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Identifying effects of land use cover changes and climate change on terrestrial ecosystems and carbon stocks in Mexico

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Abstract

Land use cover change (LUCC) has a crucial role in global environmental change, impacting both ecosystem services and biodiversity. Evaluating the trends and possible alternatives of LUCC allows quantification and identification of the hotspots of change. Therefore, this study aims to answer what the most vulnerable ecosystems and the carbon stocks losses to LUCC are under two socioeconomic and climate change (CC) scenarios–Business as Usual (BAU) and Green. The scenarios integrate the Representative Concentration Pathways, and the Shared Socioeconomic Pathways, with a spatially explicit LUCC. Distance to roads and human settlements are the most explicative direct drivers of LUCC. The LUCC projections include thirteen categories of natural and anthropogenic covers at a fine resolution for Mexico for the two scenarios. The results show that 83% of deforestation in the country has taken place in tropical dry forests, scrublands, temperate forests, and tropical evergreen forests. Considering the range of distribution of natural vegetation and the impacts of LUCC and climate change, tropical dry and evergreen forests, followed by other vegetation and cloud forests are shown to be most vulnerable. By 2011, anthropogenic covers accounted for 26% of the country's cover, and by 2050, according to the BAU scenario, they could account for 37%. The Green scenario suggests a feasible reduction to 21%. In 1985, Mexico had 2.13 PgC in aboveground biomass, but the LUCC would be responsible for 1 to 2% of LUCC global emissions, and by 2100, it may account for up to 5%. However, if deforestation were reduced and regeneration increased (Green scenario), carbon stocks would reach 2.14 PgC before 2050. Therefore, identifying which natural covers are the most vulnerable to LUCC and CC, and characterizing the principal drivers of ecosystems loss are crucial to prioritizing areas for implementing actions addressing resources to combat the loss of ecosystems and carbon stocks.

Key words: carbon emissions; deforestation; drivers of change; scenarios, Mexico.

I. Introduction

Land use cover change (LUCC) is the result of human appropriation of resources, a practice that undermines the capacity of the planet to sustain ecosystem services, including climate regulation and biodiversity (Foley, 2017; Foley et al., 2005). Moreover, positive feedbacks among forest loss, fragmentation, and climate change (CC) appear increasingly likely (Laurance William and Williamson, 2002). These interactions may exacerbate pressure on ecosystems due to changes in agricultural productivity (Asseng et al., 2013; Gornall et al., 2010), soil quality, increasing population, and demand for resources. This will in turn increase competition for arable land, thus modifying the LUCC processes (Licker et al., 2010; Ward et al., 2014) in terms of both extension and intensity. As a consequence, the changing patterns and processes in LUCC will impact the tropical and developing countries and their contribution to CO_2 emissions (Laurance, 2007).

To better understand the causes, impacts, consequences, and dynamics of socio-ecological systems, LUCC research needs to be integrated across diverse fields (Turner et al., 2007). Research into complex LUCC phenomenon has been focused on (1) analyzing historical trends and patterns (Goldewijk, 2001; Lambin and Meyfroidt, 2011) that are rooted in empirical-statistical and simulation models (Pontius et al., 2001; Verburg et al., 2004) and cellular automata (Soares-Filho et al., 2002); and (2) identifying the drivers and agents related to decision making (Berger, 2001; Pocewicz et al., 2008). LUCC models have been developed using a scenario framework (Hurtt et al., 2011; Popp et al., 2017; Rounsevell et al., 2006) that is not predictive of the future, but rather provides plausible, comprehensive, integrated, and consistent descriptions of how the future might unfold (Nakicenovic et al., 2000). Scenarios are based on quantitative projections and qualitative assumptions that constitute storylines (Rounsevell and Metzger, 2010). Quantitative projections usually refer to socioeconomic or biophysical elements, while storylines focus on the policies and technologies that influence the trajectories of those projections. Other than the examples of LUCC models under scenario assumptions, there are few case studies that consider interactive feedback between LUCC and CC under different scenarios (Oliver and Morecroft, 2014) and even fewer for those that model different natural vegetation categories under CC conditions (Beaumont et al., 2011; Gilliam, 2016; Zomer et al., 2014). Thus, LUCC research can be understood only in light of socioeconomic aspects, policies, biophysical context, and CC.

Common scenarios are necessary to understand possible futures within the same framework. These scenarios facilitate the comparison of impacts and changes on earth systems. Moreover, they are necessary to assess the adaptation and vulnerability of ecosystems (van Vuuren et al., 2014). The common scenarios proposed by the Intergovernmental Panel on Climate Change

(IPCC) in its Fifth Assessment Report display a set of four scenarios known as the Representative Concentration Pathways (RCPs), which are identified by their approximate total radiative forcing in 2100 relative to 1750: the 2.6 Wm^{-2}, 4.5 Wm^{-2}, 6.0 $W m^{-2}$, and 8.5 $W m^{-2}$ (IPCC, 2013). In a parallel process, a set of five storylines have been developed by the scientific community. These are the Shared Socioeconomic Pathways (SSPs), which describe different socioeconomic trends, including sustainable development, regional rivalry, inequality, fossil-fuel development, and middle-of-the-road development (Kriegler et al., 2012; O'Neill et al., 2017; O'Neill et al., 2014). These scenarios cover different drivers of the radiative forces according to their narratives on demography (Jones and O'Neill, 2016; Kc and Lutz, 2017), urbanization (Jiang and O'Neill, 2017), economy (Crespo Cuaresma, 2017; Dellink et al., 2017; Leimbach et al., 2017), and energy and land use (Popp et al., 2017; Riahi et al., 2017; van Vuuren et al., 2017).

There are global LUCC models that have integrated the RCP scenario assumptions (Hurtt et al., 2011) and the SSPs (Fricko et al., 2017; Popp et al., 2017), as well as combinations of both sets (Hasegawa et al., 2014). However, those models have two important limitations: (1) they consider only one category as natural vegetation, namely, forest; and (2) the finest resolution is 0.5 x 0.5 degrees (Havlík et al., 2014; Popp et al., 2014; Schaldach et al., 2011). As these models focus on possible socioeconomic rules based on global trade, they fail to provide detailed spatially explicit information of hotspots of change, making it difficult to evaluate the possible impacts on biodiversity such as the small-range species (Jetz et al., 2007).

A few studies focused on carbon (C) stocks in Mexico (Cartus et al., 2014; Rodríguez-Veiga et al., 2016) or C fluxes (Murray-Tortarolo et al., 2016), but only the latter integrates LUCC. However, studies at fine resolution that take into account LUCC drivers and the vulnerability of natural covers–understood as the propensity to be adversely affected (IPCC, 2014) in the short-, medium-, and long-term under "the common scenarios" (van Vuuren et al., 2014)–are lacking, especially for megadiverse and developing countries such as Mexico.

Mexico is one of the richest countries in biological diversity worldwide. Biologically, it is in fourth place and represents around 70% of known species (Mittermeier et al., 1997; Sarukhán and Dirzo, 2001). Mexico also has huge cultural diversity, with indigenous groups and different cultural practices that have led to biological diversity (Perales and Golicher, 2014). Considering that half of Mexico is represented by agrarian communities (*ejidos*) that are collectively and individually managed (Bonilla-Moheno et al., 2013), and that 80% of the forests are collectively managed (Bray et al., 2003), the country is an exceptional and interesting case study for analysing the possible LUCC trends under different socioeconomic and CC scenarios and its impacts on C stocks. Therefore, the key question or this research is: What are the most vulnerable ecosystems and the C stocks losses to LUCC under different socioeconomic and CC scenarios? To answer this question, we set the following aims: (1) identify which natural covers have been most vulnerable to LUCC; (2) which natural covers will be the most vulnerable to LUCC and CC in the short, medium and long term; (3) characterize the direct and indirect causes of habitat loss at a national level; and (4) quantify C stock changes and CO_2 emissions under two socioeconomic and CC scenarios.

