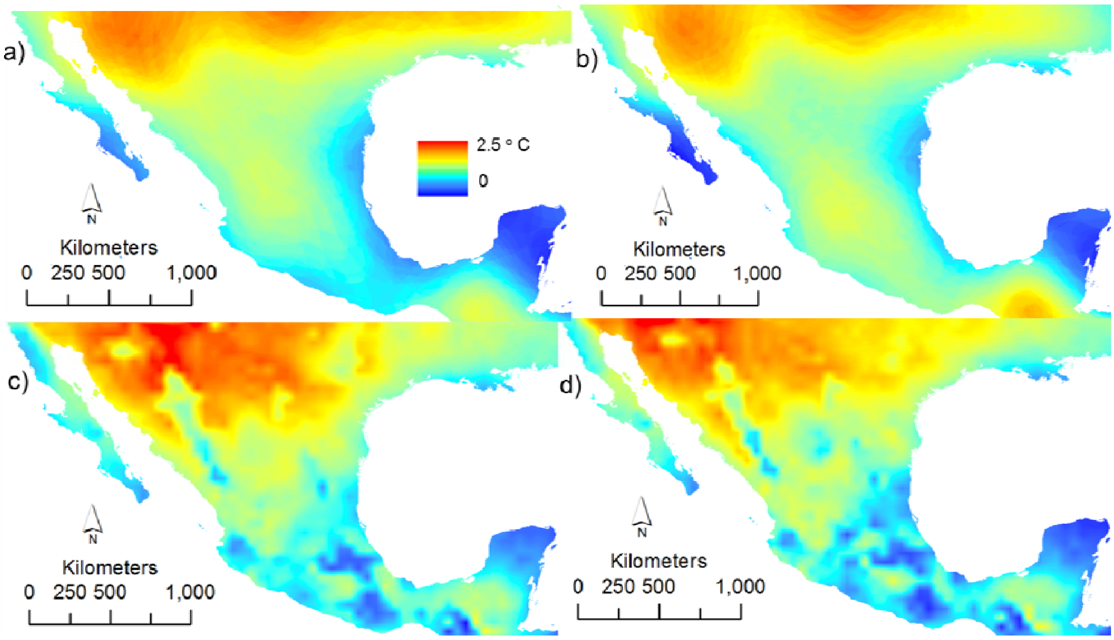

Figure 10. Difference between “historic mean temperature“ (1961-2000) and mean temperature projection by 2030s, a) B2, b) A2, c) RCP 4.5, and d) 8.5 modified from UNIATMOS (2015) and Fernández-Eguiarte *et al.,* (2015).

In summary by 2030, Mexico might face an increase in mean temperature up to 2°C under the pessimistic scenarios (A2 and RCP8.5) (Figure 10). The augment is projected to be higher by the end of the century when some northern areas of Mexico may show up to 4.5 °C higher than the current temperature, regarding to A2 scenario. However, the precipitation according to the scenarios could decrease up to 20% in northern areas (Conde *et al.*, 2006; Conde *et al.*, 2008; Cavazos *et al.*, 2013) It is important to notice the high uncertainty in the precipitation models which are as big as the net changes. Models were better at reproducing conditions in the north of the country than the South, which makes applying some strategies to prevent or mitigate changes more difficult, due to lack of representation of the dynamic of tropical weather (Cavazos *et al.*, 2013).

Besides the differences between SRES and SSPs scenarios, it is possible to see that northern areas, especially the western part of Mexico will face the major challenges considering the scarcity of water that exists in the region. This differential pattern through the country it is it is important to know the potential feedbacks between CC and LUCC keeping in mind that the changes in temperature could cause differential patterns on LUCC to detect the areas where those threats will be higher.

To conclude this chapter, it would be said that modelling and projecting CC and their forces entails the depicting the possible range of human behaviour, policy choices, technological advances, international competition and cooperation (Collins *et al.*, 2013). Dealing the complexity of the integration of all the variables and their feedbacks in the long-term has promoted the use of scenarios as plausible future pathways. However, it has not been possible to assign likelihoods to individual scenarios; rather, a set of alternatives is used to span a range of possibilities (Collins *et al.*, 2013). The outcomes from different forcing scenarios provide policymakers with alternatives and a range of possible futures to consider Because of these reasons this study support the use of scenarios that although are not the newest are still important in order to depict the possibilities of future pathways of which it is potential to identify the most vulnerable areas to CC and their relation to LUCC under certain scenarios assumptions such as SRES.

Chapter 3. Socio-economic projections under different scenarios for Mexico

3.1 Introduction

Scenarios are used to explore the uncertainties of potential impacts of Global Environmental Change (GEC). They create understanding of the magnitude and locations of change, and help to identify the need for adaptation and mitigation to reduce vulnerability. Contextualisation of global scenarios to national or regional level is less common and is especially rare for developing countries which are experiencing rapid change. These countries would benefit from access to socio-economic projections at a sufficiently detailed spatial resolution to understand future changes, including land use/cover change (LUCC) and decline in ecosystem services provision. This chapter illustrates how global scenarios, such as those of the International Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES), can be contextualised for Mexico, by developing multi-scale spatially explicit socio-economic projections, at fine resolution (1km^2), for different time slices (2020, 2050 and 2080) following deterministic and probabilistic methods.

3.1.1 Global environmental change and scenarios

During the 21st century, the world will face major challenges in coping with a suite of interacting changes, including population growth, resource depletion, biodiversity decline, climate change (CC) and LUCC (MEA, 2005; Steffen *et al.*, 2005; Steffen *et al.*, 2007; IPCC, 2013). Understanding these complex changes, including their inherent uncertainties, is one of the greatest challenges humanity has ever faced (Heikkinen *et al.*, 2006; Peterson, 2006). Scenario analysis has emerged as a means of characterising the future and its uncertainties through structured, but imaginative thinking (Rounsevell and Metzger, 2010). It is now one of the most used methods to explore GEC and its potential impact, e.g. by the IPCC (Nakicenovic *et al.*, 2000) and the Millennium Ecosystem Assessment (MEA, 2005).

This research aims to contextualise socio-economic variables through projections under different scenario-assumptions at sub-national level and fine grid resolution for Mexico. The aims are divided into: 1) detailed local data overcoming the problems of national census data, 2) contrasting one bottom-up projection deterministic and one downscaling probabilistic projection at different scales, 3) making the socio-economic projections spatially disaggregate at 1km x 1km resolution showing the real inhabited area by different time slices and scenarios.

Scenarios can be defined as plausible, consistent and coherent descriptions of alternative futures under different assumptions related to drivers and their uncertainty (Nakicenovic *et al.*, 2000; Raskin and Kemp-Benedict, 2004; Rounsevell and Metzger, 2010). Qualitative storylines help reflect the assumptions within scenarios about the drivers of change (e.g. population growth, energy consumption and technological development) that ultimately determine greenhouse gas emissions. Although such scenarios cannot be considered predictions given the inherent uncertainty of the long-term future drivers (Rotmans *et al.*, 2000; MEA, 2005; Abildtrup *et al.*, 2006; Zurek and Henrichs, 2007), they simulate, provoke and communicate the range of change the future may hold (Rounsevell and Metzger, 2010).

The need for greater understanding about the future is relevant at all levels, from global to local. Developed countries have published a plethora of scenario-studies in recent years (EEA, 2011), both at the regional and national scale (Kaivo-oja *et al.*, 2004; Sleeter *et al.*, 2012). These studies generally develop contextualised national or EU socio-economic scenarios (Rounsevell *et al.*, 2005; Rounsevell *et al.*, 2006; Verburg *et al.*, 2006a; Costantini *et al.*, 2007) within a global scenario framework. By contrast, national scenario studies are virtually non-existent in developing countries, despite the fact that developing countries are experiencing some of the most rapid changes and are generally more vulnerable to CC (IPCC, 2001; Yohe *et al.*, 2006).

Global scenario data are readily accessible through various portals (CIESIN, 2004; IIASA, 2012). For instance, global climate change datasets are available at a wide range of spatial resolutions; however, socio-economic scenarios remain coarse (Arnell *et al.*, 2004; Gaffin *et al.*, 2004; Grübler *et al.*, 2007; Riahi *et al.*, 2007; van Vuuren *et al.*, 2007). Table 1 provides an overview of six socio-economic scenarios described in the SRES (Nakicenovic *et al.*, 2000). The finest resolution available for the majority of developing countries is 0.5^{o} x 0.5^{o} (~55x55 km in Mexico) (Grübler *et al.*, 2007), which is too coarse, making difficult the interpretation for identifying spatial differences which are useful to evaluate environmental planning and strategies (Verburg *et al.*, 2006b).

3.1.2 Deterministic and probabilistic scenarios

Scenarios generally describe developments in drivers which can be either predetermined or uncertain (Porter, 1985). Population is an example of a predetermined variable because of its gradual change (Schwartz, 1991), and it can be projected with accuracy (Postma and Liebl, 2005). By contrast, the development of economic variables has far greater uncertainty and their projections have high level of uncertainty at long term. The IPCC scenarios (Nakicenovic *et al.*, 2000; IPCC, 2007b, 2013) consider both predetermined drivers (e.g. population growth) and highly uncertain drivers (e.g. economic growth).

Scenario projections can be modelled using either deterministic or probabilistic methods. Deterministic projections offer a narrow range of possibilities about future trends, without providing a level of uncertainty (O'Neill, 2005). Probabilistic projections, by contrast, offer a large group of likely events with their associated uncertainty and the possibility of their occurrence (Lee, 1998; Guzmán and Ralph, 2002). Some scenario-studies have combined these approaches, using probabilistic projections under deterministic scenario assumptions (O'Neill, 2004; Sanderson *et al.*, 2004; O'Neill, 2005), while others have integrated statistical methods into the assumptions of a scenario framework (Önkal *et al.*, 2013).

Table 1. Global downscaling of socio-economic drivers related to SRES.

Study	Variables	Purpose	Resolution	Method	Sources	Countries
Gaffin et al. (2004)	Population and GDP	To provide background information for the databases at the country and geo-spatial gridding level.	2.5 ° x 2.5 °	Linear downscaling	IIASA projections (1996) for A1, B1 and A2 scenarios, and UN (1998) for B2 GDP UN (http://unstats.un.org), WB (2000) and WRI (1997)	184
Arnel et al. (2004)	Population GDP Land cover	To characterise SRES at national and sub-national levels to assess the implications of food security, water stress, coastal flood risk, malaria exposure and terrestrial ecosystems.	0.5° x 0.5°	Linear downscaling	IIASA projections (1996) and CIESIN (http://ciesin.columbia.edu/datasets/downscaled/)	228
Bengtsson et al., (2006)	Population	To produce a suite of grid maps of future populations, which are suitable for long-term global scale CC and water assessments	0.5° x 0.5°	Differentiation between rural and urban, and application of uniform population growth.	CIESIN and Landscan (http://www.ornl.gov/sci/landscan/)	184
van Vuren et al. (2007)	Population, GDP and GHG	To provide downscaled data of SRES at the national and grid level.	0.5° x 0.5°	Partial convergence and linear scaling	UN projections (2004) World Bank (2004)	224
Grübler et al. (2007)	Population and GDP	To bracket the uncertainties in the spatial density of population and economic activity.	0.5° x 0.5°	Decomposition and optimisation techniques for regional and national trajectories.	Original SRES (http://sres.ciesin.org/final_data.html)	185
Duval and Maisonneuve (2010)	GDP	To develop and apply a framework for long-term GDP projections.	Country	Conditional growth of GDP.	OECD Economic Outlook (2009) and IMF World Economic Outlook (2009).	76

3.1.2.1 IPCC scenarios

The fourth assessment report (AR4) of the IPCC were based on scenarios from SRES (Nakicenovic *et al.*, 2000). After these scenarios, scientific community started to work on a set of new scenarios (the representative concentration pathways or RCPs) (Moss *et al.*, 2010) based on the fifth assessment report (AR5) of the IPCC. AR4 and 5 and the scenarios (SRES and RCPs) have changed, making a comparison with earlier literature challenging (Rogelj *et al.*, 2012).

SRES consider as principal driving forces population, economic growth and technological advances which are combined emphasizing differences in political governance (from local to global) and "environmental awareness" or willingness of economic growth. These combinations are the storylines related to families of scenarios called A1, A2, B1and B2 (Nakicenovic *et al.*, 2000). In terms of its driving forces, SRES can be schematically represented using two axes (Figure 11). Vertical axes show differences in political governance which ranges from local to global emphasis. Horizontal axes characterise "environmental awareness" versus willingness for economic growth.

The results of combinations of these axes are the storylines called A1, A2, B1 and B2. Each storyline is related to a family of scenarios (A1, A2, B1, B2) (Figure 11). Family A1 is subdivided in three scenario-groups which differ among themselves in technological assumptions related to the source of energy used. Each storyline is subdivided in turn into 40 quantitative scenarios.

Differentially to the SRES, RCPs are not associated with a unique socio-economic or emission scenario that means that RCPs can result from different combinations of the assumptions (Kriegler *et al.*, 2012). The RCPs base their socio-economic drivers on the Shared Socio-economic Pathways (SSPs) which are quantitative projections focus on exploring the long-term consequences of anthropogenic climate change and the availability in response depending on the different ways that societies could unfold (Kriegler *et al.*, 2012). These new scenarios not only consider total population size in addition to GDP, but also they provide alternative population projections by age, sex and six levels of education (Kc and Lutz, 2014). For example, SSP3 represents a world that faces large challenges to both adaptation and mitigation, while SSP2 is a world in which these challenges are more manageable. SSP1 and SSP4 represent worlds in which challenges are large for mitigation or adaptation, respectively, but not both. SSPs overlap to some degree because they are not based on 2 axes as SRES are, so the interpretation of them may make it difficult to disentangle reference and policy effects, complicating the interpretation of the shared pathways (Kriegler *et al.*, 2012). However, their practical focus leads to integrated impact assessment and vulnerability, and due to this reason they are focused on mitigation and adaptation challenges.

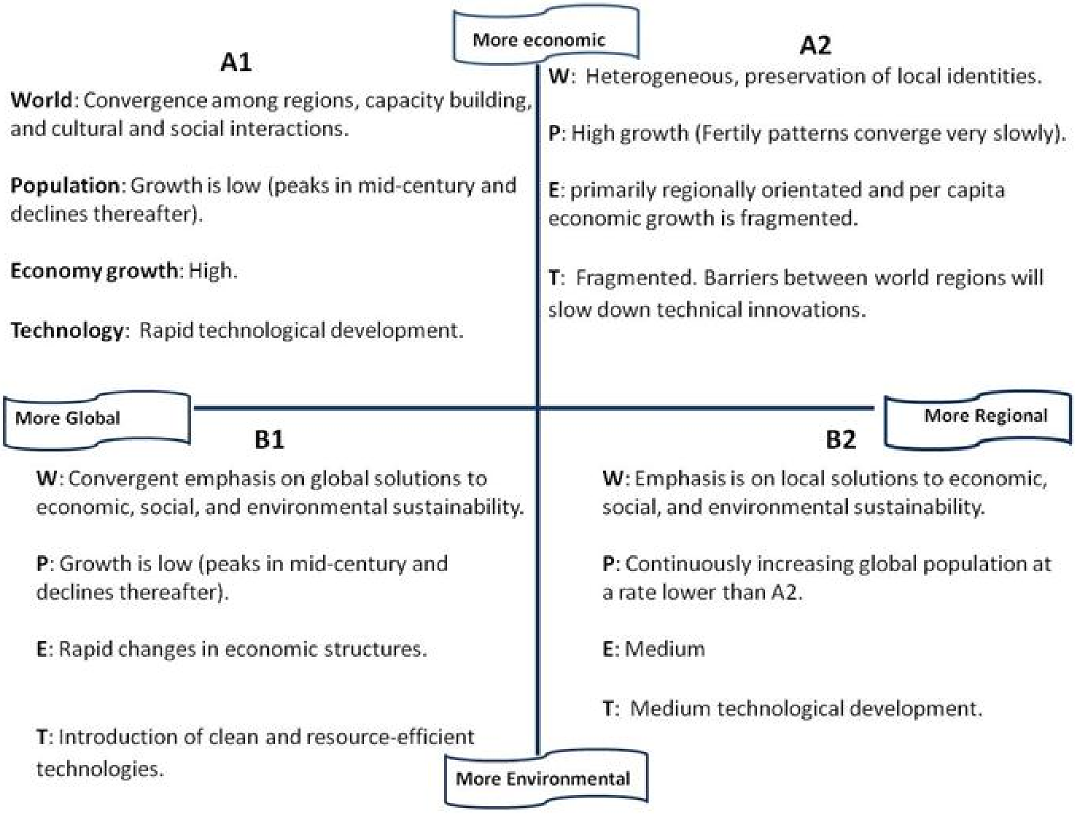

Figure 11. Schematic description of SRES families and their assumptions (Nakicenovic *et al.*, 2000).

It is important to notice that scenarios use GDP as an economic indicator because it is the most widely used measure of economic activity. However, GDP is a concept related to measure market production, not a measure of economic well-being (Stiglitz *et al.*, 2009) which in turn shows biases in the scenario approach. These biases are addressed to measure the market production that is shown, especially in the cities; however, the information that

GDP gives as the social condition of rural areas is scarce. Different indicator such as the Human Development Index could reflect in a better way the social human conditions. In this context, it is suggested that at the countries should improve those indicators that carry to potential for a shared view of how social progress is happening and how it can be sustained over time.

3.1.2.2 Mexico's geographical and socio-economic context

Mexico has 32 states divided into 2,456 municipalities with a high heterogeneity in area, population and population density (Table 2). Mexico's mean population density is about 57 persons per km^2. However, population density varies enormously across the country at the state, municipal and locality level. This situation is related to the dynamic of population growth, which in turn, depends on the basic demographic components (birth and death rates, and migration). From 1950 to 2005 Mexico's population increased fourfold from 25.8 million to 103.3 million. However, this increase was not homogenously distributed. For instance, some Mexican states grew to over fortyfold their 1950 population while others only doubled their population during the same period (Rhoda and Burton, 2010). According to the National Institute of Statistics and Geography of Mexico (INEGI (2010c) and the National Council of Population CONAPO (2009), Mexico showed an annual average growth rate of 1.8, a total fertility rate (TFR) of 2.2, and life expectancy of 75 years during the period 2005-2010. In contrast, Mexico's neighbours Guatemala and the US featured a TFR of 4.6 and 2.1, respectively (UN, 2010). Besides this, there is large heterogeneity among the Mexican municipalities, for instance some of them show TFR values less than 1, and others greater than 7. The same applies for the other two demographic components.

Table 2. Summary statistics of Mexican municipalities in 2010 (INEGI, 2010).

	Mean	Median	S.D.	Variance	Minimum	Maximum
Area	796	231	2,104	4,426,654	2	53,256
Population	45,739	12,730	132,802	17,636,443,984	93	1,815,786
Pop. density	279	52	1,171	1,371,725	0.1	17,656

The heterogeneity of TFR is related to the socio-economic context in Mexico, where indigenous women in marginalised localities have less access, knowledge and rights about contraceptive methods (Camarena and Lerner, 2008; Szasz, 2008). Due to these differences, the criteria of rurality of municipalities should be taken into account in order to integrate this information into the demographic projections (Appendix 2).

Rurality or urbanity can be defined based on the number of inhabitants, population density or certain socio-economic indicators. INEGI (2010e) considers 2,500 inhabitants as the threshold for rurality. As a result, in 2010, 77.8% of Mexico's population lived in urban localities. Applying the same criterion at the municipality level, according to INEGI, in 2010 Mexico had 370 and 2,086 rural and urban municipalities, or 15.1% and 84.9%, respectively. By contrast, the OECD (2010) suggests a methodology based on population density instead of the number of inhabitants. The OECD suggests that if the population density of an entity is below 150 inhabitants per km^2 it can be considered as rural. As a result, 1,904 of Mexico's municipalities are rural, and 552 urban; consequently, 78% of Mexican municipalities are rural. This shows the importance of the criteria that are used for the typology of a region. In this case, Mexico can be mostly considered as either rural or urban depending on the classification and methodology.

In terms of the economy, Mexico is the 11th largest economy in the world (Hoornweg *et al.*, 2010). The rates of growth of Mexico's economy since 1993 have oscillated from -6.2 to 7.2%, with an average of 2.6% (INEGI, 2012a). However, because of the heterogeneity in the Mexican territory it is possible to detect major historical differences in the economic development. For instance, northern states close to the border to the US after NAFTA showed great economic growth, while southern states' growth decreased in terms of Gross Domestic Product (GDP), especially those that depended on petroleum prices (Rodríguez-Oreggia, 2005).

3.2 Methods

Socio-economic projections were annually developed until 2080 for high, medium and low growth scenario. Population projections were developed by two approaches: 1) a deterministic method and 2) a time-series-probabilistic method. Demographic projections were compared to the IPCC SRES scenarios and the recent SSPs (Hunter and O’Neill, 2014).

GDP projections were developed based on the deterministic variants of a time-series-probabilistic method developed by the Institute of Economy of the Universidad Nacional Autónoma de México (López *et al.*, 2011) and its deterministic variants (very high, high, medium and low). The scenarios were then spatially disaggregated to produce high resolution maps (1km x 1km) for 2010, 2020, 2050 and 2080. Figure 12 provides a summary of the approach.

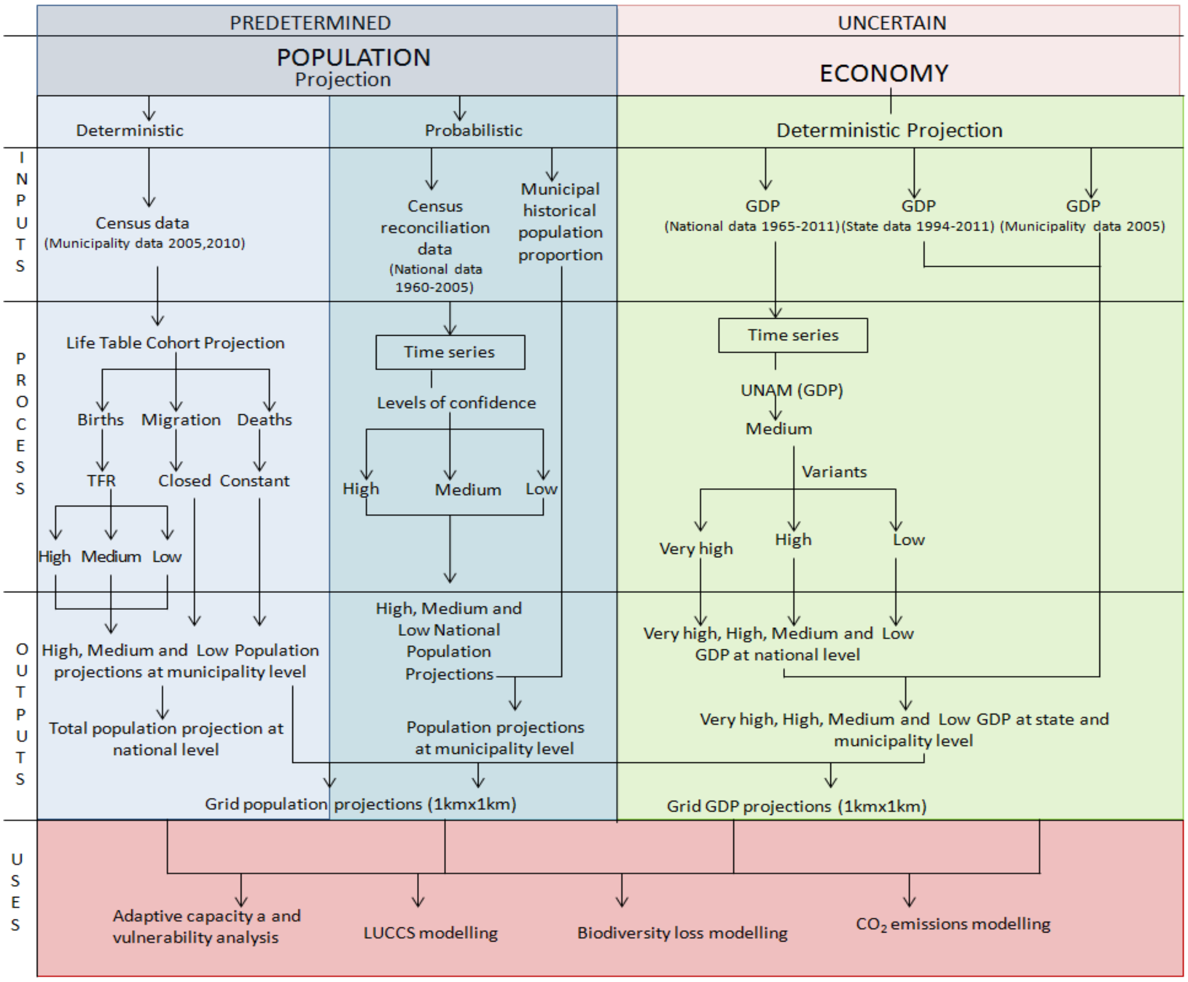

Figure 12. Flow chart summarising the development of the socio-economic projections.

3.2.1 Population projections

3.2.1.1 Deterministic projection

The deterministic population projection was developed at municipality level and then up scaled at state and national level by adding the results of the total municipalities of each state and then by calculating the total states to obtain the national figures. This deterministic method used a cohort-component method,[1] based on a life table projection. This method is composed of the three basic demographic components: fertility, mortality and migration. Fertility is measured as the Total Fertility Rate (TFR), which is calculated from a set of Age-Specific Fertility Rates for a single year (ASFR) (Equation 1); TFR is the sum of the single ASFR (per thousand), expressed as a rate per woman (Equation 2) (Rowland, 2006); mortality is given by calculating the survival ratios and vital rates for each age and sex specific rate (Klosterman *et al.*, 1993); and net migration is obtained by the difference between the natural growth rate and the data of the last year, given in absolute numbers. The model can be modified by changing the fertility assumptions for the cohorts, the volume of net migration, and the survival ratio data. Life tables allow the calculation of survival to the next cohort forward in five year steps. The inputs for the cohort component life table projection were municipality data from the Mexican censuses of 2005 and 2010 (INEGI, 2010c). Due to the lack of data and their quality at municipality level, mortality remained constant and migration was not taken into account because the national censuses do not integrate precise information for accurately estimating both components estimating negative population at short term.

Eq. 1
$$\text{ASFRx} = \frac{Number\ of\ births\ to\ women\ aged\ x}{Mid{-}year\ population\ of\ women\ aged\ x} * 1000$$

Eq. 2

$$TFR\ (per\ women) = \frac{\text{Sum of the five year ASFRs} * 5}{1000}$$

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[1] The cohort- component method is widely used, for example, the US Census Bureau and UK's Office for National Statistics use this method for developing their population projections.

Where: ASFR = age-specific fertility rates, x = a specific cohort, TFR = total fertility rate. The sum of the ASFRs is multiplied by 5 because the data were divided in five year age groups.

The assumptions of TFR were adjusted based on the rurality or urbanity of municipalities, because for Mexico the rural and marginalised municipalities tend to show higher fertility rates (INEGI, 2006). For this purpose, rurality was determined by using the OECD and INEGI criteria, which were explained earlier in the introduction. However, when the typology for characterising a municipality was different, the index of marginalisation of 2010 (CONAPO) was used as a criterion for defining if it would be considered as rural or urban (Appendix 1 explains variables incorporated in the index of marginalisation). For example, in 2010 the municipality of "Calvillo" reported 54,136 inhabitants, 58.63 inhabitants per km^2 and a low index or marginalisation. Subsequently, based on the national criteria this municipality would be urban while following the OECD criterion it would be rural. However, because of the index of marginalisation, that was low, it was considered as urban.

This study used the TFR proposed by the UN for high, medium or low variant (Appendix 2) depending on the rurality and the scenario assumption, due to the heterogeneity of this variable through the municipalities. That means that for the high scenario, urban and rural municipalities showed high TFRs rates, whilst the medium scenario had medium and high TFRs for urban and rural municipalities, respectively. The same criterion of different TFR was applied for the low scenario (Appendix 2). The results were three different cohort population projections under different TFRs with no migration and a constant survival ratio (Figure 12).

3.2.1.2 Probabilistic population projection

Probabilistic population projection was developed at national level and then downscaled at municipality level. This probabilistic method is based on the cohort-component method in which each demographic component (mortality, fertility and migration) is projected independently by age to reconstruct the entire population (Lutz *et al.*, 2004; Hyndman and Booth, 2008), in contrast to the deterministic projection. The method consists of three steps: 1) projecting the surviving population in each subgroup at the beginning of the next interval,

2) adding immigrants and subtracting emigrants in each subgroup to project those who will survive to the beginning of the next interval, and 3) computing the births for each subgroup during the interval and the survivors to the beginning of the next interval. These steps are repeated until the entire projection horizon is complete. In a probabilistic context, these steps are repeated thousands of times according to the projected variability for each demographic component. Once the survival function is obtained for each cohort and group it is necessary to project the principal demographic components (mortality, fertility and migration) with the aim to get the inputs for the survival functions by cohort and sex.

The Lee-Carter method was used to project mortality and net migration (Lee and Carter, 1992; García-Guerrero and Ordorica, 2012; García-Guerrero, 2015). The Lee-Carter method is one of the best known techniques to forecast population components with stochastic models; this model allows the extrapolation of the rates based on its historical information, which means that it is based on a statistical analysis of the time series. The inputs of the model were taken from the demographic conciliation for the period 1960-2005 (INEGI-CONAPO-COLMEX, 2006).

3.2.2 Economic projections

The economic projections presented here were based on a single scenario developed by the Institute of Economics at the Universidad Nacional Autónoma de México (López *et al.*, 2011). This projection was used as BAU (business as usual) based on its historical trend. This projection was the result of a univariate vector autoregressive model (VAR). VAR is a stochastic process which allows us to explain the endogenous variables solely by their own history, and does not need information about the factors that are influencing the growth of GDP. Moreover, VAR generates stationary time series with time invariant means, variances and covariance structure, given sufficient starting values (Pfaff, 2008). GDP projections were developed at a national level using data from the period 1994-2012 at Mexican constant pesos 2003. Scenarios for very high, high and low were constructed as variants on the basis of a very high, high and low rate of growth considered as ± two standard deviations. Although national projections were developed since 2012, the downscaling exercise was conducted from 2010, developing the first GDP information at municipality level for 2010 which are not available at municipality scale.

Spatial disaggregation of the GDP scenarios comprised of two steps. First, national projections were downscaled to state level by taking into account the historical contribution of each state to the national GDP (Equation 3). Then the downscaling at municipality level was used as a basis for the information published for a single year (2005) of GDP at municipality level provided by the National System of Municipality Information (SNIM, 2013).[2] Finally, GDP was adjusted on the basis of the historical data trend, assuming a linear trend where historical data were not available; to make sure that the sum of total municipalities was equal to the national GDP.

Eq. 3

$$GDP_{mun\ t+1} = GDP_{t0}\left(\frac{GDP_{mun\ t0}}{GDP_{nat\ t0}}\right)$$

Where: $GDP_{mun\ t+1}$ = GDP at municipality level at time 1; GDP_{nat} = national GDP at time 0. The GDP projections are reported in US dollars (US$), while the Mexican constant pesos based in 2003 were converted to US$ considering the mean annual exchange rate of 2003, that was 10.79315 Mexican pesos per US$. It is worth pointing out that GDP is not reported in Purchasing Power Parity (PPP) because this study is only focused on one country.

3.2.3 Disaggregation from municipality to a 1km grid

To represent the heterogeneity of population distribution, high resolution maps were developed (1km x 1km). The population density of the "real inhabited area" was determined using the information of rural localities and urban polygons and Natural Protected Areas

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[2] Municipality GDP for the States of Mexico and Sinaloa are available in: http://igecem.edomex.gob.mx/descargasestadisticas.html and http://transparenciasinaloa.gob.mx/images/stories/SDE/PROGRAMAS%20Y%20SERVICIOS/estadisticas/Pibpercapita.xls . This information was used for downscaling 143 municipalities (consulted on the 26th May 2013).

(NPAs) and water bodies were discriminated under the assumption that there are no people living inside these places. Rural localities and urban polygons were converted to grids (1km x 1km), and then the population municipality table was used to calculate the population density of the real inhabited occupied area. A mobile kernel window of 3km x 3km (the minimum size in which this function can be applied at 1km resolution) was then used to calculate the weighted average. This weighted value was assigned to each central grid. As a result, national population was the sum of all the population densities of all the municipalities, multiplied for the inhabited grids (Equation 4). Economic gridding was developed following the same rational as the gridded population on the basis of GDP.

Eq. 4

$$\text{National population} = \sum_{n=1}^{N} (\text{Popden}_{\text{mun}} * \text{ria}_{\text{mun}})$$

Where: N = the number of municipalities; $\text{Popden}_{\text{mun}}$ = population density at 1km x 1km for each municipality; ria_{mun} = real occupied area of each municipality.

3.3 Results

3.3.1 Population projections

By 2050, the population projections show that the Mexican population is between 9% to 54% and from 24% to 57% bigger than the population in 2010, depending on the scenario and the method proposed. This means a population of 171 to 174 million people for the high scenario, 145-162 million for the medium scenario and 121-138 million for the low scenario according to the probabilistic and the deterministic methods. The highest similarity between both procedures is by 2050, in which both methods show a population 55% and 52 % bigger in relation to the population in 2010. By 2080, the differences between both methods increase, showing the greatest difference in the medium scenario when the deterministic method shows an increase of 75% in relation to 2010, while the probabilistic method depicts an augment of 44%, indicating a difference of ~52 million (114 million people using the probabilistic method and 167 million for the deterministic method). For the high scenario the population is 46% and 77% in relation to 2010 (162 million and 197 million people for the probabilistic and deterministic methods, respectively) (Figure 13). Finally, the low scenario has contradictory results because according to the probabilistic method the population is 36% less in comparison to 2010, and based on the deterministic method it is 3% higher than the base year (72 million and 115 million people, respectively).

Rurality increases or decreases in the same scenario depending on the method used (see section 3.1.2.2). Based on the deterministic projection the low scenario shows a reduction of rural municipalities of 15% and 7% by 2050 and 2080, respectively. However, the probabilistic projection for the same scenario depicts an increase of 5% and 57% for the same time slices, respectively. The high and medium scenarios follow the same pattern in both methods. Rural municipalities increase by 5% and 11%, and 22% and 29% for the high scenario and the same time slices with deterministic and probabilistic projections, respectively.

Extreme values in population density at the municipality level depend on the method chosen as well. By 2010 there were between 0.14 and 17,656.14 inhabitants per km^2. However, by 2050 the extreme values become more extreme, with a density of 0.05 / 32,109.09 using the probabilistic method for the high scenario. In contrast, by the same time slice and the same scenario, with the deterministic method the lowest value double to 0.24 and the highest increases to 25,430.14 inhabitants per km^2.

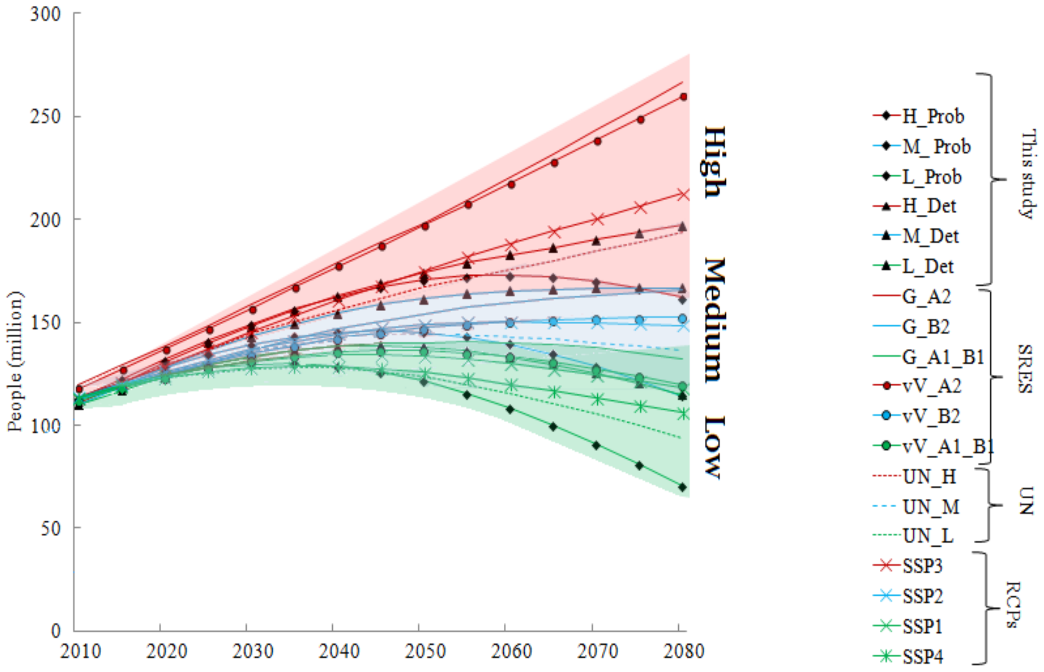

Figure 13. Different published population projections available for Mexico. H, M and L refer to high, medium and low projection; Prob and Det refer to the probabilistic or deterministic method; G = Gaffin et al. (2004) and V = van Vuuren et al. (2007) (both representing the SRES scenarios of the IPCC); UN = United Nations (2004); SSP1, 2, 3 and 4 refer to the new IPCC scenarios (Shared Socio-economic Pathways according to the RCPs); the red lines show the high scenario for each method, the blue lines show the medium scenario and the green lines show the low scenario.

3.3.2 Economic projections

In 2010, 41 municipalities contributed with more than 50% of the national GDP. Moreover, 14 municipalities produced almost 25% of the national GDP; of these, five municipalities (delegations) are in Mexico City. In 2010, only 16 municipalities produced more than US$10 billion (2003) while 1,806 municipalities contributed with less than US$0.1 billion (2003). In the same year, only 0.6 % of Mexican municipalities showed more than US$20,000 (2003) *per capita*, the majority of them being in Campeche – one of the states where petroleum is extracted –, Mexico City and Nuevo León. A great part of the country (81% of municipalities) showed a GDP *per capita* lower than US$5,000 (2003) (Figure 14).

Economic projections for the period 2010-2080 show a mean GDP growth rate of 4.5%, 4.0%, 3.0% and 3.5%, for the very high (A1), high (B1), medium (B2) and low (A2) scenarios, respectively. By 2050, under the A1 scenario and considering the probabilistic demographic projection, 61 municipalities exhibit a GDP *per capita* higher than US$100,000 converted from Mexican constant pesos 2003. However, 1,687 municipalities remaining this means that more than 58% show a GDP *per capita* less than US$20,000. It is important to notice that 13 of the 20 highest GDPs *per capita* belong to the northern state of Chihuahua. In the same time slice, but under the medium scenario only, four municipalities show a GDP *per capita* higher than US$100,000, while 94% present a GDP *per capita* of less than US$20,000 (Figure 14).

3.3.3 Gridded population and GDP

Figure 15 shows the real inhabited area contrasting with many other studies which have shown population density in terms of the whole area of each municipality. The map helps to provide a better approach regarding the rurality or urbanity across the national territory instead of criteria based on the number of inhabitants or population density of complete areas (municipalities), which depend more on political divisions than distribution of people. Figure 15 shows the great heterogeneity in the real inhabited area, concentrated in the centre of the country and around two of the most important cities of Mexico. By 2010, the mean real inhabited area was 59 inhabitants per km^2 and under the high, medium and low scenario by 2050 the population density increases, reaching 99, 91 and 78 inhabitants per km^2, respectively. By 2080, under the high scenario the real inhabited population density reaches 112 inhabitants per km^2 and the medium scenario 94 inhabitants per km^2 increases very slightly in comparison with 2050, while the low scenario decreases the real inhabited population density showing a mean value of 64 inhabitants per km^2 (see maps in Appendix 3). However, it should be considered that real inhabited area will be affected basically on the policies and the strategies of urban expansion.

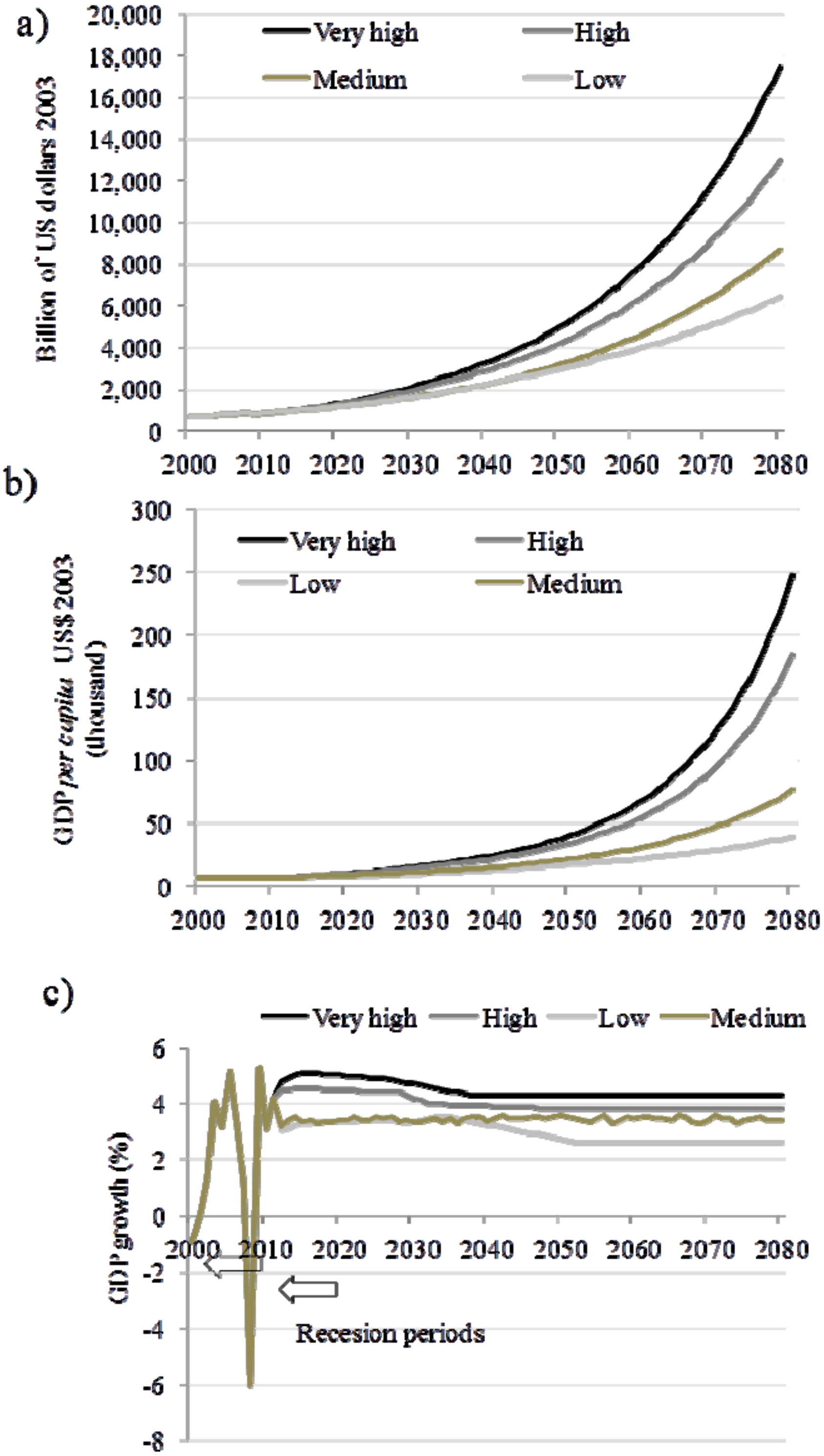

Figure 14. GDP projections: a) GDP projections transformed from Mexican constant pesos 2003 to US$ (2003); b) GDP annual growth rate; c) GDP *per capita* US$ (2003). Graph c) shows the effects of the economic recession of 2000 and 2008.

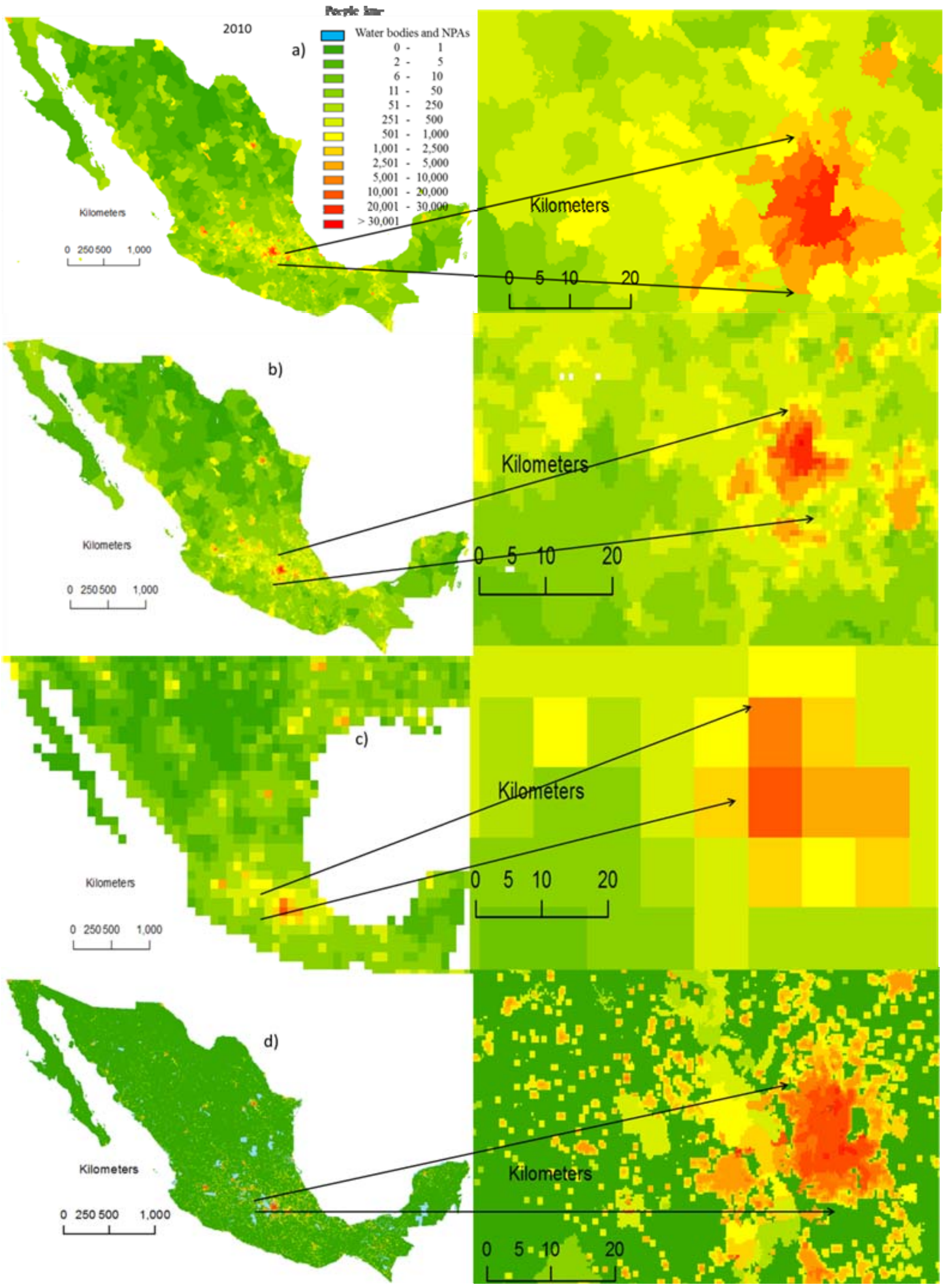

Figure 15. Population density maps for Mexico: a) population density using all the municipality area; b) gridded population of the world population density (1990) at 2.5^o x 2.5^o resolution, available in http://sedac.ciesin.columbia.edu; c) Gübler et al. (2007) show population density at 0.5^o x 0.5^o of resolution; d) population density in this study for 2010. Right column shows a zoom in on the metropolitan area of Mexico showing the differences in methodologies.

