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Impacts of land management and climate change in a developing and socioenvironmental challenging transboundary region

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A R T I C L E I N F O

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A B S T R A C T

Land-use/cover change is the major cause of terrestrial ecosystem degradation. However, its impacts will be exacerbated due to climate change and population growth, driving agricultural expansion because of higher demand of food and lower agricultural yields in some tropical areas. International strategies aimed to mitigate impacts of climate change and land use-cover change are challenging in developing regions. This study aims to evaluate alternatives to minimize the impacts of these threats under socioeconomic trajectories, in one of the biologically richest regions in Guatemala and Mexico. This study is located at the Usumacinta watershed, a transboundary region that shares a common history, with similar biophysical properties and economic constraints which have led to large land use/cover changes. To understand the impacts on deforestation and carbon emissions of different land-management practices, we developed three scenarios (1): business as usual (BAU), (2) a reducing emissions scenario aimed to reduce deforestation and degradation (REDD+), and (3) zero-deforestation from 2030 onwards based on the international commitments. Our results suggest that by 2050, natural land cover might reduce 22.3 and 12.2% of its extent under the BAU and REDD + scenarios, respectively in comparison with 2012. However, the zero-deforestation scenario shows that by 2050, it would be possible to avoid losing 22.4% of the forested watershed (1.7 million ha) and recover 5.9% (0.4 million hectares) of it. In terms of carbon sequestration, REDD + projects can reduce the carbon losses in natural vegetation, but a zero-deforestation policy can double the carbon sequestration produced by REDD + projects only. This study shows that to reduce the pressures on ecosystems, particularly in regions highly marginalized with significant migration, it is necessary to implement transboundary land-management policies that also integrate poverty alleviation strategies.

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1. Introduction

Land-use/cover change (LUCC) is the foremost direct cause of biodiversity loss with the largest relative global impact (UNEP, 2019). LUCC is related to the expansion of agriculture, mining, and human settlements, driven by a growing population (Foley, 2017). LUCC will be reinforced by climate change not only because of changes in species distributions, but also due to impacts on agriculture like yield reductions, livestock distribution and productivity (IPCC, 2019). Thus, understanding the LUCC dynamics to mitigate current or potential impacts in areas holding high biological diversity is necessary to develop land-use planning strategies (Hersperger et al., 2018).

Alternatives for land-use planning become challenging when more than one country is involved. Transboundary management and a joint perspective are essential to fulfill the international commitments that each country establishes, such as the Sustainable Development Goals (SDG's) of the 2030 Agenda, and the Nationally Determined Contributions (NDCs) of the Paris Agreement (Hammill and Price-Kelly, 2017; Shawoo et al., 2020). To accomplishment these commitments it is necessary to have sustainable local management related to international, national, and subnational political effectiveness. Therefore, identifying the major drivers of change is required to develop adequate policies to achieve these goals. Particularly, NDCs are challenging for both developed and developing countries as they require a significant shift in countries' priorities for allocating resources to combat poverty alleviation, climate change, food security, and environmental degradation. Developing countries face socioeconomic inequalities and environmental degradation; nonetheless, they still have to meet their commitments following the principle of common but differentiated responsibilities (Rajamani, 2006). Furthermore, application of policies and distribution of environmental responsibilities needs to be transparent and sensitive to avoid the negative impacts of adopting restrictive policies (Pauw et al., 2020).

Carbon (C) emissions from LUCC are a significant component of total emissions (IPCC, 2019). However, these emissions vary widely across regions. For example, by 2050, Mexico could produce 11.6 ± 1.9 Tg CO_2 annually only by deforestation, with contrasting differences in its ecosystems (Mendoza-Ponce et al., 2018). Both Mexico and Guatemala are committed to increasing their adaptation to climate change, the resilience of their socioecological systems, and the mitigation of national emissions. By 2030, both countries should stop deforestation and reduce greenhouse gas emissions (GHG) by 22 and 20% for Mexico and Guatemala, respectively (Mexico's INDCs, 2015). Therefore, sectorial actions are needed to halt deforestation and improve land management with the corresponding increments of C sequestration.

Areas holding high poverty levels, that are biologically relevant, and within transboundary landscapes are critical to meeting global environmental commitments. In the Mexico-Guatemala border, the Usumacinta watershed fulfills all these requirements, making it a suitable area to contextualize global commitments to local realities. The Usumacinta watershed is socially and environmentally relevant. The Maya civilization flourished in this region, but now their descendant communities live in high marginality and poverty en conditions, despite the strong potential for sustainable development practices (Gandin, 2012). This region is also a priority area for biodiversity conservation in Mesoamerica (Carrara et al., 2015) and freshwater reservoir, thus providing ecosystem services of incalculable value (Mendoza-Carranza et al., 2018). The region comprises the Lacandona rainforest, one of the largest remnants of tropical forests in Mexico and Guatemala, and one of the richest biological diversity areas (Meli et al., 2015). Moreover, the watershed accounts for 30% of Mexico's (Andrade-Velázquez and Medrano Perez, 2020) and 49% of Guatemala's total surface runoff (GWP, 2015).

The human population in the Usumacinta watershed is mainly rural. The main activities in the region are agriculture and livestock (Christman et al., 2015). Local populations remain among the poorest in Guatemala and Mexico, marked by a livelihood affected by environmental degradation (Gandin, 2012; Mendoza-Ponce et al., 2019), the unsustainable use of natural resources. This condition tends to be exacerbated by LUCC, climate change, and population growth. The Usumacinta river basin is highly vulnerable to climate change (Enríquez et al., 2016), which affects water quality and environmental flows, directly impacting aquatic ecosystems, species conservation, and population welfare (Villela and Montero-Martínez, 2018). Reductions in yields due to climate change, environmental degradation, yield gaps and growing demand for agricultural commodities can lead to an expansion of the agricultural area to fulfill the local demand, mainly for self-consumption (Enríquez et al., 2016; Suh et al., 2020). Eakin et al. (2015) suggested that shift of farmers to the manufacturing or tertiary sector would not necessarily lead to forest regeneration but probably livestock or monoculture expansion, like oil palm plantations (Abrams et al., 2019). Consequently, to avoid or mitigate LUCC, some projects have been implemented in the region, such as REDD+ (Reducing Emissions from Deforestation and Forest Degradation) (Figueroa et al., 2015; CONAFOR et al., 2016). However, the potential for mitigating LUCC under a global change scenario has not been entirely understood. Therefore, it is necessary to build scenarios evaluating the influence of future socioeconomic and climate change impacts on the LUCC dynamics and its consequently C stocks, including the effects of climate change on agricultural yields, with and without mitigation strategies.