II. Materials and methods

The LUCC model was developed in Dinamica EGO (version 3.0.17.0). The model includes: (1) the definition of the land use and cover categories and the calculation of transition matrices; (2) the categorization of continuous variables; (3) estimations of the weights of evidence of the explanatory variables; (4) analyses of the correlation between variables; and (5) a short-term simulation to validate the model and long-term projections under different trajectories (Soares-Filho et al., 2009) into which the socioeconomic and the CC scenarios were incorporated (Figure A1, Appendix A).

II.1 Classification of land use cover and calculation of transition matrices

The most complete and detailed (1:250,000) national land use cover maps are available for different years from the National Institute of Statistics and Geography (INEGI) (1985; 1993; 2002; 2007; 2011). These maps include several categories that vary from 375 classes in the map of 1985 to 175 for 2011 in the most disaggregated classification. These categories were reclassified into thirteen classes, eight natural covers, four anthropogenic uses and covers, and one for barren land (Table A1). Considering the thirteen categories and excluding the permanence, there are 156 possible transitions of which only 56 were modeled. The total extent for Mexico in this study was 1,932,347 km^2 and the transitions related to deforestation and regeneration that were modeled, explained more than 70% of the total changes (Table A2).

II.2 Explanatory variables, categorization, and drivers of change

A set of 24 explanatory variables (13 socioeconomic and 11 biophysical) were used to identify the principal drivers of change (Table A3). Continuous variables were categorized following a modification of Agterberg and Bonham-Carter's method (1990), in which ranges are calculated creating breaking points based on the original data structure (Soares-Filho et al., 2009). The weights of evidence (WoE) method was used to quantify the significance of the explanatory variables (Bonham-Carter, 1994; Goodacre et al., 1993) and to produce a transition probability map that depicts the areas prone to change (Soares-Filho et al., 2004; Soares-Filho et al., 2002). WoE is a Bayesian approach, in which the effect of a spatial variable on a transition is calculated independently (Soares-Filho et al., 2009). Next, a correlation analysis was performed to select the most relevant, as well as the non-correlated variables for each transition.

Socioeconomic historical data were taken from the national census from INEGI (Table A3). Future national socioeconomic projections (population and Gross Domestic Product (GDP)) were taken from the International Institute for Applied Systems Analysis (IIASA) (2016). Demographic figures were downscaled to municipality level by assuming a constant municipality representation over time, based on the mean historical contribution taken from the national census for population (Table A3; Equation 1). The same method was used for the economic data, using the National Information Systems for Municipalities (SNIM, 2005) for GDP. The sum of socioeconomic data at municipality level equals the total national value. Finally, climatic variables were taken from Worldclim (Table A3; Fick and Hijmans (2017)).

Equation 1

$$Var_{mun\,(x,y)} = \frac{Var_{nat\,(y)}}{n} * \sum_{i=1}^{n} \left(\frac{Var_{\,mun\,(x,i)}}{Var_{\,nat\,(i)}} \right)$$

In this formula, Var_{mun} refers to the socioeconomic variable (population or GDP) of a municipality *x* in a time *y*, and Var_{nat} refers to the same variable at a national level in a time *y*. The *y* denotes the time from which the national observations are downscaled. The *i* refers to the time when the observations were collected (national census). The *n* is the total number of national datasets.

II.3 Set up, simulation, and validation of the model

The land use and cover maps of 1993 and 2007 were used to calibrate the model. A short-term simulation was set up to project the land use and cover map of 2011. The model was independently validated by comparing the observed and the simulated maps for the year 2011. The performance of the model was spatially and quantitatively evaluated. The spatial validation was conducted using an exponential and multiple-window constant decay function, following the method proposed by Soares-Filho et al. (2009).

II.4 Long-term projections and scenario building

Two scenarios were modeled by combining socioeconomic, climatic variables, and LUCC rates—the business as usual (BAU) scenario and the Green scenario.

Business as usual (BAU) scenario

This scenario uses the SSP2 assumptions defined as middle of the road, in which social, economic, and technological trends do not change markedly from historical patterns (O'Neill et al., 2017; Riahi et al., 2017). In terms of demography, for this scenario, Mexico is considered to be a country designated as low fertility (O'Neill et al., 2017), which means that fertility, mortality, and migration is medium. Education is conceived by two elements a slow shift of the country to develop and to improve. Consequently, educational cumulative capability over the past 40 years is medium (Kc and Lutz, 2017; O'Neill et al., 2017). Similarly, the economy shows moderate development–there are significant heterogeneities across the country and LUCC trends that fall into the middle of the historic trends. To incorporate these trends of change quantitatively, we calculated all rates by combining the available national maps and using the Food and Agriculture Organization (FAO) equation (1995) to calculate deforestation (Equation A1). The period selected was 1993-2007 (Table A4). Finally, the climatic data was updated including the RCP 4.5 scenario by different available time slices (2050s and 2070s; Fick and Hijmans (2017)).

Green scenario

This scenario is considered to be the sustainable path (O'Neill et al., 2017) for which SSP1 socioeconomic data were used. This scenario depicts low fertility, mortality, and migration leading to a rapid demographic transition for countries like Mexico (Kc and Lutz, 2017; O'Neill et al., 2017). Education shows the most rapid expansion in recent history, as does cumulative experience (Kc and Lutz, 2017). In terms of economy, SSP1 reflects shifts toward a broader emphasis on human wellbeing. GDP growth is higher in SSP2, but in SSP1 there is less population growth and reduced inequality. This scenario shows a consumption-oriented path toward low material growth and lower resource and energy intensity, with a strong reduction in tropical deforestation (Popp et al., 2017). Consequently, this scenario takes into account the lowest historical deforestation rates and the highest historical regeneration rates for every natural cover (Table A5). The Green scenario uses RCP 2.6 bioclimatic data. This scenario supports the active participation of sectors to reduce radiative forcing, such as an increase in forest growth for activities like bioenergy with carbon capture and storage (van Vuuren et al., 2011).

The climatic variables used in the models (RCP 4.5 and 2.6) were taken from four general circulation models (GCM) (CNRMC M5; GFDL CM3; HADGEM2 E5; and MPI-ESM LR). These models were selected to integrate the variability among the most contrasting GCMs on climate change for Mexico (INECC, 2016) and to make our results comparable to the National Vulnerability Atlas to Climate Change (INECC, 2016). As a result, four different maps of future land use and cover under climate change and socioeconomic scenarios were produced. This information also helped us to evaluate the uncertainty of the scenarios. The uncertainty of the models was based on the transitions from natural covers to anthropogenic covers and vice versa for every single pixel. A total agreement for deforestation or regeneration is when the four resulting maps coincided in the same projected changes.

II.5 Aboveground biomass, C stock estimates, and uncertainty

To estimate the aboveground biomass (AGB) we used two elements: (1) the National Forest Inventory of Mexico (NFI 2004-2009) (CONAFOR, 2012) (CONAFOR, 2012) (CONAFOR, 2012) (CONAFOR, 2012) and (2) a set of allometric equations available for Mexico and tropical ecosystems. The NFI database consists of rectangular and circular plots (depending on the ecosystem) of $400 m^2$ each. Within each plot, diameter at breast height (DBH), tree height, and species classification were recorded. The sampling design follows a systematic grid with the distance between plots varying from 5 km in temperate, cloud, tropical evergreen, and hydrophilic forest including other vegetation, 10 km in tropical dry forest, and 20 km in arid regions and grasslands. This study included 58,198 plots of data of live trees with DBH ≥7.5 cm. We considered that the high density of the field plots would reflect the degradation of the ecosystems on the mean AGB, an observation similar to that reported by Cairns et al.