3.4 Discussion

The discussion section is developed in sections based on the different socio-economic drivers. The sections are 1) population projections, and their differences in this study and in comparison with other available data, 2) economic projections, and 3) geo-spatial grids for socio-economic projections. These are discussed on the basis of the methods and the assumptions and implications of each scenario for a Mexican context.

3.4.1 Population

There are some studies which incorporate information of population projections about Mexico, such as Gaffin et al. (2004) and van Vuuren et al. (2007). These studies used information taken from UN and IIASA data. These projections were published before 2010, so they do not take into account the most recent information for many countries, such as Mexico's latest census of 2010. Comparing Mexico's official data (census 2010) with Gaffin et al. (2004), van Vuuren et al. (2007) and the probabilistic method it was found that the biggest difference is for the high scenario (A2), with a greatest difference value of 6.5 % in relation to the official data; then the medium scenario (B2) with differences until 0.7%. Finally, the greatest similarities were for the low scenario (A1B1), which showed the biggest value of differences of 0.6%. In the case of the deterministic method and the latest UN projections, this study did not take into account the difference because these projections integrated the latest available information, so it was not possible to obtain the difference between the projected data in relation to the official data.

Probabilistic projections tend to show lower numbers in this study. For instance, the probabilistic method for the high scenario is similar to the medium scenario of the deterministic projections, and other studies such as Gaffin et al. (2004) and van Vuuren et al. (2007). The same applies for the medium scenario (B2), which is similar to the low scenario (A1B1) of the deterministic projections (Figure 13). This study suggests that differences in these demographic outputs are the result of the lack of integration of every demographic component, and specifically migration, which has been demonstrated as a crucial driver for Mexico's population (Partida, 2010; Verduzco, 2010).

This means that the deterministic projections assume that, for example, in low growth scenarios the TFR decrease, life expectancy and migration is high through all the periods of study. Another point is that the lower values of the probabilistic projections could be because of the migration patterns and the deterministic methods based on UN projections because they show a steady migration from 2050. This leaves in evidence that population projection methods should be analysed by the ongoing comparison of results with real data. This continued revision of projections in relation to the assumptions of scenarios would allow us to improve the methodologies and the understanding to the assumptions of the scenarios.

In terms of demographic results, all the scenarios show a decrease in TFR. However, it is advisable that scenarios and their quantitative projections are able to incorporate different values according to social contexts. In this study, the deterministic approach showed that although there is decrease in TFR in the three scenarios, municipalities with high levels of marginalisation, especially in the south, keep showing higher TFR than those northern or central. States such as Oaxaca or Chiapas, which have most of the municipalities living in very high and high marginalisation, will show the highest TFR values. Although new SSPs scenarios try to integrate different aspects such as education and poverty (Jiang, 2014; Kc and Lutz, 2014), these quantitative projections with their associated storylines need to be contextualised at local level.

By 2050 Mexican population might reach between 121 to 174 million people majorly distributed in urban areas. This increase in population will demand resources such as energy, food, and services which Mexican government and society will face. These information such as the spatial information about the real inhabited could help determining not only the increase in services but also joined to the National Centre for Prevention of Disasters (CENAPRED) to estimate how many people might be in danger under different climatic events as floodings or droughts in the short, medium and long term, trying to develop strategies to diminish the municipalities and the people who live in under this threats.

3.4.2 Economy

GDP is the most widely used measure of economic activity. However, GDP has been often used to express the well-being of people ignoring that GDP measures market production and that this indicator cannot reflect the social or economic inequality or the quality of life of societies (Stiglitz *et al.*, 2009). GDP does not reflect information about the sustainable market production. In order to show social or environmental information between societies and their changes, there are necessary different indicators such as the Human Development Index (HDI) or the Ecological Footprint (EF) (Moran *et al.*, 2008). Nevertheless the limitations and problems of the GDP as an indicator of economic development it has many strengthens. GDP can overcome the problems of the subjectivity that face other indices as HDI when definitions or parameters of well-being are applied in different societies and cultures. Moreover, the lack of information to build that index at a subnational level.

In this context, it is worth pointing out that even though the limitations of the GDP to show the development of people it was the only available measure in several time-slices and spatial scales. However, once that GDP has been chosen as a measure, its long-term projection have a lot of problems, some of them related to the data where they are taken from, the methodologies applied and the assumptions of growth (Duval and de la Maisonneuve, 2010). Despite the difficulty of long-term projections for economic indicators, for many countries such as Mexico, it is the quality and sources of data which are not equally reported, and sometimes the numbers for the same years vary depending on the national or international source, even when GDP is reported at the same constant or current values for the same year. This makes it more difficult to compare projections or some data even for historical trends. Another problem that this study faced was the lack of information of GDP data under state level for more than one year, and from different trusted sources. This can cause higher uncertainties in the outputs if the relationship between GDP at the municipality level is different in relation to 2005. Moreover, it is worth pointing out that in the case of Mexico City – the major contributor to the national GDP –, there are not available data in the national sources such as INEGI, so the information for the 17 delegations was taken from different sources. Besides the lack of information, future economic projections should be able to incorporate information which allows an answer to how economic growth may impact the dynamic of urban centres and poor municipalities (Rubalcava, 2010), and how economic practices will impact key sectors such as agriculture, which in turn will affect the LUCC processes (Dyer, 2010; Garza, 2010; Partida, 2010).

It is important to notice that some agents that have an effect on the GDP and national economy were not included in the model due to the lack of information such as the role of black market and the shadow economies. These illegal activities has been suggested to be around 25% of the national GDP (INEGI, 2015a). These activities employed around 60% of the working population in Mexico, these people do not pay taxes and they do not have any health insurance or benefits. It is worth pointing out that according to INEGI people involved in black market or shadow economies have been increasing from 7.3 million people in 2003 that contributed with 27.2% of national GDP to 16.3 million people in 2015 contributing with 23.7% of the national GDP (INEGI, 2015b). That means that more than double produce less through the time. Besides the contribution of these activities and the slightly increase between 2008 to 2015 they were not considered when projecting the national GDP. That was decided due to the lack of reliable information in order to keep simpler and clearer the quantification of the model.

Finally, GDP, black and shadow economies are projected to be increasing at low rates through the time; however, it is uncertain the contribution of the black market and the shadow economies and their impacts to the Mexican economy. In this context, regarding the comparison of the SRES to SSPs scenarios, the assumptions are very different, even if new projections developed by IIASA and the OECD are diverse for each scenario. New SSPs scenarios show a continuous decreasing trend in average GDP growth rate, while SRES depict a stabilisation. According to IIASA projections, the average growth rate of GDP from 2015 to 2080 oscillates between 1.35% (SSP4) and the OECD's projection between 1.95% (SSP3) and 3.14% (SSP5). However, there is a difference using the directional and lineal scenarios such as SRES in relation to the new assumptions, which produces a plethora of combination.

3.4.3 Gridded population and GDP

Gridded data for socio-economic drivers at the global level are available in the CIESIN data collection (2004) or IIASA (2009); both explicit spatial data help understanding at the global scale, where the most important changes will be performed. However, the resolution (0.5^o x 0.5^o) is too coarse for assisting the process of the decision making on the basis that it is not possible to prioritise municipalities smaller than 55 km^2 (n = 406 municipalities), in which the poorest and the most marginalised people are. Moreover, downscaled global available data use population density at a municipality level for many developing countries such as Mexico using regional growth rates, on the basis that all Latin American countries follow the same trend. For this reason, contextualisation of scenarios in areas where factors such as marginalisation and rurality impact the demographic components, especially TFR and mortality, is important, as Mexico does (Camarena and Lerner, 2008; Szasz, 2008). This heterogeneity is taken into account in the deterministic projection where the TFR is based on the rurality or marginalisation of every single municipality. This new bottom-up approach allows incorporation of the differences inside the country. As a result, the grid population projections reflect possible changes of the real inhabited area. However, future studies need to incorporate the impact of policies and urban expansion strategies, which will impact the real occupied area of the country in the medium and long-term, and which in turn will affect the land use/cover change process (Garza, 2010) and the availability of ecosystem services provision.

3.5 Conclusion

National and sub-national downscaling exercises are important for contextualising scenarios and analysing the implications of the scenarios assumptions. Presumptions of global scenarios do not mean the same for each country on a national, regional or local level. This is one of the first studies which contextualise the socio-economic drivers of GEC under different assumptions at the sub-national level in a developing country, by generating explicit spatial information of the most important anthropogenic drivers such as population and GDP, which could be used as inputs for environmental, vulnerability, mitigation and adaptation modelling such as demand of resources as energy, food, and services which Mexican government and society will face.

Chapter 4. Modelling Land Use Cover Change (LUCC) under different Socio-economic and Climate Change (CC) Scenarios in Mexico

4.1 Introduction

The aim of this chapter is to determine the hotspots of Land Use Cover Changes (LUCCs) under different Climate Change (CC) and socio-economic scenarios at the national level. The LUCC models were developed in the Dinamica EGO platform by using maps (1:250,000) from the years 2000, 2003 and 2007. The LUCC models were projected for three time slices: 2020s, 2050s and 2080s under A2 and B2 assumptions of the Special Report on Emissions Scenarios (SRES) by Intergovernmental Panel on Climate Change (IPCC). This chapter first provides a general overview of the different LUCC models and approaches. Secondly, the methods are outlined including an explanation of the inputs used and the steps involved in the training of the model and the development of the scenario projections. Thirdly, the results are highlighted in two key outcomes: 1) what natural land covers have been more affected by LUCC under different socio-economic and CC scenarios; and 2) analyses of the principal socio-economic and biophysical explanatory variables for these changes. The fourth section provides a discussion of the comparison of the results with previous reports in Mexico and an analysis of the strengths and limitations of the approach used. The final section explores the implications of this study and proposes future research directions.

4.1.1 LUCC

Land use (for human purposes) and land cover (the biophysical attributes of the earth's surface) changes (LUCCs) (Turner *et al.,* 1990; Lambin *et al.*, 1999) play a pivotal role in the Global Environmental Changes (GECs) that affect biodiversity (Sala *et al.*, 2000; Jetz *et al.*, 2007; Newbold *et al.*, 2014), soil (Trimble and Crosson, 2000) and climate (Pielke *et al.*, 2002; Kalnay and Cai, 2003; Pielke, 2005; Houghton *et al.*, 2012).

Knowledge and understanding of LUCC processes and their causes and effects are requisites to reducing and managing impacts and consequences of LUCC (Kolb *et al.*, 2013).

Modelling LUCC can help to understand the dynamics of changes by: 1) projecting future land-use trajectories in order to develop targeted management decisions (Schoonenboom, 1995); 2) relating underlying forces (population, economic growth, policies of land management, etc.); and 3) understanding the direct forces of change (i.e. agricultural expansion) (Geist and Lambin, 2002).

4.1.2 LUCC models

Agarwal et al. (2002) categorise LUCC models based on three critical dimensions: 1) time; 2) space; and 3) decision-making context. Time refers to temporal scale, which includes step and duration. Time step is the smallest temporal unit of analysis for change to occur for a specific process in a model, while duration is the length of time in which the model is applied. Space includes both resolution and extent. Resolution is the smallest geographic unit of analysis within the model and the extent describes the total geographic area of interest. As analogues to the time step, duration, resolution and extent, Agarwal et al. (2002) propose that agent and domain are the components of the context of human decision-making. On the one hand, agent refers to the human actor or actors. In the LUCC model the minimum refers to the individual human, but agents can be organisations, households, neighbourhoods, counties, states, provinces, or nations.

A plethora of quantitative LUCCs models based on the dimensions described above can be classified into mathematical equation-based models, machine learning, statistical techniques, system dynamics models, expert system, cellular models, agent-based models and hybrid models (Parker *et al.*, 2003) (see Table 3). Mathematical equation-models are based on a cause-effect relationship where the forces of change are socio-economic (Sklar and Costanza, 1991; Kaimowitz and Angelsen, 1998) and/or biophysical (Chuvieco, 1993). As Parker *et al.,* (2003) mention, a major drawback is that this kind of model assumes a linear causality thus making it difficult to create certain complex systems such as feedback between variables. In contrast, system dynamics models include feedback by representing stocks and flows of different variables in time steps as a set of differential equations (Sklar and Costanza, 1991).

Other models, such as statistical models, include different kinds of regressions based on relationships between variables and specific changes (Mertens and Lambin, 1997). These models can be associated to a geographical space such as a pixel or polygon. However, they cannot consider qualitative information such as land tenure, institutions or social conflicts based on the behaviour of the agents. On the contrary, expert models can include expert judgment by combining qualitative knowledge and quantitative techniques; however, the subjectivity of the experts can produce biases in the results with gaps and inconsistencies (Parker *et al.*, 2003).

Cellular automata (CA) models are based on an idealisation of a physical system in which time and space are discrete, and the physical quantities take only a finite set of values (Chopard and Droz, 1998). Moreover, the discrete nature of the spatial and temporal frameworks of the CA model take into account characteristics of the neighbour-unit (resolution) and boundary conditions under some transition rules in which all the units in the extent change synchronously at the same time step (Hoekstra *et al.*, 2010). CA models have weaknesses related to their discrete nature; CA requires systematic averaging processes which causes statistical noise and little flexibility to adjust parameters of the rules of the transitions. In order to overcome some of these drawbacks Markov models have been introduced by using the probability of occurrence of change of the spatial units through time, giving a dynamic plasticity to the system (Li and Reynolds, 1997).

Agent Based Models (ABMs) were originated from the field of artificial intelligence. They consist of a number of “agents” which interact both with each other and with their environment, and can make decisions and change their actions as a result of this interaction (Ferber, 1999). Agents can contain their own model, and the behaviour of the whole system depends on the aggregated individual behaviour of each agent. This allows the incorporation of the influence of the decision making process on the environment. Agents can interact either indirectly through a shared environment and or directly through markets, social networks or institutions. ABMs have many of the characteristics of the CA except that the environment and population sides of the systems are kept apart. In terms of aggregation, ABMs tend to be more successful at smaller scales than the region although some have been applied at larger scales (Batty, 2012). In some sense at one level CA models can be seen as simplified varieties of ABM where the cells do not move if they change their state.

The key difference between the CA and ABMs is that the system is driven in the ABMs is endowed with purposive behaviour which conditions, causing specific and individual behaviour of each agent, in contrast to aggregated models where this behaviour is part of a collective (Batty, 2012).

The primary strength of ABMs is a testing ground for a variety of theoretical assumptions and concepts about human behaviour. As a result, the social process is a behaviour-driven phenomenon. However, ABMs tend to be traditionally less concerned with realistic representation of the physical environment (Stanilov, 2012). Therefore, they are rarely used as predictive models for real-world sites where the concern is that they can be overly fitted to existing data, thus losing their power of generalization or ability to explore alternative systems (Stanilov, 2012). Finally, ABMs are better used at smaller regions because of the complexity in the integration of the agents (Batty, 2005).

Finally, hybrid models arise from the combination of different models such as Markov chains models and CA models. This combination helps to overcome some of the weaknesses of a single model approach. Markov Chain models treat the LUCC as a stochastic process (Weng, 2002). The later state (land cover type or class) of a spatial unit is only related to its immediate preceding state, but not to any other previous states (Levinson and Chen, 2005). The assumption that LUCC phenomena are stationary processes is the principal drawback due to the complex and dynamic variables and processes involved (Lambin *et al.*, 2001; Lambin *et al.*, 2003; Myint and Wang, 2006). In order to overcome this, CA models can be used to improve the spatial contingency of future land uses based on dynamic rules. The CA process creates a suitability map for each class based on a set of factors (biophysical or socioeconomic), ensuring that LUCC occurs in proximity to similar existing land use classes, and not in a random manner. The incorporation of Markov chains and CA models combined in CA-Markov models have been successful when used for predicting LUCC (Pontius and Malanson, 2005). Nevertheless, the utility of this combination is not without challenges when attempting to incorporate human decision-making and expert knowledge into more complex and dynamic systems.

Table 3. Comparison of different modelling approaches used to explore Land Use and Land Cover Change.

	Characteristics	Pros	Cons	Examples
Mathematical equation-models (may include some statistical models)	Based on cause- effect relationship.	Simplicity and easily repeatable	Assumption of a linear causality making difficult to create complex systems and the feedback between variables	Urban expansion in China (Huang *et al.*, 2008).
Dynamic models (which can include CA, ABM or hybrid models)	Include different variables such as socio-economic and biophysical and their interactions	Include feedbacks between variables in time and space	They are no easily repeatable due to the complexity in the system building.	Different examples about LUCC models their inputs requirements and the outputs (Pontius *et al.*, 2008)
Statistical models	Relation between variables and specific changes.	Simplicity, transparency about the process and objectivity.	They cannot consider qualitative information such as land tenure, institutions or social conflicts.	LUCC in mountainous landscape in the Alps (Rutherford *et al.*, 2008)
Expert models	They include expert opinions based on qualitative and quantitative information.	It is possible to integrate the expertise, advice and reasoning about the system and their interactions.	Subjectivity that can produce biases and they are nor easily repeatable.	Urban expansion and spatial planning (Klosterman and Pettit, 2005).
Cellular automata (CA)	Time and space are discrete. The cells can be considered 1) simple actors with fixed neighbourhood relations and update rules or 2) state and dynamics of the environment. Changes are based on the fixed rules based on the state of its neighbours.	CA models can capture important dynamics, based on specific rules. They can represent endogenous interactions and feedbacks (Brown *et al.*, 2004). These models have been widely used combined with Markov chains	The establishment of the rules that govern system behaviour cannot easily extrapolated. Simplification of rules make difficult to explore the effect of the individuals, decision makers, social groups, or institutions.	Urban expansion in the US and comparison between models (Clark and Gaydos, 1998; Verburg *et al.*, 2004).

		resulting in hybrid models.		
Markov models (Mkv)	Transitions between the states of the system are recorded in the form of a transition matrix that records the probability of moving from one state to another. A finite number of well-defined states that mutually exclusive.	Statistically strong justification of the results. Repeatable and objective.	Probability of occurrence of change depends only on the state today. Changes do not consider the state of the neighbour's cells. Moreover, the assumption regarding constant transition probabilities is often rejected when tested as a statistical hypothesis. Finally, the transition probabilities estimated in most empirical applications are a function of data availability and take the length of transition periods as given.	These models have been used in combination with other approaches such as CA (Guan *et al.*, 2011).
Agent Based Models (ABM)	Combination of different models overcoming the weaknesses of singular models.	Flexibility due the incorporation of different qualitative and quantitative data.	They are not spatially explicit at least they use some other tools such as CA Assumptions about that under certain conditions human behaviour keeps constant Less concerned about the biophysical environment than human choices. They cannot be generalized because of the specific conditions that ruled the agent behaviour; as a result they are better used in smaller scales than regions.	Comparison about approaches in AGB (Matthews *et al.*, 2007; Robinson *et al.*, 2007) and some case studies in Europe (Murray-Rust *et al.*, 2013) and Argentina (Bert *et al.*, 2011).
Hybrid models	Combination of different models overcoming the weaknesses of singular models.	Flexibility due the incorporation of different qualitative and quantitative data.	They can become very complex because of the integration of methods and approaches. These models cannot be easily repeatable to the assumptions in each step, especially in the use of qualitative information.	Many examples such as the Brazilian case studies (Ferreira *et al.*, 2012; Soares-Filho *et al.*, 2013).

4.1.3 Tools for modelling LUCC

There are different kinds of software based on the approaches outlined above that are spatially explicit and often related to Geographic Information Systems (GIS). Commonly used software packages include: 1) Conversion of Land Use and Its Effects (CLUE) (Veldkamp and Fresco, 1996b); 2) Conversion of Land Use and its Effects at Small regional extent (CLUE-S) (Verburg *et al.*, 2002); 3) Dynamic Conversion of Land Use and its Effects (Dyna-CLUE) (Verburg and Overmars, 2009); 4) Land Change Modeller (LCM) (Eastman, 2006, 2007, 2009); 5) Geomod (Pontius *et al.*, 2001a); 6) CA_Markov (Cellular Automata_Markov) (Pontius and Malanson, 2005); and 7) Dinamica EGO (Soares-Filho *et al.*, 2002) (see Table 4).

Based on the features described above the criteria for choosing Dinamica EGO for this study were: 1) the flexibility to incorporate different updated information (see Appendix 3) and create feedback in a dynamic and non-linear system to create scenarios; 2) similarities in tropical Latin American countries where Dinamica EGO has been successfully applied, and 3) Dinamica EGO is a freeware.

4.1.4 CC and LUCC

The intrinsic relationships and feedbacks between LUCC and CC have become increasingly prominent in recent decades. The projected changes in climate will not only affect vegetation (vegetation demonstrates resistance, resilience and adaptive capacity to CC (FAO, 2013)) but also LUCC patterns related to the adaptation of humans to CC (Dale, 1997; IPCC, 2007a) as a result of new climatic variables that alter agricultural productivity (Oliveira *et al.*, 2013). The fourth assessment report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) used scenarios from the Special Report on Emissions Scenarios (SRES) (Nakicenovic *et al.*, 2000) to depict possible futures that may unfold if certain factors are present. SRES are combinations of different storylines related to families of scenarios called A1, A2, B1 and B2 (Nakicenovic *et al.*, 2000). Each scenario considers population, economic growth and technological advancements within certain political governance (from local to global) and "environmental awareness" circumstances (Nakicenovic *et al.*, 2000).

Table 4. LUCC software comparison.

Software	Characteristics	Requirements	Pros	Cons	Source
Conversion of Land USE and its Effects (CLUE)	CLUE simulates LUCC using empirically quantified relationships between LUC and its driving factors. It is based on the competition between land-use types (Veldkamp and Fresco, 1996a; Verburg *et al.*, 1999).	Land use/cover maps. Data about the drivers of change incorporating information about the social demand related to the extent of the LUC areas.	It quantifies relationships between land use and its driving factors. CLUE was developed to be applied at the national and continental level.	CLUE cannot be directly applied at the regional scale (Verburg *et al.*, 2002).	Institute for Environmental studies (http://www.ivm.vu.nl/) Freeware
Conversion of Land USE and its Effects at Small Extent (CLUE-S)	It is sub-divided in: 1) a non-spatial demand module which calculates the area of change based on the demands; and 2) a spatially explicit allocation module in which the demands are translated into land-use changes. Allocation is determined by the local conditions, and the regional demands that affect the competition between the land uses “overruling” the local suitability (Verburg *et al.*, 2002)	One of the requirements for land-use change models is multi-scale characteristics that incorporate iterative continuous interactions between macro-scale demands and local land-use suitability.	Calculation of the land-use demand module that implies different choices from simple trend extrapolations to complex economic models. The integration of social and biophysical variables, based on the demand, the availability and the competition.	Difficulties to get data for land use and driving factors at finer spatial resolutions. Problems in extrapolating local demands to local changes.	Institute for Environmental studies (http://www.ivm.vu.nl/) Freeware
Dynamic Conversion of Land USE and its Effects (Dyna-CLUE)	More sophisticated than the other CLUE’s versions. It integrates areas driven by demand at the regional level and areas do not aggregated in the regional demand (semi-natural covers) (Verburg and Overmars, 2009). It allows the combination of the top-down allocation of LUCC to grid cells with a bottom-up determination of conversions for specific land use transitions.	Same as CLUE-s and information about the demands that could be originated outside the studies system such as the importation of products related to external LUCC processes.	Incorporation of many variables at different scales that allow the creation of scenarios based on the real demands in dynamic systems that use feedbacks between variables.	Same as CLUE-S and exacerbated to the difficulties to get information about the demands of exported sources.	Institute for Environmental studies (http://www.ivm.vu.nl/)

Software	Characteristics	Requirements	Pros	Cons	Source
Land Change Modeler (LCM)	It evaluates the relationship between drivers of deforestation (anthropic and biophysical), constraints and areas of LUCC derived from at least two land cover maps (Eastman, 2006, 2007, 2009).	At least two land cover maps and data about socio-economic and biophysical drivers of change.	Statistical regressions between forces of change of both LUC maps and Markov chain matrices allow LCM to project future changes at defined durations and time steps.	Acquisition of available information and the cost of the software.	Clark labs (https://clarklabs.org/terrset/land-change-modeler/) Module of IDRISI software.
GEOMOD	Geomod works using the input of one land cover map, a start date and end date, and the amount of each land cover type expected by the end date. Geomod can produce a suitability map for change based on the driver data and by using a weighted sum approach.	At least two land cover maps and data about socio-economic and biophysical drivers of change.	Geomod identifies areas likely to change with the input of four optional parameters: 1) permanence of the transition, 2) strata (or regions), 3) neighbourhood change and 4) suitability (Pontius *et al.*, 2001b; Pontius and Chen, 2006).	It can only consider one land cover transition at a time and the software is not free of charge.	Clark labs (https://clarklabs.org/terrset/land-change-modeler/) Module of IDRISI software.
CA-Markov	CA_Markov uses two maps for modelling; quantity of change is predicted by category at time *t2* by extrapolating both gain and loss of each category from time *t1*. Spatial allocation of changes is based CA and the suitability of change and quantity of change is given by Markov model. Suitability maps can be obtained using a deductive approach such as Multi-Criteria Evaluation or an inductive approach such as logistic regression (Pontius and Malanson, 2005).	At least two land cover maps and data about socio-economic and biophysical drivers of change.	It allows for the modelling of any number of categories and simulates transitions from any category to any other	Software is not free of charge.	Clark labs (https://clarklabs.org/terrset/land-change-modeler/) Module of IDRISI software.

Software	Characteristics	Requirements	Pros	Cons	Source
Dinamica Environment Geo-processing Objects (Dinamica-EGO)	It is a spatially explicit simulation model of landscape dynamics based on CA. It presents multi-scale vicinity-based transitional functions, incorporation of spatial feedback to a stochastic multi-step simulation engine, and the application of logistic regression to calculate the spatially dynamic transition probabilities (Soares-Filho *et al.*, 2002).	Two land use/cover maps and information of socio-economic and biophysical forces of change.	Dinamica EGO is a more comprehensive platform that allows the design of complex spatio-temporal models and the ability to conduct calculations on various types of data, such as values, tables, matrices and raster graphics. It shows great flexibility with its functions allowing advanced dynamic models that involve nested iterations, dynamic feedbacks, bifurcating and joining execution of chain processes.	Could be very complex and due to the integration of several feedbacks. Moreover, as the integration of several variables and information types is possible, the models cannot be easily repeatable especially in the creation of scenarios due to the integration of the assumptions in the different steps.	Centro de Sensoramiento Remoto/ Universidades Federal de Minas Gerais http://csr.ufmg.br/dinamica/) Free ware

Contrasting trends in LUCC are observed for scenarios A2 and B1, being the pessimistic and the optimistic in terms of vegetation loss, respectively. The A2 narrative storyline depicts high GHG emissions, describes widespread agricultural expansion and illustrates that suitable land for agriculture that will be used for farming by 2100 to support the increasing global population (Nakicenovic *et al.*, 2000; Feddema *et al.*, 2005; IPCC, 2007a). The B1 narrative storyline depicts low GHG emissions where the abandonment of farms occurs, assumptions of an increase in agricultural efficiency to provide food to a declining population are made and an incremental increase in forests (Nakicenovic *et al.*, 2000; Feddema *et al.*, 2005; IPCC, 2007a). A1 and B2 scenarios show a medium trend in CO_2 emissions due to LUCC; but differences in other variables such as population or technological applications on agricultural land have a differential effect on the LUCC processes and patterns. The B2 scenario uses Business as Usual (BAU) while the A1 scenario tends to diminish the loss of natural vegetation for provisions due to an decreasing population and technological improvements (Nakicenovic *et al.*, 2000).

4.1.5 CC and LUCC modelling under scenario assumptions

The interrelationships that exist between LUCC and CC include the role of vegetation and the phenomenon of LUCC on the climate and *vice versa* (Fig. 16). LUCC affects the carbon cycle by increasing ecosystem types that act as CO_2 sinks or by creating additional sources of CO_2 emissions; this depends upon on how the ecosystem is managed (Fischlin *et al.*, 2007; Bonan, 2008) and which vegetation types are found within the ecosystem (Snyder *et al.*, 2004). Conversion from forestland to agriculture is a major source of CO_2; tropical forests are considered to be sources of CO_2 (Santilli *et al.*, 2005) or neutral (Pan *et al.*, 2011) and boreal and temperate forests are considered to be sinks of CO_2 (IPCC, 2007a; Lal, 2012). Other studies have focused on determining the effect of CC on certain species and the distribution of vegetation zones that are predicted to change due to changes in temperature and/or precipitation (Shvidenko *et al.*, 2005).

The response of the Earth System to anthropogenic forcing cannot be described using simple cause-effect relationships. The Earth System's responses to increasing anthropogenic forcing are more complex (Steffen *et al.*, 2004). Consequently, the incorporation of feedbacks between climatic variables (temperature, precipitation, aridity index or evapotranspiration) and non-climatic causes of land-use change (socio-economics and politics) should be included in LUCC models in order to have a better understanding of the processes, trends and possible effects (Fischer *et al.*, 2005; Salmun and Molod, 2006). Studies which integrate socio-economic projections and biophysical variables as forces of change require an interdisciplinary approach and framework in order to craft strong science (Bonan, 2008). As a result, this study is focusing on integrating the biophysical and the socio-economic variables which are related to the process of LUCC and CC and their possible effects on the natural covers of Mexico. The assumption of the scenarios using in the LUCC model are described in tables 5 and 6.

Table 5. Socio-economic scenarios for Mexico.

	A2	B2
Population	↗	↗
Immigration (rural to urban)	↗	→
Indigenous values	↘	↗
Economy growth rate	↗	↗
GDP	↗	↗
LUCCs	↗	↗
Urbanization	↗	→
Agriculture area	↗	→
Crop production	→	↗
Agriculture subsidies	→	↗
Agriculture investment	↘	↗
Organic agriculture	↗	↗
Forest area	↘	↘
Technology	→	→
Fossil fuel	↗	→
Renewable energy investment growth rate	↘	↘
Waste production	↗	→
CO_2 emissions growth rate	↗	↗

Table 6. Mexican context of SRES.

A2: Pattern: Heterogeneity through Mexico.

Population trends: Continuous population growth. Fertility patterns between rural and urban municipalities will converge slowly (~ 2050), but they will show a persistent heterogeneity between regions. This will cause a delay in the demographic transition from high to low, depending on the type of municipality.

Socio- Economic development: It will be more fragmented. The poor stay poor. The combination of the high population with limited income growth results in an internal and external migration. People will move from rural areas to cities. This scenario has the highest level of urbanization rate. There will be an increase of migration from rural municipalities to the US.

Increasing temperatures and changes in rain patterns will cause dangerous periods of drought through Mexico, especially the north. However, subsidies keep distributing only to alleviate short-term short effects of these climate events rather than developing mitigation or adaptive to medium or long-term**.**

Dynamic among municipalities: Great differences between rural and urban municipalities. It is more prone to clashed cultures and ideas and places a high priority on indigenous values. Technological improvements will not arrive at the agricultural sector; as a result, there will be a low crop yield. Farmers and peasants will migrate into cities or to the US. Farmers who stay in rural areas will expand their agricultural lands, practicing traditional management. Illegal harvesting increases.

Technology and energy:

Rural areas: It is assumed that malicious subsidies keep going to the agricultural sector. There will be a scarce investment to research, technology and planning for improving agriculture and forestry yield or for mitigation and adaptation to climate change.

GHG emissions: GHG emissions will increase, as a result of the increasing, the augment in fossil fuel use, but also because of the land use change (agricultural expansion an illegal harvesting).

B2: Pattern: Heterogeneity through Mexico and focus on local solutions.

Population trends: Increasing population at a rate lower than A2. Strong convergence in fertility levels toward replacement levels, ultimately yielding a stabilization of country population level.

Socio- Economic development: It may converge at some extent until demographic transition does. Peaks of per capita income growth are therefore assumed to coincide with the fertility transition. Rural municipalities have higher TFR values than the urbans; cultural practices applied in agriculture have an effect on the improvements on yields which in turn would contribution in major extent to national GDP.

Dynamic among municipalities: urbanization rates are intermediate. There will be scarce investments to improvement to the agricultural sector, malicious subsidies remain. However, local solutions pop up in specific areas spreading slowly out.

Technology and energy: Rural areas will slowly show improvements in agriculture and forestry, as a result of the middling use of technological investments.

GHG emissions: GHG emissions will increase at a medium rate due to the population growth the low investments in clean technology and energy and the LUCC.

4.1.6 Aims, justification and novelty of the approach

The aim of this study is to determine the areas where LUCCs under different CC and socioeconomic scenarios at the national level will be more severe. This is a novel approach as Dinamica EGO has not been used at a national scale before. This research uses available information as inputs for determining the most vulnerable areas of LUCC under CC to create new geospatially explicit information at a $1km^2$ resolution for Mexico. This approach is suitable for further regional or local studies that aim to identify places where climate related changes will be more severe, especially in developing and megadiverse countries. The main research questions include:

- How have Mexico's natural land covers been affected by LUCC in the past (1993-2003-2007?
- Where are the most vulnerable areas to LUCC and CC in Mexico?
- What are Mexico’s natural lands covers in these hotspots of change?

4.2 Methods

This study was conducted at the national scale at 1km x 1km resolution. The extent was 1,907,382 km^2 excluding islands and water bodies. The following methods section is divided into three main parts: 1) the description of the inputs for building the model; 2) a detailed description of the model; and 3) the model validation.

4.2.1 The selection of input variables

To create the LUCC model, three national land cover maps from 1993, 2003 and 2007 were used (1:250,000) (INEGI, 2001, 2005, 2008). The Original classification of land uses/covers were aggregated into nine different classes (Classification 1 in Table 7). Explanatory variables or forces of change included socio-economic and biophysical data from different temporal and spatial scales (Table 8) and were mainly derived from previous studies of LUCC undertaken in Mexico (Geoghegan *et al.*, 2001; Roy-Chowdhury, 2006; Flamenco-Sandoval *et al.*, 2007; Wyman *et al.*, 2008; Currit and Easterling, 2009; Ellis *et al.*, 2010;

Mas *et al.*, 2010; Mas and Flamenco, 2011; Sahagún-Sánchez *et al.*, 2011; Pérez-Vega *et al.*, 2012). For more details see Figure 16).

Climatic variables included outputs obtained from four coupled global atmosphere-ocean general circulation models (GCMs) were used for modelling the effects of climatic variables on land uses and covers (HadCM3, CGCM2, MK2 and Nies 99). The four GCMs used were: 1) Hadley Center for Climate Prediction, Hadley Centre Coupled Model 3; 2) Canadian Center for Climate Modeling and Analysis, Coupled Global Climate Model 2 (CGCM2); 3) the Commonwealth Scientific and Industrial Research Organization, Atmospheric Research Mark2 (MK2) (Hirst *et al.*, 1996; Hirst *et al.*, 2000); and 4) the Japanese National Institute for Environmental Studies (Nies99). These GCMs were selected because they are the most commonly used GCMs for studying the impacts of climate (Loyola *et al.*, 2012; Tuanmu *et al.*, 2013; Habel *et al.*, 2014) including Mexico (Luna-Vega *et al.*, 2012).

It is worth pointing out that the climatic information used was derived from these four CGCMs which included the downscaled data (30 arcsec resolution, equivalent to 0.86 km^2 at the equator) at three different time steps (2020, 2050, and 2080). This information consists of four climatic variables: 1) Aridity Index (AI) = Mean Annual Precipitation / Mean Annual Evapotranspiration where <0.03 = hyper arid, 0.03-0.2 = Arid, 0.2-0.5 = Semi-arid, 0.5-0.65 = dry sub-humid, ≥0.65 = humid; 2) Potential Evapotranspiration (PET) = calculated as 100 times the standards deviation of the monthly values for the potential evapotranspiration; 3) Temperature Seasonality (TSD) annual range in temperature (standard deviation * 100); and 4) Temperature of growing degree-days (TMDG) on a 0 °C base (this variable represents the annual sum of daily temperatures above 0°C, a standard variable in vegetation and crop models to determine germination) (Metzger *et al.*, 2013). These variables have been shown to be important as they explain more than 99.9% of the global environmental stratification (GEnS) proposed by Metzger et al., (2013). They have been compared with nine existing global, continental and national bioclimates and ecosystems to provide a spatial and analytical framework for the aggregation of local observations, identification of gaps in current monitoring efforts and systematic design of complementary and new monitoring and research (Metzger *et al.*, 2013).

Table 7. Classification of Mexican use/covers (n=9 categories) was used in this study. Classification 2 clusters in 15 covers and uses, principal division is in temperate forests. Classification (C1) simplify in 10 land uses and covers grouping all the temperate forests, and maintaining the majority of groups of C1**.**

Classification1	**Classification 2**	**Original Classification (INEGI, 2001, 2005, 2008)[3]**
I. Temperate Forest (F)	1.Conifers	1. Ayarin forest
		2. Cedar forest
		3. Fir forest
		4. Pine forest
		5. Tascate forest
		6. Scrubland of conifer forest
		7. Forest plantations
	2.Conifer-broad leaf	8. Pine- oak forest
		9. Oak - pine forest
	3.Broad leaf	10. Oak forest
	4.Cloud forest	11. Cloud forest
II. Scrubland (S)	5. Mezquital	12. Mezquital
	6. Xeric Scrubland	13. Arid tropical scrubland (Chaparral)
		14. Crasicaulescent scrubland
		15. Microphyllous creosote bush desert
		16. Creosote bush scrub
		17. Tamaulipean thorn scrub
		18. Cactus scrub
		19. Sarcocaulescent scrubland
		20. Sarcocrasicaulescent scrubland
		21. Cloud sarcocrasicaulescent scrubland
		22. Piedmont scrub
		23. Microphyllous desert on sandy soils
III. Hydrophilic (H)	7. Hydrophilic Vegetation	24. Mangrove
		25. Riparian forest
		26. Riparian tropical forest
		27. Popal
		28. Tular (*Typha* spp, *Scirpus* spp. Phragmites communis)
		29. Riparian vegetation
		30. Vegetation of peten

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[3] Serie II (INEGI 1993-1996) used Landsat TM (combination of infrared bands and visible 4,3,2) at 1:250,000 scale. The clasification consists in more than 600 categories. Serie III was the result of the updating of the serie II using Landsat ETM+ images at a a 1:125,000 scale. Interpretation was done by specialist botanists, foresters and ecologists). The clasificatory systems is hierarchical consisting in four levels (formation, type, community and subcomunity). The most detailed level comprises 75 categories. This information was compared and corrobored with the 10,000 points of field samplings and more than 18,000 digital photographs of the same year (Palacio et al., 2000) . Serie IV was the updated information of serie III using SPOT images (857) of the year 2007; resultig the classification in 56 types of land use and covers which were verified with field work (INEGI, 2012b). Accuracy of the data used for the inputs LUCC maps is reported to be 70% for the northern regions of the country and 95% for the whole country considering all types of vegetation (Mas et al., 2004).

IV. Agriculture (A)	8. Agriculture and Livestock	31. Agriculture
		32. Grassland plantations
		33. Palms plantations
V. Tropical Evergreen Forest (TEF)	9. Tropical Evergreen and Semi Evergreen Forest	34. Tropical evergreen forest
		35. Tropical semi evergreen forest
		36. Tropical thorn low semi evergreen forest
		37. Tropical low evergreen forest
		38. Tropical semi evergreen medium forests
		39. Tropical evergreen medium forests
VI. Tropical Dry Forest (TDF)	10. Tropical Dry Forest and Tropical Semi Deciduous Forest	40. Tropical deciduous forest
		41. Tropical thorn low deciduous forest
		42. Tropical low deciduous forest
		43. Tropical medium deciduous forest
		44. Subtropical scrub
VII. Grassland (G)	11. Grassland	45. Natural grassland
		46. Piedmont grass
		47. Savanna
		48. Sabanoide vegetation
VIII. Other Vegetation (OV)	12. Other Vegetation	49. Palms
		50. Halophylic vegetation
		51. Gypsophile vegetation
		52. Sand dune vegetation
		53. Sand desert vegetation
IX. Other Covers (OC)	13. No vegetation	54. No vegetation
	14. Urban and human settlements	55. Urban and human settlements
X. Water Bodies (W)	15. Water Bodies	56. Water bodies

Table 8. Inputs of the LUCC model. (* Those used for A2 and B2 scenarios)

Biophysical				Socio-economic			
Map	Scale-resolution	Year	Source	Map	Scale-resolution	Year	Source
Land use / cover map	1:250,000	1993 2002 2007	(INEGI, 2001) (INEGI, 2005) (INEGI, 2008)	Distance to roads	1:1,000,000	1985	(Digital_Chart_of_the_world, 1985)
Altitude and slope	1: 100,000	-	(INEGI, 2000b)	Distance to NPAs	1:400,000	2012	(Bezaury-Creel *et al.*, 2009; CONANP, 2012)
Soil type	1:250,000	-	(INEGI, 2002b)	Distance to human settlements			(INEGI, 2008)
Potential vegetation	1:400,000	-	(Rzedowski, 1990)	Index of marginalization[4]	Municipality	1995 2000 2005 2010	(CONAPO, 1995) (CONAPO, 2000) (CONAPO, 2005) (CONAPO, 2010)
AI PET TSD TMDG	30 arc sec	Current 2020 2050 2080*	(Metzger *et al.*, 2013)	Population	Municipality	1993 2002 2007	(INEGI-CONAPO-COLMEX, 2006)
					Municipality	2020 2050 2080*	Chapter 3
Distance to Rivers	1:400,000	Current	(Maderey and Torres-Ruata, 1990)	Population density	Municipality	As above	As above
Mexican ecoregions	1:1,000,000	2007	(INEGI-CONABIO-INE, 2007)	GDP	Municipality	1993 2002 2007	INEGI
						2020 2050 /2080*	Chapter 3

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[4] Index of marginalization is a national index, which includes socio-economic information related to income, health, housing and education for more information see Appendix 1.

The LUCC model was developed in Dinamica EGO by undertaking the following steps: 1) calculation of the transition matrices; 2) categorisation of the continuous variables by defining classes (e.g. altitude or slope); 3) estimation of the weights of evidence of the explanatory variables; 4) analysis of correlation between variables; 5) simulation by running the model; 6) validation of the model (determining the accuracy of the location and quantity of change and the simulation by using exponential and multiple window constant decay function); 7) run the simulation; and 8) projection of different land uses and trajectories (Soares-Filho *et al.*, 2009) (Figure 16).

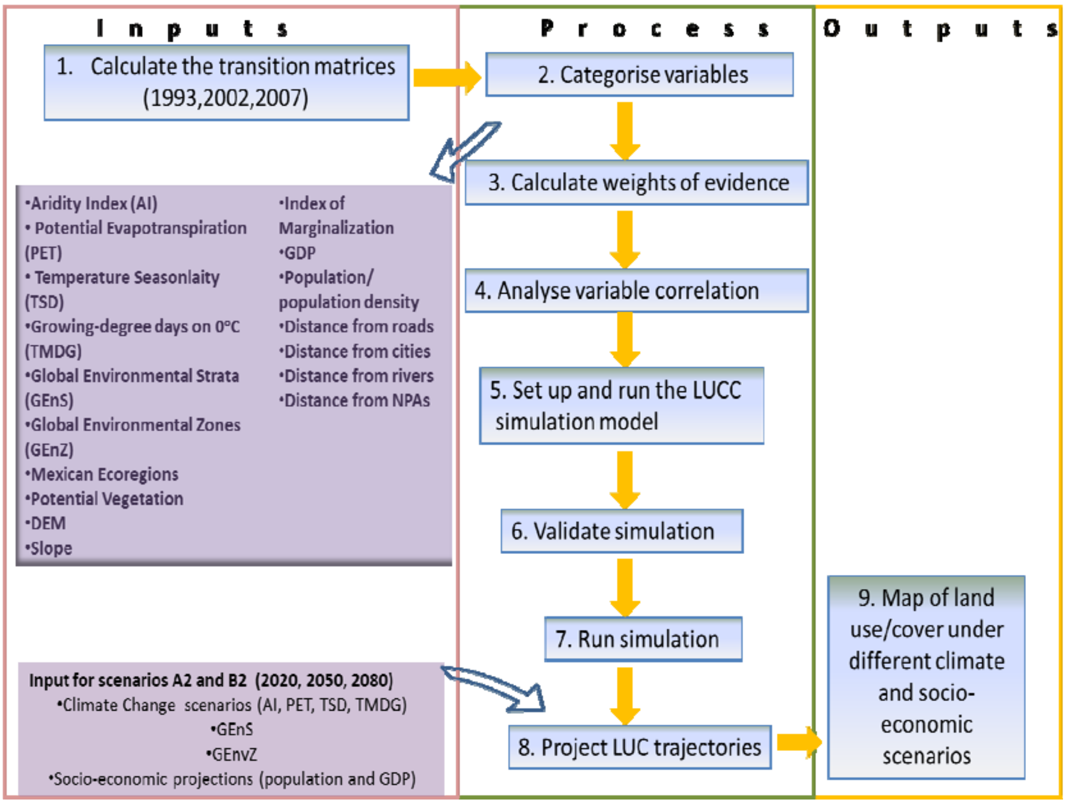

Figure 16. Steps for developing the LUCC model under different socioeconomic and CC scenarios.