Some studies have been undertaken in Mexico to understand the LUCC and C emissions synergies between socioeconomic and climate change drivers (Mendoza-Ponce et al., 2018). However, how these changes act at the local scale and within a transboundary system is yet to be analyzed. In this context, the Usumacinta watershed is ideal for understanding the interplay of socioeconomic and environmental elements and promoting joint transboundary planning between Guatemala and Mexico. This planning would reduce the adverse effects of LUCC, such as biodiversity loss and the depletion of ecosystem services. Therefore, this study aims to: 1) identify the main drivers of the LUCC in the Usumacinta watershed; 2) assess the potential impacts of climate change on the most important agricultural commodities in the region and how these impacts influence LUCC dynamics; and 3) identify possible transboundary alternatives to mitigate environmental degradation, reduce C emissions due to deforestation and climate change.

2. Materials and methods

2.1. Study site

The Usumacinta watershed covers 73,192 km^2, of which 58% is in Guatemalan territory, and 42% in Mexico. It also covers a small portion (<30 km^2) of Belize, that is not included in this research. The studied area comprises 100 municipalities, of which 70 are in Guatemala and 30 in Mexico. Annual precipitation ranges from 700 to 5400 mm, and the mean annual temperature ranges from 6 to 27 °C (Fick and Hijmans, 2017). Altitude goes from 0 to 4000 m asl (Fig. 1).

2.2. Land-use and land-cover maps and spatial co-variants

We used the official cartography of both countries. For comparison purposes, we choose the most proximate time frame between maps for both countries. Guatemala has only two available land-use/cover maps (2005 and 2012) (SEGEPLAN, 2018). Therefore, we used the 2005 and 2011 land use/cover maps of Mexico (INEGI, 2005, 2011). We harmonized all land-use/cover classes to common classes (Table S1 and Table S2). The final land-use/cover classes consisted of eight categories (Fig. 1): four natural classes that represent main ecosystem in the area (temperate forests, tropical forests, hydrophilic vegetation, and natural grasslands) (Rzedowski, 1990), three anthropogenic classes (agriculture, human settlements, and pasturelands), and water bodies (lakes and rivers). The anthropogenic covers are mostly related to pasturelands for

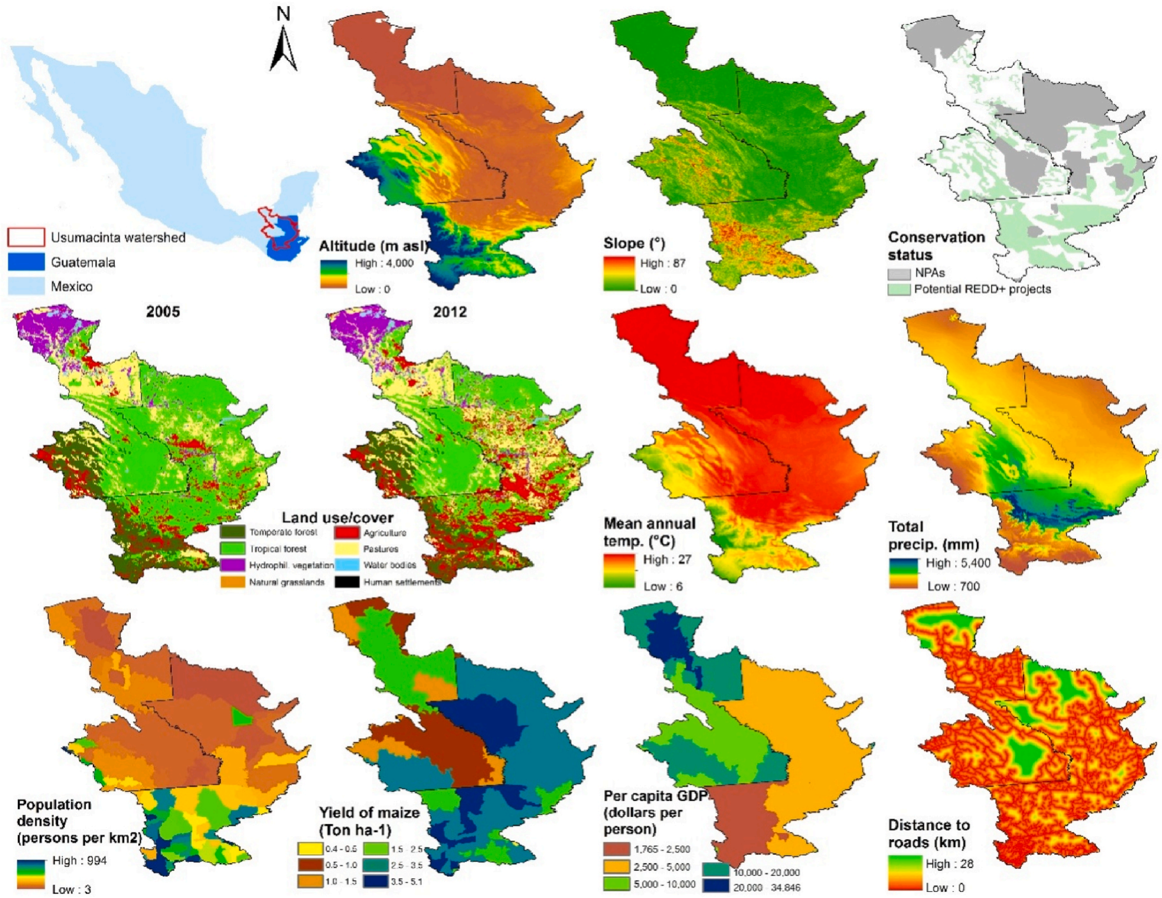

Fig. 1. Usumacinta watershed location and its biophysical, and socioeconomic elements. **Color online only. NPAs stands for Natural Protected Areas. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

livestock and agriculture, mainly for maize and beans for self-subsistence (Christman et al., 2015). However, there are also banana plantations, sugar cane, coffee, rubber plant, and oil palm and localized urban areas and multiple rural settlements (Fig. 1).