The dataset of allometric equations has 478 equations of the most common species and genera (Rojas-García et al., 2015). To complement these, we used the allometric equation developed for tropical species wherever species were not included in the Mexican dataset (Chave et al., 2014). We constructed an iterative decision-tree approach to select the optimal allometric equation for each tree based on the plot location. When more than one allometric equation was available, equations developed for the specific species were selected, especially when the equation was collected within the ranges of DBH, mean annual temperature, and rainfall. Complementarily, to estimate the AGB of anthropogenic covers, we assumed a mean of 5 MgC ha^{-1} (Ruesch and Holly, 2008) with an uncertainty ranging from 2 to 8 MgC ha^{-1}, which are similar figures to other reports for Mexico (Cairns et al., 2000; de Jong et al., 2010; Hughes et al., 2000)**.** Finally, the AGB densities (Mg ha^{-1}) were transformed to aboveground carbon (AGC) estimates (MgC ha^{-1}) by applying specific constants of carbon content in wood for each land use and cover (Corona-Núñez et al., 2018; Feldpausch Ted et al., 2004; IPCC, 2006; Lamlom and Savidge, 2003; Thomas and Martin, 2012).

Finally, we used the Monte Carlo analysis to estimate the uncertainty of the AGC. All the analyses were conducted using R software version x64 2.14 (R-Core-Team, 2014). We reconstructed the distribution of each variable using the library fitdistrplus (Delignette-Muller and Dutang, 2015), and calculated the uncertainty using the library mc2d (Poillot et al., 2013). We included sources of uncertainty of the mean AGB for each land use and cover, the conversion factor to C stocks, and the total area of each land class.

III. Results

III.1 Natural covers, historical LUCC trends, and future projections under different scenarios

Temperate forests represented 17% of the national territory in 1985, but they have been declining (Figure 1). Their highest deforestation rate was during the period 1993 to 2002 (Table A6). By 2050, the BAU scenario shows that temperate forests would cover close to 16% of Mexico and that by the end of the century they could decrease to 14.7% (Figure1). The losses are related to the expansion of rain-fed agriculture and pastures (Figure 2). Under the Green scenario, it is shown that, by the end of the century, temperate forests could cover as much as

18% of the country. The most affected regions are in the center of the trans-volcanic belt, while the major areas of regeneration are in the center and in southern parts, like the sierras of Oaxaca and Guerrero, and the Chiapas Highlands (Figure 3 and Figure A2).

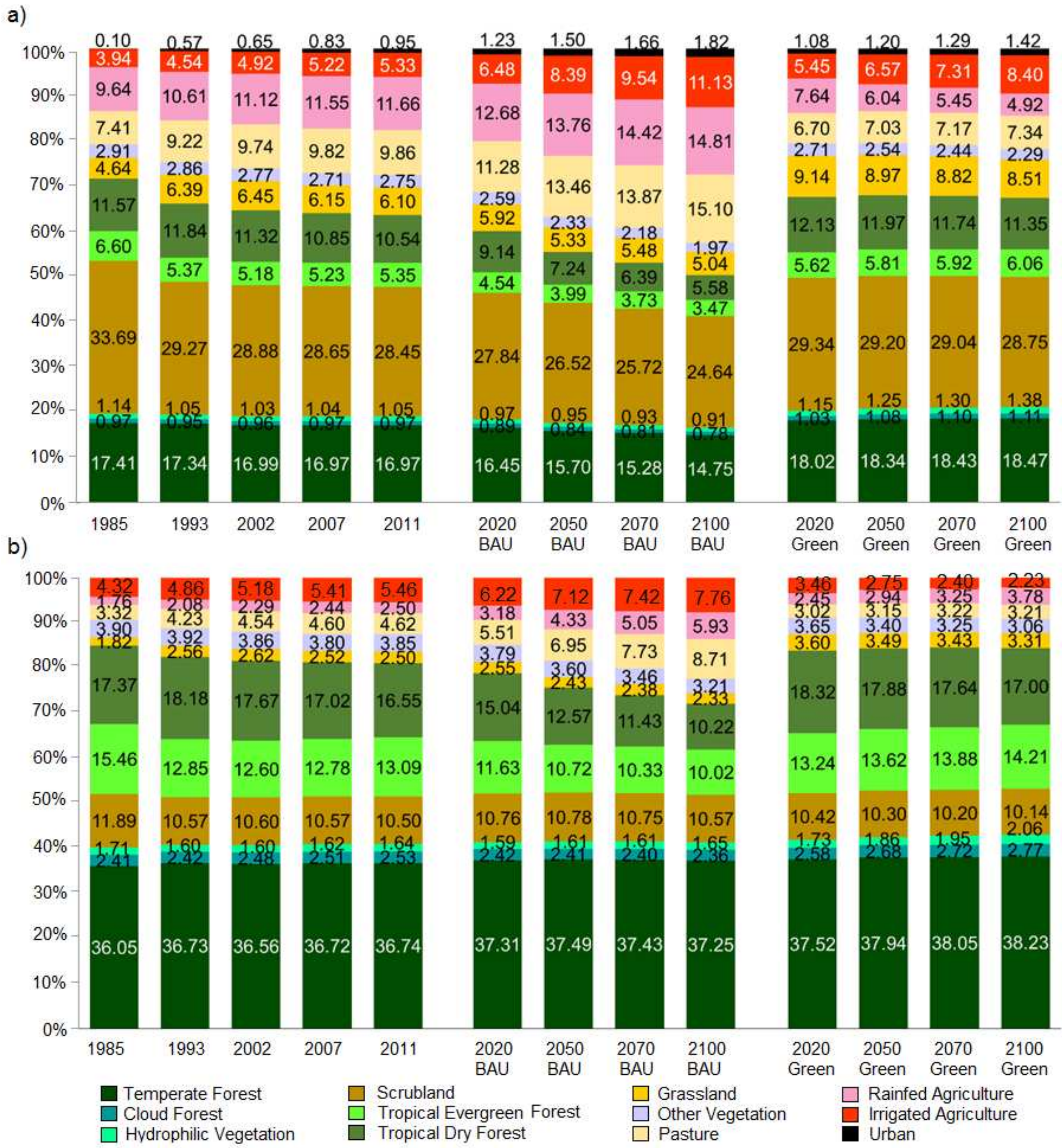

Figure 1: Representativeness of historical land uses and covers, and future projections of a) extent of land uses and covers in Mexico, and b) aboveground biomass of the land uses and covers.

Mexican scrublands represent the most widespread natural cover. By 1985, they covered more than 642,000 km^2, ~33% of the country (Figure 1). However, by 2011, they fell to 29% of Mexico's cover. Scrublands showed their highest rates of change during the period 1985 to 1993 (-1.75% yr^{-1}), after which rates diminished. Rates did however start rising again in the period 2007 to 2011 (Table A6). By 2050 and 2100, under the BAU scenario, scrublands represented 26% and 25% of the country respectively, with deforestation rates lower than 0.21%yr^{-1} after the 2030s. The Green scenario shows a slight recovery and that by the end of the century scrublands could cover ~29% of the country (Figure 1). The most affected regions are in the southern part of their distribution (up to the trans-volcanic belt) due to the expansion of rain-fed agriculture– principally in the central part of the Chihuahuan Desert, in the north of the Sonoran Desert, and the ecoregions of the southern Texas plains. The areas prone to regeneration are at the southern distribution of scrublands on the borders of the trans-volcanic belt (Figure 3).