4.2.2 Building the model

4.2.2.1 Calculation of the transition matrices

Transition matrices were calculated using the national land cover maps from 1993, 2003 and 2007. Dinamica EGO calculates two kinds of matrices, a single step matrix that is based on the period, i.e., 1993-2007, and a multi-step matrix that is the annual change for every transition. The results of the matrices were used to calculate the rate of change in area or percentage for each period of time. Considering the nine different land covers and uses there are 72 possible transitions. Only 20 transitions were considered for the model on the basis of the percentage contribution of total change of the LUCC maps (1993-20002, 2002-2007) (Table 9).

Table 9. Transitions used in the LUCC model; (F= temperate forests, S= scrublands, H= hydrophilic vegetation, A= agriculture, TEF = tropical evergreen forests, TDF = tropical dry forests, G = grasslands, OV = other vegetation, and OC = other covers.

	F	S	H	A	TEF	TDF	G	OV	OC
F		√		√		√			
S	√			√					
H				√					
A	√	√			√	√	√	√	√
TEF				√		√			
TDF				√					
G	√	√		√					
OV				√					
OC									

4.2.2.2 Categorisation of the explanatory variables (socio-economic and biophysical)

Dinamica EGO uses categorical variables so, for example, continuous variables such as altitude or distance maps should be categorised by creating ranges. This categorisation is based on an adaptation from Agteberg and Bonhan-Carter's (1990) method, which consists of creating categories or intervals for every transition, respecting the distribution of the data structure. The ranges are defined by linking the breaking points of the thresholds and the buffers applied to them. The result of the ranges are the best fitting curve and the straight-line segments that define the curve, creating the breaking points and the categories for a continuous variable (Soares-Filho *et al.*, 2009).

4.2.2.3 Weights of evidence (WofE) of the explanatory variables of change

Dinamica EGO is based on genetic algorithms to train the model and WofE (Soares-Filho et al. 2001), which is a Bayesian method that estimates the effect of spatial variables on a specific event by calculating the probability of absence or presence of each variable in some event (Goodacre *et al.*, 1993; Bonham-Carter, 1994) (Equation 5 and 6). The WofE is applied to produce a transition probability map that determines the likelihood of change of a cell from one state to another over a certain period of time (Soares-Filho *et al.*, 2001; Soares-Filho *et al.*, 2002). The WofE is calculated for each variable for every transition (Figure 17).

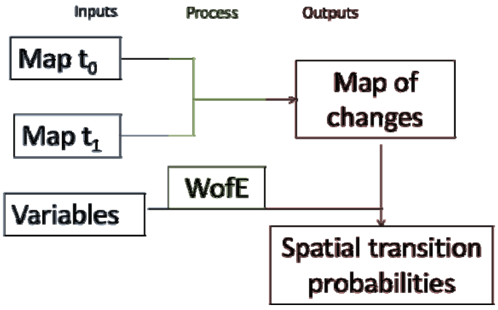

Figure 17. Calculation and application of Weights of Evidence (WofE) to produce a transition map of probabilities. Map t0 (1993) Map t1 (2002); variables included are showed in Table 9. The outputs are a map of probabilities of change for every transition.

A positive value of WofE indicates that there is a strong relationship between the event and that variable than would normally occur due to chance; while a negative value indicates that fewer points occur than expected. A value of zero, or very close to zero, indicates that the training points are distributed randomly with respect to that class; the difference between the WofE values (positive and negative) is known as contrast. Absolute values from >0 to 0.5 are mildly predictive, from 0.5 to 1 are moderately predictive, from 1 to 2 are strongly predictive, and greater than 2 are extremely predictive (Agterberg and Bonham-Carter, 1990; Goodacre *et al.*, 1993; Bonham-Carter, 1994). Positive values show a positive association between the explanatory variable and a specific transition; on the contrary, the negative value rejects it (Soares-Filho *et al.*, 2009).

As Dinamica EGO works with categorical variables the resulting weight is given for each category, each variable and a range for every transition. This means that Dinamica EGO does not report an overall weight for the entire variable. To overcome this and to compare the importance among variables per transition, the total value of the WofE was estimated by an absolute area-weighted mean (Equation 5).

Eq. 5

$$TW^{+}ofE_{xy} = \frac{\sum_{i_{xy}=1}^{n_{xy}} \left| W^{+}ofE_{i_{xy}} \right| \cdot A_{i_{xy}}}{TA_{y}}$$

Where: $TWofE_{x,y}$ is the total $WofE_{xy}$ of each variable; x = variable, y = transition, A_i = area in km^2 per variable and range and TA_y = total area per transition (including all the ranges from 1 to n).

4.2.2.4 Correlation of the explanatory variables

There is one assumption for the WofE, which is that the explanatory variables have to be spatially independent, so correlated variables must be disregarded or combined into a third map that will replace the correlated pair in the model (Soares-Filho *et al.*, 2009). Correlation of all the variables was analysed by using Crammer's value which is based on chi-squared and relates to the association between variables for every single transition; when correlation values were high (>0.5) one of the pairs of variables was chosen by taking into account the variable with higher WofE value.

4.2.2.5 Simulation and validation of the model

The model was trained using LUCC maps of 1993 and 2002; then a five time-step simulation was run to obtain the simulated map for the year 2007. Validation in terms of accuracy in location and quantity of change between observed and simulated maps reflects the reliability of a model. This occurs when grid cells in the simulated maps match with the corresponding grid cell in the map of empirical LUCC (Pontius *et al.*, 2001b). Validation in this study was done by using two methods.

The first method is included in Dinamica EGO, which compares the similarity of the maps by using a modification of the Kappa Fuzzy (*KFuzzy*) proposed by Hagen (2003) that takes into account the fuzziness of location and category within a cell neighbourhood. Dinamica EGO uses a modification of the KFuzzy and calls it *Reciprocal Similarity* by adding an exponential decay function to assess the model's spatial fit at various resolutions (Soares-Filho *et al.*, 2009). The similarity fitness value obtained by comparing the observed and simulated map is produced by a window as a result of the decay function.

The second method for validating the LUCC model was figure of merit. This method is used to detect the differences and similarities between the real map and the simulated map for the same year; in this study the year was 2007. Figure of merit is the ratio of the intersection of the observed change and simulated change, expressed as the percentage of every cover in relation to its own area (Klug *et al.*, 1992; Perica and Foufoula-Georgiou, 1996). If the model's prediction was perfect, then there would be a perfect intersection between the observed change and the predicted change (Perica and Foufoula-Georgiou, 1996), and the value of the figure of merit would be 100%. On the contrary, if there were no intersection between the observed change and the predicted change, then the figure of merit would be zero (Pontius *et al.*, 2008). Based on the figures of merit, Pontius and Millones (2011) proposed the concepts of agreement and disagreement in allocation and quantity between the observed and modelled maps.

Figures of merit include errors in commissions or omission of a category between the observed and the simulated map. Quantity disagreement is defined as the amount of difference between the observed map and a simulated map that is due to the less than perfect match in the proportions of the categories. Allocation disagreement is defined as the amount of difference between the observed map and the simulated map that is due to the less than optimal match in the spatial allocation of the categories, given the proportions of the categories in the both maps (Pontius and Millones, 2011).

4.2.2.6 Projections of LUCC model and under different socio-economic and CC scenarios

The LUCC model produces a map of probabilities of change for every single transition. Then an aggregated map is produced on the basis of these probabilities. This simulated or aggregated map of LUCC is the result of the WofE for each transition and the probability of change related to the presence of the explanatory variables. These explanatory variables or driver data can be updated in order to create future scenarios such as future population, GDP and climate conditions.

In this study, the model was updated for 2020, 2050 and 2080 by incorporating socio-economic projections of population size and population density (high scenario for A2 and medium scenario for B2), GDP (low scenario for A2 and medium scenario for B2 (Chapter 3) (Appendix 4) and climatic variables which consists of AI, PET, TSD and TMDG (see Table 8) (Metzger et al., 2013). These two scenarios were chosen due to the availability information for bio-climate variables at a finer resolution (Metzger *et al.*, 2013).

A2 and B2 scenarios were updated with the socio-economic and climatic projections (Chapter 2) (Metzger *et al.*, 2013). The A2 scenario is considered pessimistic in terms of population growth and the impacts on LUCC trajectories. In order to project these assumptions the Markov change matrices were modified for A2 by using the assumptions of the scenario. Selected transitions from natural vegetation to agriculture and urban covers were considered for 2020, 2050 and 2080. For agriculture this was done using the highest increase in population growth and demand for agriculture (Nakicenovic *et al.*, 2000). For the urban transition this was done using the relationship between socio-economic growth and cities expansion cover conversions. Finally, it is important to note that as four GCMs were used, consequently, four possible maps of land use and cover for each time slice were obtained for each scenario: A2 (2020): HadCM3, CGCM2, MK2 and Nies 99 and the same possibilities for the B2 scenario and the other time slices.

4.3 Results

4.3.1 LUCC for the periods 1993-2003 and 2003-2007

During the period 1993-2002, temperate forests (F) were the most affected natural cover by LUCC, followed by scrublands (S), tropical dry forest (TDF) and tropical evergreen forests (TEF). In the same period F, S, TDF and TEF lost between 4,000 km^2 to 10,000 km^2 (Table 10); with deforestation rates ranging between 0.20% yr^{-1} for S to 0.46% yr^{-1} for TEF (Figure 18). Agricultural expansion was ~3,100 km^2 yr^{-1}, growing at a rate of 0.65% yr^{-1}. By the period 2002-2007, TDF and grasslands were the most affected covers losing > 5,800 km^2 (Table 11), which means ~1,170 km yr^{-1}, while the agriculture maintained its expansion rate (Figure 18).

4.3.2 Forces of change

Agricultural expansion (including pasture for cattle) was the principal cause for the loss of natural vegetation. During the period 1993-2002 and 2002-2007, agriculture was the major cause of loss of natural cover, explaining ~49% and ~65% of the conversion of forest, for each period, respectively. The remaining percentage was explained by the changes to other land cover types in each period (Figure 18). In the next section the main results are presented with a focus on transitions from forest, TEF and TDF, to agriculture and the forces of change based on the WofE values.

4.3.2.1 Socio-economic variables

From a socio-economic perspective, conversion from natural covers to agriculture was primarily explained using information related to the distance to human settlements, distance to roads and GDP, followed by distance to Natural Protected Areas (NPAs) and the index of marginalization (Table 12). However, the explanatory power of these socio-economic variables depends on the transition, but distance to settlements and GDP were very important in all the transitions to agriculture in comparison to the other socio-economic variables.

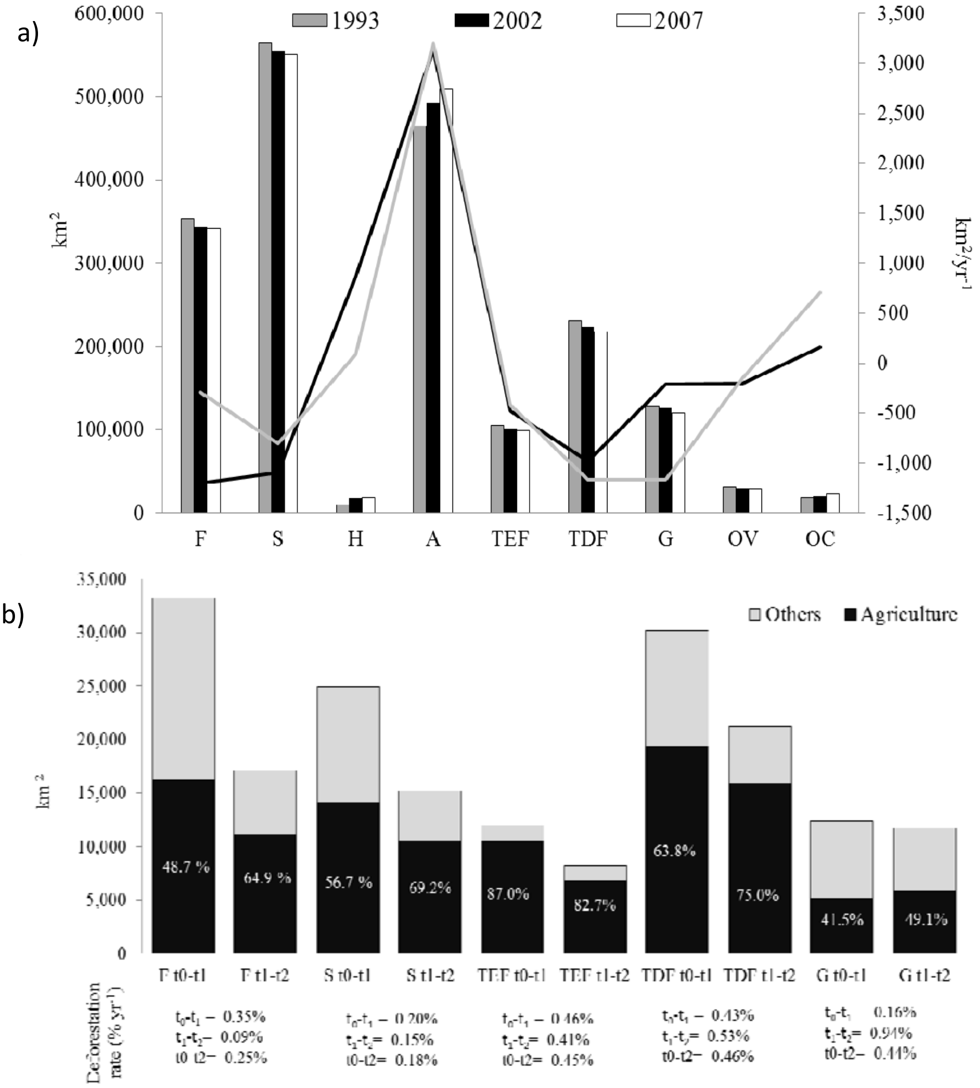

Figure 18. a) Area covered by the nine land uses and covers in 1993, 2002 and 2007. F = forest, S = scrubland, H = hydrophilic vegetation, A = agriculture, TEF = tropical evergreen forest, TDF = tropical dry forest, G = grassland, OV = other vegetation and OC = other covers. b) Losses of natural covers divided into losses due to agricultural expansion and other which includes changes to other kinds of vegetation and covers such as urban.

Table 10. Transition matrices during the period 1993-2002 (km^2).

Transition matrix (1993-2002)											
											Gross
2002 1993	F	S	HV	A	TEF	TDF	G	OV	OC	Total 2002	loss
F	320,305	1,479	137	10,896	575	6,130	3,112	97	44	342,775	22,470
S	1,209	538,949	294	6,599	0	2,440	3,344	949	243	554,027	15,078
HV	7,601	318	8,382	786	302	112	81	240	83	17,905	9,523
A	16,230	14,148	826	424,220	10,447	19,245	5,146	1,467	1,121	492,850	68,630
TEF	1,035	0	100	4,893	92,988	1,532	121	1	18	100,688	100,688
TDF	4,758	3,185	77	12,367	449	201,765	296	130	80	223,107	21,342
G	2,376	4,172	85	2,537	108	430	115,886	728	92	126,414	10,528
OV	16	1,151	80	431	4	40	181	27,249	180	29,332	2,083
OC	79	498	109	1,855	119	235	118	267	17,004	20,284	3,280
TOTAL 1993	353,609	563,900	10,090	464,584	104,992	231,929	128,285	31,128	18,865	1,907,382	
Gross gain	33,304	24,951	1,708	40,364	12,004	30,164	12,399	3,879	1,861		
Net balance	-10,834	-9,873	7,815	28,266	-4,304	-8,822	-1,871	-1,796	1,419		

Table 11. Transition matrices during the period 2002-2007 (km^2).

Transition matrix (2002-2007)											
	2007										Gross
2007 2002	F	S	HV	A	TEF	TDF	G	OV	OC	Total 2007	loss
F	325,652	853	11	9,685	335	3,208	1,533	5	17	341,299	15,647
S	779	538,807	124	5,561	0	468	3,633	497	151	550,020	11,213
HV	237	188	16,476	770	243	166	130	76	60	183,346	1870
A	111112	10,531	846	455,809	6,760	15,886	5,793	1,243	845	508,825	53,016
TEF	346	0	238	4,474	92,515	883	137	6	34	98,633	6,118
TDF	3,503	284	74	10,651	535	201,912	236	40	55	217,290	15,378
G	994	1,767	53	2453	106	202	114,617	262	110	120,564	5,947
OV	65	833	46	437	4	15	105	26,978	92	28,575	1,597
OC	87	764	37	3010	190	367	230	225	18,920	23,830	19,073
Total 2002	342,775	554,027	17,905	492,850	100,688	223,107	126,414	29,332	20,284	1,907,382	
Gross gain	17,123	15,220	1,429	37041	8173	21,195	11,797	2,354	1,364		
Net balance	-1,476	-4,007	441	15,975	-2,055	-5,817	-5,850	-757	3,546		

Table 12. Absolute WofE values of socioeconomic forces.

	F to A		S to A		TEF to A		TDF to A		G to A	
	1993-2002	2002-2007	1993-2002	2002-2007	1993-2002	2002-2007	1993-2002	2002-2007	1993-2002	2002-2007
Index of marginalisation	0.19	0.18	0.27	0.29	0.19	0.21	0.18	0.04	0.44	0.39
Distance to human settlements	0.61	0.51	0.69	0.73	0.29	0.34	0.35	0.41	0.42	0.55
Distance to roads	0.47	0.48	0.59	0.36	0.47	0.45	0.32	0.38	0.64	0.60
Distance to NPAs	0.23	0.24	0.63	0.43	0.06	0.11	0.24	0.09	0.80	0.64
GDP	0.54	0.84	0.38	0.51	0.64	0.71	0.46	0.29	1.12	0.65
Population density	0.18	0.18	0.12	0.13	0.082	0.11	0.13	0.12	0.14	0.27

If the WoE for different categories of each socio-economic variable are considered instead of absolute WofE values, this study found that rural areas in F, TEF and TDF with medium or high marginalisation are associated with agricultural expansion (WofE = 0.60) contrasting with cities which show very low or low marginalisation (0.90 and 1.44). Population density values of > 200 inhabitants per km^2, were related to conversion from F and TDF (0.86 and 1.8, respectively), while values > 500 inhabitants per km^2 were associated to agricultural conversion from TEF and scrublands (WofE = 1.9 and 2.5). NPAs showed to be effective in avoiding the changes to agriculture, especially in TEF (WofE = 1.86) and in less extent for other covers. Distance to human settlements (< 2km) was strongly correlated with changes to agriculture in F (WofE = 1.4), scrublands (1.2), TEF (0.85), TDF (1.1) and grasslands (1.44). In the same contexts, distance to roads (< 1km) was an important driver associated with agricultural expansion in forests (0.95), scrublands (WofE = 0.79), TEF (0.91), TDF (0.88) and grassland (0.98): these values showed statistical significance, $p < 0.05$. Moreover, distance to rivers had less association to the transition to agriculture, with values < 0.41. Regarding economic variables, GDP *per capita* between 400 to 2,500 million of Mexican pesos (2003) was related to changes of F, TDF and TEF to agriculture while higher values were associated with changes to other covers.

4.3.2.2 Biophysical variables

Low PET values and slopes explained changes from TF and grasslands to agriculture (Table 13). AI and altitude explained the transition from scrublands and grasslands, while TSD was important in two transitions from TF and grasslands. In general terms, transitions from natural covers were more prone to occur in the minimum intervals of natural distribution of altitude on the lowest slopes. For example, although 92% of TF is distributed at altitudes from 700 to 3000, and only 3.9% of this forest is spread at < 500 meters of altitude, transition to agriculture was strongly associated at these altitudes (WofE = 3.6). Slope was also used to assess change, 72% of TF are on slopes from 0-20^o, slopes < 4^o were strongly associated with agricultural changes (WofE = 2.2).

Table 13. Mean absolute TWofE values of biophysical variables.

	Forest to Agriculture		Scrubland to agriculture		TEF to agriculture		TDF to agriculture		Grassland to agriculture	
	1993-2002	2002-2007	1993-2002	2002-2007	1993-2002	2002-2007	1993-2002	2002-2007	1993-2002	2002-2007
Altitude	0.23	0.28	0.54	0.37	0.13	0.30	0.27	0.14	0.98	0.62
Slope	0.46	0.59	0.55	0.43	0.16	0.13	0.36	0.36	0.49	0.52
AI	0.29	0.24	0.72	0.52	0.37	0.28	0.29	0.15	0.94	0.62
PET	0.46	0.53	0.29	0.28	0.34	0.23	0.34	0.32	1.06	0.63
TSD	0.47	0.27	0.30	0.43	0.41	0.29	0.42	0.28	1.09	0.57

4.3.3 LUCC model validation

Maps from 1993 and 2002 were used to calibrate the model using the explanatory variables to project until 2007. In order to compare the performance of the model the observed map from 2007 and the simulated map were compared. (Figure 19 a, and b). The similarity of the simulated and observed maps used the model fitness with different window sizes. Figure 19 c) shows the similarity from 1km^2 window to 9km^2. Maps of probability related to the validation of the model are in Appendix 5).

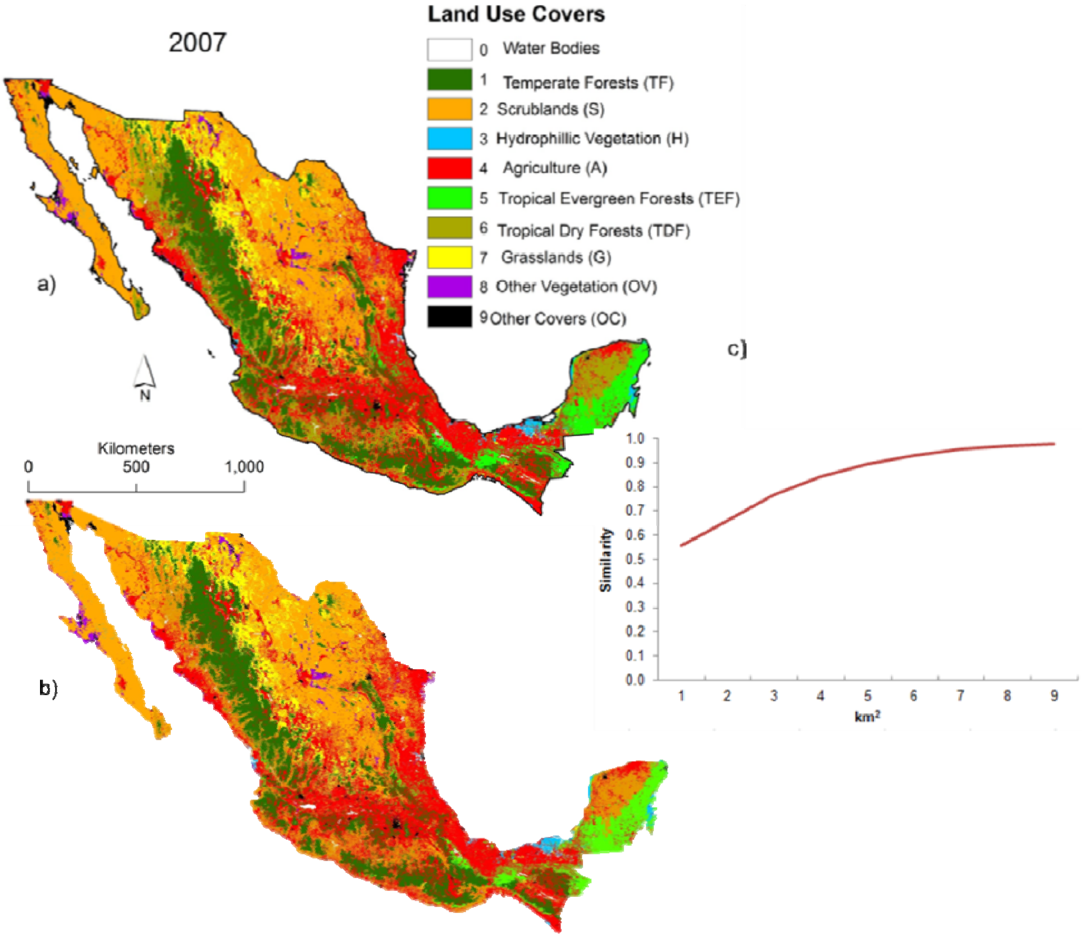

Figure 19. a) Observed map for 2007 and b) simulated map for 2007; c) Simulation reaches a similarity fitness value over 70% at a spatial resolution of 5km^2 window.

According to the figures of merit (Pontius *et al.*, 2008) the Kappa value standard is 94%, with disagreement values of allocation and quantity of 4% and 1%, respectively. However, it is important to notice that these high values incorporate the persistence of land uses and covers (Figure 20).

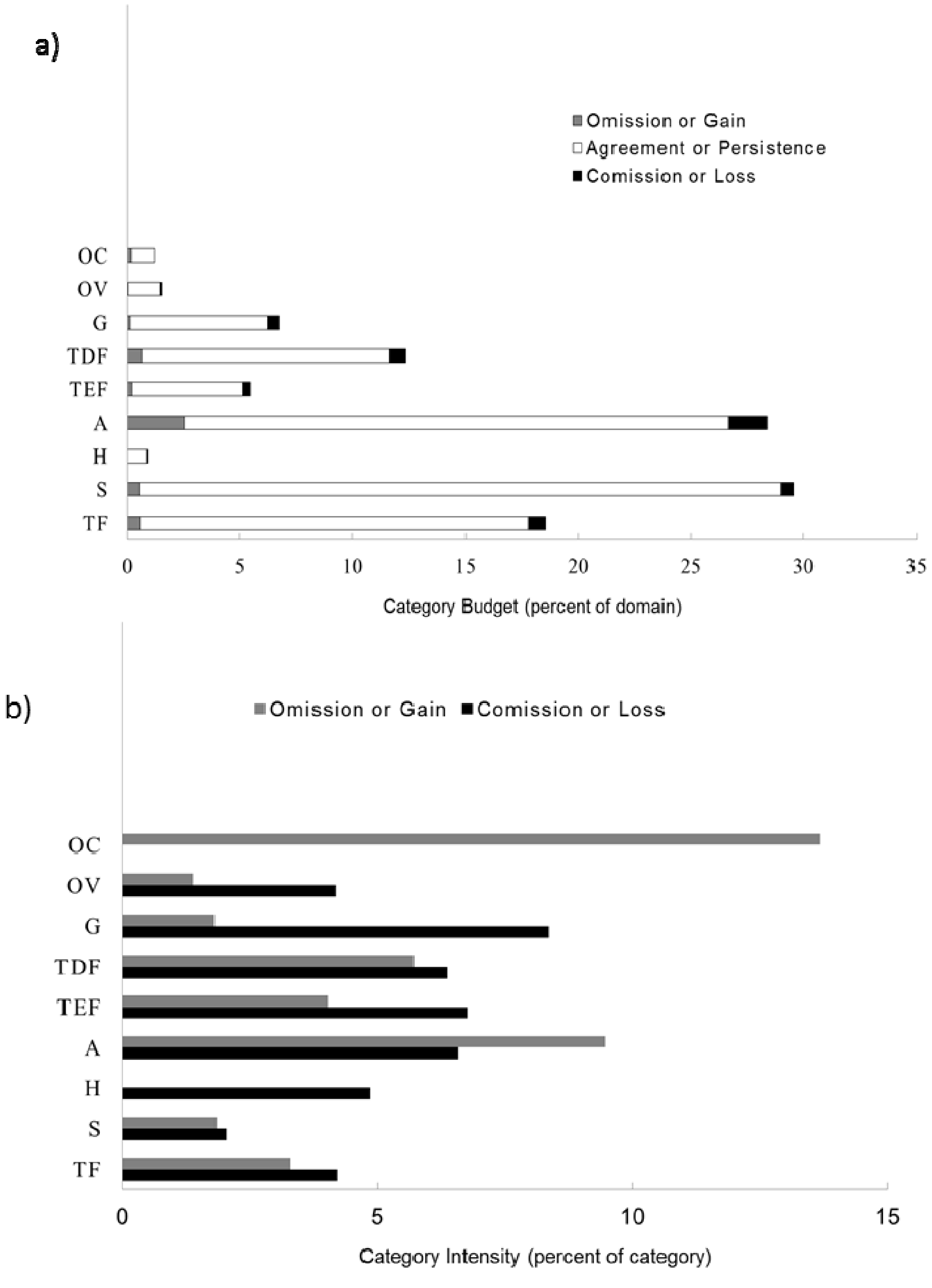

Figure 20. Quantity and allocation percentage of correct and error of the LUCC model according to the observed map vs simulated map; taken from (Pontius and Millones, 2011).

4.3.4 LUCC under socio-economic and CC scenarios (SRES A2 and B2)

By 2020, 2050 and 2080, the area of grasslands, forests and scrublands are the most affected covers by LUCC processes under both scenarios, followed by TEF, and TDF (Figure 21 and 22). However, in terms of percentage of its original area grasslands, hydrophilic vegetation and TEF were the most affected covers, due to their small extent of remaining distribution (Figure 21). On the contrary, agriculture increases by 6-7%, 14-28% and 17-56% under A2 and B2 scenarios for each of the time slices, respectively. For instance, in 1993, agriculture occupied 24.4% of the country but by 2050, it may represent between 30 to 34% (A2 and B2) and by 2080, 31% to 42% (A2 and B2) (Figure 21).

4.3.5 Agreement between models

The observed agreement of change from natural cover to an anthropogenic cover was higher for A2 than B2 scenario as the modelled changes moved from one category A to another one between LUCC models under the CC scenarios based on four GCMs. This agreement refers to the changes from the observed map to the simulated projections, which simulate the changes from one category in the observed map to another transition in the time slices (Figure 23). For instance by 2020, an agreement of 100% (all the GCMs modelled the changes to the same category) was observed in 38% and 31% of the total area. By 2050, the total agreement decreased to 28% and 26%, for each scenario respectively. By 2080 agreement decreased to 22% for both scenarios. The LUCC models using the different CGCMs agreed in major extent in the Northwest of the country and the lowland in the north. On the contrary, the Peninsula of Yucatan in south of the country and the state of Chiapas were the areas with most disagreement, especially by 2050 and 2080.

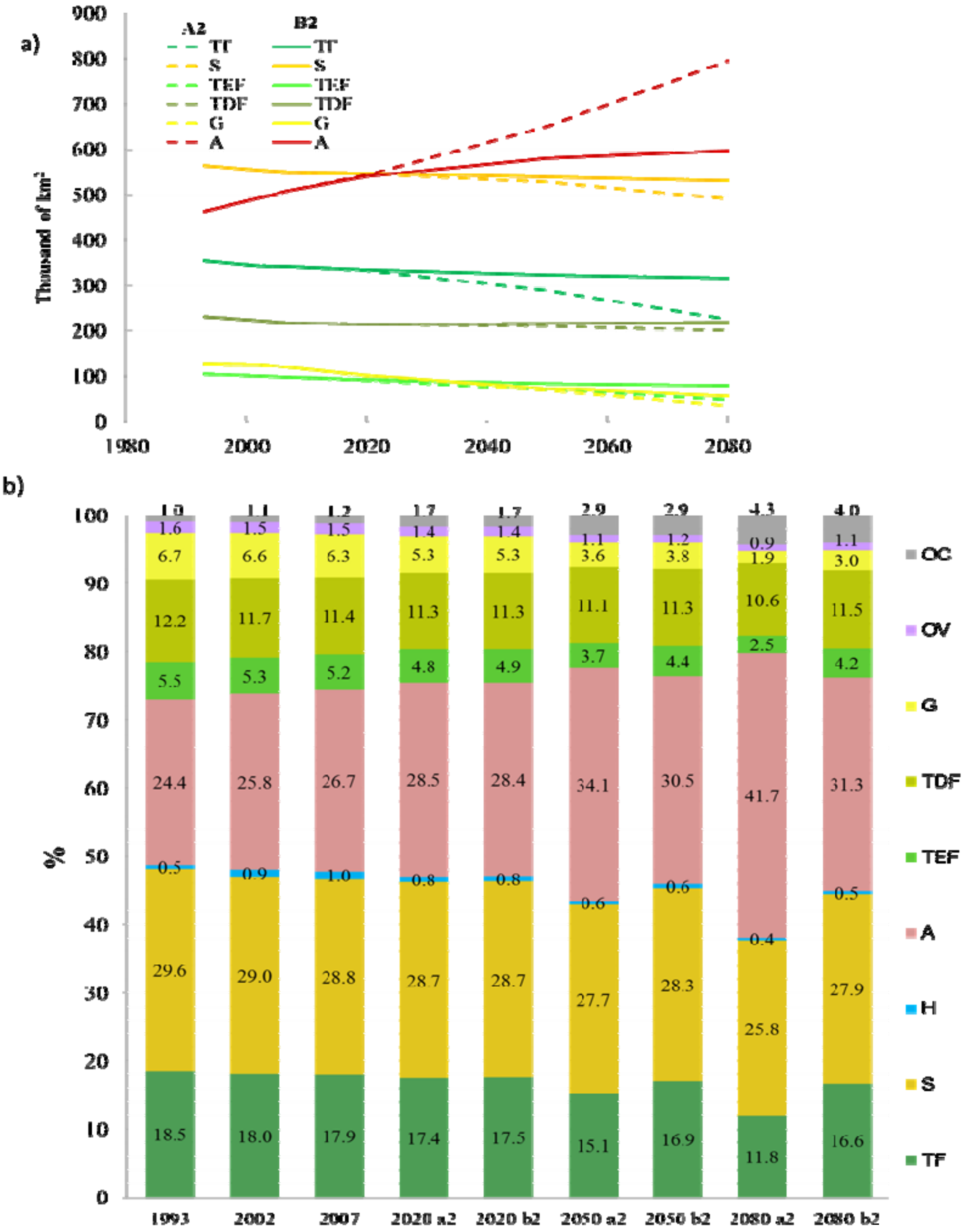

Figure 21. a) Past and future trends of the principal LUCC in the country under CC scenarios (A2 and B2); and b) percentage of surface of each land use/cover in the past and the future time slices under CC scenarios (A2 and B2).

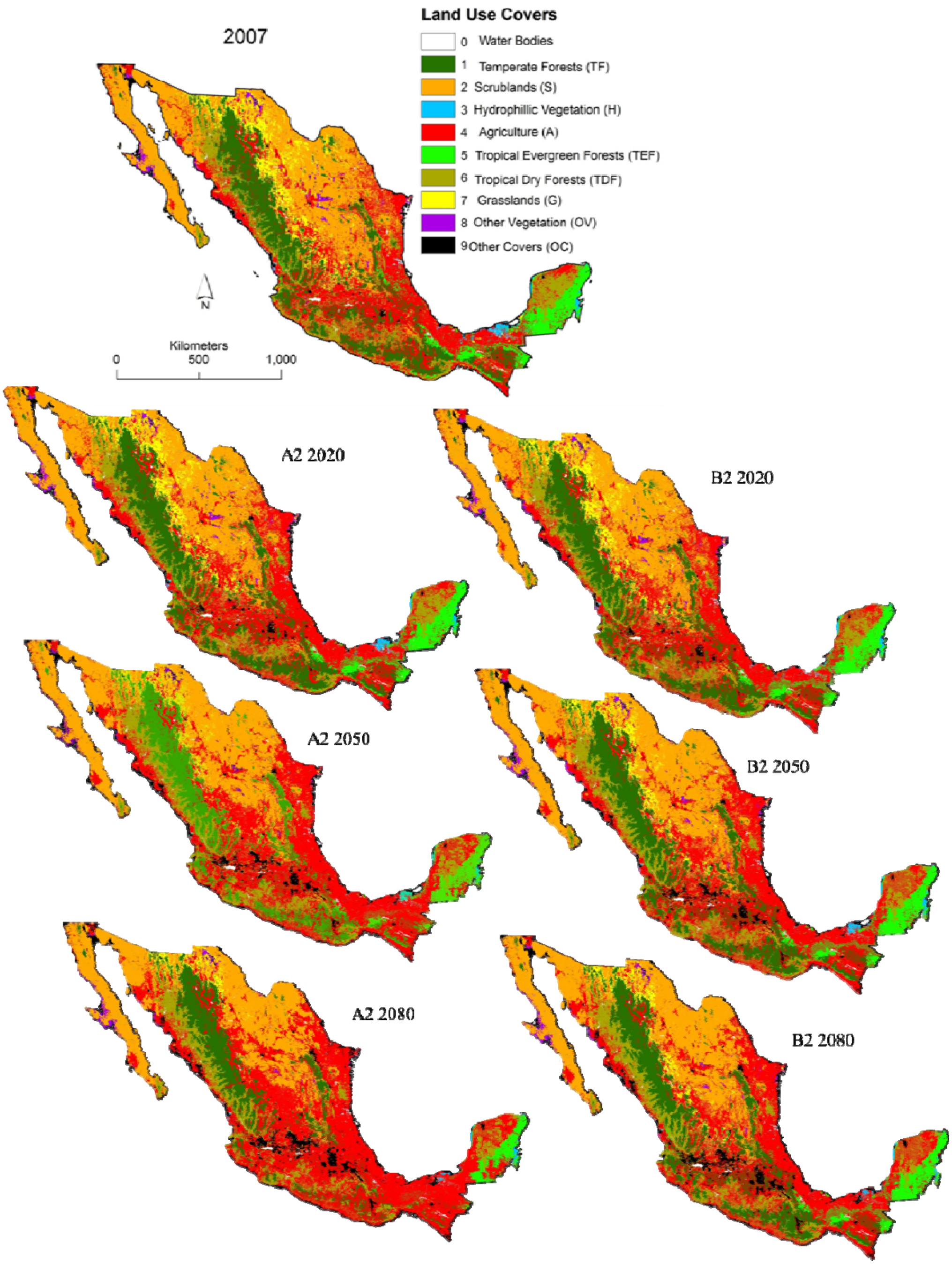

Figure 22. LUCC maps in 2007 and 2020, 2050 and 2080 under A2 and B2 scenarios (GCM2). Main regions of change of agricultural expansion are on the East coast of the country until the South Eastern part of the country (Chiapas state) and the Trans Mexican volcanic.

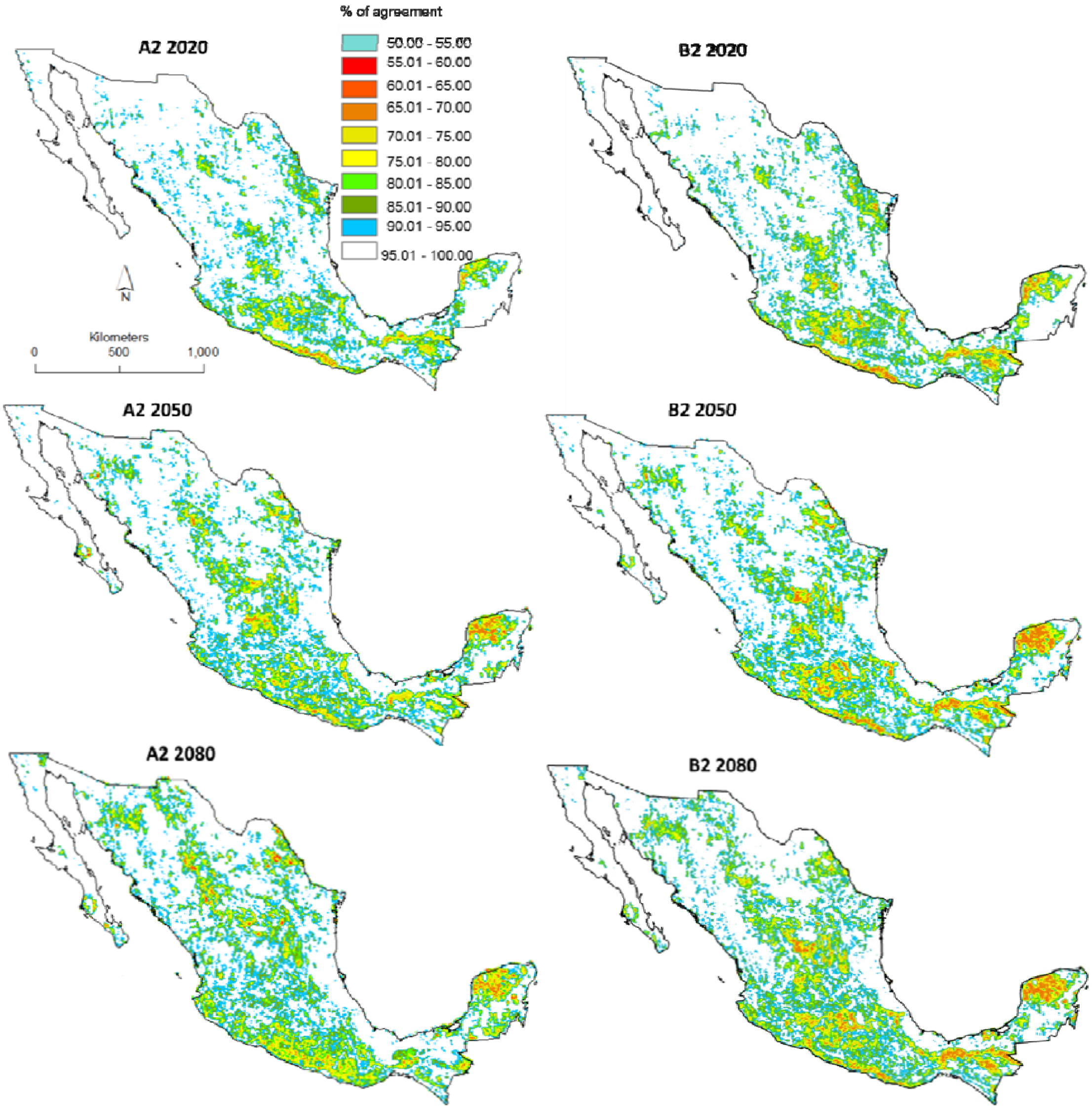

Figure 23. Agreement in projected changes from natural covers to anthropogenic covers between four GSMs according to the LUCC models. White areas agreed projecting the same LUCC and orange, red and blue zones agreed from 70% to 50%. Lighter areas are the best zo zones where the GCMs agreed the most; in contrast, darker areas differ among the GCMs.

4.4 Discussion

4.4.1 LUCC in Mexico

Results of LUCC from the periods 1993-2002, 2002-2007 and 1993-2007 are similar with other reported data. However, the groupings of the covers differ, making comparison difficult for the same groups of natural covers (Figure 24).

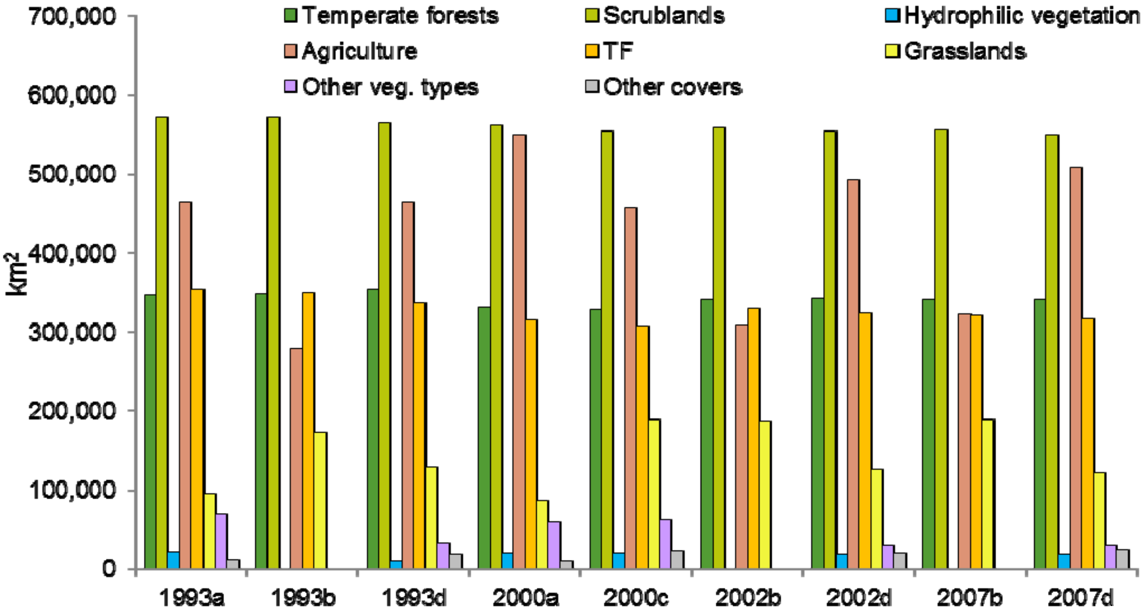

Figure 24. Area of different covers according to other published studies. a)Velázquez et al., (2002), Mas et al., (2010), c) Palacio-Prieto et al., (2000), and d) this study. The percentage of each cover in relationship to the extent. Data taken from previous studies were grouped into categories to make it comparable.

According to the published findings, and out with the classification of land use and covers used, there is an overall agreement that the increase of agriculture and other anthropogenic covers (including urban) is detrimental to natural vegetation cover throughout the studied periods (Palacio-Prieto *et al.*, 2000; Velázquez *et al.*, 2002; Mas *et al.*, 2010). Due to differences in approaches, classifications, methods and uncertainty regarding the accuracy of data, rates of deforestation have been heavily debated in Mexico (Mas *et al.*, 2009). Deforestation data reported for Mexico during the periods 1993-2002 and 1990-2000 are 3,514 km^2yr^{-1} (SEMARNAT, 2008) for the first period, and 3,540 km^2 yr^{-1} for the second period. The most recent data for the periods 2000-2005 and 2005-2010 provided by the FAO (2010) are 2,350 km^2 and 1,550 km^2 , respectively. Nonetheless, the rate of natural cover loss has been reducing (Durán *et al.*, 2011) natural vegetation continues to decrease especially in municipalities where livestock populations are increasing (Bonilla-Moheno *et al.*, 2013). In this study, during the period 1993-2002, TF, scrubland and TDF were the most affected covers in terms of area. However, TEF and natural grasslands were the most affected in relation to their original extent because of their restricted distribution and the pressure that is placed on them. For instance, distribution of TEF matches with many of the most marginalised and poorest people in the country.