We selected various spatial explanatory variables to identify the main drivers of change. Variable selection was restricted to data availability for both countries. We integrated socioeconomic and biophysical variables at the finest resolution available. The socioeconomic variables at the municipality level are population, gross domestic product (GDP), and maize yield. We included maize yield because this crop represents more than 70% of the watershed's total agricultural area (SEGEPLAN, 2018; SIAP, 2018) (Table S3). We selected the following biophysical variables: altitude, aspect, slope, terrain curvature, and topographic index, derived from a digital terrain model with a spatial resolution of 90-m from the SRTM (Shuttle Radar Topography Mission V.2.1, NASA). We also built a hydrological network, and from it, we calculated the distance to runoffs. The hydrological network integrated the perennial river contours from Maderey and Torres-Ruata (1990) and stream networks created from a digital elevation model from which we identified sinks, determined flow direction, calculated flow accumulation, delineated watersheds, and created stream networks. Complementarily, we included mean annual potential solar irradiance, mean annual temperature, and total precipitation to evaluate their influence to restrict the distribution of the anthropogenic covers, particularly agriculture (Fick and Hijmans, 2017) (Table S2). We derived the mean annual potential solar irradiance by varying the azimuth and projecting the shades on the terrain. When possible, we applied different transformations to the data to improve the fit. We used QGIS (QGIS-2.6.0, 2014) and the 'raster' library in R (Hijmans et al., 2020) to carry on all spatial analyses. All variables were tested for spatial correlation (Spearman $r^2 \geq 0.7$) and removed from the analysis those with the lowest explanatory power (Table S4).

2.3. Land use/cover change modeling and scenarios

We developed the land use/cover change (LUCC) model in Dinamica EGO (version 4.0) (Soares-Filho et al., 2009). We calculated a transition matrix for the period 2005–2012 to identify the dynamics and magnitude of changes. We considered sixteen LUCC transitions of the 42 potential transitions because they explained 99.7% of the total LUCC area (Table S5). We categorized continuous variables following a modification of Agterberg and Bonham-Carter's method (1990), which creates ranges based on the breaking points maintaining the original data structure. Then, we calculated the weights of evidence (WoE) to determine the statistical importance of each explanatory variable for every modelled transition.

We validated the model in terms of allocation and quantity of predicted changes. We made an exponential decay comparison between the real changes (observed) and the modelled changes. This test assesses the model's spatial fitness to predict changes at various spatial resolutions, known as *Reciprocal Similarity Map* (Soares-Filho et al., 2009). Due to the limitation of available data, we performed two periods of validation. The first period refers to the predicted changes for the year 2012 for the whole watershed. The second refers to an independent validation for the year 2015 of the Mexican part of the watershed (Fig. S1). Then, we projected annual LUCC trajectories until 2050. Our projections assume that the statistical influence of the explanatory variables on the modelled transitions will be similar in the future as in the past.

We created three scenarios considering three elements: 1) a socioeconomic projection, 2) climate change (mean annual temperature, total precipitation, and maize yield), and 3) LUCC trajectories (Fig. S2). The socioeconomic projection was kept the same for the three scenarios; we used the Shared Socioeconomic Pathway 2 (SSP2) (Kc and Lutz, 2017). The first scenario consisted of a Business as Usual (BAU) trend, for which we considered the Representative Concentration Pathway (RCP) 6.0 (Fujino et al., 2006), and for the LUCC trajectories, we projected the historical rates of change. The RCP6.0 is a pathway that describes trends in long-term, global emissions of greenhouse gases (GHGs), short-lived species, and land-use/land-cover change leading to a stabilization of radiative forcing at 6.0 Watts per square meter (Wm^{-2}) in the year 2100 without exceeding that value in prior years (Masui et al., 2011).

The second scenario has the assumption of REDD + policy implementation focused on developing countries. Such projects assess the impacts of implementing the Paris Agreement commitments for Guatemala and Mexico, in which both countries agreed to reduce at least 20% the GEI emissions by 2030, in comparison with the baseline. The reduction of deforestation and degradation assumes improvement and diversification of agricultural and livestock practices to avoid their expansion. The spatial allocation of the REDD + projects was based on the national restoration proposals developed by Guatemala and Mexico (Mesa de Restauración del Paisaje Forestal de Guatemala, 2015; Tobón et al., 2017) (Fig. 1). The third scenario consisted of a modification to the REDD + scenario from 2030 onwards, assuming a zero-deforestation policy. This scenario considered a REDD + policy only for the first period (2020–2030) and the reinforcement with a zero-deforestation policy between 2030 and 2050 (Table S1 and S2). The second and third scenarios used the RCP 2.6 for the climatic data. The RCP2.6 scenario is representative of the literature on mitigation scenarios aiming to limit the increase of global mean temperature to 2 °C. It is shown to be technically feasible, assuming full participation of all countries (Van Vuuren et al., 2011).

We downscaled the demographic and economic projections at the municipality level based on IIASA projections (IIASA, 2016) and the national census for Guatemala (SEGEPLAN, 2018; INE, 2019) and Mexico (INEGI, 2010), and integrated the impacts of climate change on maize for both climate change scenarios (see Section 2.5). Climate projections were obtained from three General Circulation Models (GCMs) (HADGEM2-ES, IPSL-CM5A-LR, and MIROC-ESM-CHEM).

2.4. Carbon stocks

To estimate the above-ground carbon stock (AGC) we used two elements: 1) the National Forest Inventory of Mexico (NFI, 2004–2009) (CONAFOR, 2012) and 2) a set of allometric equations available for Mexico. The NFI database consists of plots of 400 m^2. Within each plot, diameter at breast height, tree height, and species classification were recorded. Carbon stocks were assumed as the 50% of the dry above-ground biomass. For more details about how the AGC per plot was calculated refer to Mendoza-Ponce et al. (2018). By integrating the multiple thematic land use/cover maps from Mexico (1983–2016), we built chronosequences and related them to the mean AGC for each ecosystem, following the approach of Paine et al. (2012). We developed time series for each pixel of the watershed by integrating current (2005 and 2012) and future (2012–2050) land use/cover maps to estimate the age of the vegetation for each time-period. Finally, the age of each pixel was transformed to a mean value of C stock. In Guatemala, there is no available information about field observations to estimate AGC. Therefore, we considered that the high density of the field plots (N = 1061) allocated in the Mexican territory of the watershed would also reflect the conditions of the Guatemalan ecosystems.