In 1985, tropical dry forests covered 12% of the national territory (Figure 1). Although for the period 1985 to 1993, an increase in these forests is depicted. The forests start diminishing after 1993, showing their highest deforestation rate during 2002 to 2007 (Table A6). It is important to note that although the rate of deforestation decreased, these forests have the highest rates of change in comparison with other natural vegetation. By 2050, the BAU scenario shows that tropical dry forests account for 7% of land cover in Mexico, and that by the end of the century this figure could decrease to 6%. In contrast, within the same time frame, the Green scenario depicts that tropical dry forests could nearly reach their 1985 extent. This vegetation has been principally affected by rain-fed agriculture and pastures (Figure 2), mainly in Sinaloa state, matching an ecoregion known as the Sinaloa coastal plains, as well as by pasture expansion in the southern Pacific coastal plains and hills (Figure 3 and Figure A2).

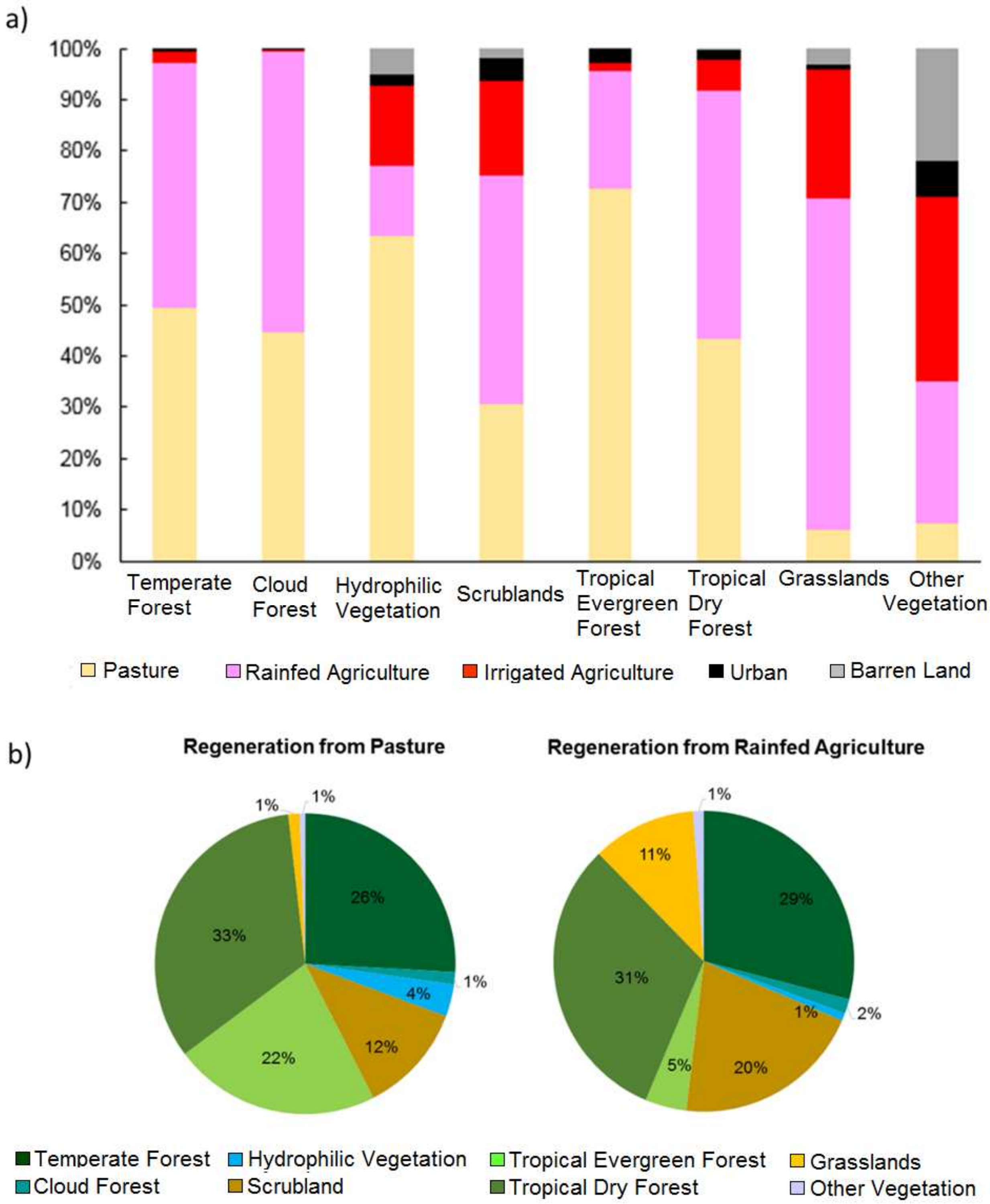

Figure 2: Deforestation and regeneration patterns (1993 to 2007). a) Conversion to anthropogenic covers from natural covers; and b) regeneration from two anthropogenic covers to natural vegetation.

Tropical evergreen forests have a constricted distribution. By 1985, they occupied around 7% of land cover, and they have been continuously decreasing (Figure 1). This vegetation has the highest deforestation rate in comparison with other forests, losing 2.57%yr^{-1} (Table A6). It has mainly been converted to pastures and rain-fed agriculture. By 2050, the BAU scenario depicts a decrease in the representation of tropical evergreen forests in the country, and by 2100, they could halve (Table A6). In contrast, the Green scenario shows a slight recovery at a rate of 0.07%yr^{-1}, but even by the end of the century the contribution (6%) of tropical evergreen forests do not reach the representativeness they had in 1985 (Figure 1). The most perturbed areas are on the coast of the Gulf of Mexico (Figure 3).