4.4.2 Forces of change

4.4.2.1 Socio-economic forces

Socio-economic forces such as population density (Mas *et al.*, 2010; Vaca *et al.*, 2012), income (Vaca *et al.*, 2012) marginalisation index and distance from existing land uses or infrastructures have previously been found to be important forces of LUCC in Mexico (Sahagún-Sánchez, 2012; Kolb *et al.*, 2013). The results of this study show that changes to agriculture are related to medium and high values of marginalisation, in major extent, in contrast to extremely high or low marginalisation. In the same context, medium values of population density are more important in explaining changes because very low population density areas use their lands for self-consumption and very high population density areas are more prone to develop urban covers. However, there is a lack of information to allow the integration of data about internal migration between municipalities from rural areas to cities which could impact LUCC dynamics.

Regarding the distances to roads, rivers, and human settlements all of these factors were triggers of change from natural vegetation to agriculture, especially between 0-5 km from roads for all the natural covers. Another explanatory variable was the presence of NPAs and distance from them, which helped to avoid changes towards agriculture therefore supporting assumptions that some NPAs have been successful in helping biodiversity conservation in Mexico (Figueroa and Sánchez-Cordero, 2008).

Generalising the weight of drivers for an entire country is complicated because of the heterogeneity of conditions throughout the country. However, national studies assist in determining the most significant forces of change. As a result, it was observed that marginalisation associated to the expansion of agriculture was an important; this is supported by other studies in the Central Mexican Region (San Luis Potosí) (Sahagún-Sánchez, 2012) and southern states such as Oaxaca, Veracruz and Chiapas where marginalisation is associated with agricultural expansion (Bonilla-Moheno, 2011). However, differences throughout the country reflect the heterogeneity of LUCC processes, which vary according to time and space at diverse scales. For example, in northern areas of Mexico (Chihuahua or Coahuila) the commerce with the US (NAFTA) and the implementation of industries that manufacture and assemble textile products (called maquiladoras) have reduced the impact of LUCC (Currit and Easterling, 2009) thus it has had a positive effect on scrubland regeneration (Bonilla-Moheno, 2011). Other factors such as the increasing violence in Mexico are impacting the LUCC (Durán *et al.*, 2011); however, relationships among agents, corruption, drugs, and violence cannot easily be incorporated in LUCC models, especially at national level (Durán *et al.*, 2011).

4.4.2.2 Biophysical forces

In terms of biophysical forces, altitude, slope and climate variables have been reported as important explanatory variables for LUCC processes in Mexico (Chowdhury, 2006; Kolb *et al.*, 2013). This study supports that lower altitudes and gentle slopes favoured transitions to agriculture and other covers as urban use. Climate variables (AI, PET and TSD) were associated with changes to agriculture as Zomer et al. (2014) have previously reported. These values of PET and AI might be related to the suitability to better and humid places. This means, that agricultural expansion was associated to the highest AI, which means that dry-sub humid and humid areas are more prone to change than drier places due to the availability of water. The pattern is the same for PET, where places with low PET were more likely to change to agriculture than places with higher values. This is important in terms of CC scenarios in which the humidity conditions related to AI and PET will be affected, triggering processes of LUCC. The results of this study show that suitable (more humid) ecosystems in the centre of Mexico and the southeast will be converted in major extent to agricultural lands in comparison to the northern and dryer areas of Mexico. This will impact specific covers such as temperate forest (Trejo *et al.*, 2011) and natural grasslands in the northern prairies as reported in studies of the south of the US (Cameron and Scheel, 2001).

The heterogeneity of the explanatory variables at different scales, the socio-economic and biophysical variables, and the use of scenarios allow the identification of hotspots of LUCC. Expansion of dry zones related to scrublands and xeric vegetation will be present in the north due to CC and increasing temperatures and due to the abandonment of agricultural areas related to the establishment and expansion of manufacturing industries (Bonilla-Moheno, 2011). Other kinds of processes are depicted in the south of the country where marginalisation and the increasing population will continue to augment pressure on ecosystems, especially in TEF being converted to agricultural lands thus creating a warmer, drier climate such as in previous studies of this type of vegetation (Bonan, 2008). In relation to TF, climate variables and feedbacks are very uncertain. They are vulnerable to human LUCC, abandonment (Galicia and García-Romero, 2007) and CC; however, it has been shown that ecotones for temperate forest could be higher under CC scenarios for Mexico (Gómez-Mendoza and Arriaga, 2007).

Although has been recognized that there is a biogeochemical impact of the increasing CO_2 on plants because they can obtain it more efficiently from the atmosphere closing their stomata more often, which reduces evapotranspiration (Cox *et al.*, 2004; Friedlingstein *et al.*, 2006; O'Ishi *et al.*, 2009) the effect of CO_2 as was not included in the model. That was decided because of the lack of information in the different kinds of ecosystems, the successional stages of them and the uncertainty that could have been involved. As a result, a possible sub-estimation in the recovery of ecosystems could be associated, especially in the A2 scenario. In this context future studies at finer scale could include this information if it is available.

4.4.3 LUCC model limitations

Regarding the credibility scenarios and the uncertainty of models it is important as Dendoncker et al. point out (2008) that scenario studies rarely consider uncertainties arising from spatial data. It is crucial to keep in mind those uncertainties and errors are intrinsic to spatial data (Burrough and McAlpine, 1998) because ignoring uncertainty in spatial data may result in unreliable scenarios (Fang *et al.*, 2006). In order to maximise the reliability of the scenarios some issues should be considered. First, it should be considered the intrinsic errors of the data inputs; 2) different criteria in the classification of land uses or covers in classification (Wickham *et al.*, 1997); 3) errors associated to mixing vectors or grids as vectors lines or polygons (Schmit *et al.*, 2006) or errors about downscaling and transformation between different formats such as sources (Bregt *et al.*, 1991; Wade *et al.*, 2003; 4) the spatial autocorrelation between variables; 5) the process of statistical validation; 6) the assumptions of scenarios as the result of many drivers of change and their interaction which can easily vary through the time, and especially in a long-term; 7) the bias of the expert opinion when the drivers are qualitatively positive or negative changed that have an impact in the validation process, and 8) the uncertainty of the model that integrate the former points.

Firstly, there are problems related to the accuracy of national maps associated to errors in classification which affect the estimations derived from them (Mas *et al.*, 2004). Accuracy of the data used for the inputs LUCC maps is reported to be 70% for the northern regions of the country and 95% for the whole country considering all types of vegetation (Mas *et al.*, 2004). However, this study experienced difficulties related to hydrophilic vegetation when the transition matrices were calculated. This vegetation type is distributed on the coast and is therefore affected in spatial context by the continental borders and the seashore. Consequently, when the extent of the study is fixed, area of this vegetation is lost, not necessarily due to LUCC but due to the limitations of the inputs.

Variations between diverse LUCC models are result of the criteria of classifications used, and problems linked to the input information chosen. That issue about classification has made more difficult the comparison between national or local studies in Mexico. Besides the diverse formats, scales and resolutions of Mexican data are not homogenised causing accumulative errors that are not easily quantified.

The spatial autocorrelation is not easily avoided. Consequently, the use and the selection of variables and their correlation is extremely important trying to achieve the statistical independency about the used data. Even tough, spatial LUCC data tend to be dependent (Overmars *et al.*, 2003). That means, values over distance may be more similar or less similar than expected for randomly associated pairs of observations. In this study Dinamica allowed the analysis of correlation in order to avoid this problem, selecting only the variables that were not correlated for each transition. However, by comparing the agreement of the 4 GCMs (Figure 25), it is possible to look at some clustering of values that can be thought as the values are more similar than expected due to the geographic proximity. However, although spatial dependency could be seen as a methodological disadvantage, it may offer information of certain spatial pattern that allow us to see that lowest places in terms of altitude are more variable between the GCMs.

The validation of the model using the Kappa fuzzy similarity index was high (> 70%) and showed a good spatial resolution (2.5 km^2) for a national study. It should be noted, however, that that the permanence of the land uses or covers increases Kappa values and due to this drawback (Pontius and Millones, 2011) an additional validation was performed that refers to the error of commission or omission. Moreover, for categories such as grasslands and agriculture the error is higher; this may be due to the accuracy of spatial borders of natural grasslands and the small parcels of farmlands in the input maps. It could also be a result of the lack of the precision in the model for spatializing the changes associated to socio-economic variables at the national level and the inclusion of information related to black market that have not been included in the LUCC models. Therefore, the comparison with previous studies highlights the fact that, although many similarities can be found at coarse scales, some characteristics of the landscape dynamics are intrinsic, and can only be locally assessed (Maeda *et al.*, 2010).

Although models of LUCC at national scale have been developed in Mexico, long-term scenarios using different climatic and socio-economic variables have not been undertaken to date. Nevertheless, this novelty it is necessary to be aware that long-term projections, especially using the available information to calibrate and validate the model have many assumptions. By using Markov matrices to quantify the change from one state to another and using to project the changes there is the assumption that quantity will remain the same through the time. However, thanks to the flexibility of Dynamic-Ego it is possible to change the quantity of changing cells and the feedbacks between variables (WofE) to produce different scenarios with optimistic or pessimistic rules. These rules are the result from: 1) changing in socioeconomic conditions 2) policies, and 3) integration of new conditions that constrain the expansion in no suitable areas.

As Alcamo et al. (2006) point out the key question in long-term projection is how to maximize the credibility of scenarios. They describe that sometimes credibility is associated with likelihood but this does not always hold for scenarios for two reasons. First, information about the likelihood of a scenario is usually not available (as the IPCC scenarios). Second, even unlikely scenarios can serve a useful purpose, as the assumption of accidents in nuclear power plants or revolutions; the credibility of them is not always related to its likelihood. As an alternative, the credibility can be associated with its internal logic, consistency and coherence. That is, the more logical, consistent and coherent the scenario, the higher its credibility. On these bases this study developed for Mexico has been an attempt to incorporate from a logic and transparent approach some of the possibilities if the conditions of these scenarios assumption keep going for the three time slices. Finally, it is important to keep in mind that besides the cons of the long-term projections, they help understand non-linear behaviour, resulting from the interaction between fast and slowly changing components of the same system. Moreover, a long-term perspective allows the study of LUCC as a process undergoing predictable transitions with economic development (Ramankutty *et al.*, 2006).

In this context, this study is aware of the limits of doing a study at a national level by using the available information and to use the model for long-term projections. Despite the limitations associated with the data sources, this is the first attempt to depict a general diagnosis concerning possible future scenarios under changing conditions. In this context, this study was focusing on detecting large areas that can be more affected by LUCC and CC and the resulting information should be analysed and improved when better and more complete data are available. However, it is agreed that the quantification of the uncertainty associated to the inputs, processes and outputs are a new future challenge to overcome to provide maps of future scenarios.

4.5 Conclusions

This study shows a useful approach to determine the hotspots of LUCC under different socio-economic and CC scenarios in Mexico. This approach incorporates available information of the variables, the forces of change and their effects on LUCC to project different possible and plausible trajectories. Resulting information could guide strategies for prioritisation of places where changes will be more severe and therefore lead to the development of actions oriented towards improved resilience and mitigation. The results of this study show that TF,, natural grasslands and TEF will be the most affected land covers by LUCC in A2 and B2 scenarios. Socio-economic forces related to economic factors, distance to human settlements and roads and biophysical forces such as altitude, slope and potential evapotranspiration are clearly associated to agricultural changes. Further studies should be conducted at regional or local scales by incorporating spatial information about migration from rural areas to cities, which could lead to the regeneration of natural covers and agricultural abandonment. This would assist in determining the direct effects of LUCC and CC on specific ecosystems as indicators of change. This approach and methodology could be repeated in other developing countries where economic and political resources are scarce.

Chapter 5. Mapping GEC Vulnerability Hotspots in Mexico: Priority Sites for Biodiversity Conservation

5.1 Introduction

This chapter describes a general framework for spatial conservation prioritisation and the concepts and tools involved at a national level exercise. This chapter links the spatial information about LUCC and CC (Chapter 4) to biodiversity. The concepts of 'irreplaceability' and 'vulnerability' are used to build a model framework to help to prioritise regions for biodiversity conservation. The methods section explains the inputs used for determining the vulnerability of biodiversity in terms of exposure, sensitivity and adaptive capacity. The results are divided into 1) the vulnerability assessment, discussing the mentioned components and 2) the identification of endemic and threatened species of vertebrates which are distributed in the most vulnerable areas to LUCC and CC (Figure 25).

5.1.1 Global Environmental Change and biodiversity loss

A growing human population, rapidly changing global economy and the modern life-style change are principal drivers of land use/cover change (LUCC) and climate change (CC), collectively referred to as Global Environmental Change (GEC) (Steffen *et al.*, 2005). GEC is a multi-component phenomenon that involves not only driving forces, but also their interaction and feedbacks. LUCC and CC have been pointed out as the principal threats to global biodiversity (Sala *et al.*, 2000; Leadley *et al.*, 2010; Oliver and Morecroft, 2014a).

LUCC in tropical forests is associated to agricultural expansion (Chowdhury, 2010). For instance, in highly biodiverse countries such as Mexico, nearly 50% of natural land cover has been lost in the last century (Velázquez *et al.*, 2003). Principal causes are agricultural and livestock expansion as direct forces of change, and growing population and marginalization as indirect forces (Bonilla-Moheno, 2011; Bonilla-Moheno *et al.*, 2012).

Although LUCC is expected to be the major force of impact change in the tropics, the effects of CC on the LUCC process and their combined effects on biodiversity are still uncertain (Oliver and Morecroft, 2014a) (Brooks *et al.*, 2006). Prioritisation of biodiversity conservation is necessary because it is not possible to establish conservation strategies everywhere to prevent long-term biodiversity loss and because it is necessary to use efficiently and effectively the scarce funds and resources (Sarkar *et al.*, 2004; Wilson *et al.*, 2011).

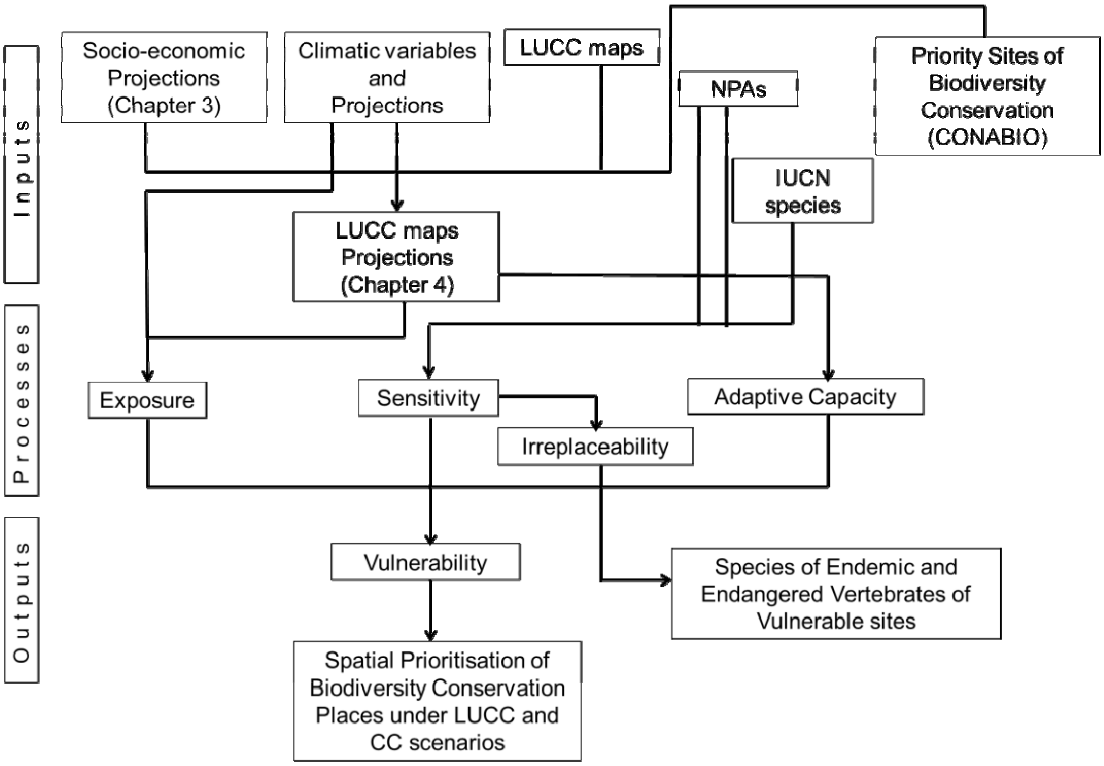

Figure 25. Summary of the approach used to quantify spatial vulnerability to LUCC under different CC and socio-economic scenarios. Inputs of the first level were obtained from different sources; socio-economic projections were derived from Chapter 3, the priority sites for biodiversity conservation (PSBC) from CONABIO (2007a), climate variables from Metzger et al. (2013), LUCC maps from INEGI (2012b) and the information about national protected areas (NPAs) from CONANP (2014). Socio-economic and LUCC projections (Chapter 3 and Chapter 4) were used as inputs to quantify the exposure and the adaptive capacity (AC). Sensitivity was considered on the basis of previous national work about a spatial prioritisation (details in 5.1.6). Finally, the IUCN Red List was used as the criterion for estimating irreplaceability in terms of endemicity (IUCN, 2014).

5.1.2 Spatial conservation prioritisation

Approximately 100 species of mammals, birds and amphibians became extinct in the last century (~1% of the described species) (Mace *et al.*, 2005). Between 1984 and 2004, the International Union for Conservation of Nature (IUCN) recorded 27 extinctions, thirteen of them, due to habitat loss (Baillie *et al.*, 2004). Biodiversity threats, such as LUCC or CC, are unevenly distributed, so spatial prioritisation of conservation effort is crucial, especially when resources are constrained (Brooks *et al.*, 2006).

Spatial conservation prioritisation is understood as the process of quantitatively analysing data to identify locations for conservation purposes (Wilson *et al.*, 2009). Spatial conservation prioritisation has introduced some pragmatic concepts and quantitative approaches are mostly based on two key concepts: 1) irreplaceability and 2) vulnerability (Pressey *et al.*, 1994; Margules and Pressey, 2000).

5.1.3 Irreplaceability

The irreplaceability of a site has been defined in two ways. 1) The likelihood that a site will be required to meet a given set of conservation targets, and 2) the extent to which these targets can be achieved if the area is lost (Pressey *et al.*, 1994; Ferrier *et al.*, 2000; Margules and Pressey, 2000). The irreplaceability cannot be considered as the number of species alone because several areas can share the same number of species. In contrast, areas with high levels of endemism have been considered a better indicator for irreplaceability because of their uniqueness (Krupnick and Kress, 2003; Mittermeier *et al.*, 2011). Endemic vertebrates species have been used as indicators for prioritisation conservation goals (Loyola *et al.*, 2007).

5.1.4 Vulnerability

The concept of vulnerability is used across a range of disciplines, including finance, public health, environmental hazards, and CC (Janssen *et al.*, 2006). Consequently, a plethora of definitions are available. There is no single ‘correct’ or ‘best’ conceptualization of vulnerability that would fit all assessment contexts. This study constrained its framework to relate the vulnerability of biodiversity to LUCC and CC. The Intergovernmental Panel on Climate Change (IPCC) defines vulnerability as the propensity or predisposition to be adversely affected (IPCC, 2014b). Vulnerability in the context of biodiversity is the propensity or predisposition to which a species, population or ecosystem is threatened (Dawson *et al.*, 2011). Vulnerability (V) in quantitative terms is a function of exposure (E), sensitivity (S), and adaptive capacity (AC) (Turner *et al.*, 2003; Adger, 2006) (Equation 6). Potential impacts (PI) are a function of exposure and sensitivity (Equation 7). Therefore, vulnerability can also be defined as a function of potential impacts (PI) and adaptive capacity (AC) (Equation 8) (Metzger *et al.*, 2006):

Eq. 6 $V= f(E, S, AC)$

Eq. 7 $PI = f(E, S)$

Eq. 8 $V= f(PI, AC)$

5.1.5 Exposure and Sensitivity (Potential Impact)

The IPCC (2014a) defines exposure as the presence of entities in places and settings that could be adversely affected. These entities can be people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social or cultural assets. In quantitative terms, exposure, refers to the degree, duration, and/or extent in which the system, or a part of it, is in contact to the harm (Kasperson *et al.*, 2005; Adger, 2006). Sensitivity is defined as the susceptibility to be harmed (IPCC, 2014b). In terms of biodiversity, sensitivity includes endemicity and the status of threat. Endemicity is considered because of the assumption of the restricted distribution and the status of the threat because of the population trends of the species (Dawson *et al.*, 2011). In the context of LUCC and CC, the function of exposure and sensitivity (PI) can be quantified as the difference between the baseline and the future scenarios (Metzger *et al.*, 2006; Nicholls *et al.*, 2008).

5.1.6 Adaptive Capacity

Adaptive capacity (AC) is understood as the process of adjustment to actual or expected conditions and their effects (IPCC, 2014b). Adaptive processes encompass scales from the organism or individual to the population of a single species or an entire ecosystem (Krimbas, 2004). In this study, AC is given as a spatial property, as the relationship between the area of natural cover that has been lost and the extent of natural cover under protection (Hoekstra *et al.*, 2005). This study uses the Critical Risk Index (CRI) as an indicator of AC. The CRI is related to the Crisis Ecoregions project which determines the places in which biodiversity and ecological function are at great risk due to extensive habitat conversion and limited habitat protection (Hoekstra *et al.*, 2005). The assumption behind is that natural cover that has been less modified and that is under some protection is more capable to deal with the potential impacts of LUCC and CC.

5.1.7 Global Prioritisation Efforts

During last decades some efforts about prioritising places to conserve biodiversity have been developed based on the irreplaceability and vulnerability framework. Some efforts are 1) Crisis Ecoregions (see section 1.4.2 in this chapter) (Hoekstra *et al.*, 2005), 2) Endemic Bird Areas (EBAs) (Stattersfield *et al.*, 1998), 3) The Centres of Plant Diversity (CPDs) (UNEP-WCMC, 2013) and 4) Biodiversity Hotspots (Myers *et al.*, 2000a).

The BirdLife Organization Project proposes the EBAs which established that 4.5% of the earth's land surface is high priority for broad-scale ecosystem conservation (Stattersfield *et al.*, 1998). EBAs are based on the register of ~ 2,500 endemic species, restricted to an area smaller than 50,000 km^2. The EBAs overlap with other restricted-range species of animal and plants. For example, there is an overlap of

70% between the location of EBAs and areas for endemic plants (Stattersfield *et al.*, 1998). Mexico has 22 EBAs covering a total area of ~11,000 km^2 (BirdLifeInternational, 2015).

The United Nations Environment Programme (UNEP), The International Union for Conservation of Nature (IUCN) and the World Wide Fund for Nature (WWF) developed a project to identify The Centres of Plant Diversity (CPD) (UNEP-WCMC, 2013). The result was a total of 234 sites, 12 of them are in Mexico, covering ~256,000 km^2. Another important effort is Biodiversity Hotspots; these are defined by the same concepts of irreplaceability and vulnerability. Biodiversity hotspots should contain more than 0.5% of endemic vascular plants of the world and show 30% or less of its original area (Myers *et al.*, 2000a). A global analysis has revealed 34 biodiversity hotspots covering 23.5 % of the Earth's land surface with an extent of ~24 million km^2, 15.7% of the world's land area (Mittermeier *et al.*, 2010). This area holds no fewer than 50% of vascular plants and 42% of terrestrial vertebrates as endemic (Mittermeier *et al.*, 2004). However, only 3.4 million km^2 (2.3%) of these hotspots remain intact, due to LUCC (Mittermeier *et al.*, 2010). Mexico is one of 17 megadiverse countries that together are home to 70% of known species (Mittermeier *et al.*, 1997; Sarukhán and Dirzo, 2001). Mexico has three biodiversity hotspots, representing 5% of the global area of biodiversity hotspots and 45% of the total area of Mexico (Californian Floristic Province, Madrean Pine-Oak Woodlands and Mesoamerica).

5.1.7.1 Spatial Conservation Prioritisation in Mexico

Global efforts such as those outlined in section 5.1.5 could be useless in Mexico for biodiversity conservation purposes due to the coarse spatial information. Consequently, national efforts have been developed includingthe Priority Terrestrial Regions (PTRs n=152, area= 515,558 km^2), Priority Marine Regions (PMR, n=70, area=1,378,620 km^2), Priority Hydrological Regions (PHRs, n=110, area= 777, 248 km^2) and Important Birds Areas in Mexico called AICAs (AICAs, n= 219, area= 309, 655 km^2). However, in terms of prioritization PTRs and AICAs together propose to conserve ~ 43% of the terrestrial country and some of these areas match with implemented NPAs.

One of the most recent and important efforts to determine the gaps in efforts to prioritise important places for biodiversity conservation in Mexico was undertaken by CONABIO (2007a). This project used data from terrestrial vertebrates (including mammals) (Ceballos, 2008), birds (Navarro and Peterson, 2007), reptiles and amphibians (Flores-Villela, 2008) and plants (Soberón *et al.*, 2007) to produce the priority sites for biodiversity conservation (PSBC). This project utilised models such as Genetic Algorithm for Rule-set Production (GARP) (Stockwell and Peters, 1999) at a $1km^2$ resolution to estimate the potential distribution of the species. After determining the strategic areas for biodiversity conservation of the different taxa, several workshops were held during 2005-2006 (CONABIO *et al.*, 2007c). These workshops included the participation of The National Commission of Natural Protected Areas (CONANP), Pronatura, The Nature Conservancy Program Mexico, The Mexican Fund for the Conservation of Nature (FMCN) and The National Institute of Ecology (INECOL). Moreover, spatial biological data and the resulting ouputs of the workshops; these information was analysed using Marxan software version 1.8.8 (Ball and Possingham, 2000). The final outpues were 8,045 polygons of $256km^2$ of which 2,448 are terrestrial (CONABIO *et al.*, 2007a), showing that 33% of Mexico requires some degree of biological conservation. The categories and the extent of prioritization show that 14.7% of Mexico has been deemed extremely high priority for conservation while 15.4% shows high priority and 2.4% medium priority (CONABIO *et al.*, 2007b).

5.1.8 Aim of this work

Mexico is a megadiverse and developing country (Mittermeier *et al.*, 1997; Myers *et al.*, 2000b) where the resources for conservation management are scarce (Salcido *et al.*, 2009). Global and national efforts for prioritizing biodiversity conservation show that ~33% to 45% of Mexico should be protected. The width of these desired targets makes extremely difficult to lead economic and social resources. Therefore, this work aims to prioritize these efforts by:

1. Determining the vulnerability of the priority sites for biodiversity conservation to LUCC and CC under different socio-economic and CC scenarios for 2020, 2050 and 2080.
    1.1 Identifying what PSBC show more exposure to LUCC and CC.
    1.2 Identifying what PSBC show more sensitivity to LUCC and CC.
    1.3 Identifying what PSBC show less adaptive capacity to LUCC and CC.
    1.4 Identifying the endemic and threatened species of vertebrates from the most vulnerable PSBC.

5.2 Methods

To estimate the vulnerability of Mexican PSBC to LUCC and CC and to identify the most endangered species within these sites, exposure, sensitivity and AC were quantified separately for two different CC scenarios (A2 and B2), for three future time slices (2020, 2050 and 2080) and using four different GCMs (CGCM2, HadCM3, MK2 and Nies99) (Figure 26). For detailed information about the LUCC under different socio-economic and CC scenarios see Chapter 4.

5.2.1 Exposure

5.2.1.1 Exposure to LUCC

Exposure to LUCC was determined by using the spatial outputs of Chapter 4 which includes the A2 and B2 scenarios by 2020, 2050 and 2080. The resulting maps show information about the permanence of natural cover and changes, taking the year 2007 as a baseline.

LUCC exposure was categorized from 0 to 100, where zero represents no change, (no exposure at all), and 100 was a complete change from natural vegetation to an anthropogenic cover (deforestation) (Table 14). Permanence of anthropogenic cover was evaluated as no data, because exposure remains the same through time and 50 was given to changes from an anthropogenic cover to a natural one, this was done because places where succession is taking place are more prone to revert back to agriculture (Chapter 4).

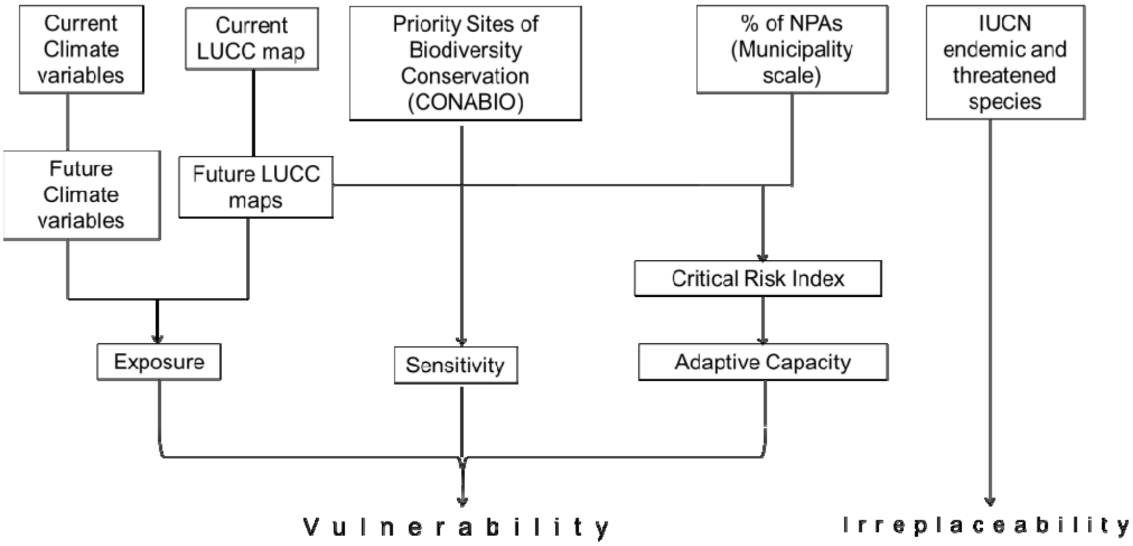

Figure 26. Spatial prioritization for biodiversity conservation scheme methodology incorporating two key concepts: 1) vulnerability and 2) irreplaceability. Vulnerability can be understood as a function of Exposure, Sensitivity and AC. Exposure is quantified by the differences between the climatic variables and the extent of natural cover vs anthropogenic cover through the time. Sensitivity is based on CONABIO (2007a). Finally, AC is developed on the basis of Hoekstra (2005) methodology to measure the risk of index based on the ratio of the percentage of changes from natural vegetation to anthropogenic cover and the extent of NPAs. Irreplaceability is based on the endemicity of different groups of vertebrates.

Table 14. Criteria to estimate exposure to LUCC. 1) Zero reflects that there is no exposure to LUCC (no change), 2) 50 that there is regrowth of natural cover, 3) permanence of anthropogenic cover was evaluated as no data, and 4) 100 was given to changes from natural cover to an anthropogenic cover**.**

T1 / T2	Natural Cover	Anthropogenic Cover
Natural Cover	0	100
Anthropogenic Cover	50	No Data

5.2.1.2 Exposure to CC

Exposure to CC was determined by calculating the difference between the current and the future values of three climatic variables (aridity index (AI), potential evapotranspiration (PET) and seasonality (TSD) provided by Metzger et al. (2013). These variables were used because they explained more than 90% of the of the variability of the basic bioclimatic regionalization (Metzger *et al.*, 2013). Maximum differences between the four GCMs (GCM2, HadCM3, MK2 and Nies99) were used to produce weighted maps in order to quantify the different time slices and scenarios (A2 and B2 for 2020, 2050 and 2080). The resulting maps were categorised from zero to 100, where 100 showed the biggest differences in that variable in relation to the current values and zero shows no changes at all.

5.2.2 Sensitivity

Sensitivity was expressed using the criteria defined by CONABIO (2007a) (see section 1.6). These PSBC were considered as a sensitivity indicator because they incorporate information about: 1) the richness of vertebrate and plant species, 2) a higher degree of endemicity, 3) the degree of transformation of land cover between 2002 to 2007 and 4) the status of protected surrounding area (Koleff *et al.*, 2009) (Figure 27). In the current study CONABIO’s sampling grids were categorized from 0 to 100, where 100 is extremely high, 50 is high, 25 is medium and 0 is no important in terms of biodiversity conservation (CONABIO *et al.*, 2007a). This variable was constant through time because 1) the information about the richness and endemicity was not modelled through time and 2) the spatial threat of the LUCC was incorporated as an exposure indicator.

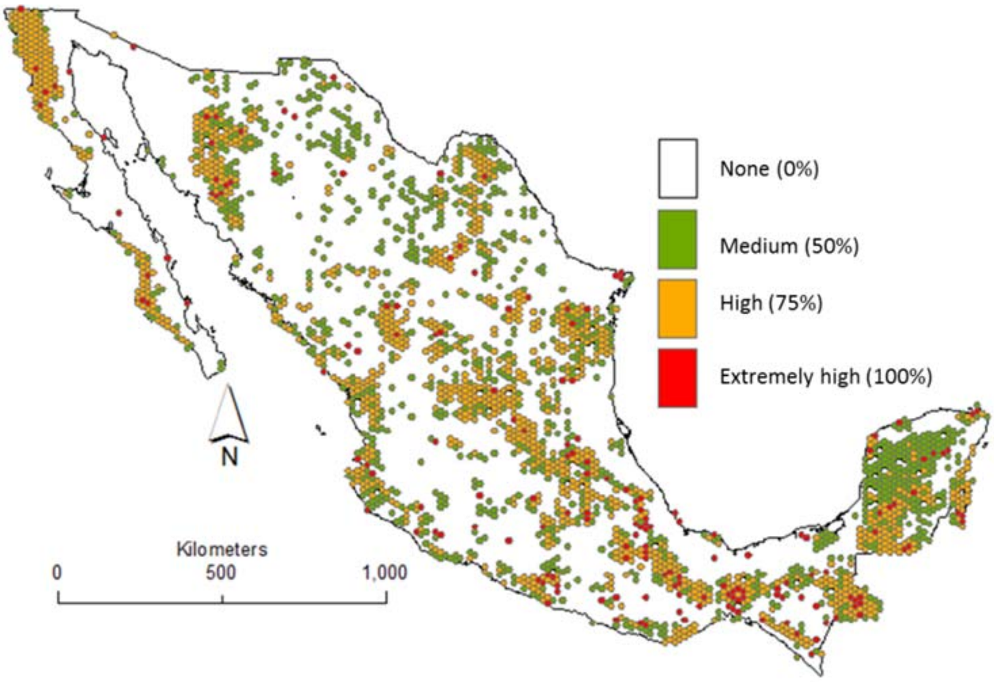

Figure 27. Mexican PSBC (CONABIO *et al.*, 2007a). Extremely high values show the highest endemicity, endangered or threatened species which are unprotected and therefore have extremely high irreplaceability. The categories high and medium follow the same criteria. However, the irreplaceability is higher, based on the restricted distribution of the species**.**

5.2.3 Adaptive Capacity

Adaptive Capacity (AC) was estimated using the Critical Risk Index (CRI) proposed by Hoekstra et al. (2005). CRI shows the ratio of percent of converted area (natural to anthropogenic) and the percent of protected area (natural protected areas, NPAs). The CRI value was estimated at municipality level in order to calculate the ratio between the protected municipal area and the municipal natural cover loss for the three time slices and both scenarios (based on the reclassification of the resulting maps of Chapter 4). The final ratio was categorised from zero to 100. It is important to note that because of the variables used (changes to anthropogenic cover) the highest value refers to the lowest AC and the lowest values refer to the largest capacity to cope with threats. The B2 scenario was estimated on the assumption to achieve the Aichi targets that strongly suggest that the terrestrial protected areas by 2020 are 17% of the country and by 2050 and 2080 the NPAs are 20% and 22% of Mexico.

5.2.4 Vulnerability of biodiversity to LUCC and CC

Vulnerability (V) of PSBC to LUCC and CC was considered as a function of exposure (E), sensitivity (S) and adaptive capacity (AC) (Equation 9):

In this study vulnerability is further defined as:

Eq. 9 $$V = f\,(NCC, AI, PET, TSD, PSBC, CRI)$$

Where NCC is Natural Cover Change, AI is Aridity Index Change, PET is Potential Evapotranspiration Change, TSD is the standard deviation of temperature, PSBC is Priority Sites of Biodiversity Conservation and CRI is the Conservation Risk Index.

Exposure includes four different indicators of change (LUCC, AI, PET, and TSD) (Equation 10), consequently 50% of the exposure was considered as a result of LUCC processes and the other 50% as a result of CC (Table 15). Equation 5.3 gives an example of the total vulnerability value to LUCC and CC where: 1) Exposure is equal to NCC=50 (that means that there is a change from anthropogenic cover to a natural cover). AI= 80(that is the resulting categorisation about the changes from the current and the future AI values). PET= 30 (that is the resulting categorisation about the changes from the current and the future PET values). TSD= 80 (That is the resulting categorisation about the changes from the current and the future TSD values) this value show a medium exposure to this variable. 2) Sensitivity is equal to PSBC=50 (that means that is an area of medium importance for biodiversity conservation). 3) Adaptive Capacity, given by the CRI=60 (that value reflects the ratio between the converted natural cover to an anthropogenic cover and the NPAs at municipality level).

Eq. 10 $$E = (NCC*0.5) + (((AI + PET + TSD) / 3) * 0.5)$$

For example, the vulnerability index is calculated as follows:

$$V = ((50 * 0.5) + (((80 + 30 + 60) /3) * 0.5) + 50 + 60) /3)$$

$$V = 54.4$$

Table 15. Elements to calculate the vulnerability of biodiversity to LUCC and CC scenarios.

Potential Impact							
Exposure				Sensitivity	Adaptive Capacity	Total/3	Vulnerability
NCC	AI	PET	TSD	PSBC	CRI		
100	100	100	100	100	100	100	High
50	80	30	60	50	60	54.4	Medium
0	0	0	0	0	0	0	Low

Exposure: LUC (natural vegetation change) = 1, and Permanence = 0

AI, PET and TSD = ~1 show the biggest differences between current and future values.

Sensitivity: Extremely high = 100, High =75, Medium =50, None = 0.

Adaptive Capacity: CRI = 100 low Adaptive Capacity. Values of Vulnerability are categorized and 60 was considered as medium, 70 as high, 80 very high and >90 extremely high.

5.2.5 Endemic or endangered species living in the most vulnerable sites

Resulting maps of vulnerability were used to identify the endemic and threatened species that overlap within the vulnerable sites. Geographical information about the species was obtained from the IUCN for mammals, reptiles and amphibians (IUCN, 2014), and information about birds was taken from BirdLife International (BirdLife_International and NatureServe, 2014). Endemic species were used to support the idea that species that are more vulnerable to extinction are 1) species with a narrow (or single) geographic range, 2) only one or few populations, 3) species with a small population size, 4) species with a declining population size, 5) species hunted or harvested by people and 6) species that require specialised habitat and niche conditions (Primack, 2006).

5.3 Results

5.3.1 Exposure to LUCC

By 2020, Mexico may lose ~5 % of its natural vegetation due to conversion to agriculture or urban cover. By 2050, the figures increase to 10% and 13% of natural vegetation loss (to see the details of specific transitions see chapter 4). The differences between scenarios are more severe by the 2080s, when according to A2 scenario, Mexico could lose 21% of its natural vegetation, while B2 scenario depicts that 12% of natural cover may be transformed to anthropogenic uses. Different areas are highlighted due to their high exposure to LUCC 1) the east part of the country including the coast of the Gulf of Mexico and in the north the states of Tamaulipas, Veracruz until the border to Tabasco and Chiapas (this region is represented particularly by tropical evergreen forest, TEF) 2) the southern part of the Mexican plains and the border with the Central Volcanic Belt (see Chapter 2), especially affected since the 2050s, these areas are represented by TF, scrublands and natural grasslands on their highest parts and 3) the Pacific Coast in the states Jalisco, Michoacán, Guerrero and Oaxaca, where the TDF is distributed (Figure 28).

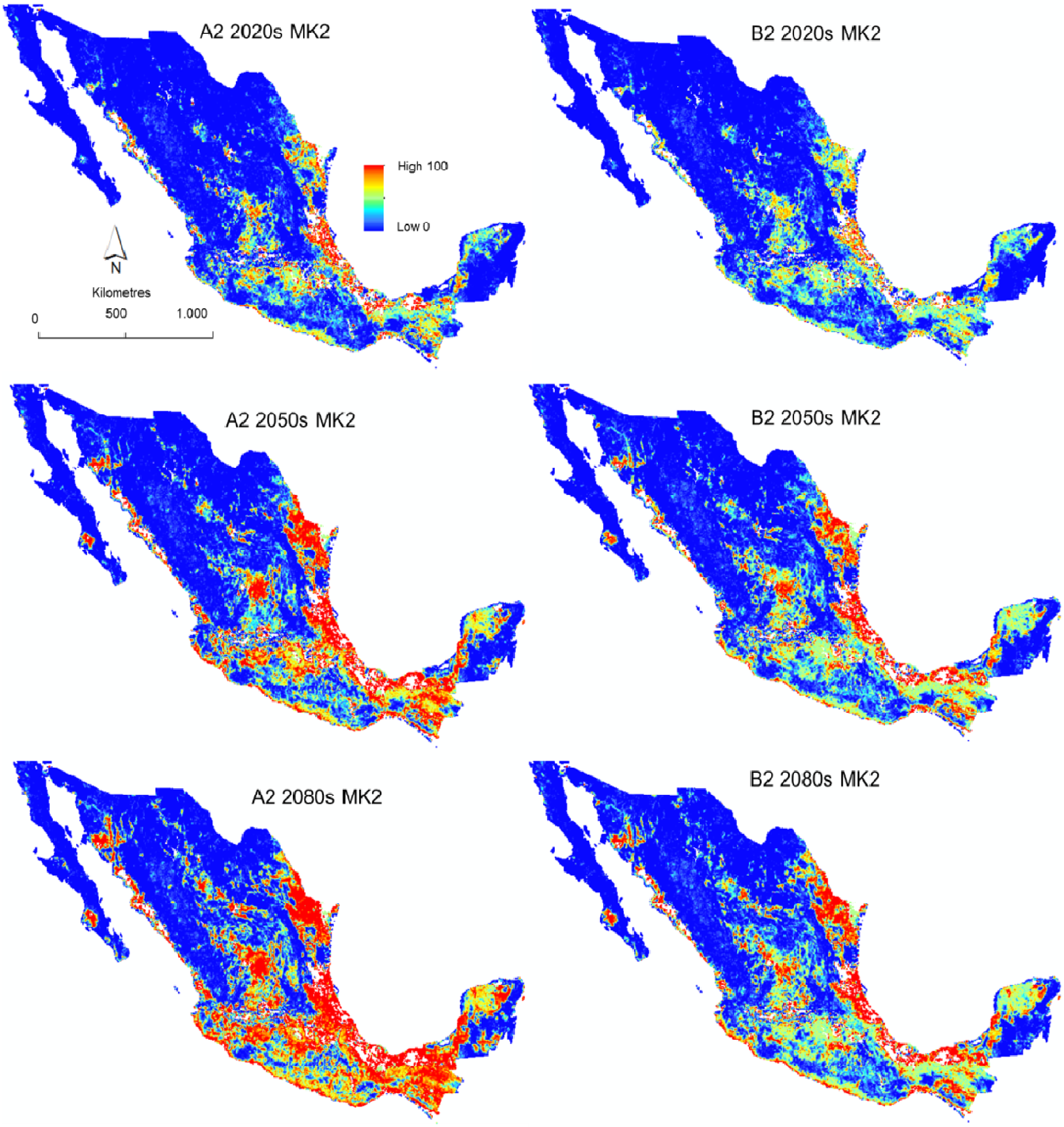

Figure 28. Exposure of Mexico to LUCC under A2 and B2 scenarios by 2020, 2050 and 2080 using one of the four GCMs (MK2). The highest values show the propensity of sites to change from natural vegetation to an anthropogenic cover. The coast of the Gulf of Mexico, the central plains and the Pacific coast show the highest exposure to LUCC. These areas are represented by TEF and TF, TD and scrublands.

5.3.2 Exposure to CC

5.3.2.1 Exposure to Aridity Index (AI)

By 2020, 2050 and 2080, the biggest differences between current and future AI values are especially severe in the northwest part of Mexico, represented by the Sierra Madre Occidental (see Chapter 2). The parallel mountain chain Sierra Madre Oriental shows fewer changes. However, these, changes are especially spread on temperate ecosystems. Another region that shows a high difference in AI, is located in the southeast of Chiapas, especially by the 2080s where TEF and TF (including cloudy forest) are distributed (Figure 29). These regions will become drier according to the four GCMs.

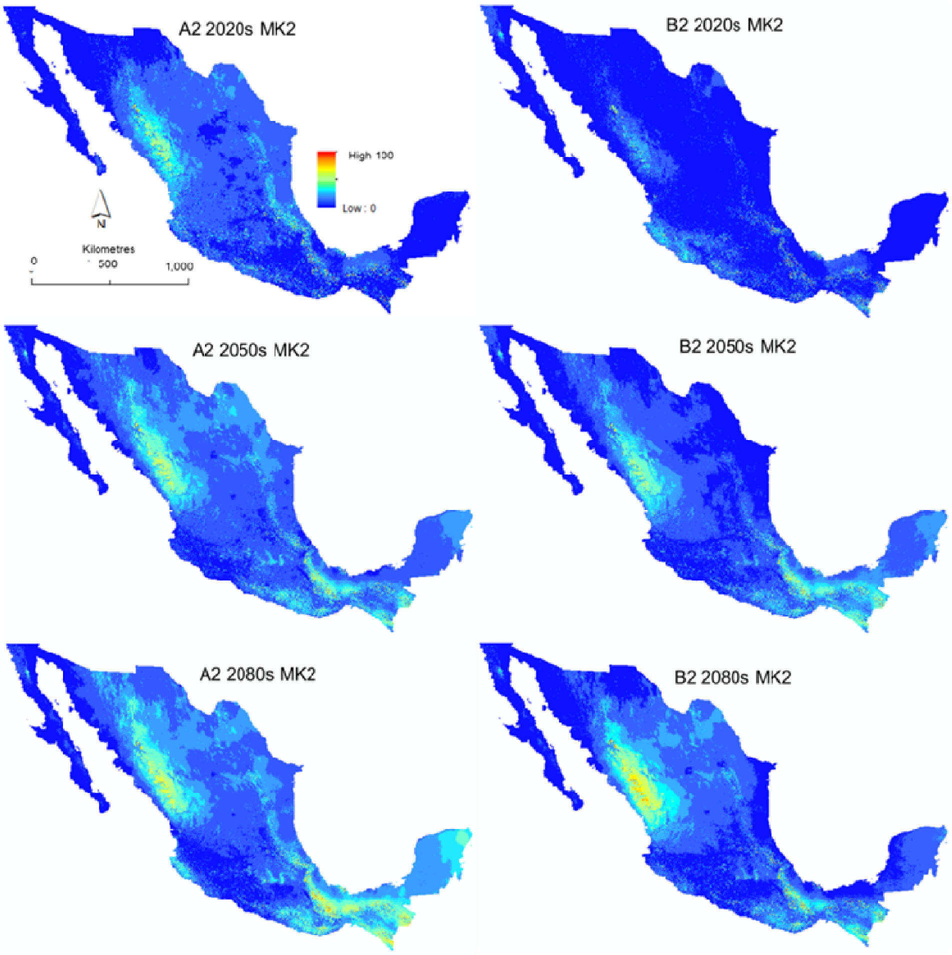

Figure 29. Exposure to Aridity Index (AI), highest values show the biggest differences to current AI values. This variable shows the biggest changes in the Sierra Madre Occidental and the south of the Pacific Coast.