2.5. Climate change impacts on maize yields

We used official sources for maize yields at the municipality level for 2005–2012 for both countries, Guatemala, and Mexico (SEGEPLAN, 2018; SIAP, 2018; INE, 2019). Maize yield changes were based on the Agricultural Model Intercomparison and Improvement Project (AgMIP) (Rosenzweig et al., 2013) and the AIRCCA model (Estrada et al., 2020). We used two RCPs (2.6 and 6.0) and three GCMs according to the EPIC agricultural model for assessing the impacts of these RCPs on maize yields. The BAU scenario was combined with the impacts of RCP6.0 and the other two scenarios with the RCP2.6. The future climate conditions are characterized using the ensemble mean, as well as the 5th and 95th percentiles, of annual temperatures (max, min and mean), total annual precipitation and relative humidity. The climate data was obtained from the Atlas of Global and Regional Climate Projections of the IPCC's Fifth Assessment Report (IPCC et al., 2013) using the Climate Explorer tool (https://climexp.knmi.nl/).

3. Results

3.1. Land-use/cover change dynamics and carbon stocks

The Usumacinta watershed showed a deforestation rate of 1.1 million ha at an annual rate of −3.3% during the period 2005–2012 (Table 1). The tropical rain forest was the ecosystem with the largest loss (0.9 million ha) at a rate of 3.9% $year^{-1}$. This ecosystem accounted for 50.2% of the total area in the Usumacinta watershed in 2005, and it decreased to 37.9% in 2012. The losses of forests were in the southern part of the watershed (Fig. 2). The BAU and REDD + scenarios indicate that the tropical rain forests could cover 22.6 and 26.9% of the total area by 2030, respectively (Fig. 3). Furthermore, by 2050, it might lose 50% of its extent relative to 2005; however, if the zero-deforestation commitment is fulfilled, it could recover 76% compared to the base year, representing 38% of the watershed. Temperate forests showed a loss rate of 2.7% $year^{-1}$; this ecosystem accounted for 14.4 and 11.9% of the area in 2005 and 2012, respectively. By 2030, it would account for 9.6 and 11.1% of the watershed, respectively, and 8.4 and 11.9% for each scenario by 2050, respectively. The results suggest that REDD + projects would be less effective in temperate forests than in tropical forests, avoiding 262 thousand ha and 484 thousand ha, respectively by 2050. However, the zero-deforestation scenario showed that the temperate forests could increase to 16.0% of the watershed by 2050. The hydrophilic vegetation and natural grasslands show a minimal reduction (84 ha during the historical period). Agriculture and pasture explained 98.4% of the deforestation, increasing at an annual rate of 10.9 and 3.1% $year^{-1}$, respectively. Human settlements expanded 14,479 ha, at a rate of 10.3% $year^{-1}$.

Combining all the natural ecosystems in a single category (natural cover), we found that the BAU scenario showed a constant decrease of natural cover, 1.3 and 1.7 million ha by 2030 and 2050, respectively, compared to 2012. The REDD + scenario shows a reduction in deforestation (0.9 million ha), representing an avoided deforestation of 0.5 and 0.8 million ha, especially in tropical forests (Fig. 3) for 2030 and 2050, respectively. On the contrary, in the zero-deforestation scenario, the region would recover 0.4 million ha of natural vegetation compared to 2012 (Fig. 3).

Guatemala and Mexico show different LUCC patterns. The lowest agricultural expansion and larger permanence of natural covers, mostly tropical forests, were in the central portion of the watershed, in Mexico, and within the protected areas in northern Guatemala (Figs. 2 and 4). In turn, the most extensive deforestation processes due to agricultural expansion occurred mostly in the eastern portion of the watershed, on the Guatemala side. Forest regeneration mainly took place in the tropical and temperate forests of the Mexican side (Figs. 2 and 4).

In terms of C stocks, we estimated that by 2012 the watershed had 299.1 TgC and under the BAU scenario this stock could reduce in average 20.0 TgC by 2020 (Fig. 5). By 2030, 2050, these reductions are less significant due to the large potential of C sequestration in secondary forests (1.1 and 0.6 TgC annually, respectively) (Fig. S3). The REDD +

Table 1
LUCC transition matrix of the period 2005–2012 of the Usumacinta watershed in Guatemala and Mexico. The transitions are in thousand hectares for the whole period. Values within the matrix expressed as 0.0 refer to areas <49 ha, while the symbol "-" refers to NULL. The rates of change are represented in percentage per year. They were calculated based on the FAO equation (FAO, 1995) (Rc = [(A2/A1)^1/n]^-1)*100%; where *A* refers to the area in the time 1 or time 2, *n* is the number of years of the period, and *Rc* is the rate of change in percentage per year.

Land use/cover	Temperate forest	Tropical forest	Hydrophilic vegetation	Natural grassland	Agriculture	Pastures	Human settlements	Bare soil	Total 2005	Rate of change (2005–2012)
Temperate forest	853.9	–	–	–	189.9	42.3	0.8	3.9	1090.8	−2.7
Tropical forest	–	2727.1	–	–	550.1	522.7	3.4	0.0	3803.3	−3.9
Hydrophilic vegetation	–	–	484.3	–	4.4	19.2	0.0	0.0	508.0	0.0
Natural grassland	–	–	–	0.2	–	–	–	–	0.2	0.0
Agriculture	29.9	35.9	2.1	–	521.5	109.7	3.3		702.4	10.9
Pastures	18.2	112.9	20.8	–	187.5	1113.6	7.0	0.0	1460.0	3.1
Human settlements	–	–	–	–	–	–	14.7		14,7	10.3
Bare land	0.0	0.0	0.7		0.0	0.2		3.0	3.9	8.7
Total 2012	902.0	2875.9	507.9	0.2	1453.5	1807.7	29.1	7.0		
Change (2005–2012)	188.8	927.5	0.0	0.0	751.1	347.7	14.5	3.1		