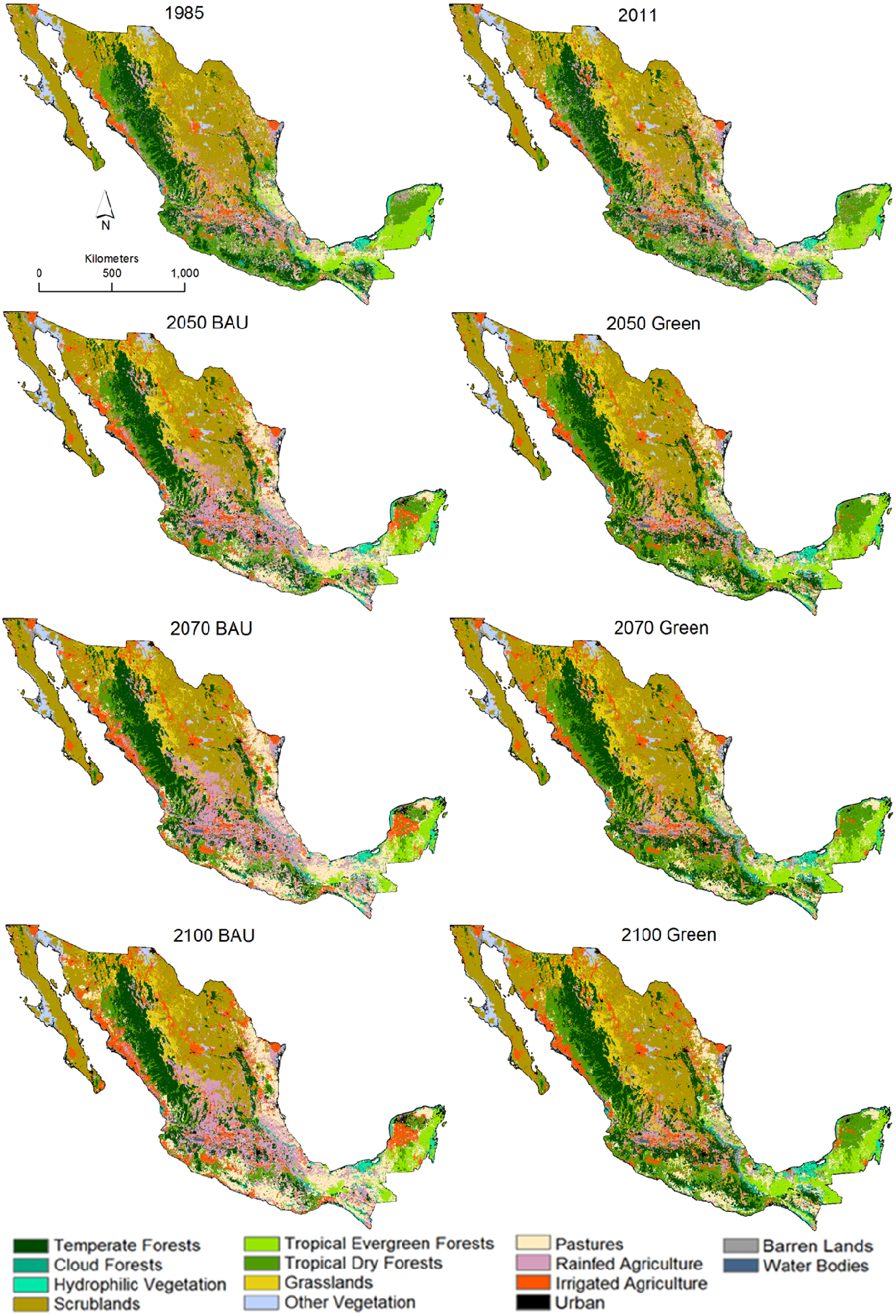

Figure 3: Land use and land cover historical and projected maps under two scenarios: BAU and Green (GCM: CNRMC M5).

In 1985, natural grasslands accounted for less than 5% of cover in Mexico, although their extent increased in the periods 1985 to 1993, and 1993 to 2002. Natural grasslands started to show recovery in the latest historical periods (2002 to 2007, and 2007 to 2011; Table A6). The projections show that by 2050, grasslands might represent 5.3% to 8.9% of Mexico in the BAU and the Green scenarios. According to the BAU scenario, by the end of the century it shows a similar extent to that of 1985 (Table A6). The direct drivers of this change were mainly the expansion of rain-fed agriculture (Figure 2), followed by irrigated agriculture and pastures in the southern part of their distribution (Figure 3).

Cloud forests and hydrophilic vegetation have the narrowest distribution of any vegetation in Mexico. By 1985, they represented 0.9% and 1.1% of Mexico's cover, respectively (Figure 1). These kinds of vegetation show the highest deforestation rates during 1985 to 1993 (Table A6). The BAU scenario depicts a continuous decrease, which is worse for cloud forest. By 2050, both vegetation types decrease and represent only 0.8% and 0.9% of the country's cover (Figure 1). In contrast, the Green scenario shows that both vegetation types could reach the same extent as they had in 1985. Cloud forests were mainly affected by the expansion of rain-fed agriculture and pastures, while hydrophilic vegetation was more vulnerable to pastures and irrigated agriculture (Figure 2 and Figure 3).

The category, other vegetation, which includes palms or desert ecosystems, covered almost 3% of Mexico in 1985 and during the period 1993 to 2002 showed the highest deforestation rate (Table A6). Both scenarios depict a reduction in this vegetation compared with historical figures, and by the end of the century, they cover only 1.9 and 2.2% of the country in the BAU and Green scenario respectively, (Figure 1). They are threatened mainly by irrigated agriculture, rain-fed agriculture, and the expansion of barren lands in the north of the country (Figure 3).

III.2 Deforestation and drivers of change

In the period 1993 to 2007, more than 83% of deforestation in the country was accounted for by tropical dry forests (30%), scrublands (22%), temperate forests (18%), and tropical evergreen forests (13%). 45% was accounted for by the expansion of rain-fed agriculture, 41% by pasture, and 11% by irrigated agriculture.

In 1985 and 2011, pastures covered 7% and 9% of Mexico respectively (Figure 1). Pastures show their highest historical expansion during 1985 to 1993, growing at ~3%yr^{-1} after which, they begin to decrease (Table A5). Pastures are especially widespread in tropical evergreen forests, temperate forests, and hydrophilic vegetation (Figure 2). The principal element pushing their expansion was closeness to localities, roads, and population. However, biophysical variables related to those transitions were annual mean temperature, range of annual temperature, seasonality, and precipitation, which favor settlement of this land (Figure A3). In terms of pasture expansion on natural grasslands, the biophysical elements were more important than the socioeconomic (Figure A3). The BAU scenario depicts a substantial increase, possibly accounting for 13% and 15% in the 2050s and 2100, but growing at lower rates than in the historical periods (Table A6). The Green scenario illustrates a reduction in pasture cover to ~7% of the country, as it was in 1985 (Figure 1).

Rain-fed agriculture was the second most important anthropogenic cover in terms of extent in all historical periods. In 1985, it covered ~10% of Mexico (Figure 1) and had the highest expansion rate during the period 1985 to 1993 (Table A6). Cloud and temperate forest were the most affected by this type of cover (Figure 2). The most important elements in the expansion of rain-fed agriculture were distance to roads, cities, and localities, and population size. Protected areas

(PA) played an important role by avoiding this transition–particularly in tropical evergreen forests. From a biophysical perspective, type of soil, and seasonality were significant for all the natural covers, except for tropical dry forests and cloud forests (Figure A3). Slope was an element restricting the expansion of rain-fed agriculture in temperate forests. Precipitation was related to this transition in grasslands, and the range of annual temperature was influential in grasslands, hydrophilic vegetation, and scrublands (Figure 2 and Figure A3). The BAU scenario showed that by the end of the century rain-fed agriculture could cover ~15% of Mexico, expanding especially in the center of the country in the trans-volcanic belt and the surrounding areas, and also in the ecoregion known as the southern semi-arid highlands (Figure 3). Although rain-fed agriculture was the second most widespread anthropogenic cover in historical periods, for the Green scenario it became the third most widespread, covering 5% of the country (Figure 1).

Irrigated agriculture showed a continuous increase since 1985, accounting for 4 to 5% in 2011 (Figure 1). The period with the highest rates of change was 1985 to 1993 (Table A6). The natural covers most affected by the expansion of this anthropogenic cover were other vegetation, scrubland, and hydrophilic vegetation (Figure 2). The relevant socioeconomic variables for these transitions were the distance to roads and population density. For cloud forests and hydrophilic vegetation, precipitation was essential and in the case of grasslands and cloud forest, distance to protected areas was important in terms of restricting its expansion (Figure A3). In terms of biophysical variables, it was found that type of soil and temperature were important for all the natural covers, and that altitude was relevant for scrublands, grasslands, and tropical dry forests (Figure A3). The BAU scenario shows that this cover might increase to 11% by 2100, while in the Green scenario it will cover 8% of the country (Figure 1).

In addition, socioeconomic variables were extremely predictive regarding transitions to urban covers (Figure A3). Transitions to urban covers were more representative in other vegetation, scrublands, and tropical evergreen forests (Figure 2). The most important elements were the socioeconomic ones: distance to the existing cities and human settlements, distance to roads, localities, population size, and GDP. Regarding biophysical variables, altitude was shown to be the most important. This category had the highest rate of change during the period 1985 to 1993 with an expansion of 24%yr^{-1} (Table A6). For both scenarios, this cover shows a continuous increment until the end of the century of between 1% and 2% of the territory (Figure 1). The places where these transitions occur are in the metropolitan area of Mexico City, Monterrey (State of Nuevo Leon), and Guadalajara (Jalisco) (the three biggest cities in the country) (Figure A2). However, the southern cities of Cancun (Quintana Roo) and Merida in the Peninsula of Yucatan also increased their extent (Figure 3 and Figure A2).