5.3.2.2 Potential Evapotranspiration (PET)

By 2020, 2050 and 2080, the northwest Mexican border and the coast of the Gulf of Mexico from Tamaulipas to the state of Chiapas shown to be the most affected areas by changes in PET (Figure 30). These areas are represented especially by scrublands in the north and TEF in the south. On the contrary, the Pacific coast, where the TDF is principally distributed, shows less change. However, by 2080 under A2 scenario the northwest part of the country represented by natural grasslands in the state of Chihuahua seems to be highly affected.

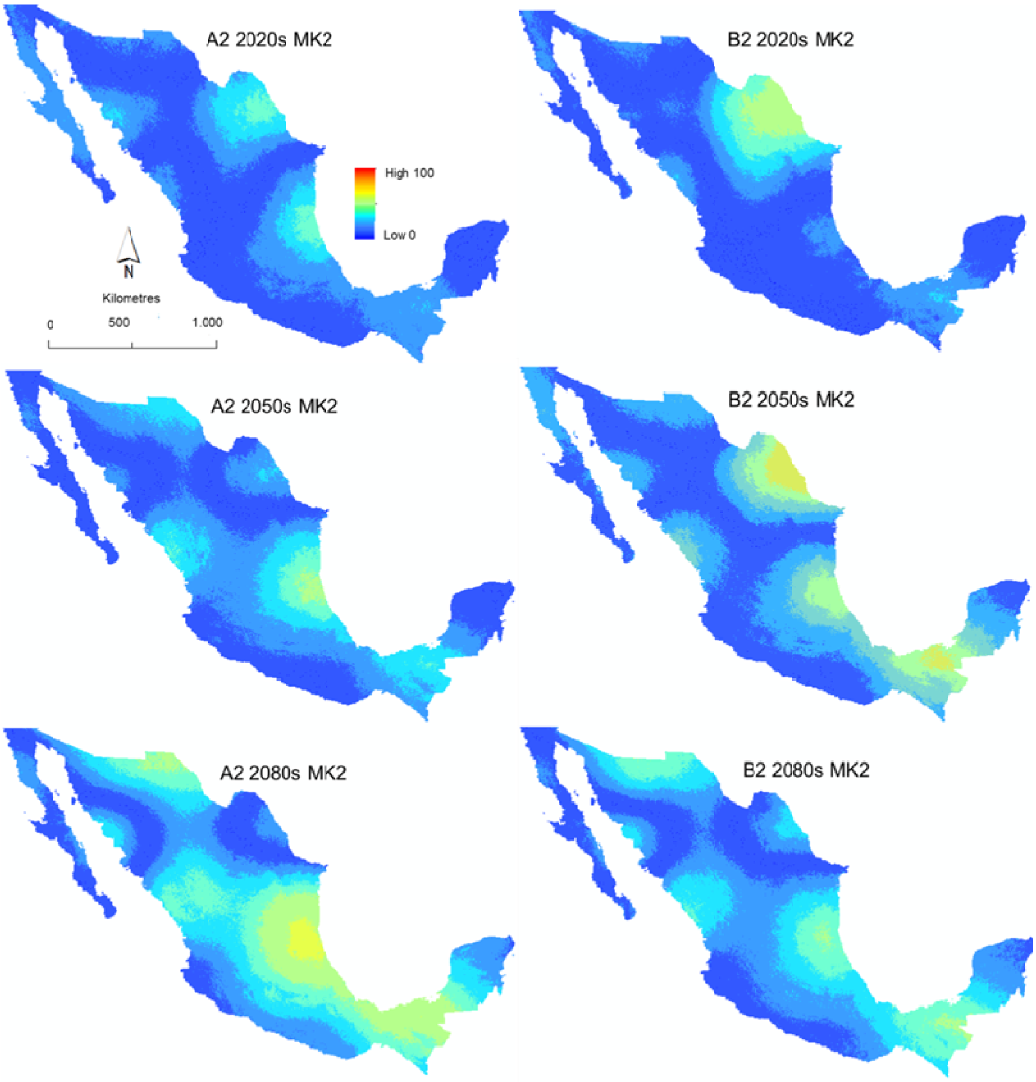

Figure 30. Exposure to Potential Evapotranspiration (PET), highest values show the biggest differences to current PET values. Most affected areas are the northeast of the country, bordering to the US and the Gulf of Mexico coast.

5.3.3 Adaptive Capacity

AC represented by the Conservation Risk Index (CRI), was calculated at national and municipality level. Highest values of CRI show the lowest ability to cope with potential impacts. CRI values indicate that by 2020 63%, 27% and 10% of Mexico will face low, medium and high vulnerability under A2 scenario and 67%, 23% and 10% for the B2 scenario, respectively (Fig 31). That means that expansion of current NPAs only show to decrease impact in low vulnerability values. By 2080, 54% and 60% of Mexico is in low vulnerability by each scenario, while 33% and 29% is in medium vulnerability and 13% and 12% of the country is in high vulnerability for A2 and B2, respectively. North-western region and the Pacific coast of the country are the areas with less AC (figure 31).

5.3.4 Vulnerability of the PSBC to LUCC and CC

By 2020, ~23% to 26%% of Mexico's territory shows medium degree of vulnerability to LUCC and CC (50-60) for both scenarios, respectively, and 10% of Mexico is in the highest levels of vulnerability (>70). The majority of the vulnerable area (60%) shows low vulnerability (<40). Vulnerability increases through time and is higher in A2 scenario. By 2050, the results indicate that ~39% and 27% for A2 and B2 of the country may face medium vulnerability (50-60), while 11% shows high, very high and extremely high vulnerability (>70). By 2080, ~33% of the country shows medium vulnerability but there is an increment of the highest vulnerability values reaching the 17% of Mexico (Figure 32).

The most vulnerable places are distributed in six different areas 1) the western coast state of Sonora, 2) the southern areas of the Pacific Coast, 3) the northern part of Chihuahua, 4) the regional border between the states of Tamaulipas and Nuevo León, 5) the central regions of the Volcanic Belt, and 6) the Sierra Madre del Sur and the Highlands of Chiapas (Appendix 6).

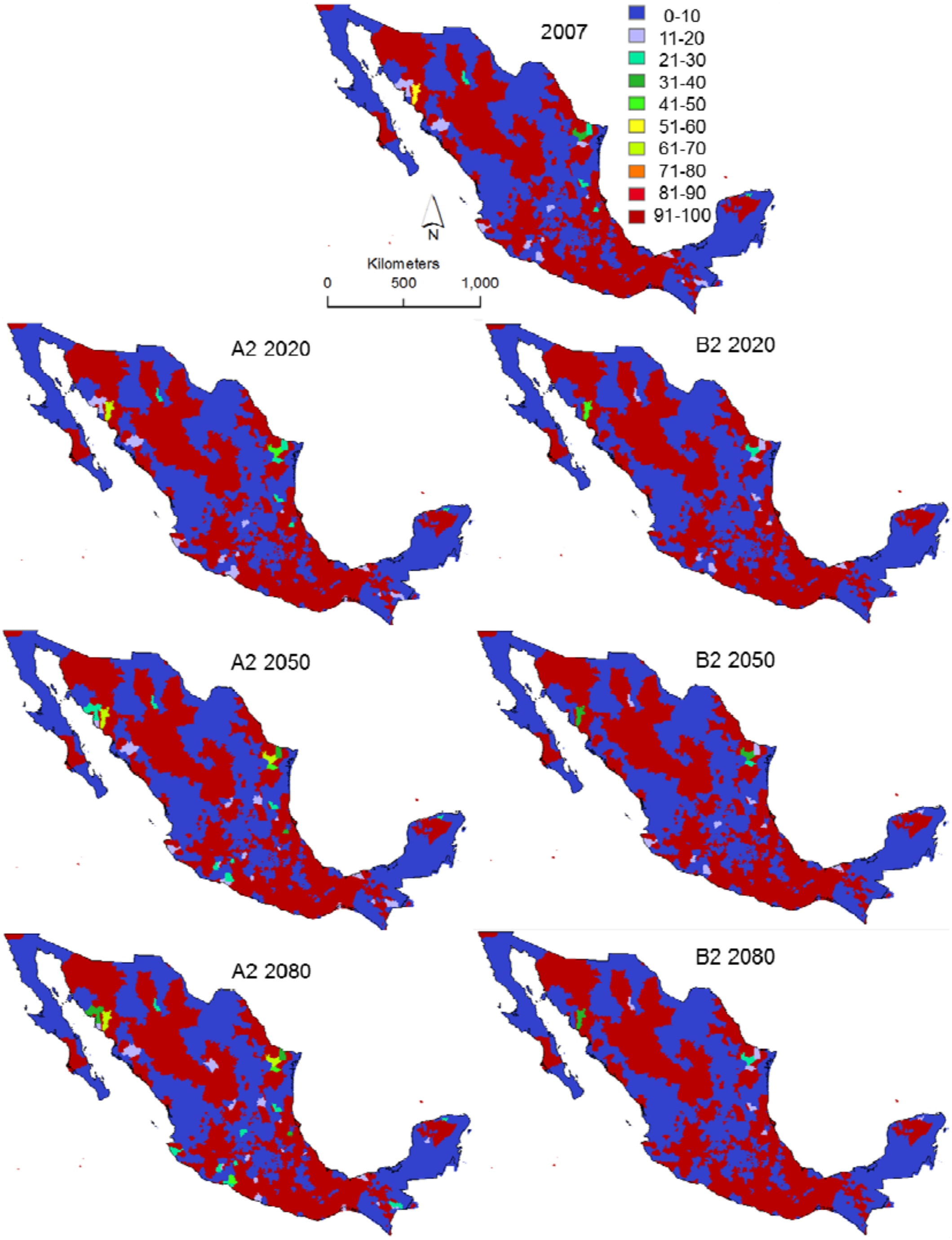

Figure 31. AC represented by the Conservation Risk Index (CRI) shows the ratio between the natural cover that has been lost and the area under protection at municipality level. Highest values are municipalities with less AC.

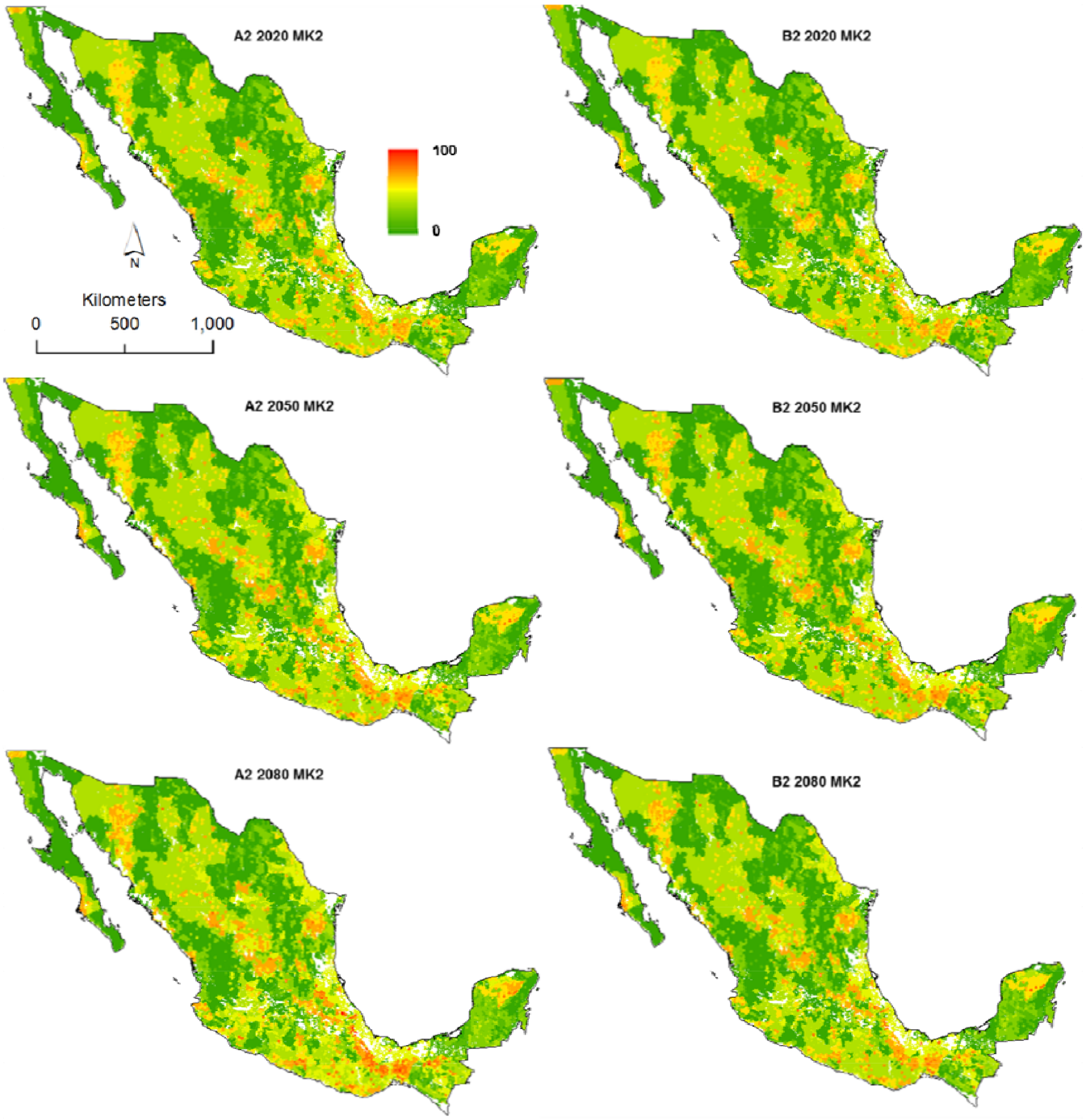

Figure 32. Vulnerability maps for the MK2 model by three time slices and the A2 and B2 scenarios (the different vulnerability maps of the other GCMs are included in Appendix 6).

5.3.5 Endemic or endangered species living in the most vulnerable sites

5.3.5.1 Mammals

Continental Mexico has 470 species of mammals according to the IUCN (2014). By 2020, the results show that 78% of the continental Mexican mammals will be in places of high vulnerability, while more than 61%, and 74%% will be found in extremely high (EH=90), vulnerable places and 39% to 64% will be in critically high vulnerability (CH=100) for each scenario, respectively (Table 16). By 2080, these figures increase to more than 70% in EH categories and 46% to 71%, could be in CH vulnerability, depending on the scenario. CONABIO (2015) reports that there are 164 endemic mammals in Mexico and of these species more 45% are in some status of threat or with deficient data (Table 16). In this study the 9% of the endemic mammals are CE, followed by 5% of E and 16% of V (Figure 33). The majority of the endemic and endangered species are distributed in TF followed by scrublands and TDF (Figure 33).

5.3.5.2 Birds

The inland Mexican area contains 1,043 species of birds (BirdLife_International and NatureServe, 2014). The results show that by 2020, 87% of the Mexican bird species will be located in places with medium vulnerability, while 61%, 46% and are in extremely high vulnerable sites(90). By 2080, the figures increases, and more than 80% are in extremely high vulnerable places while around 47% to 61% are in critically high vulnerable places (100) for each scenario, respectively (Table 16). CONABIO reports that there are 125 endemic birds in Mexico (Bezaury-Creel *et al.*, 2009) and of these species more than 23% are in some status of threat or with deficient data . One species was reported already extinct, 4% of species was CE, 9% was E, 8% of species was V, and 69% of LC (Figure 33). The majority of endemic and threatened species are distributed on TDF followed by TF and TEF (Figure 33).

5.3.5.3 Reptiles

Continental Mexico has 660 species of reptiles (IUCN, 2014). By 2020 about 55% to 60% of these species may be in places of medium vulnerability (60) depending on the scenario, while 57%, 55% and ~40% may face high, very high and extremely high vulnerability (70-90), respectively (Table 16). It is important to note that species can be present in different degrees of vulnerability due to the different exposure levels or AC of its geographical distribution through the country.

Results through time show that by 2080 more than 55% of continental Mexican reptiles will be in places with medium vulnerability, while 52%, and 21% will be in high, very high vulnerable places, respectively. CONABIO identifies 493 endemic reptile species in Mexico (Flores-Villela and Canseco-Márquez, 2004; CONABIO, 2015; Llorente-Bousquets and Ocegueda, 2008b). The results indicate that 164 endemic species are in some category of threat or they have deficient data. Figure 33 shows that 32 species of endemic reptiles are endangered, 22 are V, 5 are NT, 105 are DD and 183 are Least Concern (LC). Moreover, more than 25% of endemic and endangered Mexican reptiles are located in sites categorised from medium to extremely high vulnerability. TFs are shown to be the most important ecosystems for these endemic and endangered species, followed by TDF and S (Figure 33).

5.3.5.4 Amphibians

Mexico has 371 species of amphibians (IUCN, 2014) and 252 endemic species (Parra-Olea *et al.*, 2014b). By 2020 ~61% and 52% will be located in places with very high vulnerability (90) for both scenarios and 16% in critically vulnerability (100) under A2 scenarios (Table 16). By 2050%, the A2 scenario shows that 62% of the amphibians will be in extremely high vulnerability while the B2 scenario depicts only 16% in the same category, this great variation responds to the different patterns of exposure to CC. By 2080, 53% and 22% of the amphibians will be in the critical vulnerable areas, in each scenario, respectively (Table 16). Regarding the endemic amphibians, Mexico has 174 species of amphibians endemic to Mexico (CONABIO et al., 2007b). The results of the current study suggest that 84% of these endemic amphibians are in some status of danger or have deficient data. Comparing the geographical data with medium to extremely high vulnerable sites, it was found that 27% of the endemic amphibians are CE while 27% are E and 11% are V (Figure 33). These species are especially associated with TF, hydrophilic vegetation followed by scrublands and TDF.

5.4 Discussion

5.4.1 Exposure to LUCC

The most affected ecosystems by LUCC and CC, in terms of lost area in relation to its original distribution is the TEF, distributed on the coast of the Gulf of Mexico. Regarding biodiversity this is important because TEF is one of the richest ecosystems in number of species (Villaseñor, 2004). In Mexico some studies have reported that deforestation has led to the loss of ~ 90% of the TEF (Flores-Villela and Gerez, 1994), the same region of remnant vegetation that this study found to be highly exposed to LUCC. One of the most important areas of TEF is the region of Los Tuxtlas in the state of Veracruz which represents the northern limit of TEF distribution in the Neotropics (Dirzo and Miranda, 1991). This zone has already lost 95% of its original distribution (Castillo-Campos and Laborde, 2004). Landscape fragmentation of TEF in southern Mexico shows that there is a disaggregation of patches as an archipelago of forest islands immersed in a sea of cattle grasslands (Mendoza *et al.*, 2005). Direct causes of LUCC process in the coast of the Gulf of Mexico have been pointed out as extensive livestock, expansion of agriculture and urban sprawl, affecting not only TEF but also hydrophilic vegetation such as mangroves (Mendoza-González *et al.*, 2012).

Table 16. Total number of vertebrate species (including endemic and non-endemic, threatened and not threatened) within sites vulnerable to LUCC and CC. The range expresses the variation between the four CGCMs and the spatial information provided by IUCN and the Bird-Life Organization. The vulnerability scale is M= Medium, H=High, VH= Very High, EH= Extremely High.

		Mammals		**Birds**		**Reptiles**		**Amphibians**	
		A2	**B2**	**A2**	**B2**	**A2**	**B2**	**A2**	**B2**
2020	60 (M)	427-428 (80)	405-408 (76)	955-964 (88)	953 (87)	477-568 (60)	463-484 (55)	210-288 (67)	209-214 (57)
	70 (H)	415 (78)	415-417 (78)	978-979 (89)	978-980 (89)	489-493 (57)	492-496 (57)	214-253 (63)	215-247 (62)
	80 (VH)	416 (78)	403 (75)	935-953 (86)	941-943 (86)	462-493 (55)	466-476 (55)	252-256 (68)	217-225 (59)
	90 (EH)	393-336 (74)	316-336 (61)	850-903 (80)	851-869 (78)	327-465 (46)	336-364 (41)	194-255 (61)	204-182 (52)
	100 (CH)	335-345 (64)	198-215 (39)	572-678 (61)	430-570 (46)	31-37 (4)	0	21-95 (16)	0
2050	60 (M)	410-431 (79)	408-410 (76)	952-964 (87)	947-953 (87)	500-538 (60)	484-489 (56)	222-255 (64)	234-255 (65)
	70 (H)	412-416 (77)	414 (77)	978-980 (89)	980 (89)	491-494 (57)	489-496 (57)	223-244 (63)	223-254 (68)
	80 (VH)	396-411 (75)	400-403 (75)	946-953 (87)	941-949 (86)	465-480 (55)	462-476 (54)	248-251 (67)	215-231 (60)
	90 (EH)	366-369 (69)	336-364 (65)	886-903 (82)	869-882 (80)	407-419 (48)	364-394 (44)	224-233 (62)	41-77 (16)
	100 (CH)	194-262 (43)	171-192 (34)	567-768 (61)	480-510 (45)	105-219 (19)	51-76 (7)	58-123 (24)	0
2080	60 (M)	427-433 (80)	409-416 (77)	952-964 (87)	947-953 (87)	467-469 (54)	465-479 (55)	253-260 (69)	208-239 (60)
	70 (H)	412-431 (79)	315-403 (67)	978-980 (89)	980 (89)	424-483 (52)	406-436 (49)	223-296 (70)	214-248 (62)
	80 (VH)	403-410 (76)	397-407 (75)	946-953 (87)	941-949 (86)	192-275 (27)	158-204 (21)	212-250 (62)	202-247 (61)
	90 (EH)	371-411 (73)	367-387 (70)	886-903 (82)	869-882 (80)	0	0	225-240 (63)	219-239 (62)
	100 (CH)	352-404 (71)	233-258 (46)	567-768 (61)	490-530 (47)	0	0	116-274 (53)	79-81 (22)

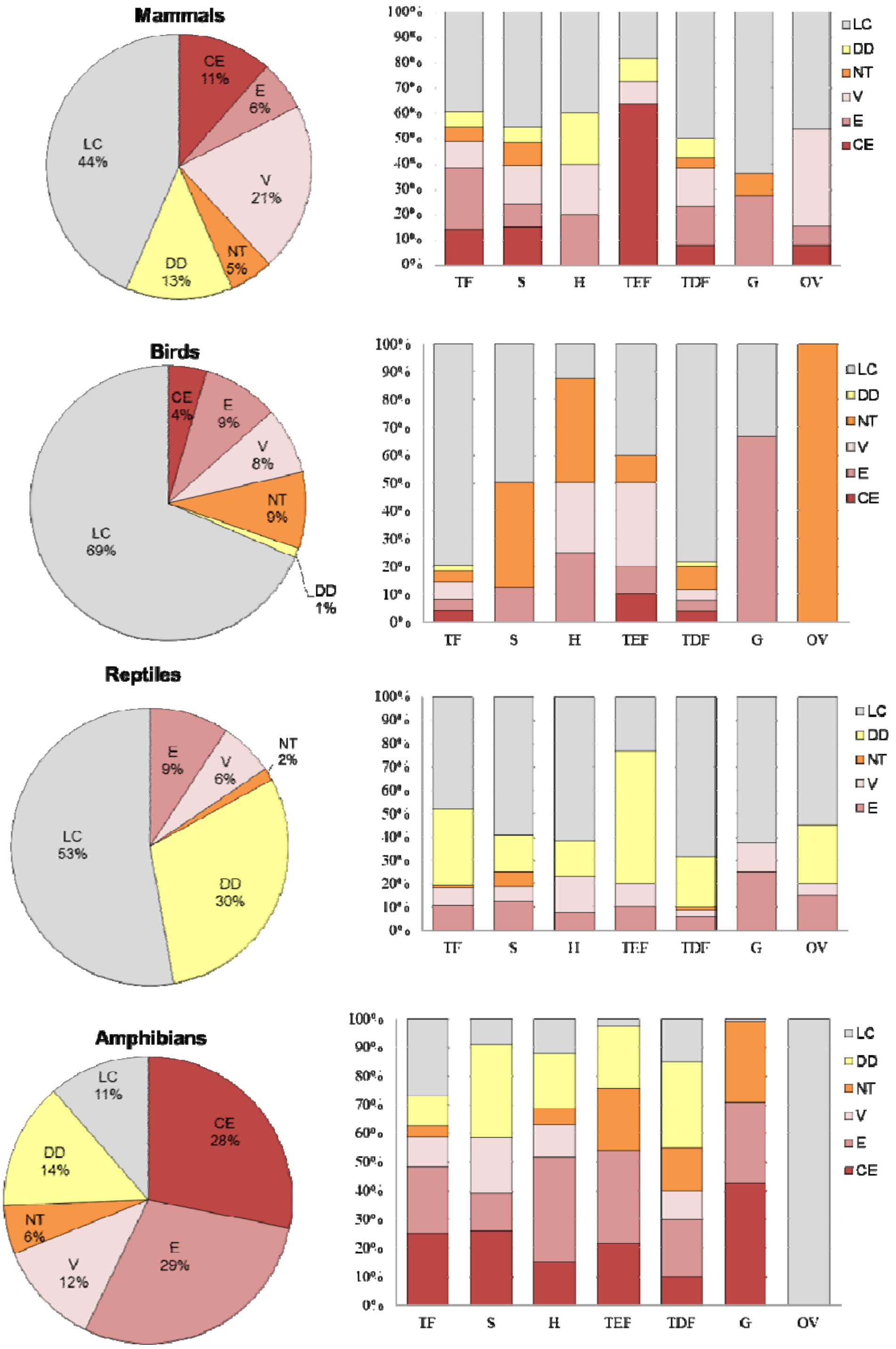

Figure 33. Percentage of endemic vertebrate species in vulnerable places (from medium to extremely high vulnerability). Bar graphs show the percentage of the endemic and threatened vertebrates in vulnerable places by ecosystem.

The second most affected area is the Pacific coast, occupying the states of Jalisco, Michoacán, Guerrero and Oaxaca and represented by TDF. TDF has been historically converted to pasture and agriculture, as a result, intact forests in the Mexican Pacific coast are very scarce (Maass, 1995; Burgos and Maass, 2004). For instance, 73% of the TDF has experienced some disturbance from slightly alterations or degradation up to a total conversion of structure and function (Trejo and Dirzo, 2000). There seems to be a trend in the Pacific region of agricultural expansion (Maass *et al.*, 2005; Corona, 2012) and urbanization due to the establishment of no successful touristic developments in the Pacific Coast, as in Oaxaca (Brenner, 2005).

The central region which shows highest exposure values to LUCC is in the states of Zacatecas and San Luis Potosí (SLP) (see Chapter 2). This region is characterised by scrublands and grasslands. Previous studies in the state of SLP have shown that even though there is a mixture of vegetation, scrubland has been the most affected (Miranda *et al.*, 2013). Other studies report TDF is the most affected vegetation in SLP due to increasing population and marginalization of the people which in turn favoured the expansion of agriculture in the region (Sahagún-Sánchez *et al.*, 2011).

Regarding exposure to LUCC, it is possible to see that different factors have triggered the expansion of anthropogenic land cover. Agriculture has been pointed out to be the major direct driver of change which in turn is affected by population, marginalization and economic drivers (Chapter 4). However, intensification of exposure to LUCC is expected due to future changing climate conditions.

5.4.2 Exposure to CC

The northern Pacific coast is shown to be the most affected region in terms of AI changes. This suggests that the greatest changes will not be in the hyper arid or arid zones but changes will be more severe in intermediate regions such as semiarid and sub-humid dry areas such as the Sierra Madre Occidental. Those changes do not suggest that arid zones will not be affected but the intermediate zones become dryer, consequently, the expansion of the driest zones will be shown in the nort. For example, Saenz- Romero et al. (2010) report that there will be an expansion of arid regions under A2 scenario, especially in north-central México. These new arid conditions will expand toward both coasts and toward the southeast by 2090 and these new aridity conditions may extend to the Sonoran desert, the Sierra Madre Occidental and the Neo-volcanic axis (Sáenz-Romero *et al.*, 2010). Moreover, Trejo et al. (2011) report drier conditions under A2 and B2 scenarios in the north of Mexico and a reduction of temperate ecosystems. This is relevant because arid regions are more prone to be affected by droughts and might experience even more severe impacts because of these extreme conditions (Maliva and Missimer, 2012).

Variation of AI and PET values could have effects on the movements of the ecotones between the TDF and TF (Sáenz-Romero *et al.*, 2010). Regarding biodiversity the effects may impact the distribution of biological groups which have shown to be differentially resistant to dryer and warmer conditions such as species of conifers (especially pines) and oaks (Sáenz-Romero *et al.*, 2006; Gómez-Mendoza and Arriaga, 2007; Gómez-Mendoza and Galicia, 2010). This is particularly relevant considering that: 1) Mexico has more than the 50% of known pine species (Styles, 1993) and 2) Mexico has been considered the hemispheric centre of the origin of oaks and includes more than 33% of the world's oak species (Nixon, 1993) and 3) Madrean Pine-Oak woodlands is a designated biodiversity hotspot (Mittermeier *et al.*, 2004).

In terms of changes to PET exposure, TDF in the Pacific coast are shown to be the ecosystem which will be less affected, contrasting with the Northeast Mexican border and the coast of the Gulf of Mexico where scrublands and remnants of TEF are located. These changes in PET may have a great effect because the northeast Mexican zone has been affected by the scarcity of available water in recent years (Seager *et al.*, 2009). This zone is especially linked to livestock production and will be face major challenges because of changes of AI and PET values under CC scenarios. The expansion of the arid zones may affect the vegetation, and consequently, have an effect on social issues related to agriculture and livestock practices (Seager *et al.*, 2007). The southeast part where changes of PET values are high, are characterized by being the most marginalized areas and the expansion of agriculture is widely uncontrolled. According to Seager et al., (2007) the southeast region is forecast to undergo important changes in climate becoming drier with CC.

These environmental changes may trigger social transformations causing different effects on patterns and process of LUCC.

5.4.3 Vulnerability of the PSBC to LUCC and CC

By 2020 and 2080 the percentages of sites are categorised from medium, high to extremely high vulnerability increase to 10%, to 17%, respectively. Vulnerable areas show different kinds of vegetation, especially TDF, in the west, TF in the centre of the country, scrublands in the north-east and TEF in the southeast.

Vulnerable areas on the Pacific Coast of the states of Jalisco, Guerrero and Oaxaca, are represented by TDF, and the southeast region of Chiapas characterised by TEF and TF. This latter area matches with another biodiversity hotspot, "Mesoamerica", reported as the 2nd most important biodiversity hotspot (Conservation-International, 2004). Nevertheless, the region has suffered from poverty, inequality and very high marginalization (CONEVAL, 2008). As a result, expansion of agriculture should be controlled; taking into account the needs of the increasing population of the region and that pressure of anthropogenic activities on the ecosystems will increase, despite the NPAs establishment.

TEF in the southeast of the country such as the states of Veracruz and Tabasco have not been found to be as highly vulnerable because the majority of the extent of this natural vegetation has already converted to agriculture. Vulnerability in this study was intended to point out the new areas which are more prone to change. This does not mean that strategies for rehabilitating and mitigating the spread of anthropogenic land cover should not be analysed at finer scales.

Vulnerability of PSBC respond to different drivers related to LUCC processes. Expansion of agriculture affects the Pacific Coast in the south east region. However, urbanization spread is more important in the centre and the northeast of the country (see Chapter 4).

5.4.4 Endemic or endangered species living in the most vulnerable sites

The richness of species, threats and endemicity do not show the same geographical distribution in many exercises aiming to prioritise biodiversity conservation (Orme *et al.*, 2005). Differences between species richness and endemicity do not have a correlation at the national level (Ceballos *et al.*, 1998). This means that it is possible to find areas with a high level of species richness but low endemicity (such as Mexican TEF) and some areas with a fewer number of species but a high degree of endemicity such as Mexican TDF (Rzedowski, 2006). Endemicity was used as an indicator of sensitivity based on the assumption that endemic species that depend on particular ecosystem types are less capable to migrate to keep up with change (Kinzig and Harte, 2000; Primack, 2006). However, there was no distinction between endemic, micro-endemic or rare species. In this context it is worth pointing out that, based on the results, there is a relationship between endemic species and endangered species. The list of species is in Appendix 7.

5.4.4.1 Mammals

More than 55% of endemic and endangered (or with deficient data) Mexican mammals live in vulnerable sites (medium to extremely high). Additionally, more than 17% of these species are E and CE. The majority of them are distributed on TF followed by TDF. This matches with information that highlights the importance of the Mexican Trans volcanic belt, western Pacific coast (Ceballos *et al.*, 1998; Ceballos and Oliva, 2005) and the Sierra Madre del Sur in the state of Chiapas (Ceballos, 2007; Vazquez *et al.*, 2009). These regions are represented by TF and TEF. Studies have revealed that more than 50% of endemic Mexican mammals have lost more than 50% of their habitat (Sánchez-Cordero *et al.*, 2005).In addition, according to Trejo et al., (2011) by 2050, under A2 and B2 scenarios many species of Mexican mammals will be facing an even greater loss of habitat, particularly 15 species of CE endemic mammals. This study complements that information by integrating all the continental mammals and using a different approach. The results show that 56% of endemic Mexican mammals are classified as in danger (including DD) and live in vulnerable places (medium to extremely high) of TF, scrublands and TDF. Some common species of mammals in these results such as species of the genus *Pteromiscus* and *Sorex* are CE, the former related to scrublands and the later to TF and TEF. Distribution of these genera includes the Sierra Madre del Sur and the border among the southern states of Veracruz, Chiapas, Tabasco and Oaxaca and although Ceballos (2007) reports that 82% of Mexican mammals are represented in NPAs, these CE and endemic species are not reported to be in NPAs. Finally, it is important to notice that 63% the endemic vertebrates of TEF are CE. The influence of the expansion of the NPAs shows that by 2080 the Mexican mammals could decrease from 71% to 46% the species that match with the critically vulnerable areas.

5.4.4.2 Birds

More than 22% of the endemic birds are in vulnerable sites (medium to extremely high), and more than 14% of these species are V, E and CE, according to the IUCN criteria. The majority of them are in the western region of Mexico which has been recognized as extremely biodiverse high (Peterson and Navarro-Sigüenza, 2000; Navarro-Sigüenza *et al.*, 2014a) where ecotones between TF and TDF converge making this region extremely important in terms of species richness and endemicity (Kobelkowsky-Vidrio *et al.*, 2014). That is because on the pacific coast there is a high endemicity of birds (Escalante *et al.*, 1993; Navarro-Sigüenza *et al.*, 2014b). By 2020, more than 60 % of the Mexican birds might live in very high vulnerable areas under A2 scenario while under B2 scenario this figure decrease to 47%, showing that the expansion of NPAs could help to mitigate the threats to the population of Mexican species of birds in more than 10%. By 2050 and 2080, the difference of 20% between both scenarios in the critically vulnerable category (100) remains. Consequently, it is possible to determine that the expansion of NPAs following the Aichi targets for 2020 could improve the strategies of conservation for the Mexican birds in more than 20%. The most important areas of expansion of NPAs in terms of birds are: Sierra Madre Occidental and Sierra Madre del Sur among the southern states of Guerrero, Michoacán and Oaxaca as well as the western Chiapas were the high vulnerable places are reported due to the extremely rich in terms of biodiversity of birds (Navarro-Sigüenza *et al.*, 2014b).

5.4.4.3 Reptiles

This study shows that by 2020 more than 55% of the Mexican reptiles will be located in very high vulnerable areas while 4% of them will be in critically vulnerable areas according to A2 scenario. By 2050, these figures increase but contrarily to the other groups of vertebrates, by 2080 only 27% of the reptiles are in high vulnerable places while the maximum categories of vulnerability show 0% in both scenarios. In terms of endemic reptiles more than 17% that live in medium to extremely high vulnerable areas are E, V or NT. Endemic and endangered species are principally distributed in TF (~60%), followed by TDF (~23%), S (15%), and TEF (~14%). Mexican species with higher environmental specialization such as endemic reptiles with restricted distributional ranges (micro-endemic species) could be more vulnerable to cope to changes in their habitat, causing in extreme cases the extinction of populations or species (Pounds *et al.*, 1999; Ballesteros-Barrera *et al.*, 2004; Ballesteros-Barrera *et al.*, 2007). However, at long term projections reptiles seem to be less affected group of vertebrates in the highest vulnerable areas. Consequently, this information points out the importance of further studies to monitoring specific populations especially in Mexican TF which have shown very high biodiversity richness and endemicity of these vertebrates in the country (Ramírez-Bautista and Cruz-Elizalde, 2013).

5.4.4.4 Amphibians

The results show that ~60% of the amphibians are in sites categorised as medium to extremely high vulnerability. That is very relevant considering that Mexico is ranked as having the 5th highest amphibian diversity in the world and a high level of endemism of around 60% of species (Flores-Villela, 1993). The majority of the diversity of amphibians is located in the states of Oaxaca, Chiapas and Veracruz (Parra-Olea *et al.*, 2014a), states that are characterised because of the high marginalisation and deforestation (chapter 4). Considering the endemic amphibians 54% of the species that are CE or E; half of them belong to three genera, *Ambystoma*, *Plectrohyla* and *Pseudoeurycea*. Some studies reports that high numbers of endemic species of amphibians in Mexico are located in the highlands of the centre or south of the country (Ochoa-Ochoa *et al.*, 2014), especially in the state of Oaxaca (Ochoa-Ochoa *et al.*, 2014); all these sites are especially represented by TF ecosystems. However, other studies such as García (2006) suggest that endemism of Mexican herpetofauna should be prioritised at lower altitudes and different areas on the Pacific Mexican coast, such as Guerrero and Jalisco where TDF is distributed.

The rate of extinctions of amphibians is higher than the rates of the other vertebrates (Stuart *et al.*, 2004; Rohr *et al.*, 2008). Fragmentation and natural habitat loss threatens 89% of neotropical amphibians (Young *et al.*, 2004). Parra-Olea et al. (2014a) point out that 43% of the Mexican amphibians are under some status of danger due to LUCC process, CC or invasive species. However, it is to notice that the figures are worse and that taking into account only the endemic amphibians the numbers are more pessimistic. However, the optimistic scenario which considers the expansion of the NPAs could avoid the pressure of these vertebrates until 33% (Table 16).

5.4.5 Prioritisation tools for biodiversity conservation and strengths and weaknesses of the approach

This study presents a methodology for a national prioritisation of conservation effort based on available information (see section 4.2). It can help to focus on regional work priorities (e.g. within municipalities) or specific ecosystems, vegetation types or species (e.g. endemic or endangered) based on threats from LUCC and CC. This flexibility can support a range of stakeholders. For instance, environmental agencies may wish to take a regional approach when considering ecosystem services provision, whilst NGOs and conservation scientists may be especially interested in endemic and threatened species. In addition, the identification of vulnerable municipalities can help target national or state policies.

Nevertheless, there are inevitably limitations to any approach that tries to synthesise and simplify the complexity of global change impacts (Metzger *et al.*, 2006). These limitations relate to the quality and water of information in terms of ecological or social variables at different temporal and spatial scales or resolutions, simplifications and temporal and spatial assumptions, inevitable arbitrary choices, and uncertainties of future change.

The reliability of scales of the LUCC maps depends on the targets of the work that are used to provide estimates of biodiversity loss when quantifying the extent of land degradation (Rouget *et al.*, 2006). For instance, global, regional or national studies which involve coarse spatial resolution, only allow the identification of big areas of change. However, information for understanding fine dynamics related to LUCC and their drivers require local studies which in turn need detailed spatial information about social and biophysical data. Multi-scale outputs should be directed towards specific stakeholders to link science to practice trying to integrate a variety of possible pathways, players and interests (Vogel *et al.*, 2007). In terms of the issue of available data, it should be said that in many developing countries the opportunity to get accurate and updated information is not common at different temporal and spatial scales. Moreover, if the data exist they are often not accessible, or prohibitively expensive (Maeda and Torres, 2012).

There is the assumption that sensitivity or distributions of endemic and endangered species are constant through time and the different existing scenarios. However, at any one location, biodiversity depends on dynamic processes across time (Fleishman *et al.*, 2006). There is also the assumption that the number of NPAs will remain constant through the time. This assumption may positively change on the basis that since the tenth Conference of Parties of the Convention on Biological Diversity (CBD) in 2010 and 2014, countries have committed to extend the coverage of protected areas (CBD, 2010), by 2020 until 17% of the terrestrial surface. This study shows that the expansion of NPAs could be a useful mitigation strategy, avoiding that by ~5%, 10% and 20% of the Mexican vertebrates face the critical vulnerability to LUCC and CC. However, the expansion of the NPAs could improve the conservation conditions of places that might face low or medium vulnerability making a challenge of conservation strategies the expansion of the high vulnerable areas that should be expanded more than 17% by 2020 in order to decrease the threats of LUCC and CC.

Issues regarding modelling of future changes include problems of the subjective nature of qualitative interpretations, the assumptions related to unfolding scenarios and the problem of validating future changes such as LUCC models and its drivers (Rounsevell *et al.*, 2006). All these problems are rooted in the same scenario approach as the assumption of the expansion of NPAs. Several drawbacks can be pointed out in the case of long-term LUCC modelling at the national level. First, the assumptions about the weights of the drivers of change remain constant through time for each scenario. This means that the effect of each variable remains constant. It also means that, although the population density changes in the projections, the influence of this on LUCC remain the same on the bases of the statistical effects. Second, modelling vulnerability to LUCC and CC is limited by the capacity to integrate the complexity of variables and their feedbacks. Variables include social, economic, political and ecological components and their interrelationships (see Chapter 4). The integration could be thought as simplistic and reductionist on the basis that a complex system can unfold in a plethora of ways which cannot include all of the components. However, there are approaches in modelling, involving different kind of variables in dynamic systems that help to visualize some possible futures on the basis of reliable past information (Young *et al.*, 1996).

In conclusion it should be noted that developing models, especially at the global or national level necessarily involves a simplification of the heterogeneity of the system. For example, national studies are focused on identifying regions that qualify as vulnerable to LUCC. Nevertheless, once these places are identified a more detailed LUCC analysis is often needed at the regional or local level (Verburg *et al.*, 2002). Consequently, the coarse resolution studies are complementary to local studies where finer understanding of the local actors is needed to implement conservation strategies as well as the integration of field work, remote sensing, and GIS tools to evaluate the effectiveness of the NPAs (Durán *et al.*, 2015).

The major purpose of creating indices is to have an instrument to compare states of particular environmental issues across time and space (Ebert and Welsch, 2004). Developing tools for measuring vulnerability helps to bridge the gaps between the theoretical concepts of vulnerability and day-to-day decision making (Birkmann, 2007). However, while these instruments are being developed, choices selected during development should be based on measurement units of known scientific relationships (Ebert and Welsch, 2004).

Despite its limitations, the methodology presented here to measure exposure, sensitivity and AC to LUCC and CC in Mexico (derived from available information), creates a comparative framework where the changes experienced through both space and time can be contrasted. This approach can be replicated in other regions or countries. However, it must be noted that that there is still a lack of available quantitative information needed to understand the dynamic of the ecosystems under LUCC and CC.

5.5 Conclusions

Modelling tools at different spatial and temporal scales that allow the integration of socio-economic and biophysical information under different scenarios are a useful tool for prioritisation strategies for biodiversity conservation. Targets for prioritisation may include ecosystems, species or populations. Prioritisation exercises allow utilising available resources in order to mitigate the effects of LUCC and CC in places that will be more vulnerable to these threats. This study provides an example of the application of these tools. Prioritisation results show that from an ecosystem point of view, tropical evergreen forests (TEFs) and natural grasslands will face an important reduction of their already narrow distribution in Mexico. However, in terms of extent the reduction is higher in temperate forests (TFs) and tropical dry forests (TDFs). Furthermore, if the information on vertebrates is included, TFs in the Sierra Madre Occidental and Chiapas, and TDF in the Pacific Coast are highlighted as priorities for conservation efforts. From a biodiverse perspective, amphibians and reptiles of Mexico are shown to be the most affected vertebrates to LUCC and CC. Moreover, from a municipality perspective the northern municipalities in the states of Sonora, Chihuahua and San Luis Potosí are highlighted because of the lack of conservation strategies such as NPAs. This study provides a basis for other prioritisation exercises which could be developed at finer scales and attempt to integrate the spatially and temporal trade-offs between different scenarios.

Chapter 6: Facing the Challenges of Applying the Vulnerability of LUCC and CC Framework on Regional Scales in a Developing Country: Vulnerability of TDF in Southern Mexico

6.1 Introduction

The aim of this chapter is to apply the vulnerability framework at regional level by focusing on three of the most vulnerable municipalities, as determined in Chapter 4, in a Tropical Dry Forest (TDF) region, in southern Mexico. The LUCC models were developed in the Dinamica EGO platform by using maps from the years 1996, 2006 and 2011, at a resolution of 30 x 30m. The LUCC models were projected for three time slices: the 2020s, 2050s and 2080s, under A2 and B2 assumptions of the Special Report on Emissions Scenarios (*SRES)* by the Intergovernmental Panel on Climate Change (IPCC). This chapter first provides a general overview of the importance and threats of TDF. Secondly, the methods include an explanation of the inputs used and the steps involved to model the Rainfed Agriculture (RFA). Thirdly, the results and the discussion are addressed via the following approaches: 1) Analysis of the trends of TDF in the region and the differences between municipalities based on their socio-economic and biophysical explanatory variables of change; 2) projection of LUCC under different socio-economic and CC scenarios. 3) Determination of the endemic and endangered species of the region; 4) highlighting of the challenges and limitations of applying TDF the vulnerability framework at regional level, and further work.