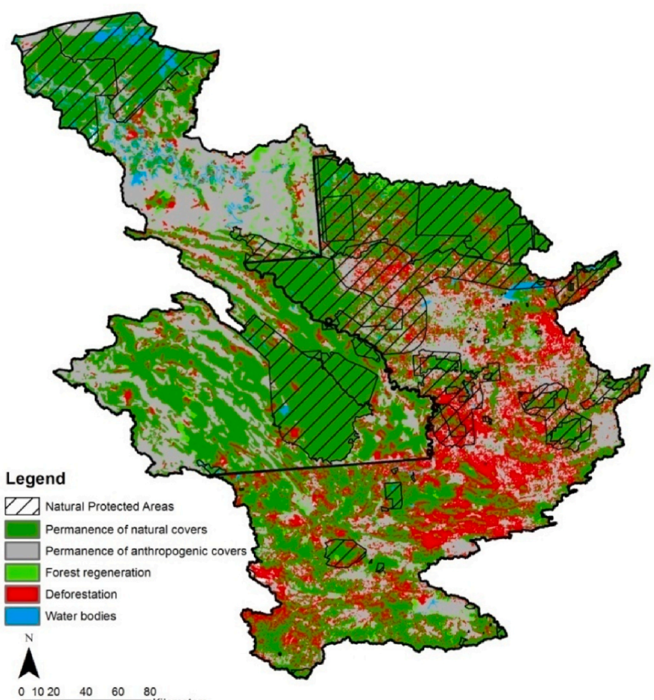

Fig. 2. Deforestation, regeneration, and permanence of natural and anthropogenic covers for the period 2005–2012. The dark line represents the boundary between Guatemala and México. **Color online only. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

scenario suggests that by 2050 it is possible to sequester up to 31.7 TgC, resulting in 10.8% of the C stocks recorded in the year 2012. More intense C sequestration is expected with the implementation of a zero-deforestation policy, reaching total sequestration of 104.3 TgC by 2050. This increment represents 35.5% compared to the baseline. In REDD+ and zero-deforestation policies, the largest C sequestrations are related to aging forest, and rapid abandonment of agricultural practices, particularly in the southern portion of the watershed and in the northern border between Guatemala and Mexico (Fig. S4, S5 and S6).

3.2. Explanatory variables behind the LUCC dynamics

Agricultural and pastureland expansion are key factors driving deforestation (Fig. 3). Guatemalan municipalities would exhibit the largest tropical forest loss, especially in the southern part of the Usumacinta watershed (Fig. 4). Municipalities like Zacualpa, San Pedro Jocopilas, San Bartolomé Jocotenango, Santa Eulalia, and Quiché, in Guatemala, and Ocosingo, Marqués de Comillas, Benémerito de las Americas, and Tenosique, in Mexico, would be the most affected. The protected areas showed the lowest LUCC impact, mainly the Mayan Biosphere Reserve, Laguna del Tigre, and San Román, in Guatemala, and Montes Azules and Laguna de Términos in Mexico. It is important to notice that although these protected areas are less affected by LUCC, there are agricultural and livestock expansions in the buffer areas.

The socioeconomic variables were more relevant than the biophysical ones to explain the changes from temperate and tropical forests to agriculture (Table S6 and Table S7). Among the former, those related to accessibility were the most important for transitions to agriculture. For example, most of the deforestation took place <2 km from human settlements and roads, mainly in rural communities. Overall, the southern portion of the watershed, located primarily in Guatemala, contained most of these transitions. Moreover, densely populated municipalities (0–100 people per km^2) exhibited higher deforestation. The transition from temperate forest to agriculture occurred in municipalities with lower income; the dominant transition from tropical forest to agriculture occurred in wealthier municipalities.

The conversion of natural vegetation to pasturelands was related to the water supply (Table S6 and Table S7). Most of the transitions from temperate forests to pasturelands took place <5 km from rivers and <17 km from water bodies. These ranges were smaller in the tropical forest conversion, at <2 km and <6 km, respectively. Pastureland expansion was observed mostly at <2000 m asl (Table S6 and Table S7). Accessibility was also relevant to explain transitions to pasturelands. In general, pastureland expansion mainly happened at <3 km from localities and <4 km from roads in tropical forests. Another variable related to the expansion of pasturelands was maize yields. Municipalities with temperate forests and low maize yield (<1.5 ton•ha^{-1}) were more prone to change to pasture than agriculture. Meanwhile, in tropical forests, the expansion of pasturelands occurred in municipalities with low population density (<50 people per km^2).

The exchange between agriculture and pastureland were closely related (Table S8). The substitution from one land-use/cover to another happened at altitudes <400 m asl and close to human settlements (<3 km) and roads (<2 km). These transitions occurred in municipalities with medium to high maize yields (2.8–4.2 ton•ha^{-1}) and population density of <50 people per km^2. Agricultural expansion over pastureland happened at temperatures of 26–28 °C, and the opposite, i.e., from pasturelands to agriculture, occurred in a range of 25–27 °C.