III.3 Regeneration and its drivers of change

Regeneration from pastures and rain-fed agriculture explained 47% and 46% of total regeneration. More than 80% of the regeneration took place in tropical dry forests, temperate forests, and tropical evergreen forests (Figure 2). In the case of regeneration from pasture to natural covers, socioeconomic variables were not as important as biophysical ones (Figure A2). However, distance to roads was relevant, especially for temperate forests, cloud forests, scrublands, and grasslands–the more distant the areas were from the roads, the higher the regeneration. Small population size was important for tropical evergreen forests, hydrophilic vegetation, tropical dry forests, and grassland in terms of allowing regeneration (Figure A3). The biophysical variables that played a critical role in regeneration were altitude, mean annual temperature, seasonality, and the mean and maximum temperatures in the warmest and wettest quarters for all the natural covers (Figure A3). Closeness to the coasts with reduced precipitation was however important for promoting regeneration in hydrophilic vegetation and tropical dry forests (Figure A3).

Most of the regeneration from rain-fed agriculture took place in tropical dry forests and temperate forests (Figure 2). These transitions followed a similar pattern to pastures, where biophysical elements were more important than socioeconomic ones (Figure A3). The steep slopes were especially key for temperate forests and cloud forest. Other biophysical variables favoring regeneration were temperature and all its variants (range, mean, maximum, and minimum) (Figure A3). Precipitation was related to the regeneration transition of cloud forests. Moreover, soils were significant in terms of explaining these transitions for all the natural covers (Figure A3). Population size was relevant in changes from hydrophilic vegetation and grasslands, while the distance to localities and roads was related to regeneration of scrublands (Figure A3).

III.4 Validation and agreement between models

The spatial validation of the model goes from 40% at 1 x 1 cell, to 80% at 8 x 8 cells (resolution ~2 km^2). However, the similarity between maps reaches 70% at ~1 km^2 resolution. Over the four GCMs, the agreement in terms of the projected changes shows that the BAU scenario has a better agreement than the Green scenario. By 2050, the BAU scenario shows that 16% of the country could undergo changes due to deforestation or regeneration, while the rest depicts permanence of the land covers. Of these changes, 77% are due to deforestation, which showed an agreement of 100% across the GCMs. By the same time, the Green scenario changes account for 20% of the cover of Mexico. Of these changes, 33% are due to deforestation and the rest to regeneration. In the Green scenario, deforestation was completely agreed upon by the four GCMs in 75% of the changes, while 12% and 13% agreed in 75% and 50% of them. The agreement regarding deforestation is principally on the Pacific coast, Peninsula de Yucatan, matching with the tropical dry forest distribution and the northern part of the trans-volcanic belt, while the regeneration areas are located in the center of the country and some areas of the Gulf of Mexico (Figure 4). By 2070, both scenarios illustrate a total agreement of 73% and 78% for the permanence of natural cover, especially in the scrublands, vegetation, and anthropogenic covers located in the trans-volcanic belt, where there is the most important concentration of human settlements, and in the Gulf of Mexico where pastures for cattle ranching are located (Figure 1).

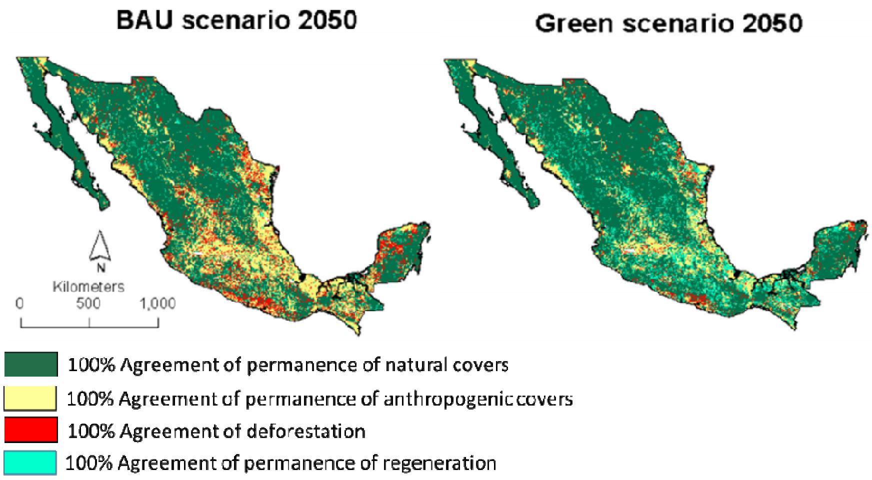

Figure 4: Agreement of permanence, deforestation, and regeneration among the four GCMs by 2050 under the BAU and Green scenarios.

III.5 Historical and future changes of C stocks and CO_2 emissions

The ecosystems with the highest AGB densities are cloud, tropical evergreen, and temperate forests, contrasting with scrublands and grasslands, which showed the lowest values (Figure A4). The major contributions to AGB in Mexico were by temperate, tropical evergreen, and tropical dry forests, which account for ~65% of land cover (Figure 1). The historical periods studied depict a reduction of total AGC stocks (Figure 5). The total C stock estimated in 1985 was 2.13±0.04 (mean ±1 SD) PgC, reducing by 2011 (2.05±0.04 PgC). By 2050, the BAU scenario shows a C stock of 1.86±0.07 PgC and by the end of the century, this shrank to 1.76±0.08 PgC. Conversely, the Green scenario describes a rapid rise in C stocks by 2020, with no significant increases after that. By 2050 the Green scenario depicts 2.14±0.09 PgC and by 2080 C stocks reach their maximum (2.15±0.08 PgC).

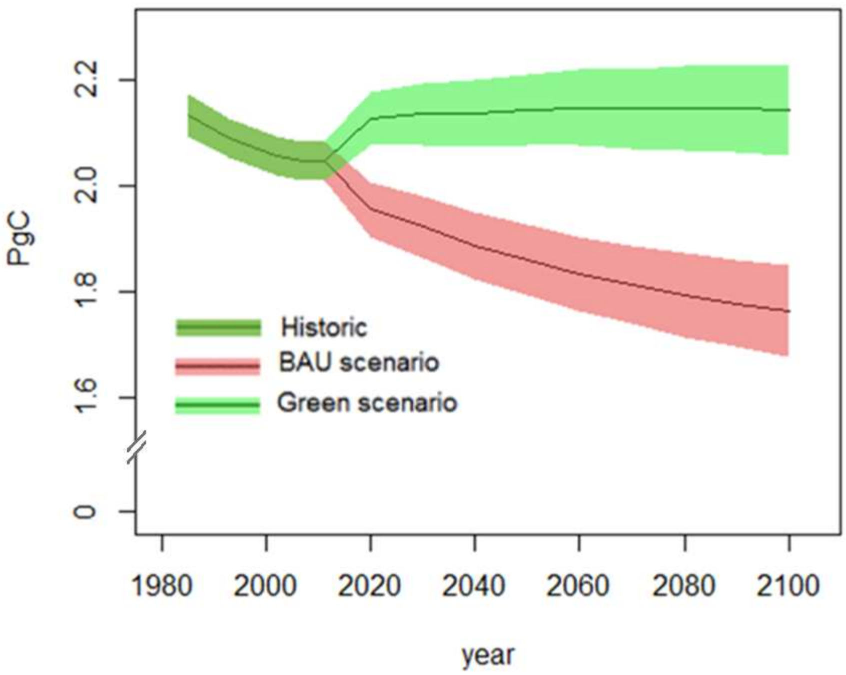

Figure 5: Historical and future total aboveground C stocks for Mexico. The shading represents uncertainty (± 1 SD).