6.1.1 TDF: Importance and Threats

The major extent of TDF is found in humid and sub-humid climates, with 67% of the global distribution found in the Americas (Miles *et al.*, 2006). TDF grows on shallow soils that flood in the rainy season, and which become dried out in the dry months. TDF spreads at mean annual temperatures above 20^{o}C and mean annual precipitation of 800 mm, showing a dry season of around 7-8 months (Challenger and Soberón, 2008). TDF is considered the thermic and hydric limit of warm and humid conditions (Pennington and Sarukhán, 1998).

Mexico contains ~38% of the total TDF in the Americas, making it the country with the greatest extent (Portillo-Quintero and Sánchez-Azofeifa, 2010). The potential distribution of TDF in Mexico was ~335,000 km^2 (INEGI, 2003); that is ~14% of the country (Rzedowski, 2006) and ~60% of Mexican tropical vegetation (Trejo and Dirzo, 2000). However, nowadays TDF represents 11.26% (79,300 km^2 as primary forests and 141,900 km^2 as secondary forests (Challenger and Soberón, 2008). In Mexico, TDF is found through the Pacific Coast from the southern part of the state of Sonora (see Chapter 2) to the low lands of the Sierra Madre Occidental. This vegetation spreads to the south of the country in the lowlands of the Peninsula de Yucatán and the south of Veracruz and Tabasco. Mexican TDF is highly biodiverse, reporting more than 6,000 plant species with a high endemic component (25% of the genera and 40% of the species) (Rzedowski, 1998).

According to Janzen (1986) TDF has been one of the most endangered major tropical ecosystems. Approximately, 48.5% of TDF has been converted to anthropogenic uses at global level (Hoekstra *et al.*, 2005). In Mexico ~73% of TDF has suffered some degree of disturbance (Burgos and Maass, 2004) and it has been lost at a rate of 0.43%yr^{-1} to 0.52%yr^{-1} (1993-2002 and 2002-2007) (Chapter 4**)**. This anthropogenic conversion from TDF to other covers and uses is the result of many local conditions such as topography, soils, length of the dry season, local traditional knowledge, demographic and economic constraints, land tenure system, and political issues (Maass, 1995; Castillo *et al.*, 2005). Forms of LUCC in TDF are related to agricultural expansion due to the good conditions for agronomic and cattle development (Fajardo *et al.*, 2005), and most recently to the development of mega-tourism projects (Sánchez-Azofeifa and Portillo-Quintero, 2011).

In Mexico the magnitude of conversion varies from shifting cultivation systems (small pieces of forest land cropped for a few years followed by long fallow periods) to large land settlements (several square kilometres of continuous cultivation systems) (Maass, 1995). Shifting cultivation or Rainfed Agriculture (RfA) is principally related to maize production which is the most important agricultural activity for subsistence farmers in Mexico (>50% of national production) (INEGI, 2009a). However, Mexican studies of LUCC in TDF have focused principally on reporting deforestation rates, showing a lack of understanding of the dynamics of the process needed to identify the forces of change (Corona, 2012) and the effects of CC on the agricultural systems, such as the case of RfA (Al-Bakri et al., 2011; Latha A. et al., 2012) in Mexico (Conde et al., 2006).

Integration of different drivers is dependent of the analysis of scale. Coarse scales are useful to expose general trends and factors, but they can obscure the variability of units and processes that can only be observed using finer scales (Verburg *et al.*, 1999). For instance, direct or proximate causes generally operate at the local level (individual farms, households, or communities) while underlying or indirect causes may originate from the regional (districts, provinces, or country) national or even global levels, with complex interplays between levels of organization (Lambin *et al.*, 2003; Lambin and Meyfroidt, 2011). Consequently, local studies improve the understanding of LUCC while the scenario framework allows the depiction of possible trajectories under different CC and socio-economic scenarios.

6.1.2 Aims

This study analyses the regional effects and the drivers of LUCC under CC and socio-economic scenarios in three vulnerable municipalities dominated by TDF (San Pedro Pochutla, Santa María Huatulco and San Miguel del Puerto) (Chapter 5) in Oaxaca, southern Mexico (Figure 34). The main aims of this study are:

- to develop the vulnerability framework at regional level in three contrasting municipalities in Oaxaca, Mexico.
- to model the LUCC under different CC and socio-economic scenarios for three contrasting municipalities in Oaxaca, Mexico.
- to identify the drivers of LUCC in the three municipalities in Oaxaca, Mexico.
- to identify the endemic and threatened vertebrate species under different CC and socio-economic scenarios for the region.

6.2 Methods

This section is divided into four main parts: 1) description of the site of study; 2) description of the inputs of the model; 3) steps for building the model, its projections and exposure to LUCC under different scenarios; and 4) identification of endemic and threatened vertebrates of the region.

6.2.1 Study Site

This study analyses the dynamic of LUCC in three municipalities in the southern Mexican state of Oaxaca, which were identified in Chapter 5. The municipalities are: 1) San Pedro Pochutla, 2) Santa Maria Huatulco, and 3) San Miguel del Puerto, located in the state of Oaxaca, in south Pacific Mexico (Figure 34). The total extent of the study region is ~1,471 km^2 excluding islands and water. This region is represented by TDF coexisting with different anthropogenic land covers such as agriculture (irrigated and rainfed) and tourism. However, the municipalities differ in social and economic characteristics which have influenced the landscape dynamics in different pathways (Table 17).

The study area is characterised by high levels of marginalization and social conflict, which contrasts with its high cultural richness (Propin and Sánchez, 2001). Rainfed agriculture (RfA) and extensive pastures for cattle-raising are the most common anthropogenic covers (INEGI, 2010b). Since the 1980s, the area has developed tourism activities and other associated services (Juárez, 2000). Towards the end of last century, the area experienced one of the highest increases in population and urbanization, above national averages (Juárez *et al.*, 1998).

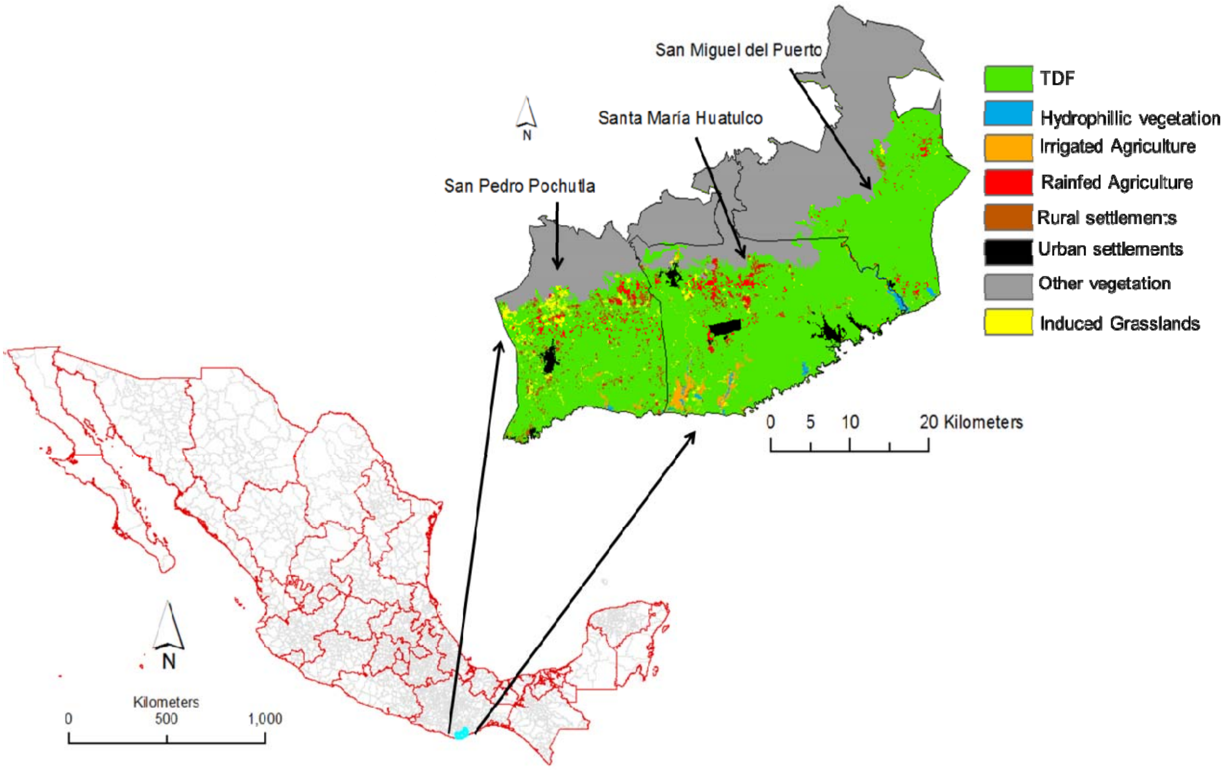

Figure 34. The three municipalities, and their LUCC, located on the Pacific coast of Oaxaca.

Table 17. General characteristics of the three Mexican municipalities of this study (INEGI, 2010a).

	San Pedro Pochutla	Santa María Huatulco	San Miguel del Puerto
Municipal extent (km^2)**	445	512	519
Localities	135	76	57
Population	43,860	38,629	8,481
Marginalization	High	Medium	Very high
Localities with < 5000 inhb.	67%	42%	100%
Illiteracy	18%	11%	22%
Coordinates	N 15°44' 40" W 96°27'55"	N 15°50'03" W 96°19'20"	N 15° 55' 21" W 96° 10'28"

6.2.2 Inputs of the Model and Identification of Drivers of LUCC

Aerial photographs from 1996, 2006 and 2011 were used to create the LUCC maps (PSIG, 2014). The photographs were orthorectified and geo-referenced to produce the LUCC maps with eight different classes (Classification 1 in Table 18). Explanatory variables or drivers of change that included socio-economic and biophysical data were considered on the basis of previous studies of LUCC undertaken in Mexico (Geoghegan *et al.*, 2001; Roy-Chowdhury, 2006; Flamenco-Sandoval *et al.*, 2007; Wyman *et al.*, 2008; Currit and Easterling, 2009; Ellis *et al.*, 2010; Mas *et al.*, 2010; Mas and Flamenco, 2011; Sahagún-Sánchez *et al.*, 2011; Pérez-Vega *et al.*, 2012) and the region (Corona, 2012) (Table 19).

Climatic variables included outputs and derivations obtained from four coupled global atmosphere-ocean general circulation models (GCMs) that were used for modelling the effects of climatic variables on land uses and covers (CGCM2, HadCM3, MK2 and Nies 99) as in chapters 4 and 5.

Table 18. Classification of Mexican LUCC (n=8 categories) used in this study.

	Land Use/Cover	Description
1	Tropical dry forest (TDF)	Local flora has been classified into more than 91 families, 391 genera, and 736 species. The dominant families in number of species are *Leguminosae* (146), *Euphorbiaceae* (48), *Asteraceae* (42), and *Convolvulaceae* (37) (Salas-Morales *et al*., 2007).
2	Hydrophilic Vegetation (HV)	Includes riparian vegetation, mangroves and wetlands (species=30) dominated by *Bravaisia integerrima*.
3	Irrigated Agriculture (IA)	It uses technology to transport water from wells and rivers. Commercial products are papaya, watermelon, banana, melon and peanuts.
4	Rainfed Agriculture (RfA)	Seasonal agriculture depends on the climatic conditions and water availability. Common crops are corn and beans.
5	Rural Covers (R)	Human settlements < 2500 inhabitants
6	Urban Covers (U)	Human settlements > 2500 inhabitants
7	Other Vegetation (OV)	Temperate forests
8	Grassland for livestock (G)	Species such as *Aegopogon cenchroides* and *Muhlenbergia emersleyi*.

The LUCC model was developed in Dinamica EGO by undertaking the same steps as in Chapter 4 (Figure 35).

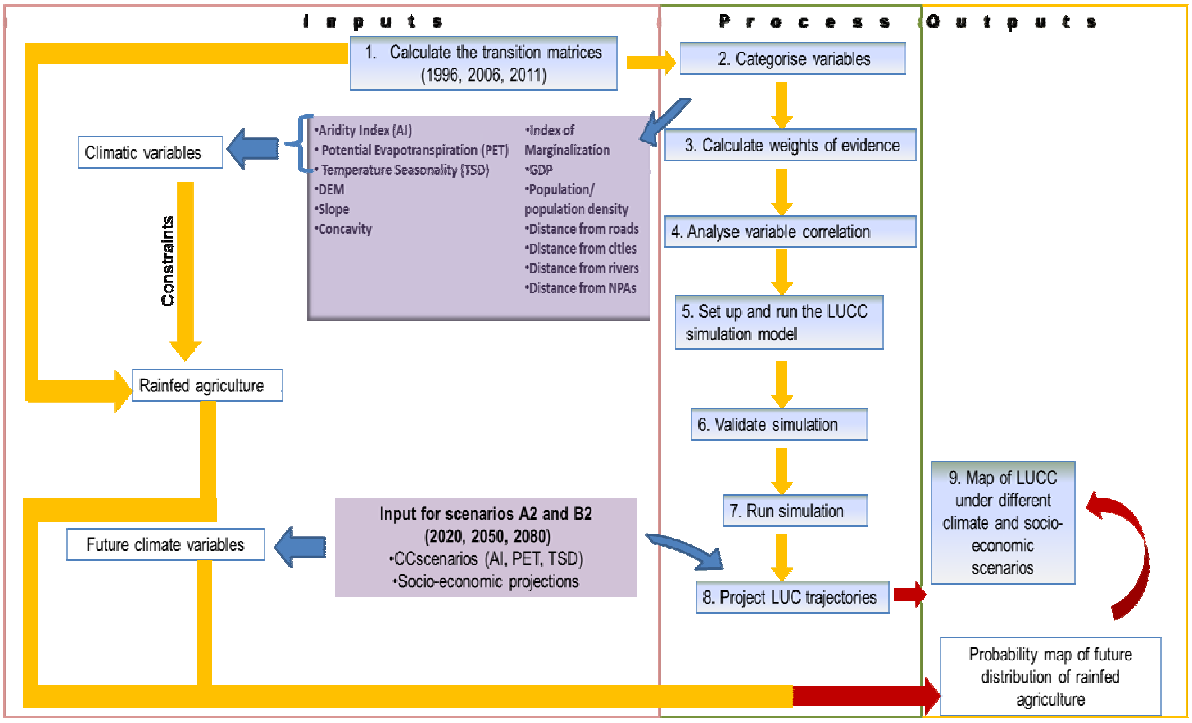

Figure 35. Steps for developing the LUCC model under different CC and socio-economic scenarios. Yellow arrows show the process in steps, blue arrows show inputs, and red arrows show the resulting information.

6.2.3 Developing the LUCC Model

6.2.3.1 LUCC Dynamics over the Periods 1996-2006 and 2006-2011

Transition matrices were calculated using the regional land cover maps from 1996, 2006 and 2011 (see Chapter 4). The results of the matrices were used to calculate the rate of change in area and percentage for each period of time. Considering the eight different LUCC there are 64 possible transitions (8 x 7). Only 11 transitions were considered for the model on the basis of the importance of contribution, in terms of extent of change (1996-2006, 2006-2011) (Table 20).

Table 19. Inputs used as explanatory variables in the LUCC model.

Biophysical				Socio-economic			
Map	Scale-resolution	Year	Source	Map	Scale-resolution	Year	Source
Land use / cover map	30 x 30 m	1996 2006 2011	(PSIG, 2014)	Distance to roads	30 x 30 m	1999-2000	(INEGI, 1999, 2000a, 2002a)
Digital contour lines	1: 50,000	1999-2000	(INEGI, 1999, 2000a, 2002a)	Distance to NPAs	1:400,000	2012	(Bezaury-Creel *et al.*, 2009; CONANP, 2012)
Digital Elevation model (Altitude)	30 x 30 m	Current	Derived from contour lines.	Distance to human settlements	30 x 30 m	2006	Derived from Corona (2012)
Slope, aspect, concavity	30 x 30 m	Current	Derived from Digital Elevation model.	Index of marginalization[5]	Municipality	1995 2000 2005 2010	(CONAPO, 1995) (CONAPO, 2000) (CONAPO, 2005) (CONAPO, 2010)
Hydrologic network	1: 50,000	Current	Derived from Digital Elevation model.	Population	Municipality	1995, 2006 and 2010	(INEGI-CONAPO-COLMEX, 2006)
					Municipality	2020, 2050, 2080*	Chapter 3
Distance to Rivers	30 x 30 m	Current	Derived from hydrologic network.	Population density	Municipality	As above	Developed using population and municipality area and real occupied area (Chapter 3)
AI, PET, TSD	30 arc sec	Current 2020, 2050, 2080*	(Metzger *et al.*, 2013)	GDP	Municipality	1995, 2006, 2010	INEGI
						2020, 2050, 2080*	Chapter 3
				GDP density and GDP *per capita*	Municipality	As above	Developed using GDP, population and the municipality area.

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[5] Index of marginalization is a national index, which includes socio-economic information related to income, health, housing and education. For more information see Appendix 1.

Table 20. Transitions used in the LUCC model (TDF = Tropical dry forests; IA = Irrigated agriculture; RfA = Rainfed agriculture; R = Rural covers; U = Urban covers; G = Anthropogenic grasslands (for livestock).

	TDF	IA	RfA	R	U	G
TDF		√	√	√	√	√
IA						
RfA	√					√
R		√				
U						
G	√	√	√			

6.2.3.2 Categorisation, Weights of Evidence (WofE) and Correlation of the Explanatory Variables (Socio-Economic and Biophysical)

Explanatory variables were grouped (transformed to categories) and the subsequent calculation of Weights of Evidence (WofE) was developed, as was explained in Chapter 4. However, RfA was modelled differentially on the basis that the significant effect on it are caused by CC (Conde *et al.*, 2006; Al-Bakri *et al.*, 2011; Latha *et al.*, 2012). This study modelled RfA by analysing the optimal climatic variables in the region in the same context as the ecological niche. Afterwards the future climate scenario was integrated to create a probabilistic map in which RfA would be constrained under future climate conditions (Gornall *et al.*, 2010).

For future scenarios, expansion of RfA was compensated based on a reduction of yields due to CC. Al-Bakri et al. (2011) proposed a reduction of 5% of maize crops due to CC. In this context, the model includes a reduction of the suitability area for RfA in every time slice for the A2 scenario (pessimistic scenario). This reduction in agricultural suitability would be compensated by an increase in deforestation, considering that G, IA, R, and U covers are more profitable than RfA. Finally, the B2 scenario was used as Business As Usual (BAU), considering the historical trend of changes which would be updated by the CC and socio-economic projections.

6.2.3.3 Projections and Validation of LUCC Models under Different CC and Socio-Economic Scenarios

Validation of the model is given in terms of location and quantity of change between the observed and the simulated maps, reflecting the reliability of the model. This occurs when grid cells in the simulated maps match with the corresponding grid cell in the map of empirical LUCC (Pontius *et al.*, 2001b) (see Chapter 4). Dinamica EGO calculate the *Reciprocal Similarity Map* by adding an exponential decay function to assess the model's spatial fitness at various resolutions as a modification of the KFuzzy (Soares-Filho *et al.*, 2009).

The model was trained using LUCC maps for the periods 1996 to 2006 and 1996 to2011. Then a 5 and 15 time-step simulation was run to obtain the simulated map for the year 2011. Once the validation of the model is performed the simulation until 2080 is created. The model simulation produces a single map for every time-step by updating the socio-economic and climatic variables for 2020, 2050 and 2080.

6.2.4 Identifying the Endemic and Threatened Vertebrates Species under different Socio-Economic and CC Scenarios

The resulting vulnerability maps were used to identify the endemic and threatened species that overlap with the vulnerable sites. Geographical information about the species distribution was obtained from the IUCN for mammals, reptiles and amphibians (IUCN, 2014), and information about birds was taken from BirdLife International (BirdLife_International and NatureServe, 2014). Endemic species were used, supporting the idea that species that are more vulnerable to extinction will be: 1) species with a narrow (or single) geographic range; 2) only one or few populations; 3) species with a small population size; 4) species with a declining population size; 5) species hunted or harvested by people; and 6) species that require specialised habitat and niche conditions (Primack, 2006).

6.3 Results

6.3.1 LUCC Dynamics over the Periods 1996-2006 and 2006-2011

During the period 1996-2006, TDF showed a regrowth rate of 0.017% yr^{-1} (from 837.6 to 839.3 km^{2}) and a deforestation rate from 2006-2011 of 0.47% yr^{-1} (from 839.3 to 819.6 km^{2}) (Tables 21 and 22). Moreover, for the total period, 1996-2011, the deforestation rate was 0.15% yr^{-1}. However, at the municipality level in 1996-2006, 2006-2011 and 1996-2011 San Pedro Pochutla showed a deforestation rate of 0.24% yr^{-1}, 0.81% yr^{-1}and 0.42% yr^{-1}. That means that by the period 1996-2006 this was the only municipality with deforestation, unlike the other two, which had deforestation during the period 2006-2011, but forest regrowth for 1996-2006 (Table 21). RfA and grasslands were the principal direct drivers of change, explaining 46% and 23% of TDF lost in the first period, and 66%, and 26% in the second period, respectively (Figure 37). Urban covers contributed with 11% and 3% for the loss of TDF (Figure 36). Rural and IA explained each one: the 11% of deforestation for the first period; ~4% for the second period (Tables 21 and 22). In terms of growth rates of anthropogenic covers at municipality level during 1996-2011, S.P. Pochutla showed 10.0%yr^{-1}, 6.2% yr^{-1}, 5.4% yr^{-1}, 3.7% yr^{-1} and 0.5% yr^{-1} for G, rural, IA, urban and RfA, respectively. Similarly, S.M. Huatulco had lower rates for the same covers: 4.6% yr^{-1}, 4.3% yr^{-1}, -0.53% yr^{-1}, 1.54% yr^{-1}, and -0.54% yr^{-1}. By contrast, S.M del Puerto showed a decrease in all anthropogenic covers except rural covers (1.62% yr^{-1}).

Table 21. Transition matrix of LUCC for the period.1996-2006. (TDF = Tropical dry forests; IA = Irrigated agriculture; RfA = Rainfed agriculture; R = Rural covers; U = Urban covers; G = Grasslands.

1996 - 2006	TDF	H	IA	RfA	R	U	G	Total (1996)
TDF	806.4	0.2	2.7	14.7	2.9	3.3	7.4	837.6
H	0.1	5.8	0.2	0	0	0	0.1	6.2
IA	2.0	0.7	10.5	0	0.1	0	1.2	14.4
RfA	24.0	0	0	11.8	0	0	1.5	37.8
R	0.4	0	0	0	4.9	0	0	5.3
U	0.1	0	0	0	0	16.3	0	16.4
G	6.3	0	0.6	0.5	0	0	3.5	11.7
Total (2006)	839.3	6.7	14.1	27.0	8.2	19.8	13.7	928.8

Table 22. Transition matrix of LUCC for the period 2006-2011.

2006 - 2011	TDF	H	IA	RfA	R	U	G	2006
TDF	802.3	0.0	1.4	22.9	1.0	1.3	10.3	839.2
H	0.0	6.6	0.2	0.0	0.0	0.0	0.0	6.7
IA	1.7	0.0	11.4	0.2	0.0	0.0	0.6	14.0
RfA	11.6	0.0	0.0	12.3	0.1	0.0	2.8	26.9
R	0.0	0.0	0.0	0.0	8.1	0.1	0.0	8.2
U	0.0	0.0	0.0	0.0	0.2	19.8	0.0	20.0
G	3.8	0.2	1.1	1.8	0.0	0.0	6.8	13.7
Total (2011)	819.6	6.7	14.1	37.3	9.4	21.2	20.6	928.9

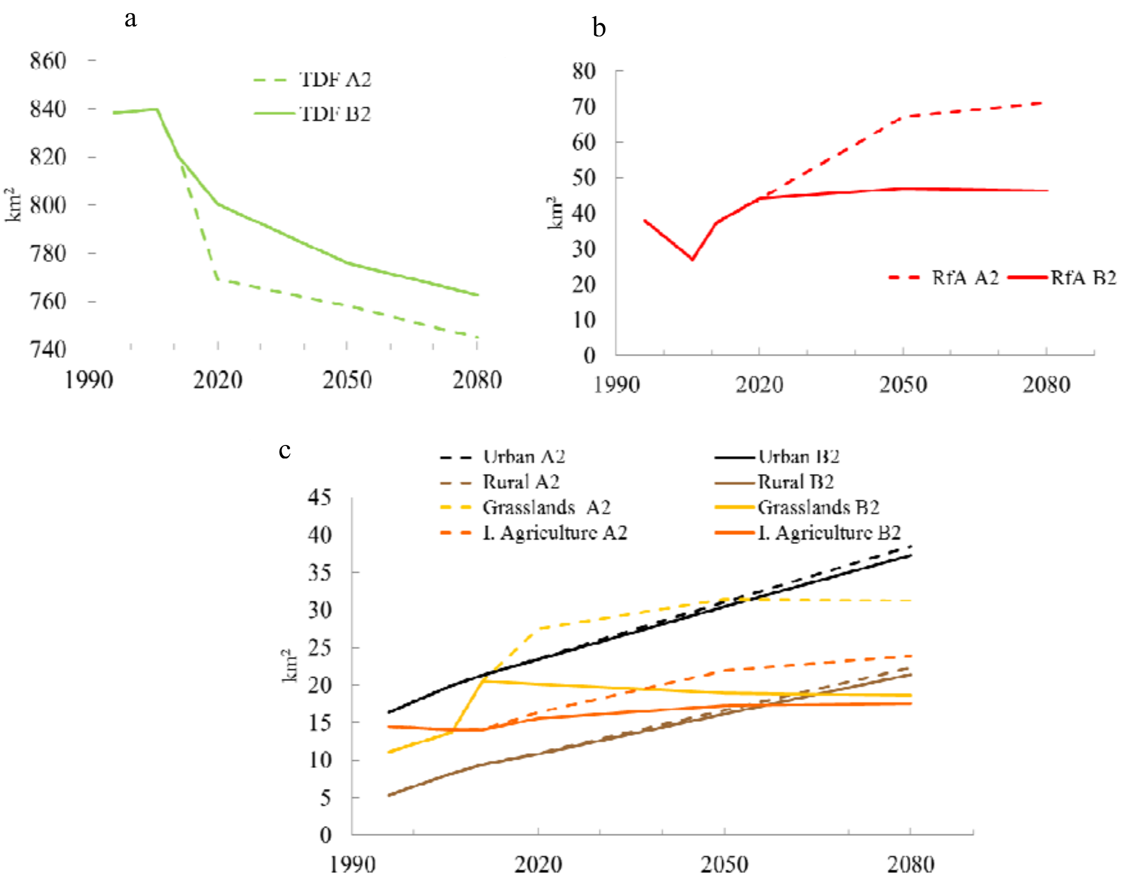

Figure 36. LUCC trends under different socio-economic and CC scenarios in km^2: a) TDF; b) RfA; c) urban, rural, induced grasslands and irrigated agriculture.

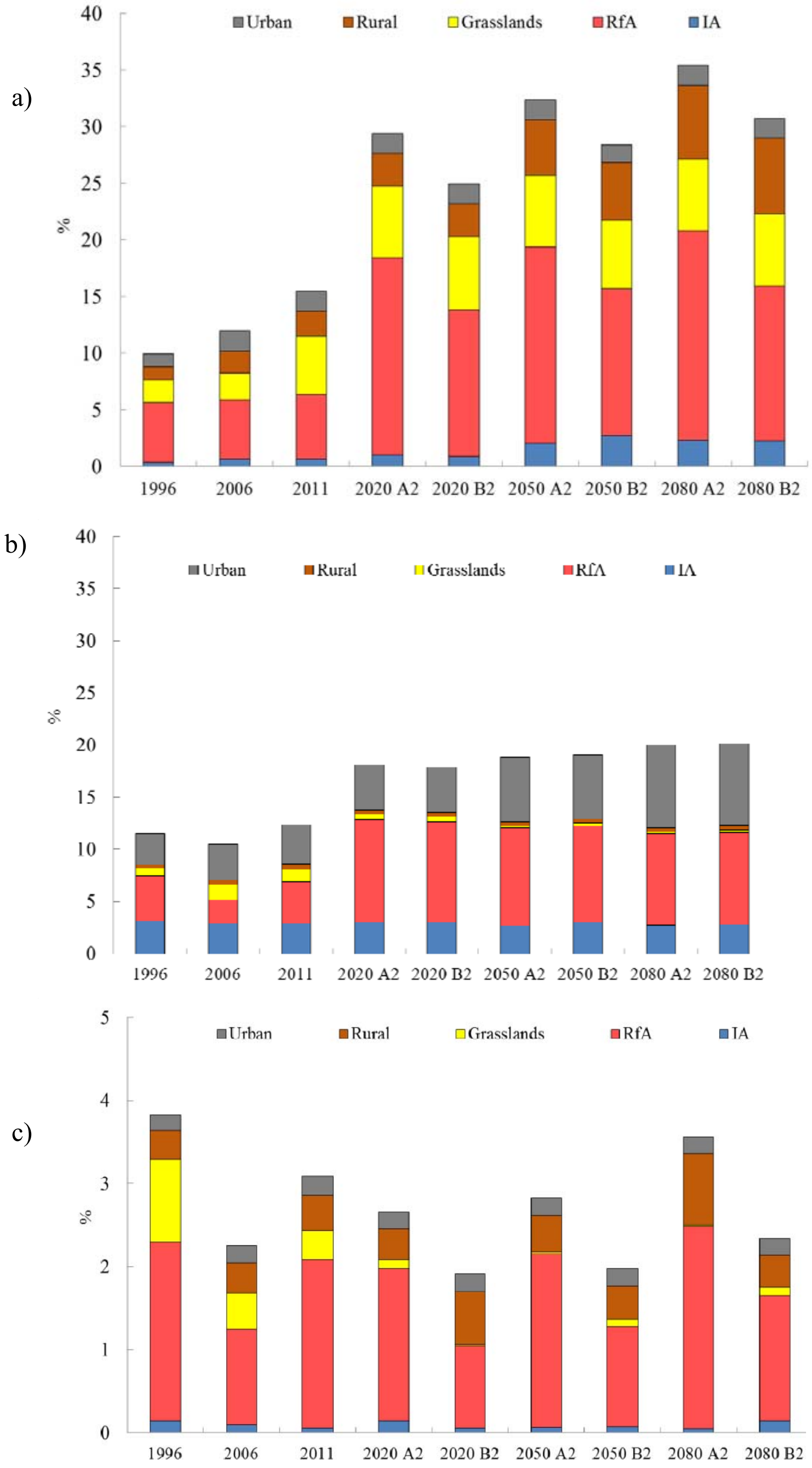

Figure 37. LUCC percentage of each municipality under different CC and socio-economic scenarios: a) San Pedro Pochutla; b) Santa María Huatulco; c) San Miguel del Puerto.

6.3.2 Identification of Explanatory Biophysical and Socio-Economic Variables of LUCC

Biophysical variables are constraints to LUCC: factors such as altitude, slope, and climatic variables are shown to have an effect on different transitions. Conversion from TDF to irrigated agriculture was very frequent (88%), between 0 to 100 m. Meanwhile transitions to urban or rural settlements, RfA and grasslands showed greater range, oscillating between 0 and 300m. The same trend applied to the slope where the majority of changes (>70%) from TDF to any anthropogenic cover happened between 0 and 5^o.

Humid places are more prone to shift from TDF to RfA and grasslands. Irrigated agriculture and human settlements were shown to be more flexible, expanding the range of tolerance to aridity. Humid parts of the region are closer to the northern border, to the TF, where the RfA and grasslands are principally distributed (Figure 39).

Distance to water bodies and rivers is important for transition from TDF to irrigated agriculture and to grasslands where >60% were performed at distances <1km. On the contrary, transition to rural and urban settlements proved more likely when further from water bodies and rivers: for urban areas ~70% of changes occurred at distances >2km.

Distance to roads and motorways are important for all the transitions from TDF to anthropogenic covers, especially for irrigated agriculture, grasslands, and urban areas: > 60% was closer than 500m. Rural establishments and RfA showed a wider range, up to 2km. The same trend applies to distance to rural settlements, which were closer to urban areas.

NPAs were shown to have an impact on the landscape, by constraining the anthropogenic changes, especially for irrigated agriculture, rural areas, grasslands and cities, and to a less extent RfA. NPAs created a buffer from 2km up to 8km to the transitions where anthropogenic transitions were avoided.

Differences in demographic characteristics affect the LUCC process. Municipalities with more inhabitants and high population density values were more prone to expand RfA and urban centres due to increasing population. This was the case with S. P. Pochutla and S. M. Huatulco. This, in turn, is related to the GDP production which is higher in urban and less marginalized places.

6.3.3 Projections and Validation of LUCC model under different Socio-Economic and CC Scenarios

The validation of the model showed that there is an agreement of 81% at 700m of resolution, but since a resolution of 300m the similarity reaches 60% (Figure 38), meaning a match of > 50% between the observed and the simulated map. The best-modelled cover was TDF followed by the urban, rural and IA. Finally, the RfA performed the worst, mainly because it is highly dynamic in space and time.

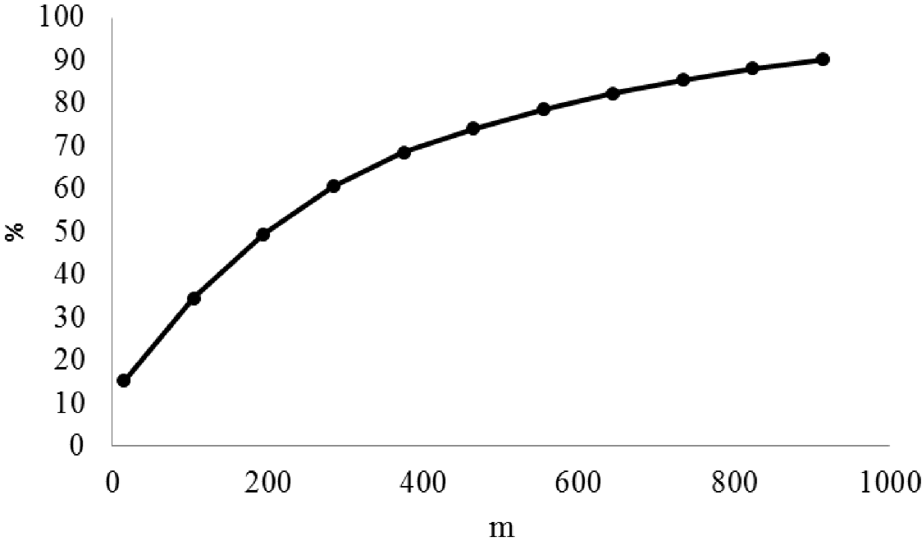

Figure 38. Similarity of LUCC model between the observed map and the simulated map with different-size windows.

By 2050, according to the scenarios, TDF might decrease in the region from between 7% and 9% in relation to the extent of 1996. On the contrary, RfA, rural areas, urban covers and grasslands increased their extension. RfA augmented its area by more than 50%, mainly allocated in the north of the region, being most active in S.P.Pochutla followed by S.M.Huatulco and then S.M del Puerto (Figure 39). According to the scenarios, by 2050 TDF will cover 70%, 80% and 97% respectively of the three municipalities. However, distribution of RfA is determined differently in the municipalities, due to the presence of touristic developments and the NPA in the south of S.M Huatulco, which causes a clustering of patches of RfA. In this time slice it is projected that ~10% of S. M. Huatulco, ~17% of S.

P. Pochutla, and ~2% of S. M del Puerto will be RfA. In contrast, IA will increase in S. P Pochutla, occupying 5% of the municipality.

By 2050, rural areas are principally represented in S.P Pochutla, which represents 5% of the municipality. Urban covers are distributed especially in S.M. Huatulco, where by 2050 it is projected to be 6% of the municipality, while in S.P Pochutla it is <1.7%, and < 0.3% in S.M del Puerto (Figure 40).

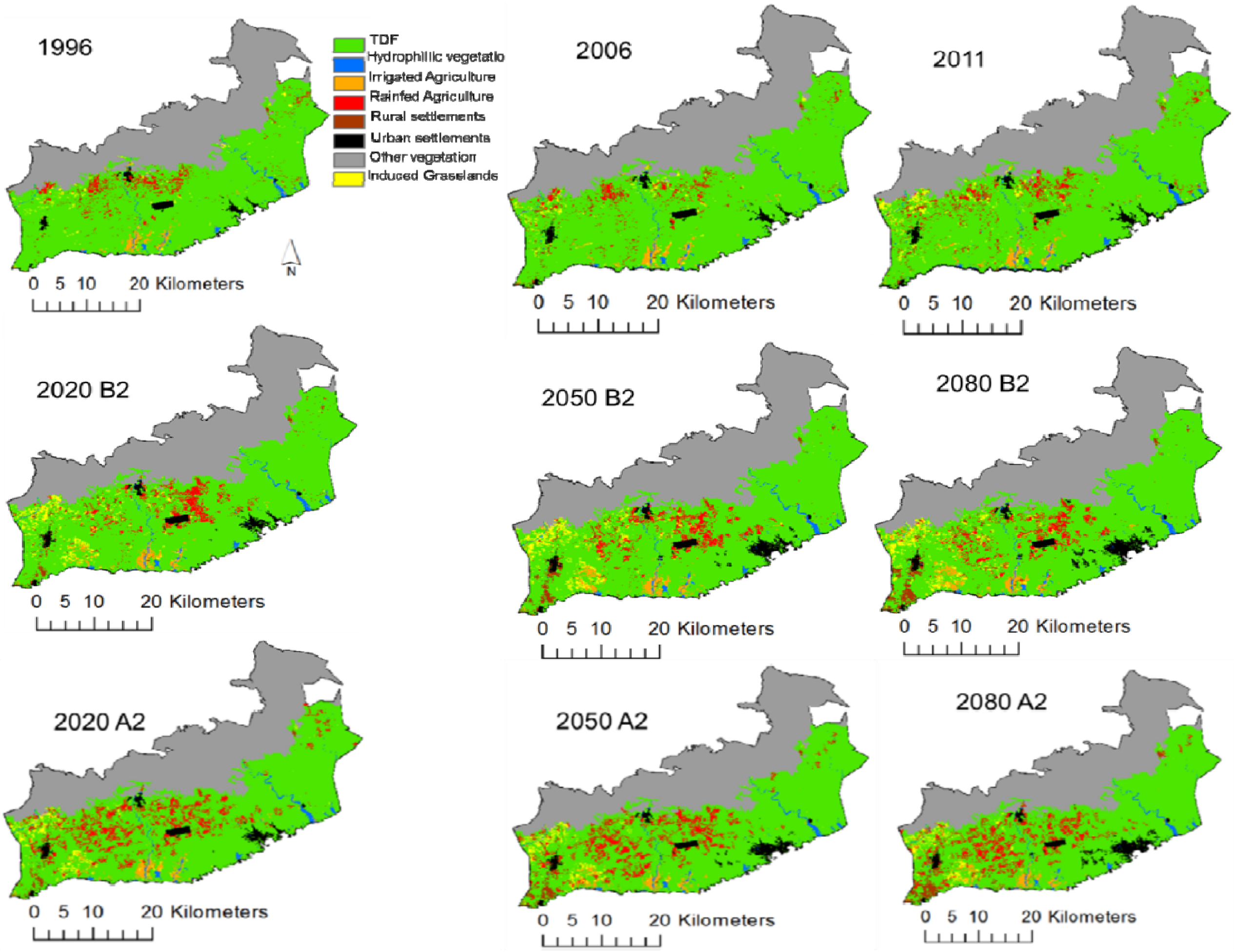

Figure 39. LUCC maps under different CC and socio-economic scenarios.

6.3.4 Identifying the Endemic and Threatened Species of Vertebrates under different Socio-Economic and CC Scenarios for the Region

There were 31 species of vertebrates under some status of threat (including data deficient) in the region of study. It is important to notice that 33% of the species of mammals, 22% of birds, 44% of reptiles and 67% of the amphibians are endemic (Figure 40). Endemic and endangered species of mammals such as *Sigmodon planifrons*, *Peromyscus melanurus* and endemic and vulnerable species *Spilogale pygmaea* are distributed in the region. Regarding the birds two species were endemic and threatened: *Cyrtonyx sallei* and *Cyanolyca mirabilis.* Four species of endemic reptiles with deficient data were matched in the region: *Geophis sallaei*, *Lepidophyma lineri*, *Micrurus bogerti*, *Tantilla oaxacae*. Finally, five species of endemic and threatened amphibians are in this region. These species are related to hydrophilic vegetation by the rivers: *Megastomatohyla pellita*, *Eleutherodactylus syristes*, *Exerodonta melanoma* and *Exerodonta juanitae*. However, one species is characterised as TDF fauna - *Dermophis Oaxacae* - and the other four are representative of the hydrophilic vegetation.

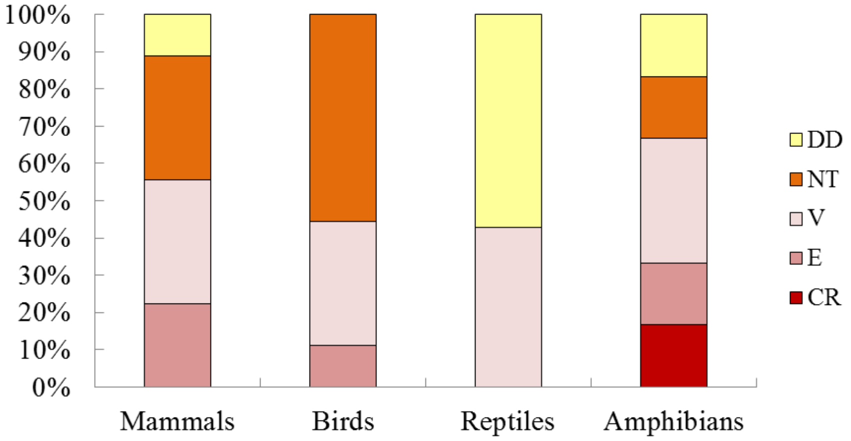

Figure 40. Distribution of threatened vertebrates, including endemic and non-endemic in the region. DD = Data Deficient; NT = Near Threatened; V = Vulnerable; E = Endangered and CR = Critically Endangered.

6.4 Discussion

6.4.1 LUCC Dynamics over the Periods 1996-2006 and 2006-2011

According to the results of Chapter 4, the national deforestation rate for the TDF during the period 1993-2002 was 0.43% yr^{-1}, and for 2002-2007 it was 0.53% yr^{-1}. This region of TDF shows a smaller rate of deforestation during the period 2006 to 2011 (0.47% yr^{-1}). However, differences among municipalities reveal that S. M. del Puerto and S.M. Huatulco show lower deforestation rates than the national estimates for 2006-2011 (0.16% yr^{-1} and 0.40% yr^{-1}) while S.P. Pochutla presents a higher rate than the national (0.81% yr^{-1}). Nevertheless, if the period 1996-2011 is taken, S. M. del Puerto shows a regrowth of TDF (0.81% yr^{-1}) while S.M.Huatulco and S.Pochutla have deforestation rates of 0.05% and 0.42%, respectively. Although there are no other studies for the region in the same period, there is information by the period 1985-2006 in which a similar deforestation rate is reported (0.44% yr^{-1}) (Corona, 2012); while other studies estimate TDF deforestation rates at state level of 0.35% for Oaxaca for the period 1993-2002 (Velázquez *et al.*, 2003). Differences in rates have intrinsically the errors in the inputs and the uncertainty of the models. In this context, further studies by comparing finer resolution with the national maps trying to identify the limitations of the resolution of the national inputs is advised through the different scenarios to evaluate the errors and uncertainties in representing landscapes and their modelling (Dendoncker et al., 2008) to look at the over or underestimation of the different land uses or covers trying to incorporate these differences to the uncertainty of the outputs (Schmit *et al.*, 2006).

RfA and grasslands covers are the principal direct causes for TDF loss in the region. RfA is related to subsistence and small production through slash and burn activities in Mexican TDF along the Pacific coast (Maass *et al.*, 2005). Mexican family farmers use 70% of their total land for the production of maize, and 60% for beans (Altieri, 2009; Altieri and Toledo, 2011). In different Mexican regions RfA has been documented as giving way to other more profitable covers such as grasslands for livestock (Corona, 2012; Díaz-Caravantes *et al.*, 2014). Consequently, natural vegetation continues to decrease, especially in areas where grasslands for livestock are increasing (Bonilla-Moheno *et al.*, 2013). Competition between forms of LUCC has a great role at all levels (Lambin and Meyfroidt, 2011); in the region studied, as well as RfA and grasslands, IA and tourism related to urban areas also have an impact.

LUCC performed differently in each municipality. S.P.Pochutla, which has the largest population, showed great heterogeneity in the LUCC dynamics based on economic activities (agriculture, rural settlements, cattle-raising and tourism). Small scale tourism impacts the south of the municipality while rural establishments, RfA and grasslands share effects on the north. Diversely, S.M. Huatulco is characterised more by its tourism in comparison to agricultural or ranching activities (SEMARNAT, 2003). Touristic projects were developed in Huatulco in the 1980s (FONATUR, 1984) while the establishment of the NPA was in 1998 (DOF, 1998). The touristic projects contemplate the conservation of the TDF which was an attraction of the region. Consequently, tourism and NPA share the south of the municipality, constraining agriculture to the north. Finally, the LUCC dynamic in S.M. del Puerto responds differentially, because it does not have touristic development or any other activity different to its primary sector. Therefore, people move to work in the touristic area of S.M. Huatulco. Nevertheless, the population is less than in the other two municipalities (< 20%); the area covered by RfA is only 1% less than in S.M. Huatulco. This can be related to the productivity of maize and bean yields which in S.M. del Puerto was lower (828 and 663 kg ha^{-1}, respectively) than in S.M. Huatulco (1,527 and 726 kg ha^{-1}), and S.P. Pochutla (1,160 and 803 kg ha^{-1}) (INEGI, 2009a). This could be a result of the improvements in techniques in the other two municipalities which produce higher incomes, but also due to the effects of very high social marginalisation in S. M. del Puerto.