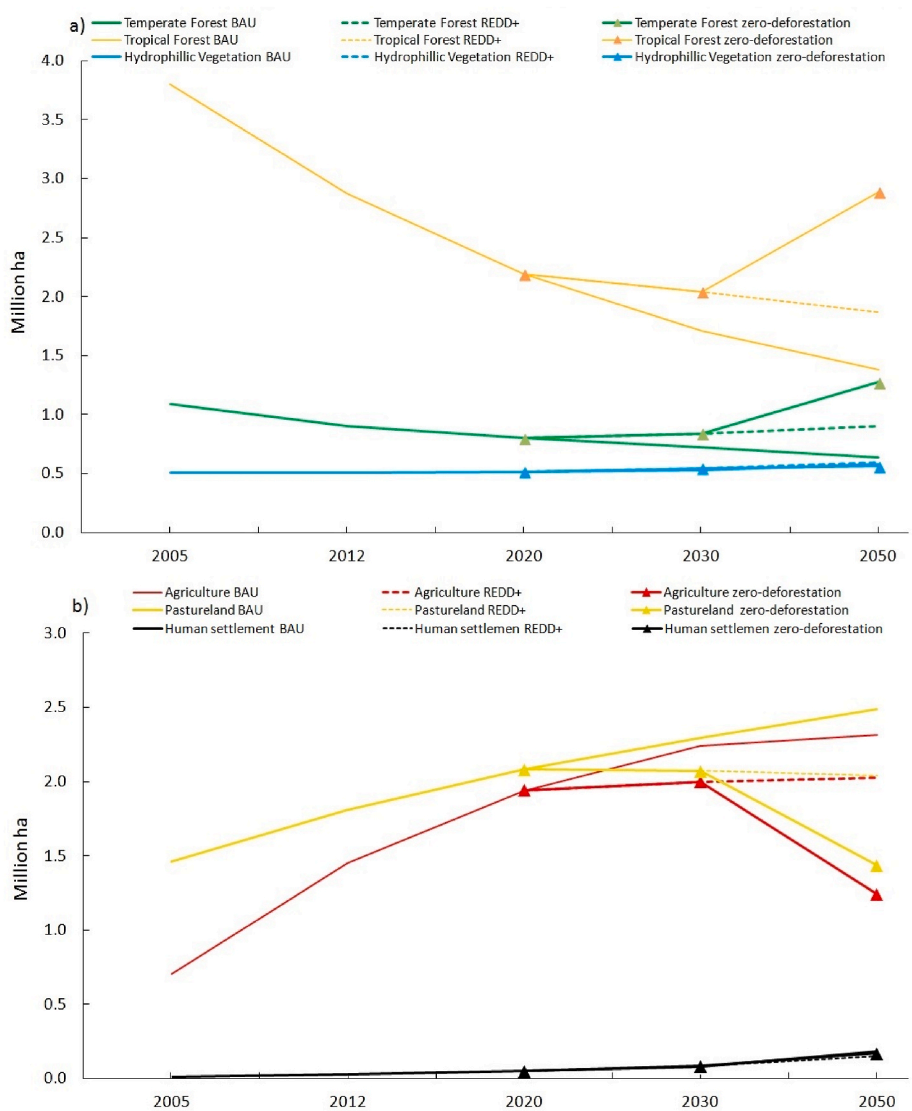

Fig. 3. Total extent of land use/cover classes of the Usumacinta watershed in decadal lapses for the period 2005–2050. The total area is expressed in million hectares. Panel (a) refers to natural covers, and (b) refers to anthropogenic covers. **Color online only. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Forest regeneration from agriculture (Table S9) occurred in isolated regions, at high altitudes, far from water bodies (>5 km), rivers (>4 km for temperate and >1.2 km in tropical forests), or human settlements (>2 km) (Table S9). Moreover, maize yields did not influence the abandonment of agricultural lands. We found that municipalities with maize yields of 2.0–4.2 ton•ha^{-1} exhibited the most extensive regeneration in temperate and tropical forests. Biophysical factors linked to agricultural and pastureland abandonment were similar in temperate and tropical forests. For instance, abandonment of large agricultural areas occurred far from water bodies (>4 km), rivers (>3.0 and 4.6, respectively), and roads (2–5 km), but <3 km from human settlements. In contrast, pasturelands abandonment was linked to municipalities with population densities <50 people per km^2.

3.3. *Socioeconomic growth, climate and maize yields projections*

The human population in the Usumacinta watershed is projected to increase from 3.9 to 4.8 and 5.7 million people by 2030 and 2050, respectively. Seventy-four percent of the population lives in Guatemala, and the southeastern portion holds the highest population density (Fig. 1). Table S10 provides a characterization of the changes in annual minimum, maximum and mean temperatures, total annual precipitation, and relative humidity, for the watershed area and for 20-year averages centered in 2035 and 2050, according to the RCP6.0 and RCP2.6. The average projections under the two emissions scenarios are similar for all variables and the time horizons. This result underlines that the radiative forcing produced by the RCP2.6 and RCP6.0 emissions scenarios remain similar until the second part of the present century, and so are the associated changes in climatic variables. Moreover, this is also true for the projected changes in maize yields which are similar for the selected time horizon: 87 and 91% of the watershed would decrease at least 10% under RCP 2.6 and RCP6.0 by 2050, respectively. The RCP6.0 implies for most of the basin about 10% larger losses in maize yields in comparison with the RCP2.6. Moreover, it should be noted that changes in climate and yield are spatially heterogeneous and some regions in the northern part of the watershed could have larger decreases in yields of up to 40.0% and close to 20.0% under the RCP6.0 and RCP2.6, respectively.