During the period 2007 to 2011 the lowest rate of change of C stocks (-0.10±0.01 TgC yr^{-1}) was observed. The BAU scenario suggests that the maximum C losses would occur during the period 2020 to 2030 at a rate of 3.6±0.6 TgC yr^{-1}, with a slight reduction between 2030 and 2050 to 3.0±0.5 TgC yr^{-1}. By the end of the century, it would decrease to 1.7±0.3 TgC yr^{-1} (2070-2100). Moreover, the Green scenario suggests that the greatest C sink would be observed during the period 2020 to 2030 at a rate of 0.7±0.6 TgC yr^{-1}. However, even in the Green scenario, a small C loss would be observed in the period 2070 to 2100 (0.1±0.1 TgC yr^{-1}).

Temperate forests, tropical dry and tropical evergreen forests, and scrubland concentrate ~80% of the total Mexican AGC. By 2050, the BAU scenario suggests that these natural covers would represent 70% and by 2100, up to 63% of the total C stocks respectively, due to the LUCC. In 1985, the anthropogenic covers accounted for 10% of the total C stocks, but by 2050 and 2100, they would rise to 19.4% and 23.6% respectively. Contrastingly, in the Green scenario and the same time slices, C stocks in temperate and cloud forests, and hydrophilic vegetation would rise from 5 to 20%, while natural grasslands would nearly double the values they had in 1985 with an increment of >30 TgC. It is important to note that even in the Green scenario by 2100, other vegetation and scrublands show a reduction in their C stocks of 22% and 15% respectively.

Mexico has experienced a substantial reduction of CO_2 equivalents because of LUCC. The values go from 7.8±0.1 Pg CO_2 to 7.5±0.1 Pg CO_2 (1985 and 2011, respectively) at a rate of 12.2±0.1 Tg CO_2 yr^1–close to the rate recorded for the period 1993 to 2007 (11.0±0.1 Tg CO_2 yr^{-1}). Moreover, the BAU scenario suggests that during the period 2020 to 2050 there would be a significant rise in CO_2 emissions (11.6±1.9 Tg CO_2 yr^{-1}), contrasting with the sequestration in the Green scenario (1.8±1.4 Tg CO_2 yr^{-1}). By the period 2050 to 2100, the BAU scenario depicts a reduction of CO_2 emissions rates (7.2±1.3 Tg CO_2 yr^{-1}), while the Green scenario illustrates close to neutrality CO_2 emissions (0.2±0.2 Tg CO_2 yr^{-1}).

IV. Discussion

LUCCs have a crucial role in the global environmental change impacting ecosystem services, such as the C cycle and biodiversity. Evaluating the trends and possible LUCC alternatives, allows us to quantify the impacts on these environmental components and to identify what natural covers and ecosystems are more susceptible to those changes. Global and national studies report that deforestation for ecosystems differs significantly in terms of localizing the hotspots of change when compared to more detailed studies that included more categories for Mexico. This study is the first national research to have modeled detailed types of natural and anthropogenic covers by looking at historical trends and their drivers of change.

Comparing LUCC models in Mexico is difficult because of the different inputs, methodologies, and categories used. Some studies at a national level in Mexico have focused on analyzing historical changes (Mas et al., 2004; Mas et al., 2009; Rosete-Vergés et al., 2014; Velázquez et al., 2010; Velázquez et al., 2002), while others have analyzed ecosystems or mosaics. Studies on tropical dry forests (Burgos and Maass, 2004; Corona et al., 2016; Návar et al., 2010) and temperate and tropical evergreen forests have used scenarios (Camacho-Sanabria et al., 2015; Cruz-Huerta et al., 2015; Flamenco-Sandoval et al., 2007; Kolb and Galicia, 2017), and other vegetation classes also incorporated CC (Ballesteros-Barrera et al., 2007).

At the national level, our results have shown that the historically highest deforestation rates of all the natural covers has been for tropical evergreen forests and scrublands between 1985 and 1993. This may be the result of policies related to agricultural expansion in Mexico and the promotion of cattle ranching in the southeast of country from the 1960s to the late 1980s (Díaz-Gallegos and Mas, 2009; Dirzo and García, 1991; Revel-Mouroz, 1980; Tudela, 1989). After the 1985 to 1993 period, the deforestation rates of tropical evergreen and cloud forests decreased, perhaps because the remnants of these ecosystems were inside the protected areas–deforestation inside the PAs has been recognized (Dirzo and García, 1991; Mendoza and Dirzo, 1999; Ortiz-Espejel and Toledo, 1998). However, the efforts are inadequate, considering that tropical evergreen forest under the BAU scenario was the second most affected cover, behind tropical dry forests. This is different to Trejo et al. (2011)'s observations, which suggest that dry ecosystems, including tropical dry forests, would naturally expand their distribution. However, our results support that tropical dry forests and natural grasslands will keep decreasing despite the influence of CC due to the LUCC. For instance, in the period 2002 to 2007, they showed the highest rate of loss ever seen for grasslands in Mexico (Ceballos et al., 2010), providing evidence that drier ecosystems have been disregarded in terms of conservation policies in comparison to tropical evergreen forests (Koleff et al., 2009). This misrepresentation of dry ecosystems such as tropical dry forests, grasslands, and even scrublands is evident when the deforestation rates are reported. According to the FAO (2016), Mexico showed lower rates of forest change for the periods 1990 to 2000 (-0.3%yr^{-1}) and 2000 to 2010 (-0.2%yr^{-1}). Those differences result from the FAO's definition of forests (FAO, 2012) in which neither scrublands nor grasslands and other vegetation, are taken into account. Although these natural covers are not forests, they should be integrated into quantifications of how much natural vegetation has been lost. This is not only because of their importance for ecosystem services and biodiversity, but also because grasslands, scrublands, and other vegetation, are more affected by irrigation agriculture that will be very sensitive to CC (Elliott et al., 2014; Schlenker et al., 2007).

There is one national study that includes LUCC projections at a national level (Mas et al., 2004). This study suggests that by 2020, temperate forests, tropical forest (including tropical dry and evergreen forests), and scrublands would show an extension of ~300,000 km^2, ~260,000 km^2, and ~520,000 km^2 respectively. These results are similar to those we derived for the BAU scenario (312,876 km^2, 260,142 km^2 and 529,442 km^2). Nevertheless, there are local studies to which we can compare our findings, even though those studies are not based on the RCP or SSP assumptions. The studies show that by 2030, the extent of tropical forest and temperate forests in the southeast could be reduced by anything from 29% to 89% in comparison to 2000 (Flamenco-Sandoval et al., 2007) or to 19% to 30% in comparison to 2007 (Ramírez-Mejía et al., 2017). Our national study shows that by 2030 these forests could lose 4% and 17%

respectively under the BAU scenario for the same natural covers. These findings support that the southeast of Mexico is one of the most exposed areas to deforestation, with higher rates than those national estimates. However, the Green scenario shows that by 2030 it would be possible to increase between 7% and 10% of the same natural covers in comparison to their extent in 2002 by reducing deforestation and increasing restoration.