IA is more intensive in S.M.Huatulco, because it is the municipality which has more incomes to support it. This kind of intensive agriculture makes use of heavy machinery, irrigation and fertilization (De Ita-Martínez, 1983). IA occupies ~1.5% of the region, but >85% of it is in this municipality. Due to the high profitability of irrigated agriculture which is characterised by large extensions of land (Fuentes and Coll, 1980) it shares the south of the municipality with the touristic areas in places with light slopes close to rivers and areas of high humidity.

6.4.2 Consequences and Challenges of Future LUCC under different CC and Socio-Economic Scenarios

The complexity of the interactions between different drivers needs the use of scenario studies using models of LUCC, to effectively analyse the consequences of particular trends and policies (Smith *et al.*, 2010). Effects of socio-economic and CC variables under different scenarios on LUCC trajectories show that the increasing population will cause an expansion of the anthropogenic covers, especially RfA and grasslands. RfA areas in Mexico account for 14 million hectares where around 23 million people live and are located in places where there is little climatic information or are ungauged at all (Arreguín *et al.*, 2011). RfA will face not only the necessity of increasing its yield to sustain the increasing population, but will also face climate constraint on its suitability and competition with other more profitable uses and covers. On the Pacific coast the most conspicuous feature of the climate is the strong seasonality in the precipitation pattern, which restricts the length of the productive season (Maass *et al.*, 2005). TDF seems to be resilient in the face of disturbances associated with cyclones and droughts (Durán *et al.*, 2002; Segura *et al.*, 2002). However, RfA is reported to be very affected in dry areas by CC (Sánchez-Cohen *et al.*, 2009), especially beans that are a temperature-sensitive crop due to their longer season, and maize that is susceptible to water stress and droughts (Gourdji *et al.*, 2015). These details are very relevant considering that Mexico will face a problem of scarcity of water and that agriculture consumes most of Mexico's water reserves (77%) (CONAGUA, 2009), which in turn might increase deforestation rates. The issue of water scarcity is highlighted here, taking into account that 80% of Mexican agriculture is principally developed during the spring-summer cycle (Conde *et al.*, 2004; Conde *et al.*, 2006) and that most rainfall occurs between June and October, compared with the rest of the year which is characterized by a dry season that forces peasants and agribusinesses to use water from dams, rivers and aquifers (Palacios and Mejía, 2011).

Besides, agricultural productivity could be doubled with the current available infrastructure (Palacios and Mejía, 2011). This technology has not been accessible to most users in the agricultural sector such as in S.M. del Puerto and S.P. Pochutla and, to a lesser extent, in S.M. Huatulco. Consequently, the increasing population and the greater demand for resources such as food will cause a greater transformation of TDF into agricultural and pastoral fields to maximize crops and cattle goods, and will involve trade-offs for water supplies between the different land uses and covers (Maass *et al.*, 2005).

Trends in IA have remained constant for the past two decades due to agricultural districts being reduced while small irrigated areas have increased (CONAGUA, 2009), with only minor variations caused by weather conditions (dry years) (Palacios and Mejía, 2011). Under CC scenarios and the scarcity of water the option of the IA could be the implementation of better technology in the region to utilise water resources better. It could do this to increase the production of crops, but also to maintain soil fertility, trying to fill the gaps between delivery and demand for ecosystem services (Maass *et al.*, 2005). That should include the integration of sustainable agriculture (such as organic coffee) but also activities as eco-touristic projects managed by local people, instead of state-planned resorts such as Huatulco Bay (Brenner, 2005), bearing in mind that the local population receives only marginal benefits from tourism (Brenner and Aguilar, 2002). It should be considered that other possibilities such as commercial forestry are not suitable within the TDF (Segura *et al.*, 2002) and that the lack of integration of local people in sustainable activities only leads to failure as has been reported in other regions of the Mexican Pacific coast (Castillo *et al.*, 2005). Thus, the incorporation of social information under different scenarios joined to ecological research could contribute dramatically to meeting the challenges of Mexican TDF transformation (Sánchez-Azofeifa *et al.*, 2005).

6.4.3 Implications for Conservation Planning for Endemic and Threatened Vertebrates Species under different CC and Socio-Economic Scenarios

Mexican TDF harbours a high number of endemic species of vertebrates (~31%) (Ceballos and Rodríguez, 1993; Escalante *et al.*, 1993; Flores-Villela, 1993). The highest percentage by groups are amphibians (79%), mammals (75%), birds (68%) and reptiles (64%) (Ceballos and García, 1995). In this study, amphibians showed the highest endemicity (67%), followed by reptiles (44%), mammals (33%) and birds (22%). Although there is no precise information at national level, it is known that between 47 to 60 species of vertebrates (Ceballos and García, 1995) (Chapter 5) are at risk of global extinction in the TDF, and many more are becoming locally extinct due to LUCC, subsistence hunting and illegal trade.

It has been reported that the distribution of many Mexican endangered species does not coincide with areas of high species richness, and that conservation strategies should therefore be addressed to areas of high concentration of endangered and endemic species with restricted distribution (Ceballos *et al.*, 1998). In this study endemic amphibians (especially *Dermophis oaxacae*) were the most endangered group, followed by reptiles, mammals and birds. This is relevant considering that amphibians are intrinsically related to restricted riparian zones closer to rivers where the IA and grasslands are expanding. Regarding endemic reptiles and mammals, distribution is located in the north of the municipalities where the expansion of RfA and grasslands is found and they are not represented in the NPA. This matters since TDF is the most underrepresented ecosystem in Mexico's conservation policies (CONABIO *et al.*, 2007b).

In this context, conservation of different patches from the south of the municipalities close to the beaches and the NPA through the north should be promoted by creating corridors adjacent to the riparian vegetation. This is on the basis that endemic and endangered vertebrates of this study are shown to be distributed in the gradient formed by TF, HV, and TDF. Consequently, the creation of corridors for small vertebrates such as the endemic and endangered species of this study could be promoted by creating buffer zones connecting areas of TDF and HV which constrain the agricultural borders. This strategy could in turn promote the ability of the RfA and the biodiversity to cope with drier conditions projected by CC by creating microclimates and maintaining microhabitats for them.

6.4.4 Study limitations and challenges

As in the development of the national model there are problems related to the accuracy of national maps associated with the availability of information. Despite these limitations this is the first attempt to depict a general diagnosis concerning possible future scenarios under changing conditions, including socio-economic, climatic and biodiversity variables. This approach allows the prioritisation of specific strategies inside regions that will become more vulnerable to two of the most important threats to biodiversity, LUCC and CC, by integrating prospective scenarios under different assumptions. As a result, municipalities could direct resources and effort at biodiversity conservation by using endemic and threatened vertebrates as surrogate species.

Despite the advantages of the vulnerability approach, this study faced drawbacks because of the lack of socio-economic information at municipality and locality level, which was overcome by creating demographic projections (Chapter 3). However, it is worth noticing that qualitative and quantitative data about biodiversity and social dynamic would help to understand better the LUCC process. These drawbacks need to be overcome by elaborating accurate local socio-economic and biodiversity surveys. On one hand, it is necessary to have accurate information about local land tenure, the economic activities of families, their incomes, and the problems that agriculture faces such as in performance, necessities and demands. On the other hand, developing local biodiversity monitoring is mandatory in order to know what species exist, what condition the species population is in, and what environmental constraints and requirements it faces, especially endemic and endangered species. This information will allow the estimation of sensitivity, exposure and adaptive capacity of the local socio-ecological systems which in turn could improve the analyses, modelling and projection of scenarios under different conditions.

6.5 Conclusions

This study presents a novel approach to developing the vulnerability framework to LUCC and CC under different socio-economic and CC scenarios at regional level in three contrasting municipalities in Oaxaca, Mexico, by 2020, 2050 and 2080. Modelling LUCC and their projections allows the conclusion that RfA is the principal direct force of change in the region. This anthropogenic cover will face many constraints under CC scenarios due to the future dryer conditions for these ecosystems. These future limitations might be addressed to increasing deforestation rates which in turn affect biodiversity. The most vulnerable group of endemic vertebrates in the region is amphibians, followed by reptiles, mammals and birds. The creation of corridors, extending from between patches for small vertebrates close to the hydrophilic vegetation south of the municipalities, up close to the NPA in the north, could be a successful strategy to conserve the endemic and endangered vertebrates of the region.

Chapter 7. General discussion and conclusion

7.1 Vulnerability and prioritisation

The principal aim of this thesis is to show and apply a methodology for mapping the hotspots of vulnerability to LUCC under different CC scenarios and to analyse their impacts on biodiversity in Mexico. Chapter 3 offers an approach to project demographic and economic drivers that can be used as inputs for modelling LUCC. These projections help to understand future human pressure on ecosystems and biodiversity, and to develop policies to mitigate its impacts. The methodology used in chapter 3 overcomes the limitations that many developing countries have, regarding the availability of spatially disaggregated demographic and economic data. The present framework also allows stakeholders to explore and analyse through the vulnerability maps how many people will face the highest exposure to the principal threats of GEC. Furthermore, the maps were developed to represent their spatial distribution across Mexico in the finest resolution ever reported. This methodology could be applied to other developing countries by using available information to prioritise places and to improve strategies to enforce resilience and mitigation strategies where changes will be more severe.

The principal results of this study show that by 2020, ~24% of Mexico's might face medium vulnerability, for each scenario while 10% of the country might be in the categories of high, very high and extremely high vulnerability. By 2080, ~30% of Mexico shows medium vulnerability while 15% of the country is likely to be in the highest vulnerability values (>70). The most vulnerable places are distributed in six different areas: 1) the western coast state of Sonora; 2) the southern areas of the Pacific coast; 3) the northern part of the state of Chihuahua; 4) the regional border between the states of Tamaulipas and Nuevo León; 5) the central regions of the Volcanic Belt; and 6) the Sierra Madre del Sur and the Highlands of Chiapas.

The results indicate that the north of Mexico (areas 1 to 5) will face great changes in terms of both LUCC and CC, principally enforcing the process of LUCC by the increase of aridity. These effects will occur in semi-arid and sub-humid dry areas such as the Sierra Madre Occidental rather than in the hyper-arid or arid zones. For instance, Saenz- Romero et al. (2010) reported that there will be an expansion of arid regions under the A2 scenario, especially in north-central México. These new arid conditions will expand toward both coasts and the southeast by 2090 and may extend to the Sonoran desert, the Sierra Madre Occidental and the Neo-volcanic axis (Sáenz-Romero *et al.*, 2010). The results of this study suggest that scrublands and xeric vegetation will expand their current distribution in the north due to changes in aridity conditions and abandonment of agricultural lands as has been reported by Bonilla-Moheno (2011). These results are supported by other studies (Trejo *et al.*, 2011) that describe drier conditions under A2 and B2 scenarios in the north of Mexico. This is relevant because arid regions are more prone to be affected by droughts and might experience more severe impact because of the extreme conditions (Seager *et al.*, 2009; Maliva and Missimer, 2012) which in turn could reinforce the processes of LUCC.

Temperate forests, natural grasslands and tropical evergreen forests will be the most affected land covers by LUCC in A2 and B2 scenarios. Variation of aridity and evapotranspiration could have effects on the movements of the ecotones between the tropical dry forests and temperate forests (Sáenz-Romero *et al.*, 2010). Regarding biodiversity the effects may impact the distribution of biological groups which have been shown to be differentially resistant to dryer and warmer conditions such as species of conifers (especially pines) and oaks (Sáenz-Romero *et al.*, 2006; Gómez-Mendoza and Arriaga, 2007; Gómez-Mendoza and Galicia, 2010).

Regarding biodiversity of vertebrates, Mexico ranks second for the biodiversity of reptiles (Flores-Villela and Canseco-Márquez, 2004). The results show that 164 endemic species of reptiles (~17%) are in some category of threat. Moreover, >25% of the endemic and endangered Mexican reptiles are located in medium to extremely high vulnerability places. Endemic and endangered species are principally distributed in TF (~62%), followed by TDF (~23%), S (~15%), and TEF (~14%). By 2020, more than 50% of Mexican reptiles may be in places of high vulnerability while 4% may face, respectively, critically high vulnerability. By 2080, more than 49-52% of continental Mexican reptiles might be reported to be in high vulnerability, while 27% might be in areas of very high vulnerability. In terms of the differences between scenarios there is not significate distinction about the effectiveness of the expansion of the NPAs for the reptiles, because of that it can be suggested that the creation of new NPAs could be more useful for these vertebrates, especially in TF.

Mexico ranks as the fifth richest country in amphibian diversity (Flores-Villela, 1993; Parra-Olea *et al.*, 2014a). By 2020, >50% will be distributed in very high vulnerability, and 16% in critically high vulnerability (100) according to the A2 scenario. By 2080, ~60% of the amphibians might be living in very extremely high vulnerability areas (90) while 22% or 53% of them remain in critically high vulnerability areas (100), depending on the scenario. It is to notice that the expansion of NPAs could avoid that 30% of the amphibians face the highest vulnerability. Consequently, expansion in NPAs for these vertebrates, especially in TF could be a useful solution for biodiversity conservation, considering that ~54% of amphibians are CE and E, mainly distributed in TF ecosystems.

Mexico is the third richest country in mammals (Llorente-Bousquets and Ocegueda, 2008a), and more than 30% are endemic (Sánchez-Cordero *et al.*, 2014). In this study it was found that by 2020, >70% of Mexican mammals will be in very high vulnerability places while 34% or 61% will be in critically high vulnerability areas for the two scenarios. By 2080, these numbers increased to the highest vulnerable category to 47% and 64%, respectively. Moreover, 11% of the endemic mammals distributed in vulnerable places are CE and 21% E; these are distributed in TF and TDF. These results match information that highlights the biological importance of the Mexican trans-volcanic belt, western Pacific coast (Ceballos *et al.*, 1998; Ceballos and Oliva, 2005) and the Sierra Madre del Sur in the state of Chiapas (Ceballos, 2007; Vazquez *et al.*, 2009).

Mexico is the eleventh country in diversity of birds and the fourth in endemicity (Navarro-Sigüenza *et al.*, 2014b). By 2020, ~46% to 61% of Mexican birds might live in critically high vulnerability, and by 2080, the numbers remain in 47% and 61%, respectively. That shows that the expansion of NPAs does not have an effect in the species of birds and that the creation of new NPAs and connectivity between them could be more useful as in the reptiles. Considering, the categories of threat of the endemic birds it is suggested that TF and TDF should be privileged in terms of bird conservation.

The local study of the three municipalities in Oaxaca (chapter 6) that was identified as one of the most vulnerable and biodiverse sites in Mexico is represented by TDF. The principal direct causes of LUCC were RfA and grasslands for livestock. RfA will not only face the necessity of expanding to sustain the increasing population, but will also face climate constraint on yield production for its suitability and competition with other more profitable land uses and covers. In terms of CC, TDF seems to be resilient to disturbances associated with cyclones and droughts (Durán *et al.*, 2002; Segura *et al.*, 2002); inversely, RfA has been reported to be very affected in dry areas (Sánchez-Cohen *et al.*, 2009). Consequently, RfA is prone to be very vulnerable considering that Mexico is facing a problem of scarcity of water and that agriculture consumes most of Mexico's water reserves (77%) (CONAGUA, 2009).

Agricultural technology for improving the use of water has not been accessible to most users in the agricultural sector (Palacios and Mejía, 2011) which in turn has an effect on crop production. As a result, the increasing population and the greater demand for resources will increase the transformation of TDF into agricultural and pastoral fields to maximize crops and cattle goods. This will involve trade-offs for water supply between the different land uses and covers (Maass *et al.*, 2005).

Applications of technology to overcome the scarcity of water as a tool for irrigated agriculture could not only increase crop productivity but could also maintain soil fertility trying to fill the gaps between delivery and demand for ecosystem services (Maass *et al.*, 2005). That should include the integration of sustainable agriculture (such as organic coffee) and other activities such as eco-touristic projects managed by local people, instead of state-planned resorts such as Huatulco Bay (Brenner, 2005). These luxurious resorts provide the local population only marginal benefits from tourism (Brenner and Aguilar, 2002), addressing the failure as in other regions of the Mexican Pacific Coast (Castillo *et al.*, 2005). In this context incorporation of social information under different scenarios joined to ecological research could contribute dramatically to facing the challenges of Mexican TDF transformation (Sánchez-Azofeifa *et al.*, 2005).

At the local level, the results show that endemic amphibians were the most endangered group, followed by reptiles, mammals and birds. This is relevant considering that amphibians are intrinsically related to restricted riparian zones closer to rivers where irrigated agriculture and grasslands are expanding. Regarding the endemic reptiles and mammals, the distribution is located in the north of the municipalities where the current and future expansions of RfA and grasslands are found and are not represented in the NPA. In this context, conservation of different patches from the south of the municipalities close to the beaches, and the NPA through the north should be promoted by creating corridors adjacent to the riparian vegetation. This is on the basis that endemic and endangered vertebrates in this study have been shown to be distributed in the gradient formed by TF, HV, and TDF. Consequently, the creation of corridors for small vertebrates such as the endemic and endangered species in this study could be promoted by creating buffer zones connecting areas of TDF and HV, which constrain the agricultural borders. This strategy could promote the ability of the RfA and biodiversity to cope with drier conditions under CC scenarios by creating microclimates and maintaining the microhabitats for them.

7.2 Limitations and uncertainties of this study

This study is one of the first to attempt to integrate two of the most important causes of biodiversity loss (LUCC and CC) in a megadiverse and developing country. This research integrates socio-economic and biophysical variables on multiple spatial and temporal scales, and by using different socio-economic and climatic scenarios to explore diverse pathways of LUCC. However, this integration of variables at national level cannot fully capture the heterogeneity of social and biophysical features of the country. The ability of communities, regions or sectors to cope with vulnerability to threats differs from one region to another. For instance, to model exposure, or adaptive capacity to LUCC at national level, it was necessary to generalise the weight of drivers, blurring the regional variations. Moreover, relationships among local agents, corruption, and the effects of drugs and violence cannot be easily incorporated into LUCC models, especially at national level (Durán *et al.*, 2011). These elements could be integrated in the same policies of scenarios; however, the arbitrary choices of the experts could affect the outputs of the model. Consequently, this lack of data limits the interactions that can be modelled by making the results from the top-down vulnerability framework only useful for a narrow selection of stakeholders or land-use planning policies, interested in multi and interdisciplinary questions in Mexico.

In addition to the lack of data, there are inevitably limitations to any approach that tries to synthesise and simplify the complexity of global change impacts (Metzger *et al.*, 2006). These limitations relate to the quality and availability of information in various terms: ecological or social variables at different temporal and spatial scales or resolutions, simplifications and temporal and spatial assumptions, inevitable arbitrary choices, and uncertainties about future change. Issues regarding modelling of future changes include problems of the subjective nature of qualitative interpretations, the assumptions related to unfolding scenarios and the problem of validating future changes such as LUCC models and drivers (Rounsevell *et al.*, 2006). Different drawbacks can be pointed out in the case of long-term LUCC modelling at the national level. Variables include social, economic, political and ecological components and their inter-relationships. The integration could be thought of as simplistic and reductionist on the basis that a complex system can unfold in a plethora of ways that cannot include all the components. However, there are approaches to modelling, involving different kinds of variable in dynamic systems that help to visualise some possible futures on the basis of reliable past information (Young *et al.*, 1996).

Developing models, especially at the global or national level, necessarily involves a simplification of the heterogeneity of the system. For example, national studies are focused on identifying regions that qualify as hot spots of LUCC. Nevertheless, once these hot-spots are identified a more detailed LUCC analysis is often needed at the regional or local level (Verburg *et al.*, 2002). Consequently, the coarse resolution studies are complementary to local studies where a finer understanding of local actors is needed to achieve the implementation of conservation strategies.

Reduction of uncertainty will increase the usefulness of the vulnerability framework. This will happen when more reliable climate scenarios or more accurate census data and biodiversity information become available, or when the ecosystems models can provide more complex and relevant indicators. In addition, it may be possible to improve the sensitivity and adaptive capacity indices. Nevertheless, it is unlikely that the limitations listed above can be reduced because much of the uncertainty is inherent in the complexity of the human-environment system.

There are also uncertainties attached to any long-term exploration of the future. This is true especially when the available data for calibrating the models is very limited (<20 years). Moreover, the integration for global environmental change impacts, which are caused by complex interactions between demographic, political and economic development under different biophysical processes that can change through the time. Besides, the vulnerability framework presented in this study has been adapted to prioritise areas for biodiversity conservation under future scenarios of global environmental change. However, there is an intuitive factor behind the use of elements such as the definition of the adaptive capacity as the ratio between the loss of natural covers and the extent of natural protected areas (Hoekstra *et al.*, 2005) and the integration of the assumption of the NPAs expansion following the Aichi targets tom 2020 and increasing the targets to the long-term. These assumptions can be only true when the information is evaluated on a regional scale by using specific boundaries such as municipalities or states. But, in a local context, this approach cannot be implemented, because of the lack of information to quantify the adaptive capacity at the local scale. Consequently, in a local context this approach fails to incorporate local knowledge and information such as differences in land tenure or land management.

The multilevel approach followed in this study was able to produce outputs for different target groups. For example, the identification of vulnerable municipalities can help target national or state policies, while NGOs and conservation scientists may be especially interested in endemic and threatened species. Also, environmental agencies may wish to take a regional approach when considering ecosystem services provision, taking into account the commitment that countries have to extend their coverage of protected areas (CBD, 2010). Nevertheless, it remains difficult to know how this could impact on the regions and the stakeholders.

7.3 Recommendations

This study points out some suggestions from different angles. To start there is a need to improve information about socio-economic projections, especially at municipal and local levels. There is high uncertainty on data collection and its projections; therefore, it is difficult to include these factors as drivers of change. For example, to develop future socio-economic projections on different scales and the contextualization of scenarios it is necessary that countries provide information about two general factors: 1) Different demographic components such as fertility, migration and mortality at municipality and locality levels, and 2) economic data such as GDP and incomes should differentiate between urban centres and rural areas at the different levels. This economic information should be able to distinguish the contribution of the municipality to national GDP and by different sectors such as agriculture, industry, tourism, etc. This information is lacking in most developing countries, Mexico being unexceptional.

Moreover, countries should provide updated and finer spatial information of land uses and covers, as well as recent environmental disasters (droughts, floodings, etc). Regarding biodiversity, it is strongly recommended that biodiversity data about species' composition, population and location should be available. The integration of this information into future modelling approaches will improve understanding of the ecosystem's dynamics, including its interaction with the human components and CC, as well as the risk of local extinctions, and can help in the implementation of strategies for biological conservation and ensuring environmental services.

Another angle reinforces prioritisation analyses for different targets at different levels. At national level, the results allow the highlighting of large areas for further development of finer studies. Complementarily, local studies allow a better understanding of the internal dynamics of systems such as the diverse interests of the stakeholders and their trade-offs. This means that once a large region in a country is detected as irreplaceable and vulnerable, it would be more appropriate to direct social, scientific and economic resources to municipalities in order to coordinate the biodiversity conservation strategies from the local level.

Finally, recommendations derived from the results of this study suggest that at national level conservation planning should encourage strategies of mitigation and adaptation for temperate forest and natural grasslands, on the basis that both ecosystems have been shown to be more vulnerable to the combination and feedbacks of LUCC and CC. From an ecosystem and conservation of vertebrates perspective, strategies of monitoring and adaptation of these ecosystems are needed, especially in the Sierra Madre Occidental, followed by the region of the trans-volcanic belt. The high endemic biodiversity of these areas could offset the effects of LUCC and CC. Other regions shown to be vulnerable and highly biodiverse are the south coast of the Pacific Ocean and the southern region of the Peninsula de Yucatán. Those regions represented by TDF and TEF can be studied in more detail due to their rate of transformation and the high endemism of their biodiversity. In particular, the regional study shows that future strategies for biodiversity conservation on a finer scale should be directed at increasing the extent of NPAs and the connectivity between natural patches of vegetation surrounded by anthropogenic covers. The implementation of strategies needs to be based on an ecosystem approach, one that is based on the requirements of surrogated species as identified by field monitoring, to produce finer spatial prioritisation in several vulnerable regions.

7.4 Conclusions

Land-use/cover change (LUCC) and climate change (CC) form major threat to biodiversity globally, and this thesis has identified significant potential impacts for Mexico. LUCC, especially associated with agricultural expansion, will be the major driver of environmental impact in Mexico. This is likely also to hold true for other tropical countries facing a similar combination of social, political, and economic problems as Mexico. Environmental deterioration and biodiversity loss is caused by differences between rural and urban socio-economic conditions including well-being, marginalization, poverty, lack of land use and urban planning. Moreover, the effects of LUCC are expected to be reinforced by CC. The combined impacts of CC and LUCC on biodiversity remain uncertain, justifying the scenario approach that identifies hotspots of change under alternative futures. Insights from such analyses can be used to prioritise conservation effort, which crucial in megadiverse countries with limited economic and social resources to establish conservation strategies.

This study shows that the most vulnerable priority sites for biodiversity conservation (PSBC) to LUCC and CC are located in six different regions: 1) the western coast state of Sonora, 2) the southern areas of the Pacific Coast, 3) the northern part of Chihuahua, 4) the regional border between the states of Tamaulipas and Nuevo León, 5) the central regions of the Volcanic Belt and 6) the Sierra Madre del Sur and the Highlands of Chiapas. Further studies at finer resolutions are now required to identify region specific drivers of change and devise conservation strategies that are robust under alternative future scenarios, which can be based on the methodology presented in this thesis.

Data availability at appropriate special and temporal scales is a challenge for LUCC modelling, especially in developing countries where data quality can be limited and bring considerable uncertainty. This study presents a methodology to overcome some of these challenges by integrating available data to prioritise locations where changes are projected to be more severe. This approach is based on readily available date such socio-economic indicators as the Human Development Index, and climatic and ecological data that can be therefore be replicated elsewhere to create similar LUCC scenarios. By identifying impacts on ecosystems as well as endemic and threatened vertebrates relevant insights can be presented to a wide range of stakeholders, including academic institutions, NGOs or different levels of government as states, municipalities or localities.

There is scope for further improvements in LUCC modelling. Better data, with greater accuracy and spatial resolution will reduce uncertainty, and allow more advanced approaches that can potentially include social processes and land-use decision making, and species' ecological traits and behaviour into the modelling framework. However, such approaches are likely to be most promising and feasible at regional and local scales, as these will be the scales of operational implementation of conservation strategies. The research presented in this thesis can inform the most relevant locations for this further research.

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9 Appendixes

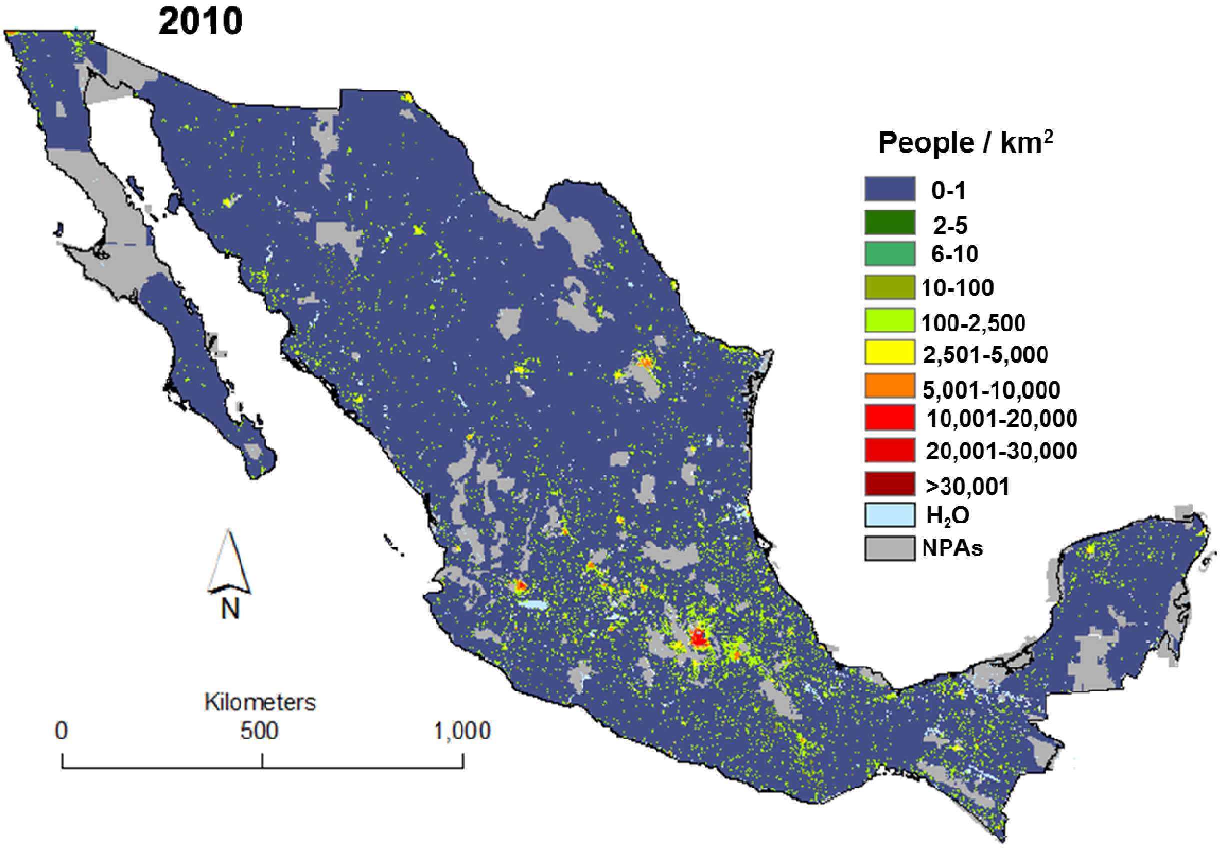
Appendix 1. IM= Index of marginalization that is based on four parameters: a) lack of education, housing conditions, rurality and incomes. Data available for 2000,2005 and 2010) (CONAPO).

Resource			Social	Level	Availability
Socio-economic	IM	1.	GDP (annual 2003-2010) (INEGI)	State	√
		2.	Population density (1990,2000,2005,2010)	Municipality	√
		3.	Economically active population (2000,2005, 2006, 2009, 2010) (INEGI)	Municipality	√
		4.	Grade of migration intensity to US (2000, 2005) (INEGI)	Municipality	√
		5.	- % of population ≤ 2 minimum wage	Municipality	√
		6.	- Localities < 5000 inhabitants	Municipality	√
Education		7.	Illiteracy rate men: women (1995, 2000, 2005) (INEGI)	Municipality	√
		8.	Professional studies ≥ 18 years old (1995, 2000, 2005)	Municipality	√
		9.	- % of population > 15 years old	Municipality	√
		10	- % of population without primary school	Municipality	√
Housing		11	- % of population without drainage	Municipality	√
		12	- % of population without electricity	Municipality	√
		13	-% of population without piped water	Municipality	√
		14	- % of population in houses overcrowding	Municipality	√
		15	-% of population in earthen floor houses	Municipality	√
Health		16	Life expectancy (2000-2007) (SINAIS)	State	√
		17	Fetal deaths (1985-2010) (INEGI)	Municipality	√
		18	Death children under one year (1995-2010) (INEGI)	Municipality	√
		19	Access to health services (1990,2000,2005) (INEGI)	Municipality	√

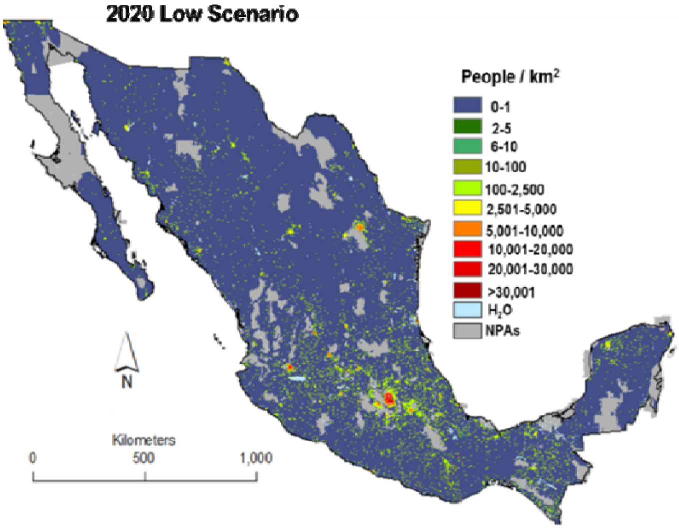
Appendix 2. UN TFR used in the deterministic method for population on the basis of rurality or urbanity of municipalities (Data were taken from **(http://www.un.org/en/development/desa/population/)**

Year	**A2 (H)**		**B2 (M)**		**A1_B1(L)**	
	Municipalities (TFR)					
	Urban (H)	Rural (H)	Urban (M)	Rural (H)	Urban (L)	Rural (M)
2010	2.4774	2.4774	2.2274	2.4774	1.9774	2.2274
2015	2.4774	2.4774	2.0724	2.4774	1.6724	2.0724
2020	2.4439	2.4439	1.9439	2.4439	1.4439	1.9439
2025	2.3417	2.3417	1.8417	2.3417	1.3417	1.8417
2030	2.2670	2.2670	1.7670	2.2670	1.2670	1.7670
2035	2.2190	2.2190	1.7190	2.2190	1.2190	1.7190
2040	2.1973	2.1973	1.6973	2.1973	1.1973	1.6973
2045	2.1972	2.1972	1.6972	2.1972	1.1972	1.6972
2050	2.2160	2.2160	1.7116	2.2160	1.2116	1.7116
2055	2.2374	2.2374	1.7334	2.2374	1.2374	1.7334
2060	2.2662	2.2662	1.7662	2.2662	1.2662	1.7662
2065	2.2978	2.2978	1.7978	2.2978	1.2978	1.7978
2070	2.3284	2.3284	1.8284	2.3284	1.3284	1.8284
2075	2.3572	2.3572	1.8572	2.3572	1.3572	1.8572
2080	2.3838	2.3838	1.8838	2.3838	1.8838	1.8838

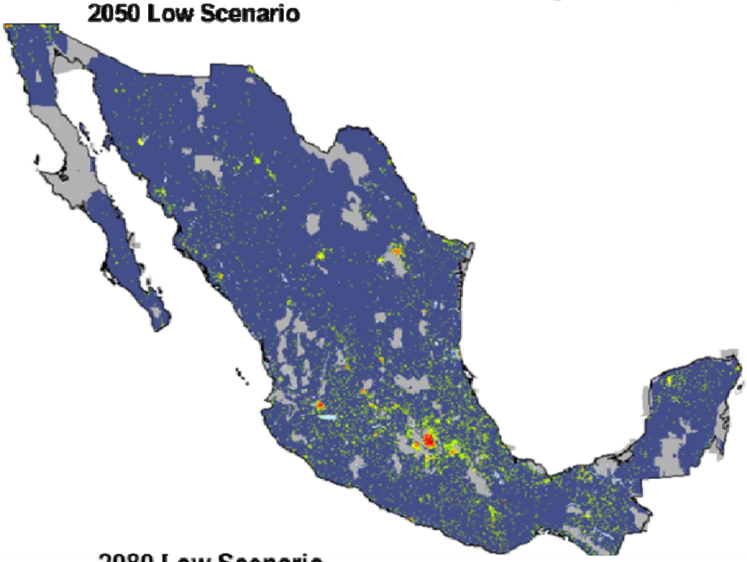
Appendix 3. Population density of the inhabited area for 2010 and 2020, 2050 and 2080 under three scenarios.



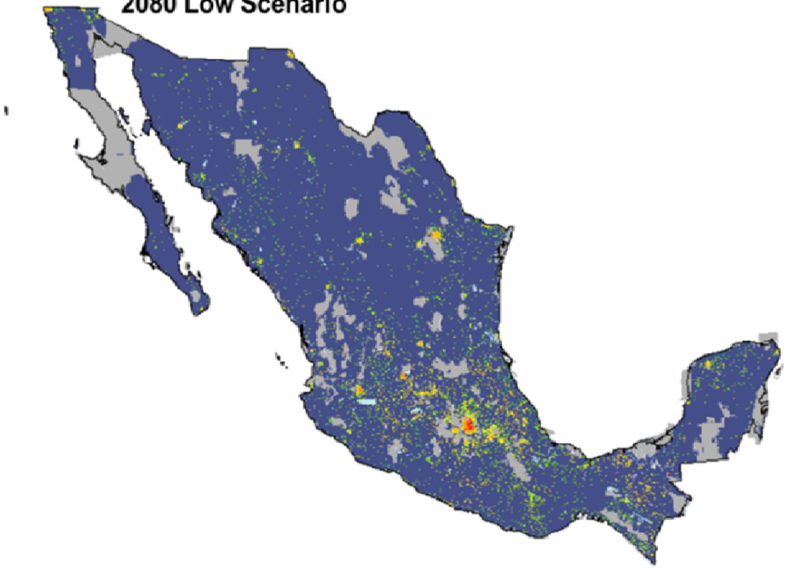
2020 Low Scenario

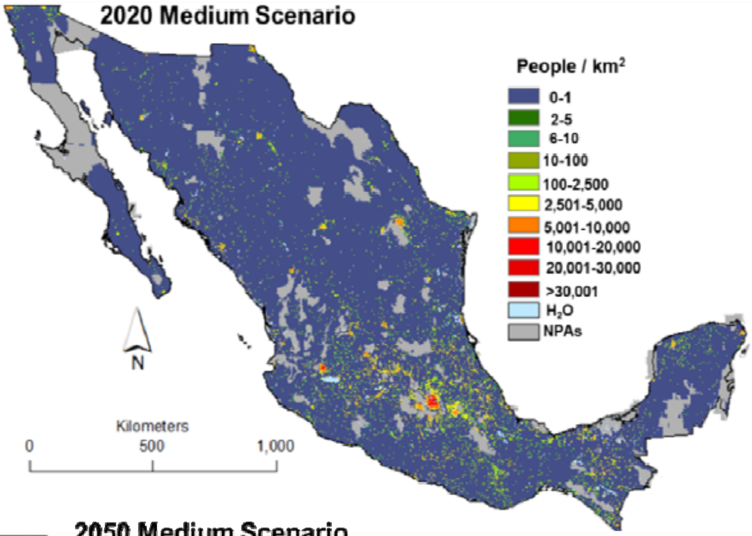


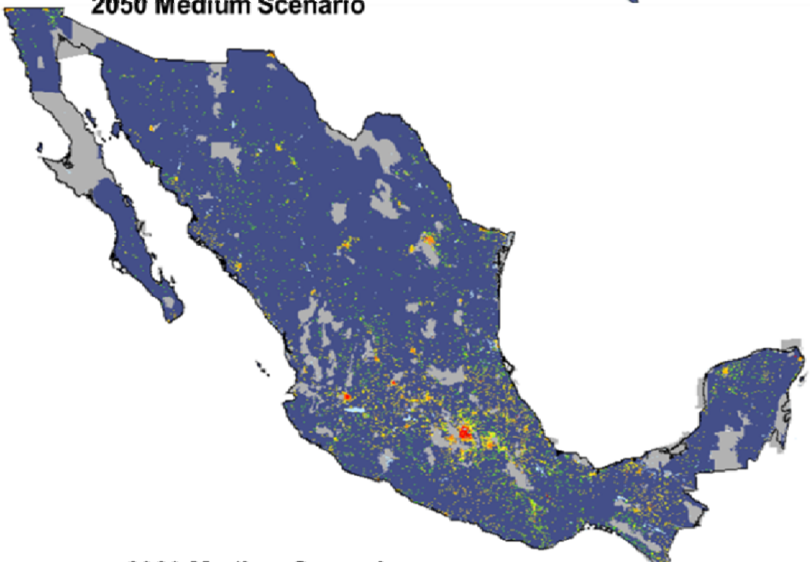
2050 Low Scenario

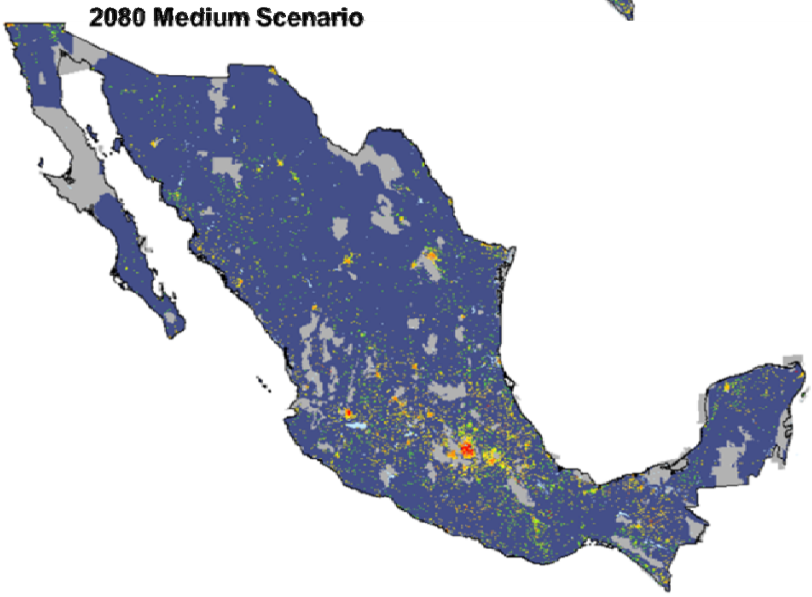


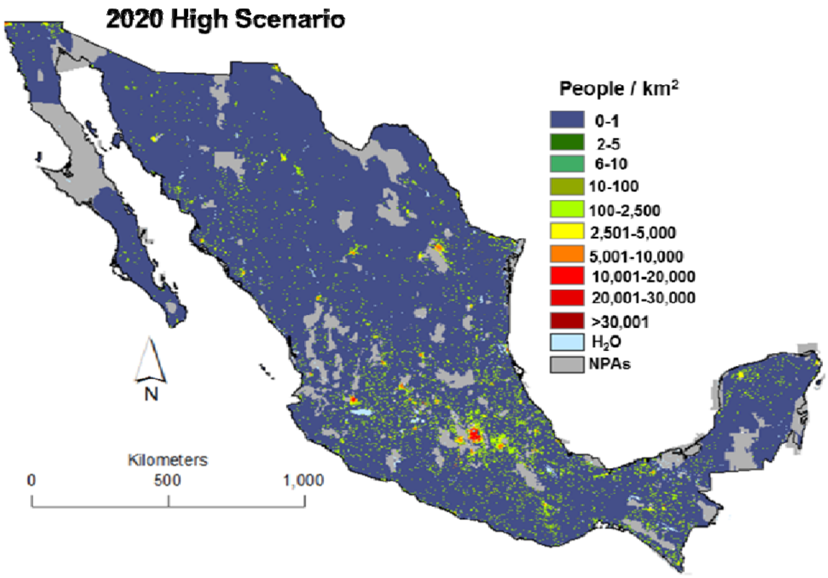
2080 Low Scenario

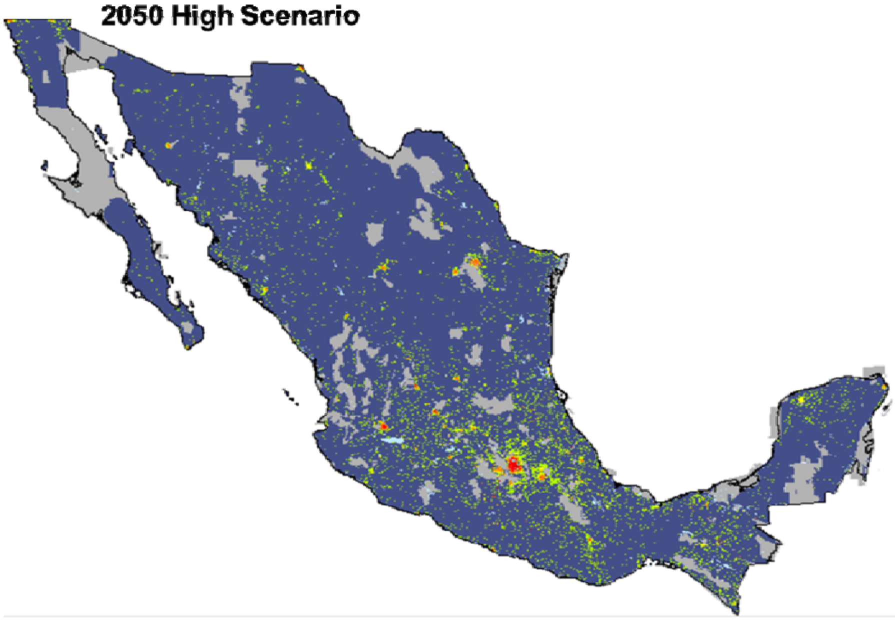


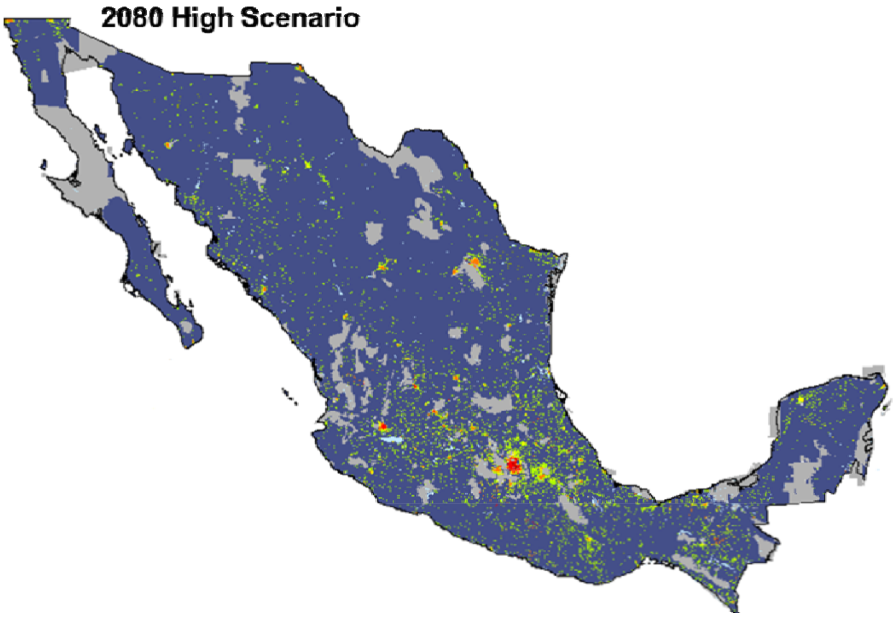

2020 Medium Scenario
People / km²
0-1
2-5
6-10
10-100
100-2,500
2,501-5,000
5,001-10,000
10,001-20,000
20,001-30,000
>30,001
H₂O
NPAs
N
Kilometers
0
500
1,000


2050 Medium Scenario


2080 Medium Scenario


2020 High Scenario
People / km²
0-1
2-5
6-10
10-100
100-2,500
2,501-5,000
5,001-10,000
10,001-20,000
20,001-30,000
>30,001
H₂O
NPAs
N
Kilometers
0
500
1,000


2050 High Scenario

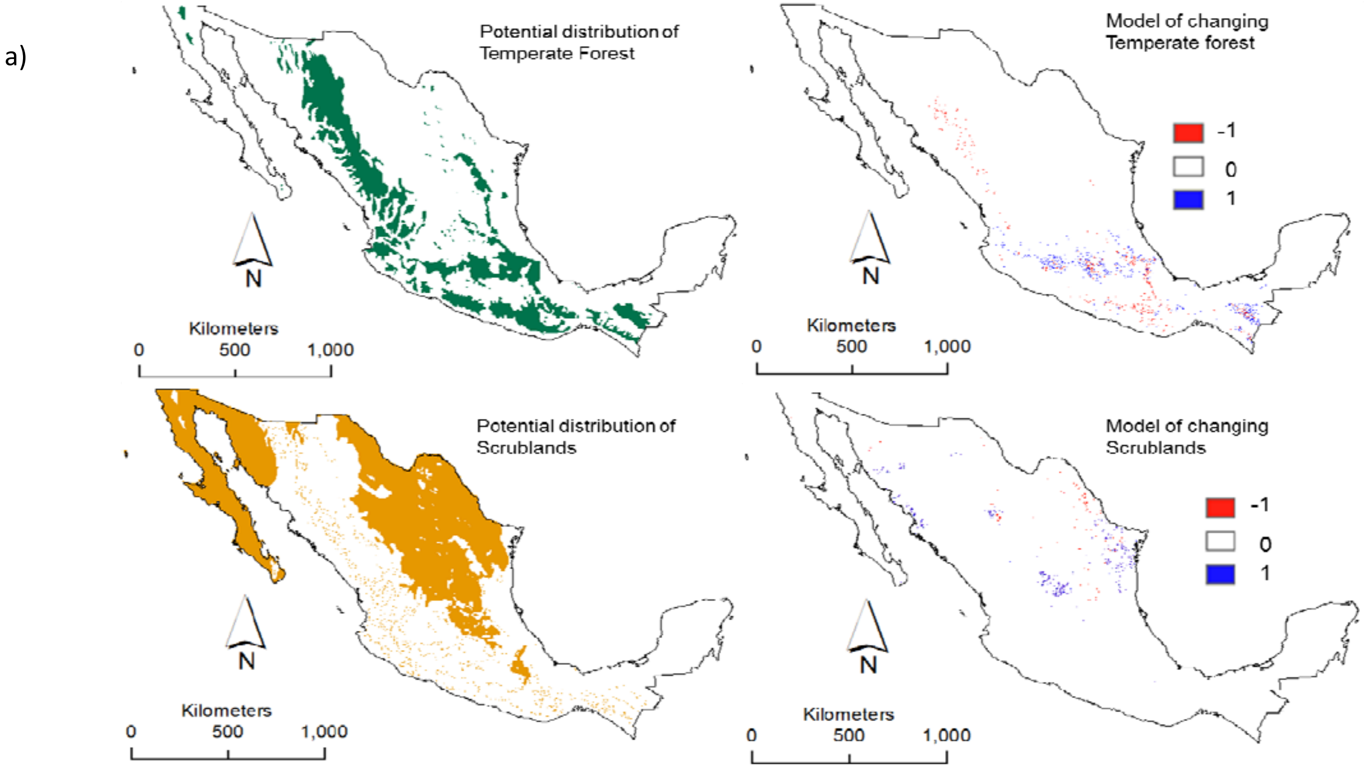

2080 High Scenario

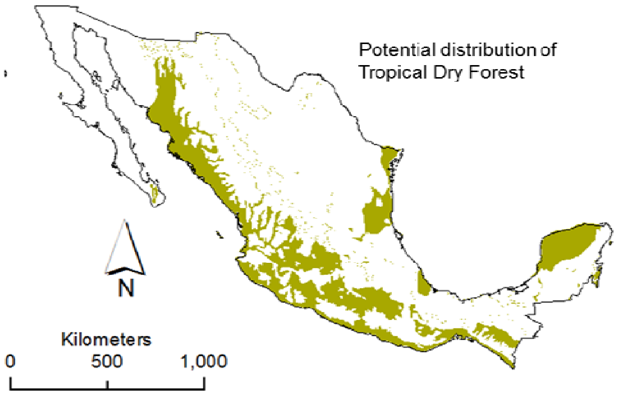
Appendix 4. Socio-economic information to update the LUCC model.