4. Discussion

The challenge to preserve forest ecosystems while covering food

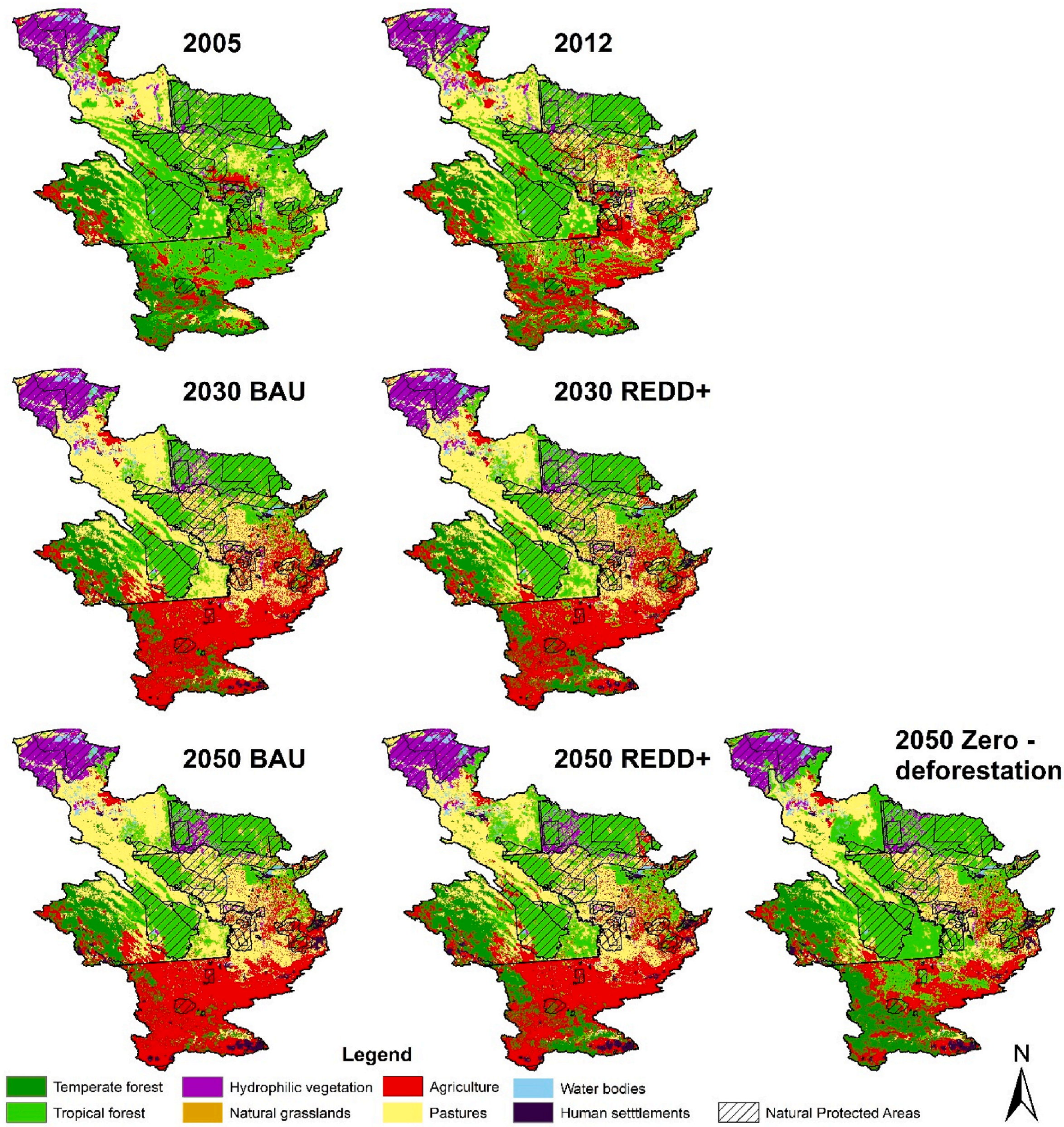

Fig. 4. Spatial distribution of the land-use/cover categories for the BAU, REDD+ and zero-deforestation scenarios (HADGEM2-ES). All other climatic models can be seen in the Supplementary Material (Fig. S7). **Color online only. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

sufficiency with a growing population is critical for developing countries facing the economic globalization pressure (Lambin and Meyfroidt, 2011). This is evident in biologically and culturally rich areas like the Usumacinta watershed. Agriculture and livestock have been expanding and replacing forests throughout Latin America (Mendoza-Ponce et al., 2018). Tropical evergreen forests have shown high deforestation rates, and those from the Usumacinta watershed are similar to other reported in Guatemala (-4.0% year^{-1} between 2001 and 2006) (Castellanos et al., 2011), and Mexico (-3.8% year^{-1} between 2007 and 2011) (Mendoza-Ponce et al., 2018). However, the deforestation rate of temperate forest three-folds the average reported for some regions of Guatemala (-1.2% year^{-1}) (Pope et al., 2015)and Mexico (-1.4% year^{-1} for a similar period) (Mendoza-Ponce et al., 2018). This is related to several factors, including the lack of protected areas in temperate forests due to a bias to protect tropical evergreen forests and hydrophilic vegetation. Besides, protected areas will face increasing pressures in the future, particularly in Guatemala. For example, some protected areas will avoid LUCC in core areas (Mayan Biosphere Reserve and Montes Azules), but large LUCC is expected in buffer areas, as observed in other regions (Bray et al., 2008).

Agricultural activities followed by grazing are the main drivers of LUCC in the Usumacinta watershed. Forest transformation is related to small production for self-consumption related to shifting cultivation (i.e., maize, beans and squash) (Palomeque de la Cruz et al., 2019). More recently has been recognized the expansion of extensive plantations, illegal drug activities, and cattle raising as important drivers of deforestation (Devine et al., 2020). Traditional shifting cultivation is generally less aggressive than livestock production and intensive monocultures. Besides, studies in the region show that shifting cultivation is usually grown in secondary vegetation (83.0%) and toa lesser extent in primary forests (17.0%) (Chancayun Kin, 2019). However, further analysis that includes the extension and impacts of management

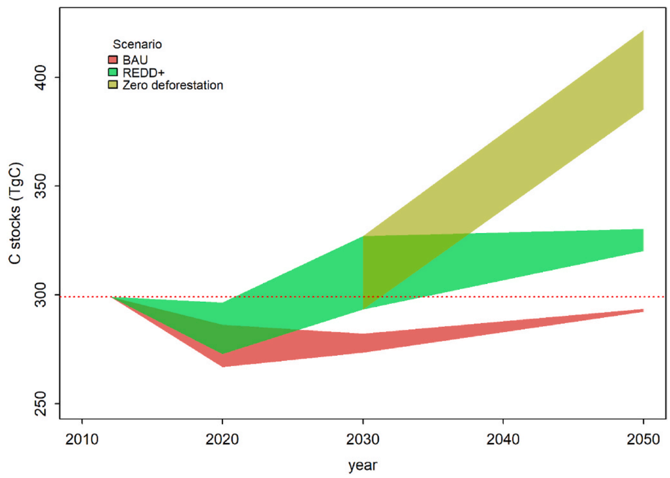

Fig. 5. Carbon stocks for the BAU, REDD+ and zero-deforestation scenarios. The shading refers to the uncertainty between climatic models for each year. The red dotted line expresses the carbon stocks calculated for the base year (2012). **Color online only. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