In this study we incorporated assumptions about future policies related to the expansion of covers for bioenergy purposes that can be promoted according to the RCP 2.6 scenario (van Vuuren et al., 2011). However, the Mexican context reflects that more than 70% of LUCC are caused particularly by the expansion of pasture for cattle ranching and rain-fed agriculture. The 70% figure includes all natural covers except hydrophilic vegetation and other vegetation with low potential for agricultural use. Consequently, we considered the importance of focusing on the expansion of agriculture and pasture, trying to depict a possible future that Mexico might face. By 2050, it has been projected that depending on diets and production systems, Mexico could use 60 to 80% more land for agricultural and livestock purposes to meet needs (Ibarrola-Rivas and Granados-Ramírez, 2017). However, our results, which do not consider dietary changes, suggest that by 2050, under the BAU scenario Mexico would require 15% more land than in 1985, which means 35% of the country. The Green scenario depicts a reduction to 19% of the country for agriculture or cattle ranching use as a result of changes in productivity.

The analysis of the effects of LUCC on the AGB suggest different successional stages in the Mexican forests in diverse natural covers with similar values for secondary and mature temperate forest, natural grasslands, and scrublands (Cairns et al., 2000; Mendoza-Ponce and Galicia, 2010), tropical evergreen forest (de Jong et al., 2010), tropical dry forests (Corona-

Núñez et al., 2018; Martinez-Yrizar et al., 1992; Mora et al., 2017; Roa-Fuentes et al., 2012), cloud forests (Cairns et al., 2000), and hydrophilic vegetation (Adame et al., 2013).

The total C stocks accounted for Mexico in the 2000s in this study (2.1±0.3 Gt C) fall within the range of other reported studies (1.7 - 2.4 Pg C) (Baccini et al., 2012; de Jong et al., 2010; Masera et al., 2001; Rodríguez-Veiga et al., 2016; Saatchi et al., 2011). However, it is important to notice that low values in the published data come from studies that did not include scrublands, grasslands, or other vegetation in their analysis, because they focus on temperate, tropical dry, and tropical evergreen forests that have shown the highest C stocks as suggested by de Jong (2010). In terms of C emissions from LUCC, Mexico has reported rates of between 17.4 and 20.0 TgC yr^{-1} (1977-1992) (Cairns et al., 2000). Those are higher than our estimate (5.47 TgC yr^{-1}) for the period 1985 to 1993. In this study, rates of C loss for the period 1993 to 2002 (-3.67±0.06 TgC yr^{-1}) were similar to those proposed by de Jong et al. (2010) (2.63±0.90 TgC yr^{-1}) for the same period. Interestingly, Murray-Tortarolo et al. (2016) reported that Mexico showed a C sequestration between 21.4 and 31.4 TgC yr^{-1} during the period 1990 to 2009 as a result of CO_2 fertilization. These figures are higher than all the other previous studies for Mexico for those periods. This could be the result of the authors' aggregation of contrasting bioclimatic vegetation classes and the use of very high woody mean AGC (eg. 229±9 MgC ha^{-1} for broadleaf evergreen forest) in contrast to other studies with mature vegetation (Corona-Núñez et al., 2017; Chave et al., 2004).

According to our results, future CO_2 emissions from LUCC are expected to decrease in Mexico, and as has been previously suggested, in the short term (2000 to 2030) (Masera et al., 1992; Masera et al., 2001). This study shows that by 2050 under the Green scenario, the total C stocks stored in vegetation would be close to those reported for the 1990s (Masera et al., 2001). Under the Green and the BAU scenario however, our results show that by 2100 Mexico would have 2.14 and 1.76 PgC respectively. These results contrast with those published by Murray-Tortarolo *et al.* (2016) who reported 3.0 and 2.1 PgC for RCPs 2.6 and 4.5 respectively, suggesting that Mexico is a sink rather than a source of C.

In the period 1850 to 2000 global deforested biomass was 63-156 $PgCO_2$ (Arora and Boer, 2010; Houghton, 2010; Houghton and Nassikas, 2017), suggesting rates of 420 to 1,040 $TgCO_2yr^{-1}$. For the period 1985 to 1993, we estimated emission rates (20.1 $TgCO_2yr^{-1}$) that would show Mexico to be responsible for 1 to 2% of these emissions, an observation similar to that reported by De Jong *et al.* (2010) . Moreover, by the end of the century CO_2 emissions from LUCC are expected to be between 222 and 2,333 $TgCO_2yr^{-1}$ (Ward et al., 2014), and according to those figures, we conclude that Mexico could be contributing 0.5 to 5.2% of global emissions under the BAU scenario (11.67 $TgCO_2$ yr^{-1}). Under a Green scenario it could be neutral (zero emissions from LUCC).

Scenario studies rarely consider uncertainties arising from spatial data (Dendoncker et al., 2008). However, the uncertainty is intrinsic to spatial data and ignoring uncertainty may result in unreliable scenarios (Fang et al., 2006). To maximize the reliability of the scenarios, we minimized, to the extent possible, different sources of error as intrinsic errors by using the best national data available for LUCC–the accuracy of which has been reported for INEGI's >90% for all covers (Mas et al., 2004). In terms of scenario building, we tried to develop scenarios in the most transparent way. However, the assumptions of scenarios may represent the major source of uncertainty because their interaction can vary over time. Besides the limitations of long-term projections for Mexico, it is important to continue developing these kinds of studies. There are still elements that future studies should try to integrate at a national or local level.

From a biophysical perspective it is necessary to consider the impacts of CC on major crops (changes in phenology, droughts, flooding and pests (Howden et al., 2007; Tubiello et al., 2007; Tucker et al., 2010)), and the feedbacks between C fluxes in order to quantify the fertilization effects of the CO_2 (Houghton, 2003; Strassmann et al., 2008). From a socioeconomic perspective it would be necessary to include: (1) inter-municipality migration (rural-urban) (Nawrotzki et al., 2015); (2) changes in labor forcing practices, for example, from agricultural activities to tourism (Corona et al., 2016; García-Frapolli et al., 2007); (3) effects of policies on crops related to bioenergy (Kato and Yamagata, 2014), REDD++ projects (Corbera et al., 2011); (4) market economy according to the international and internal trades (Lambin and Meyfroidt, 2011), especially those focused on key crops for Mexico; (5) agricultural subsidies and cultural land management practices (Roy Chowdhury, 2010); (6) relationship between land tenure on the LUCC (Bray et al., 2003); (7) the effects of increasing violence on LUCC dynamics (Durán et al., 2011); and (8) corruption (Arial et al., 2011) and drug plantations (Bradley and Millington, 2008). Challenges to future integration will be overcome with more accurate and refined data. Further work capable of incorporating the feedbacks between agents could be used to produce spatially explicit results.

IV. Conclusions

LUCC is due to the human appropriation of resources undermining the capacity of the planet to sustain ecosystem services and biodiversity. LUCC is a complex phenomenon and its modeling requires the integration of diverse fields to better understand the causes, impacts, consequences, and dynamics of change. The use of scenarios allows plausible descriptions of the future to be depicted. This work is the first study at a national level to model different and detailed natural and anthropogenic covers by integrating the scenario approach, including RCP and SSP scenarios, into a spatially explicit LUCC model at a fine resolution for Mexico. This study identified that, historically, scrublands have been the natural cover to lose most area, but due to their representativeness, tropical dry and tropical evergreen, followed by cloud forests, other vegetation, and grasslands, have shown the highest deforestation rates. This shows that conservation policies in tropical evergreen and cloud forest have been inadequate and that drier ecosystems, such as tropical dry forests, natural grasslands, and other vegetation have been lost. Moreover, Mexico has reduced its C emissions from LUCC. However, according to the BAU scenario, by the end of the century C emissions may represent up to 5% of global emissions due to LUCC. Nevertheless, by reducing the deforestation rates and increasing the regeneration of natural covers, Mexico could return to the total C stock estimated in 1985. We agree that, to better understand the dynamic of the socio-ecological systems under changing conditions, further work is needed to integrate more detailed information on the feedbacks between LUCC and CC, in addition to more accurate socioeconomic and policy data that reflect the social and political context.

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