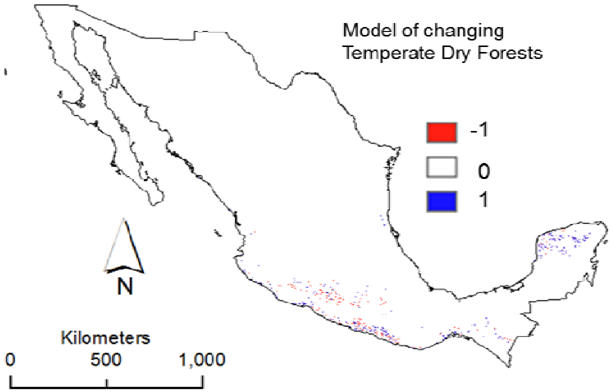
		Population (municipality)	Pop dens [1]	Pop dens [2]	GDP density*
2020 A2	Mean	53,233	66.8	72.98	6.3
	SD	151,832	400.5	609.3	6,637.9
	Min	93	0.17	0	0.01
	Max	2,135,149	20,305	81,350	6,637.9
2020 B2	Mean	52,134	65.42	71.30	6.4
	SD	149,168	391.82	602.7	70.9
	Min	93	0.1636	0	0.01
	Max	2,063,327	65.422	79,282	6,693
2050 A2	Mean	70,907	88.99	97.0	16.4
	SD	190,455	499.45	784.8	184.9
	Min	74	0.249	0	0.0
	Max	2,861,835	25430	121,341	17441.1
2050 B2	Mean	65,781	82.54	89.7	17.4
	SD	173,780	448.15	724.2	196.0
	Min	73	0.212	0	0.02
	Max	2,429,453	23,254	108,786	18489.7
2080 A2	Mean	80,197	100.65	109.3	35.6
	SD	198,244	534.52	871.2	400.4
	Min	47	0.2327	0	0.046
	Max	3,362,168	29,876	159,889	37,780
2080 B2	Mean	67818	85.10	92.1	48.2
	SD	153583	405.63	709.4	541.9
	Min	46	0.19	0	0.06
	Max	2239086	28355	125206.4	51,130.8

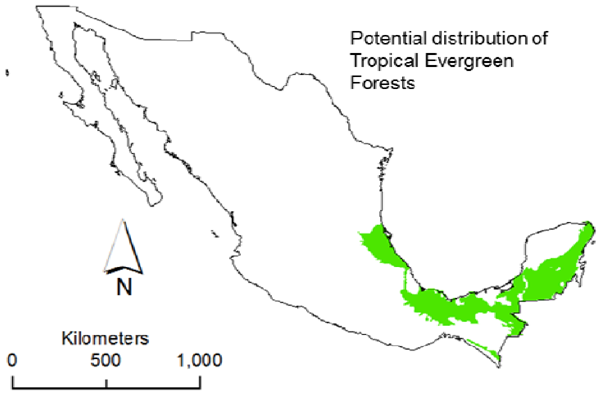
1= Population density at municipality level= Population/ municipality area; 2= Population density based on the real inhabited area (see chapter 3). GDP density= GDP/ municipality area.

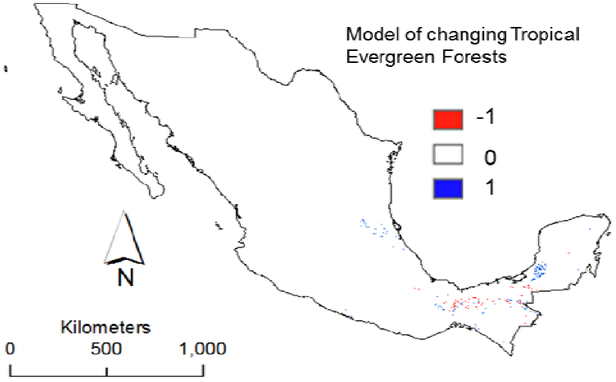
Appendix 5. a) Potential distribution of the ecosystems in Mexico (left) and the probability maps of the model (right). Values are from-1 to 1, where -1 are cells that LUCC model projected to be changed to an anthropogenic cover, but they did not change, 1 are projected cells to change to an anthropogenic cover and they did not change and zero are well projected cells. b) Graph of residuals.

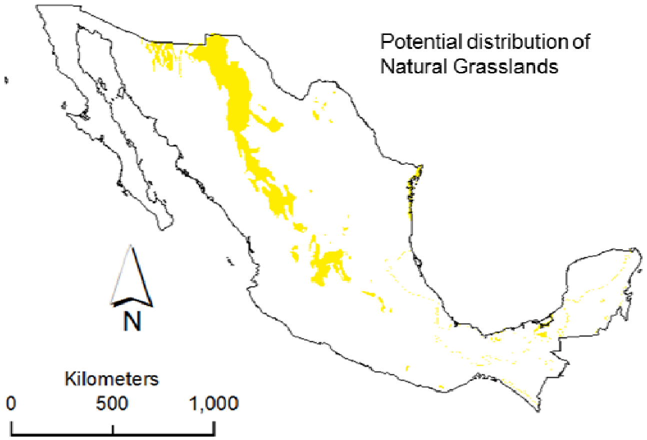


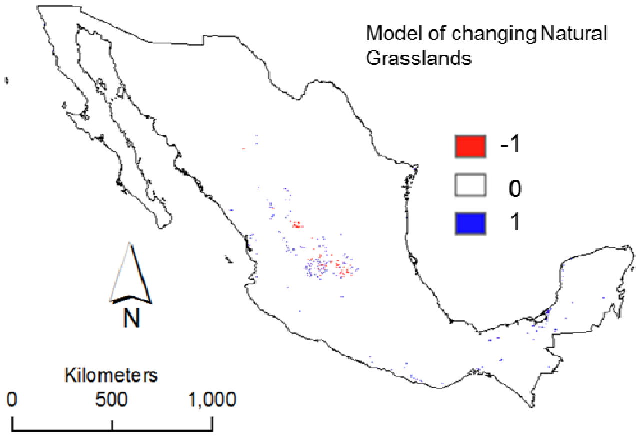

Potential distribution of Tropical Dry Forest
N
Kilometers
0
500
1,000


Model of changing Temperate Dry Forests
🟥 -1
☐ 0
🟦 1
N
Kilometers
0
500
1,000

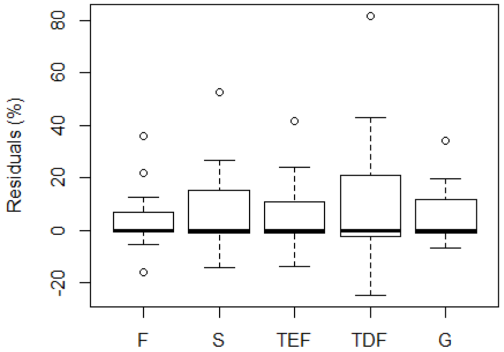

Potential distribution of Tropical Evergreen Forests
N
Kilometers
0
500
1,000


Model of changing Tropical Evergreen Forests
🟥 -1
☐ 0
🟦 1
N
Kilometers
0
500
1,000



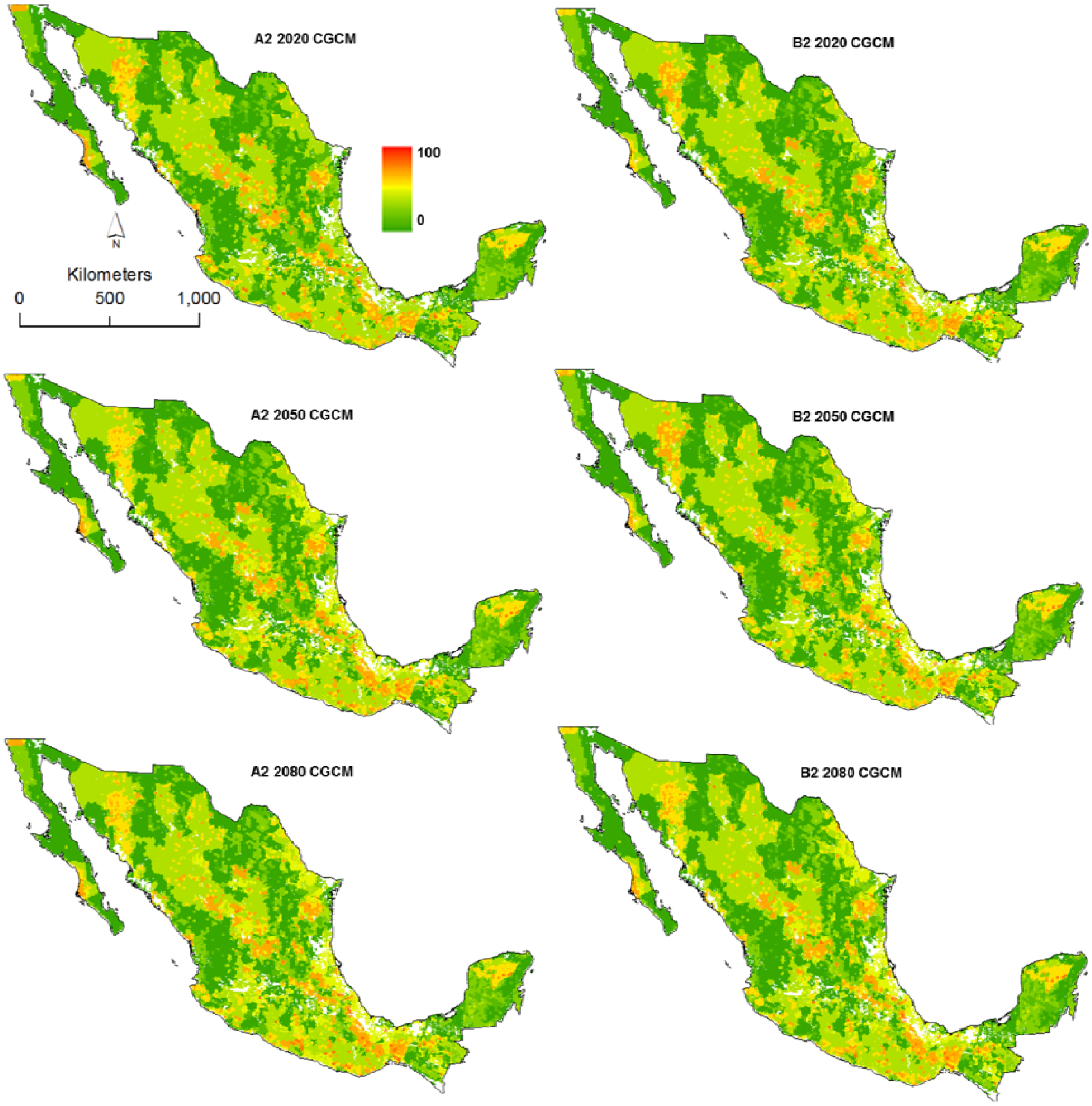


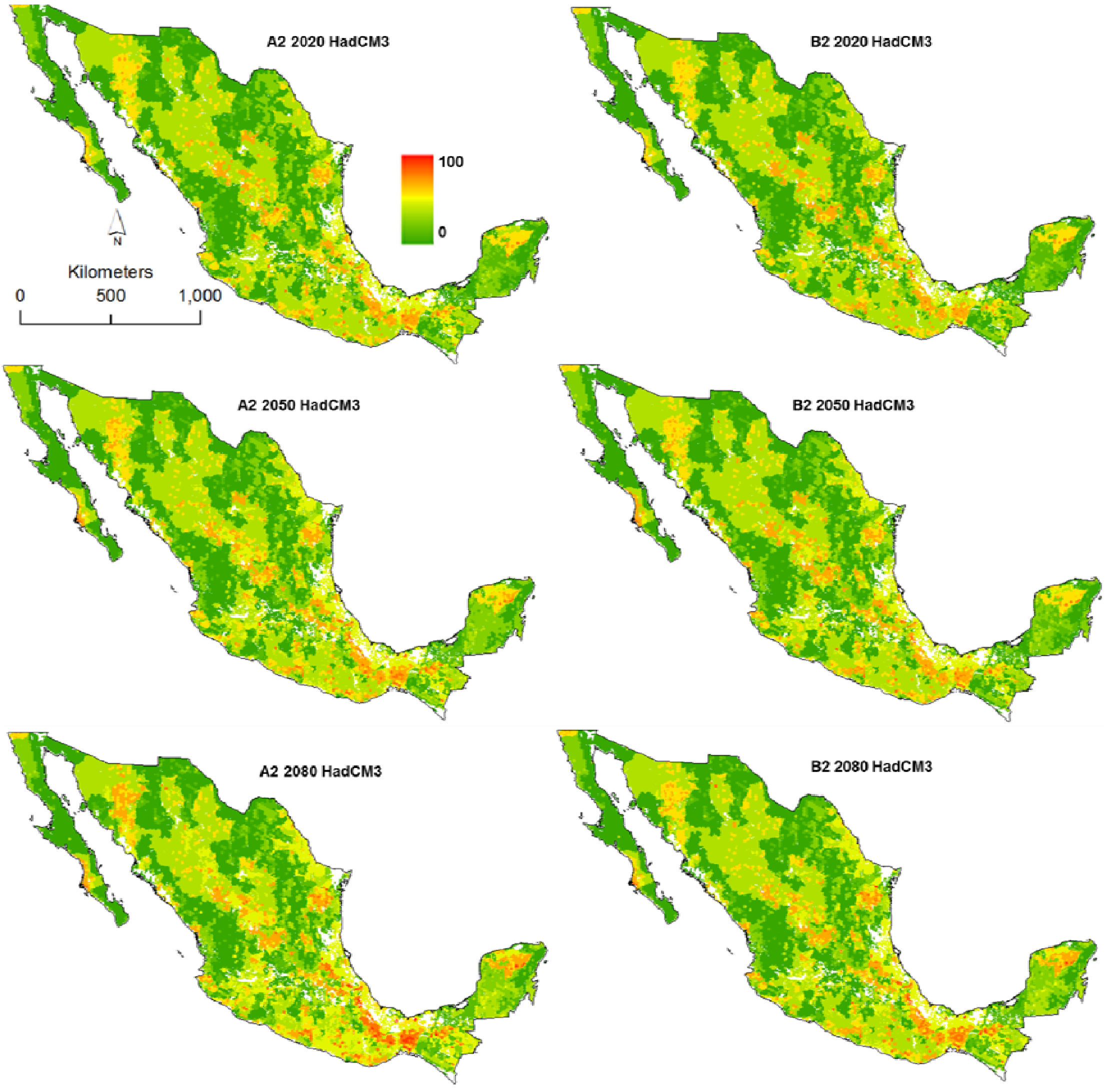
b)

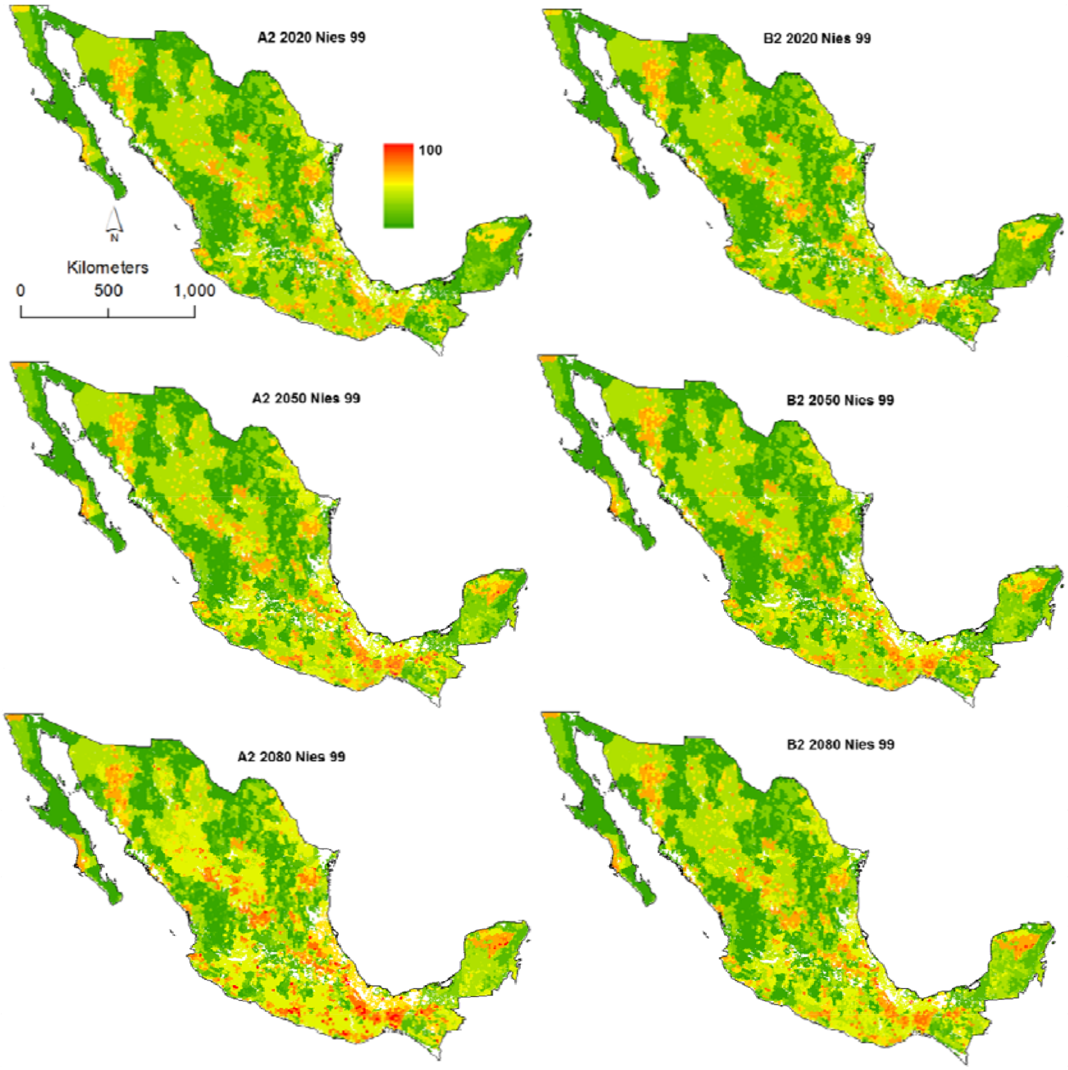


More than 95% of the residuals were under 10% suggesting that the LUCC model is reliable for the presence/absence of natural vegetation. TDF showed to have more variation among the others. This vegetation type showed the highest over estimations (>70%) in the prediction, but only true for about 1% of the total area, in contrast to the ~ 2 % of the other natural covers depicted overestimations >40%

Appendix 6. Vulnerability maps based on the results of the three CGCMs.




A2 2020 HadCM3
100
0
N
Kilometers
0
500
1,000
B2 2020 HadCM3
A2 2050 HadCM3
B2 2050 HadCM3
A2 2080 HadCM3
B2 2080 HadCM3


A2 2020 Nies 99
100
Kilometers
0
500
1,000
N
B2 2020 Nies 99
A2 2050 Nies 99
B2 2050 Nies 99
A2 2080 Nies 99
B2 2080 Nies 99

Appendix 7. Species of endemic and threatened vertebrates living in the most vulnerable sites from medium to extremely high vulnerability.

Mammals

Species	IUCN	Habitat	Species	IUCN	Habitat
Chaetodipus dalquesti	V	OV	*Orthogeomys lanius*	CE	YEF
Chaetodipus goldmani	NT	S	*Pappogeomys alcorni*	CE	TF
Chaetodipus lineatus	DD	S,OV	*Peromyscus bullatus*	CE	S,TF
Corynorhinus mexicanus	NT	TF	*Peromyscus furvus*	DD	TF
Cryptotis alticola	DD	TF	*Peromyscus guardia*	CE	S
Cryptotis magna	V	TF	*Peromyscus mekisturus*	CE	S
Cryptotis nelsoni	CE	TF	*Peromyscus melanocarpus*	E	TF
Cryptotis obscura	V	TF	*Peromyscus melanurus*	E	TDF,TF
Cryptotis peregrina	DD	H,TF	*Peromyscus ochraventer*	E	TF
Cryptotis phillipsii	V	TF	*Peromyscus polius*	NT	TF,S
Cynomys mexicanus	E	G	*Peromyscus simulus*	V	TDF
Dasyprocta mexicana	CE	TEF	*Peromyscus winkelmanni*	E	TF
Dipodomys gravipes	CE	S,OV	*Peromyscus zarhynchus*	V	TF,S
Habromys simulatus	E	TF	*Reithrodontomys bakeri*	E	TF
Geomys tropicalis	CE	TEF	*Reithrodontomys burti*	DD	S,TDF
Habromys chinanteco	CE	TF	*Reithrodontomys hirsutus*	V	S
Habromyx ixtlani	CE	TF	*Rheomys mexicanus*	E	H
Habromys lepturus	CE	TF	*Rhogeessa genowaysi*	E	TDF
Habromysschmidlyi	CE	TF, TDF	*Rhogeessa mira*	V	S,OV
Liomys spectabilis	E	S,TF	*Romerolagus diazi*	E	TF
Megadontomys cryophilus	E	TF	*Sigmodon alleni*	V	TF,TDF
Megadontomys nelsoni	E	TF	*Sigmodon planifrons*	E	TDF
Megadontomys thomasi	E	TF	*Sorex ixtlanensis*	DD	TF
Microtus oaxacensis	E	TF,G	*Sorex macrodon*	V	TF,TDF
Microtus quasiater	NT	TF,G	*Sorex milleri*	V	TF
Microtus umbrosus	E	TF	*Sorex sclateri*	CE	TF,TEF
Musonycteris harrisoni	V	OV	*Sorex stizodon*	CE	TF
Myotis planiceps	E	TF	*Spermophilus atricapillus*	E	OV,S
Myotis vivesi	V	OV	*Spermophilus madrensis*	NT	TF
Nelsonia goldmani	E	TF	*Spermophilus perotensis*	E	TF
Nelsonia neotomodon	NT	TF	*Spilogale pygmaea*	V	TEF,S,OV
Neotoma angustapalata	E	TF	*Sylvilagus insonus*	E	*TF*
Neotoma bryanti	E	TF,S	*Tamias bulleri*	V	TF
Neotoma nelsoni	CE	S,TF	*Tylomys bullaris*	CE	TDF
Neotoma palatina	V	TDF	*Tylomys tumbalensis*	CE	TEF
Neotoma phenax	NT	TDF,S	*Xenomys nelsoni*	E	TDF
Notiosorex villai	V	TF,H	*Zygogeomys trichopus*	E	TF
Orthogeomys cuniculus	DD D	TDF			

BIRDS

Species	**IUCN**	**Habitat**	**Species**	**IUCN**	**Habitat**
Amazona finschi	E	TDF	*Hylorchilus navai*	V	TEF
Campephilus imperialis	CE	TF	*Hylorchilus sumichrasti*	NT	TEF
Campylorhynchus yucatanicus	NT	S,OV	*Lophornis brachylophus*	CE	TEF,TDF
Cyanocorax dickeyi	NT	TDF,TF,H	*Passerina rositae*	NT	H,TDF
Cyanolyca mirabilis	V	TF,H	*Peucaea sumichrasti*	NT	S,TDF
Cyanolyca nana	V	TF	*Quiscalus palustris*	E	H
Cypseloides storeri	DD	TF,TDF	*Rallus tenuirostris*	NT	H
Cyrtonyx sallei	NT	TF,S,G	*Rhynchopsitta pachyrhyncha*	E	TF
Dendrortyx barbatus	V	TF	*Rhynchopsitta terrisi*	E	TF
Doricha eliza	NT	H,TDF	*Spizella wortheni*	E	S,G
Eupherusa poliocerca	V	TEF,TDF	*Thalurania ridgwayi*	V	TEF,TDF
Geothlypis beldingi	E	H	*Toxostoma guttatum*	CE	TDF
Geothlypis flavovelata	V	H	*Xenospiza baileyi*	E	G
Geothlypis speciosa	E	TDF,H	*Zentrygon carrikeri*	E	TEF
Hydrobates macrodactylus	CE	TF			

Reptiles

Species	**IUCN**	**Habitat**	**Species**	**IUCN**	**Habitat**
Abronia bogerti	DD	TF	*Lepidophyma dontomasi*	DD	OV
Abronia chiszari	E	TEF,TF	*Lepidophyma lineri*	DD	TF
Abronia deppii	E	TF	*Lepidophyma lipetzi*	E	TDF,TEF
Abronia fuscolabialis	E	TF	*Lepidophyma lowei*	DD	TF
Abronia graminea	E	TF	*Lepidophyma micropholis*	V	TDF
Abronia leurolepis	DD	TF	*Lepidophyma radula*	DD	TDF
Abronia martindelcampoi	E	TF	*Lepidophyma tarascae*	DD	TDF,TF
Abronia mitchelli	DD	TF	*Lepidophyma tuxtlae*	DD	TEF
Abronia mixteca	V	TF	*Lepidophyma gaigeae*	V	TF,S
Abronia oaxacae	V	TF	*Mesaspis antauges*	DD	TF
Abronia ochoterenai	DD	TF	*Mesaspis juarezi*	E	TEF,TF
Abronia ornelasi	DD	TF	*Mesoscincus altamirani*	DD	TDF
Abronia ramirezi	DD	TDF	*Micrurus bogerti*	DD	TDF
Abronia reidi	DD	TEF	*Micrurus ephippifer*	V	TDF
Abronia taeniata	V	TEF,TF	*Micrurus nebularis*	DD	TF
Adelophis copei	V	H	*Micrurus pachecogili*	DD	S, OV
Adelphicos latifasciatum	DD	TF	*Micrurus tamaulipensis*	DD	TF
Anguis incomptus	DD	TF	*Mixcoatlus barbouri*	E	TF
Anniella geronimensis	E	S, TDF	*Mixcoatlus melanurus*	E	S,TDF,TF

Anolis alvarezdeltoroi	DD	TEF	*Ophisaurus ceroni*	E	OV
Anolis barkeri	V	H,TEF,TF	*Ophryacus undulatus*	V	TF
Anolis breedlovei	E	TF	*Phrynosoma dirmarsi*	DD	TF
Anolis cymbops	DD	TEF	*Phyllodactylus paucituberculatus*	DD	S, TDF
Anolis duellmani	DD	TEF	*Plestiodon colimensis*	DD	TF
Anolis forbesi	DD	TDF	*Plestiodon dugesii*	V	TF
Anolis hobartsmithi	E	TF	*Plestiodon multilineatus*	DD	TF
Anolis isthmicus	DD	S	*Plestiodon parviaruculatus*	DD	S
Anolis milleri	DD	TEF	*Plestiodon parvulus*	DD	TF
Anolis naufragus	V	TF	*Pliocercus wilmarai*	DD	TF
Anolis polyrhachis	DD	TF	*Porthidium hespere*	DD	TDF
Anolis pygmaeus	E	TDF,TF	*Rena bressoni*	DD	TF
Anolis schiedii	DD	TF	*Rhadinaea bogertorum*	DD	TF
Anolis simmonsi	DD	TDF	*Rhadinaea cuneata*	DD	TEF
Anolis subocularis	DD	TDF	*Rhadinaea forbesi*	DD	TF
Anolis utowanae	DD	TDF	*Rhadinaea fulvivittis*	V	TF
Aspidoscelis opatae	DD	S, TDF	*Rhadinaea gaigeae*	DD	TF,TDF
Aspidoscelis rodecki	NT	S	*Rhadinaea macdougalli*	DD	TF
Barisia herrerae	E	TF	*Rhadinaea marcellae*	E	TF
Barisia levicollis	DD	TF	*Rhadinaea montana*	E	TF
Barisia rudicollis	E	TF	*Rhadinaea myersi*	DD	TF
Bothriechis rowleyi	V	TF	*Rhadinaea omiltemana*	DD	TF
Celestus ingridae	DD	TEF	*Rhadinaea quinquelineata*	DD	TF
Cerrophidion petlalcalensis	DD	TF, OV	*Rhadinella kanalchutchan*	DD	TF
Chersodromus rubriventris	E	TF	*Rhadinophanes monticola*	DD	TF
Coniophanes alvarezi	DD	TF	*Sceloporus chaneyi*	E	TF,S
Coniophanes lateritius	DD	TDF	*Sceloporus cyanostictus*	E	S
Coniophanes melanocephalus	DD	TF	*Sceloporus goldmani*	E	G, OV
Coniophanes sarae	DD	TDF	*Sceloporus halli*	DD	OV
Conophis morai	DD	TEF	*Sceloporus lemosespinali*	DD	TF
Conopsis amphisticha	NT	TF	*Sceloporus maculosus*	V	S,OV
Crotalus lannomi	DD	TF, TDF	*Sceloporus megalepidurus*	V	S
Crotalus pusillus	E	TF	*Sceloporus oberon*	V	TF
Crotalus stejnegeri	V	TDF,TF	*Sceloporus ornatus*	NT	S
Crotaphytus antiquus	E	S	*Sceloporus salvini*	DD	TF,TDF
Cryophis hallbergi	DD	TF	*Sceloporus subpictus*	DD	TF, S
Enulius oligocastichus	DD	TF, TDF	*Sceloporus tanneri*	DD	TF
Exiliboa placata	V	TF	*Sibon linearis*	DD	TEF
Ficimia hardyi	E	S,TDF,TF	*Sonora aemula*	NT	S,TDF
Ficimia ramirezi	DD	TDF	*Storeria hidalgoensis*	V	TF
Ficimia ruspator	DD	TF	*Tantalophis discolor*	V	TF

Ficimia variegata	DD	TEF	*Tantilla briggsi*	DD	TF,TDF
Geagras redimitius	DD	TDF	*Tantilla flavilineata*	E	TF
Geophis bicolor	DD	TF	*Tantilla johnsoni*	D	TEF
Geophis blanchardi	DD	TF	*Tantilla oaxacae*	DD	TEF,TDF
Geophis chalybeus	DD	TF	*Tantilla robusta*	DD	TF
Geophis incomptus	DD	TF	*Tantilla sertula*	DD	TDF
Geophis juarezi	DD	TEF,TF	*Tantilla shawi*	E	TF
Geophis juliai	V	TEF	*Tantilla slavensi*	DD	TEF
Geophis laticollaris	DD	TDF	*Tantilla striata*	DD	TF
Geophis latifrontalis	DD	TF	*Tantilla tayrae*	DD	TEF
Geophis maculiferus	DD	TF, TDF	*Tantilla triseriata*	DD	TEF,TF
Geophis nigrocinctus	DD	TF	*Thamnophis melanogaster*	E	H,TDF
Geophis petersii	DD	TF	*Thamnophis mendax*	E	TF
Geophis pyburni	DD	TF	*Thamnophis nigronuchalis*	DD	H,TF
Geophis russatus	DD	TDF	*Thamnophis rossmani*	DD	H
Geophis sallaei	DD	TF	*Thamnophis scaliger*	V	G,S,TF,OV
Geophis sieboldi	DD	TF	*Tropidodipsas repleta*	DD	S
Geophis tarascae	DD	TF	*Uma exsul*	E	OV, S
Hypsiglena tanzeri	DD	S	*Xantusia bolsonae*	DD	OV
Lampropeltis ruthveni	NT	S	*Xenosaurus newmanorum*	E	TDF,TF
Lampropeltis webbi	DD	TF	*Xenosaurus phalaroantereon*	DD	TF
Lepidophyma chicoasensis	DD	TDF	*Xenosaurus platyceps*	E	S,G

Amphibians

Species	**IUCN**	**Habitat**	**Species**	**IUCN**	**Habitat**
Ambystoma altamirani	E	H,TF	*Lithobates pueblae*	CE	TF
Ambystoma andersoni	CE	H,TF	*Lithobates sierramadrensis*	V	TF,H
Ambystoma bombypellum	CE	G,H,TF	*Lithobates tarahumarae*	V	TF,H
Ambystoma dumerilii	CE	TF,H	*Lithobates tlaloci*	CE	H
Ambystoma flavipiperatum	DD	S,H	*Megastomatohyla mixe*	CE	TF
Ambystoma granulosum	CE	G	*Megastomatohyla mixomaculata*	E	TF,H
Ambystoma leorae	CE	TF,H	*Megastomatohyla nubicola*	E	TF,H
Ambystoma lermaense	CE	G,H	*Megastomatohyla pellita*	CE	TF,H
Ambystoma mexicanum	CE	TF,H	*Notophthalmus meridionalis*	E	H
Ambystoma ordinarium	E	G,TF,H	*Parvimolge townsendi*	CE	TF
Ambystoma rivulare	DD	TF,H	*Plectrohyla ameibothalame*	DD	TF,H
Ambystoma silvense	DD	TF,H	*Plectrohyla arborescandens*	E	TF
Ambystoma taylori	CE	H	*Plectrohyla calthula*	CE	TF,H

Anaxyrus mexicanus	NT	TF,H	*Plectrohyla calvicollina*	CE	H
Bolitoglossa hermosa	NT	TDF	*Plectrohyla celata*	CE	TF,H
Bolitoglossa macrinii	NT	TF	*Plectrohyla cembra*	CE	TF,H
Bolitoglossa oaxacensis	DD	TF	*Plectrohyla charadricola*	E	TF,TEF,H
Bolitoglossa platydactyla	NT	TDF,TEF	*Plectrohyla chryses*	CE	TF,H
Bolitoglossa riletti	E	TDF,TEF	*Plectrohyla crassa*	CE	TF
Bolitoglossa veracrucis	E	TF	*Plectrohyla cyanomma*	CE	TF
Bolitoglossa zapoteca	DD	TF	*Plectrohyla cyclada*	E	TF,H
Bromeliohyla dendroscarta	CE	TF	*Plectrohyla ephemera*	CE	TF
Charadrahyla altipotens	CE	TF	*Plectrohyla hazelae*	CE	TF,S
Charadrahyla chaneque	E	TF	*Plectrohyla labedactyla*	DD	TF,S
Charadrahyla nephila	V	TF,H	*Plectrohyla lacertosa*	E	TF
Charadrahyla taeniopus	V	TF	*Plectrohyla miahuatlanensis*	DD	TF
Charadrahyla trux	CE	TF	*Plectrohyla mykter*	E	TF,H
Chiropterotriton arboreus	CE	TF	*Plectrohyla pachyderma*	CE	S,H
Chiropterotriton chiropterus	CE	TF	*Plectrohyla pentheter*	E	TF,H
Chiropterotriton chondrostega	E	TF	*Plectrohyla psarosema*	CE	TF,H
Chiropterotriton cracens	E	TF	*Plectrohyla pycnochila*	E	TF,H
Chiropterotriton dimidiatus	E	TF	*Plectrohyla robertsorum*	E	TF,H
Chiropterotriton lavae	CE	TF	*Plectrohyla sabrina*	CE	TF,H
Chiropterotriton magnipes	CE	TF	*Plectrohyla siopela*	CE	TF,H
Chiropterotriton mosaueri	DD	TF	*Plectrohyla thorectes*	CE	TF,H
Chiropterotriton multidentatus	E	TF	*Pseudoeurycea ahuitzotl*	CE	TF,H
Chiropterotriton orculus	V	TF	*Pseudoeurycea altamontana*	E	TF,H
Chiropterotriton priscus	NT	TF	*Pseudoeurycea amuzga*	DD	TF,H
Chiropterotriton terrestris	CE	TF	*Pseudoeurycea anitae*	CE	TF
Craugastor batrachylus	DD	TF	*Pseudoeurycea aquatica*	CE	TF
Craugastor berkenbuschii	NT	TF	*Pseudoeurycea aurantia*	V	TF
Craugastor decoratus	V	TF	*Pseudoeurycea bellii*	V	TF
Craugastor glaucus	CE	TF	*Pseudoeurycea boneti*	V	TF
Craugastor guerreroensis	CE	TF	*Pseudoeurycea cephalica*	NT	TF
Craugastor hobartsmithi	E	TDF	*Pseudoeurycea cochranae*	E	TF
Craugastor megaloptymanum	CE	S	*Pseudoeurycea conanti*	E	TF
Craugastor montanus	E	TF	*Pseudoeurycea firscheini*	E	TF
Craugastor occidentalis	DD	TDF	*Pseudoeurycea gadovii*	E	TF
Craugastor omiltemanus	E	TF	*Pseudoeurycea galeanae*	NT	TF,S
Craugastor pelorus	DD	H	*Pseudoeurycea gigantea*	CE	TF
Craugastor polymniae	CE	TF	*Pseudoeurycea juarezi*	CE	TF
Craugastor pozo	CE	TF	*Pseudoeurycea leprosa*	V	TF

Craugastor rhodopis	V	TF	*Pseudoeurycea lineola*	E	TF
Craugastor silvicola	E	TF	*Pseudoeurycea longicauda*	E	TF
Craugastor spatulatus	E	TEF	*Pseudoeurycea lynchi*	CE	TF
Craugastor tarahumaraensis	V	TF	*Pseudoeurycea maxima*	DD	TEF
Craugastor taylori	DD	TF	*Pseudoeurycea melanomolga*	E	TF
Craugastor uno	E	TF	*Pseudoeurycea mystax*	E	TF
Craugastor vulcani	E	H	*Pseudoeurycea mixcoatl*	DD	TF
Craugastor yucatanensis	NT	TDF	*Pseudoeurycea naucampatepetl*	CE	TF
Cryptotriton adelos	E	TF	*Pseudoeurycea nigra*	CE	TF
Cryptotriton alvarezdeltoroi	E	TF	*Pseudoeurycea nigromaculata*	CE	TF
Dendrotriton megarhinus	V	TF	*Pseudoeurycea obesa*	DD	TF
Dendrotriton xolocalcae	V	TF	*Pseudoeurycea orchileucos*	E	TF
Dermophis oaxacae	DD	TDF	*Pseudoeurycea orchimelas*	E	TF
Duellmanohyla chamulae	E	TF	*Pseudoeurycea papenfussi*	NT	TF
Duellmanohyla ignicolor	E	H	*Pseudoeurycea parva*	CE	TF
Ecnomiohyla echinata	CE	H,TF	*Pseudoeurycea praecellens*	CE	TEF
Ecnomiohyla miotympanum	NT	TF	*Pseudoeurycea quetzalensis*	DD	TDF
Ecnomiohyla valancifer	CE	TEF	*Pseudoeurycea robertsi*	CE	TF
Eleutherodactylus angustidigitorum	V	TF	*Pseudoeurycea ruficauda*	DD	TF
Eleutherodactylus dennisi	E	S	*Pseudoeurycea saltator*	CE	TF
Eleutherodactylus dilatus	E	TF	*Pseudoeurycea scandens*	V	TF,S
Eleutherodactylus dixoni	CE	TF	*Pseudoeurycea smithi*	CE	TF
Eleutherodactylus grandis	E	S	*Pseudoeurycea tenchalli*	E	TF
Eleutherodactylus interorbitalis	DD	TDF	*Pseudoeurycea teotepec*	E	TF
Eleutherodactylus longipes	V	TF	*Pseudoeurycea tlahcuiloh*	CE	TF
Eleutherodactylus maurus	DD	TF	*Pseudoeurycea tlilicxitl*	DD	TF
Eleutherodactylus modestus	V	TDF	*Pseudoeurycea unguidentis*	CE	TF
Eleutherodactylus nivicolimae	V	TF	*Pseudoeurycea werleri*	E	TEF
Eleutherodactylus pallidus	DD	S,TDF	*Ptychohyla acrochorda*	DD	TF
Eleutherodactylus rufescens	CE	TF,TDF	*Ptychohyla erythromma*	E	TF
Eleutherodactylus saxatilis	E	TF	*Ptychohyla leonhardschultzei*	E	TF
Eleutherodactylus syristes	E	TF	*Ptychohyla zophodes*	DD	TF
Eleutherodactylus teretistes	DD	S,TDF, TF	*Smilisca dentata*	E	G,H
Eleutherodactylus verrucipes	V	TF	*Thorius arboreus*	E	TF
Eleutherodactylus verruculatus	DD	TF,TEF	*Thorius aureus*	CE	TF
Exerodonta abdivita	DD	H,TF	*Thorius boreas*	E	TF
Exerodonta bivocata	DD	TF	*Thorius dubitus*	E	TF
Exerodonta chimalapa	E	TF	*Thorius grandis*	E	TF
Exerodonta juanitae	V	TF	*Thorius infernalis*	CE	H

Exerodonta melanomma	V	TF	*Thorius insperatus*	DD	TF
Exerodonta pinorum	V	TF	*Thorius lunaris*	E	TF
Exerodonta xera	V	H,S	*Thorius macdougalli*	V	TF
Hyla arboricola	DD	TF,H	*Thorius magnipes*	CE	TF
Hyla euphorbiacea	NT	TF,G,H	*Thorius minutissimus*	CE	TF
Incilius cavifrons	E	TF	*Thorius minydemus*	E	TF
Incilius cristatus	CE	TF,H	*Thorius munificus*	CE	TF
Incilius cycladen	V	TDF,TF	*Thorius nargismagnus*	CE	TDF
Incilius gemmifer	E	TDF	*Thorius narisovalis*	CE	TF
Incilius perplexus	E	TDF,H	*Thorius omiltemi*	E	TF
Incilius pisinnus	DD	S,H	*Thorius papaloae*	E	TF
Incilius spiculatus	E	TF,H	*Thorius pennatulus*	CE	TF
Lithobates chichicuahutla	CE	S,H	*Thorius pulmonaris*	E	TF
Lithobates dunni	E	H	*Thorius schmidti*	E	TF
Lithobates johni	E	TF,H	*Thorius smithi*	CE	TF
Lithobates lemosespinali	DD	TF	*Thorius spilogaster*	CE	TF,H
Lithobates megapoda	V	H,S,TF	*Thorius troglodytes*	E	TF
Lithobates neovolcanicus	NT	TF,G,H	*Tlalocohyla godmani*	V	TF,H
Lithobates omiltemanus	CE	TF			
Lithobates psilonota	DD	TF,H			