systems on soil properties should be performed. Moreover, new crops in the region such as teak, rubber, and oil palm are more profitable and induce an expansion of agricultural lands since the early 2000s (Christman et al., 2015; MARN, 2019). The higher remittances of these agricultural commodities or livestock, compared to the incomes of maize production, might induce new conservation challenges to reduce the impact of LUCC (Eakin et al., 2015; Mendoza-Ponce et al., 2019). LUCC mitigation projects are not new in the region. In Guatemala it was recently published the National Strategy for Addressing Deforestation and Degradation in Guatemala (MARN et al., 2021) which includes all the requirements of project implementation, monitoring and benefits sharing (MARN et al., 2021); however, real applications and results are still missing. For instance, there is one REDD + project in the Mayan Biosphere Reserve in the northern Guatemalan Usumacinta watershed. This project spans from 2012 to 2042 (CIFOR et al., 2015) and is founded on a community-based conservation management scheme of forest concessions that rely on the extraction of certified forest products (Stults, 2018). The preliminary results from 2014 indicate a 40% reduction in deforestation (Figueroa et al., 2015; Stults, 2018). REDD + framework in Mexico aims to develop and implement mitigation and adaptation strategies in policies supported by fundings through sustainable development in the communities. The goals are avoiding deforestation and degradation of ecosystems while improving economic conditions of people. Additionally, Mexico has implemented REDD + projects in the Lacandona region since 2007. There is the Special Early REDD + Action Programme related to the Payment for Ecosystem Services (PES) scheme. In 2010, this Program was linked to the National Strategy for Reducing Emissions from Deforestation (ENAREDD+) (CONAFOR et al., 2016) that establishes the guidelines to implement the REDD + projects and to pursue the international commitments by 2030 (CICC and CICC CONAFOR, 2017). The project in the Lacandona region included 17 municipalities aimed to reduce LUCC specifically from livestock, coffee plantations (Los Altos region), maize, and oil palm expansion (Covaleda et al., 2014). According to Ortiz et (2015) payment for ecosystem services in the region led to reducing deforestation; however, the effectivity varied depending on specific traits in the communities and their organization (Izquierdo-Tort, 2020), similar to our results. Interestingly, by 2050 a zero-deforestation policy could double the C sequestration than REDD + projects only. Since the implementation of REDD+ in Mexico in 2010, 25 major projects have been implemented with REDD + related funding (CONAFOR, 2019) with mixed results (Ellis et al., 2020). In Guatemala there is the National Strategy for Addressing Deforestation and Degradation in Guatemala (MARN et al., 2021). The country has three important REDD + projects "Lacandon- Bosques para la Vida", "GuateCarbon" and "Costa de la Conservación". The National REDD + Strategy of Guatemala include all the requirements of project implementation, monitoring and benefits sharing (MARN et al., 2021); however, real applications and results are still missing.

Deforestation rates decreased but abandoned areas are not recovering because people rent these lands to grow more profitable crops and for livestock (Eakin et al., 2015). However, a slight decrease in deforestation is not enough to preserve the regional biodiversity. Thus, an extra political effort is urgently needed to stop deforestation, even more, when climate change projects reinforcing LUCC dynamics to expand pasturelands on regions where agriculture shows less suitable conditions such as lower precipitation and higher temperatures.

Our study suggests the necessity to enforce REDD + projects to recover the C stocks of the base year. REDD + projects may result in economic incentives that would break the ties and reliance on the land and engage people in non-agricultural occupations (Shriar, 2002). The payment of ecosystem services is a good alternative to face poverty and marginalization problems. However, to ensure its effectiveness and achieve the national NDCs, different options should be enhanced and supported by national and local governments and NGOs, not only to decrease but to stop deforestation. These alternatives may include sustainable forestry of valuable tree species and non-timber species (Stults, 2018). Besides, analyses of results based on biodiversity and ecological forestry are needed to assess the effectiveness of REDD + projects (Duchelle et al., 2018). Furthermore, comprehensive transboundary planning in the region may improve the environmental and social conditions to foster adequate and sustainable management. Nevertheless, our analysis shows that this policy not only may induce the reduction of deforestation. But promotes forest growth, ageing and C sequestration in natural vegetation.

It is worth mentioning that both countries recognize the importance of the international community to financially support developing countries. Guatemala has developed and implemented the National Climate Change Fund and has promoted the Latin American Network of Municipalities, Cities and Territories in the face of Climate Change (Comisión Europea, 2019). This international cooperation is crucial to ensuring the effectiveness of instruments such as REDD+ and zero-deforestation commitment in the Usumacinta watershed.

5. Conclusions

One of the priorities and challenges of the global environmental commitments is to focus the efforts on areas with high levels of poverty, biologically relevant, and within transboundary landscapes, like the Usumacinta watershed. The anthropic pressure will be exacerbated by the increasing population that demands more resources and by climate change. On the one hand, human population in the Usumacinta watershed is projected to increase from 3.9 to 4.8 and 5.7 million people by 2030 and 2050, respectively; on the other hand, maize yields would decrease from up to 20% in 2030 and between 10.0 and 40.0% for some regions of the watershed in 2050, under the RCP6.0. If the historical trend of land-management practices is kept, we can expect that up to 22.3% of the natural ecosystems could be lost by 2050, also increasing its C emissions. However, REDD + projects and the implementation of a zero-deforestation policy may recover the forested area recorded in 2012 and sequester important amounts of CO_2. These scenarios showed that even with penalizing the demand of food in relation to the upcoming human pressure it is possible to reduce deforestation and increase carbon uptake. However, these projects should include resilient agroforestry, improvement of agricultural practices to sustainably increase their yields, preserving soil, water, and ecological traits. While they should be embedded in transboundary policies to combine efforts between countries aiming to reduce deforestation. We consider that these mechanisms could help to ensure the permanence of ecosystem services and biodiversity. Also, human population would reduce its risks to climate change, particularly rural population that depend on self-subsistence production, might cope potential hunger due to reduction in maize yields, soil degradation and water deficit.

Credit author statement

Alma V. Mendoza-Ponce and Rogelio O. Corona-Núñez worked on the original idea, the modeling, the structure of the paper, the figures and writing. Luzma Fabiola Nava-Jiménez, Francisco Estrada Porrúa and Enrique Martínez-Meyer collaborated with the discussion of the ideas and writing. Oscar Calderón-Bustamante developed the maize yield projections. Adriana H. Larralde-Corona, Mercedes Barrios and Pedro D. Pardo-Villegas helped with getting data. Julia Carabias developed the original idea of the FORDECYT project and supported importantly the funding for the project.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2021.113748.

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