Applying a systems approach to assess carbon emission reductions from climate change mitigation in Mexico’s forest sector

by

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Chapter 1. Introduction

Mexico consumes the most fossil fuels of all Latin American countries (IEA 2016), contributing about 1.4% of total global greenhouse gas emissions (GHG) (INECC-SEMARNAT 2015). The Government of Mexico has committed to monitor and reduce its net GHG emissions to the atmosphere (SEMARNAT-INECC 2016)

in forests, carbon storage in harvested wood products (HWP) and changes in emissions from displacing emissions intensive products and fossil energy sources (Nabuurs *et al.* 2007, Lemprière *et al.* 2013, Kurz *et al.* 2016b). This is the first comprehensive forest sector-based mitigation analysis using the same primary data employed in Mexico´s
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Figure 1.Durango (DGO) and Quintana Roo (QROO) study areas with main land-use/land-cover classes.

The state of Quintana Roo (QROO; Figure 1) is located on the east side of the Yucatan Peninsula, covering an area of 4.4 M ha (INEGI 2011). The climate is sub-tropical, hot and sub-humid, with dry winters and wet summers. MAP and MAT are 1200 mm and 26 °C, respectively (García 1998). Topography is characterized by a limestone platform with little elevational profile ranging from 0 to 300 m asl. Soil types are mainly Leptosols (~50%), but also Gleysols, Phaeozems and Vertisols (Fragoso-Servón *et al.* 2017). Forest lands cover an area of about 3.7 M ha (INEGI 2011), characterized mainly by tropical semi-

this study, we used the same spatial approach, comprising 4 ecoregions for DGO and 2 for QROO (Figure 2). Together, these SPUs contain about 14% of the forest land in Mexico (INEGI 2011).

Figure 2. Distribution of the 6 Spatial Units resulted from the intersections of North American Ecoregions-Level I polygons (in colors) and Mexican states boundaries (in black) selected as pilot areas for Mexico: four in Durango and two in Quintana Roo.

To better characterize key drivers of change within each SPU, we included more detailed information on: *i) Ecoregions level IV* (e.g., detailed ecological variables such as climate, topography, and vegetation types) (CEC 1997); *ii) forest classes and other vegetation types* from Land-Use/Land-Cover maps published by the National Institute of Statistics and Geography of Mexico (INEGI 1993, 2002, 2007, 2011) reclassified into five forest types and five non-forest/other type classes (Table 1), harmonized with IPCC Land-Use categories, Mexico´s Biennial Update Report (BUR) (INECC-SEMARNAT 2015) and MAD-Mex system labels (Monitoring Activity Data for the Mexican REDD+ program, Gebhardt *et al*. 2015); *iii) regulated silvicultural activities* (e.g. spatial information regarding areas with natural forests and plantations); *iv) conservation practices*, including protected areas (federal, state and municipal), environmental services payment areas, wildlife management units, from spatial databases available from the National Commission for Forestry (CONAFOR), the National Commission for Protected Areas (CONANP) and the Secretariat of Environment and Natural Resources (SEMARNAT) (CEC 2010); *v) early actions for REDD*+ (CONAFOR 2015); and *vi) municipal boundaries* (INEGI 2016).

Table 1.Classification scheme for INEGI´s Land Use/Land Cover labels into general classes used in this study, harmonized according to IPCC, Biennial Update Report (BUR) and Monitoring Activity Data for the Mexican REDD+ program (MAD-Mex) categories.

et al

Forest lands

permanent monitoring plots (each having four circular subplots of 400 m^2) systematically established throughout the country by CONAFOR, between 2004 and 2007 and re-measured from 2009-2013 (CONAFOR 2012).

To generate merchantable volume and biomass growth curves, we first identified all plots available from the national database for measurements at time 1 (T1), and re-measurements (T2), that shared the same ecoregion level IV identification present in the two selected states. This stratification criterion allowed us to ensure having enough plots to conduct the growth analysis, regardless of political boundaries (Figure 3). We then selected those plots that had the same forest cover type at T1 and T2, with no missing information (four subplots by plot), and extracted live tree biomass information in both periods (Forest land remaining Forest land; FL-FL).

Figure 3. Example of INFYS plots selection for growth curves in QROO, using information on (a) ecoregion level IV (Tropical Dry in red, Tropical Humid in purple, Temperate Sierras in green), (b) plot locations (dots) and number of plots measured and re-measured, and (c) permanent forest cover (green color with different forest cover types in various shades of green).

A growth curve simulation routine was created by Gregorio Ángeles (

Table 2. Example of a Land-Use/Land-

From the change matrices, we observe that total forest land area in both periods equals 5.5 Mha in DGO (88% of the total area) and 3.2 Mha in QROO (90% of the total area). The remaining areas are predominately agriculture and grasslands. The magnitude of the LULC change varied greatly among the states, but there was always more gross deforestation relative to gross forest recovery resulting in net forest cover loss. The cause of some forest land cover changes could not always be identified because of potential error in the polygon labeling or an error in spatial boundaries of the polygons.

remaining as forestland category. It is likely that the same problem may have occurred among non-forest categories. Because there are many challenges in estimating area changes from the intersection of land-cover maps (Olofsson *et al*. 2013), we conducted additional simulations to understand the sensitivity on emissions estimates if deforestation rates and forest recovery rates were underestimated (see section 2.4).

The IPCC requires that carbon fluxes are reported according to six land-use categories: Forest land, Cropland, Grassland, Wetland, Settlements, and Other land (IPCC 2003). In the case of Forest Land (FL), this category was divided into coniferous, broadleaf, tropical humid, and tropical dry. However, there was limited information available to conduct a more detailed analysis of carbon dynamics in non-forest land categories and thus, we grouped them into the Other Land (OL) category. Although we did not simulate activities on this land, we included it to ensure area consistency in the simulations and to track the GHG emissions due to deforestation events (IPCC 2006).

Harvests. Information on the amount of industrial roundwood harvested (in m^3) per forest type was compiled from annual reports at the municipal level from 1991 to 2014 (INEGI 2015a, 2015b). We used maps provided by CONAFOR on managed a

Table 3 summarizes information on average values of the merchantable round wood authorized and harvested from 2005 to 2014 according to the last ten years of data available in annual reports published at the municipal and state levels. Information was compiled for CBM-CFS3 modeling parameters including: percentages of stand-eligibility to harvest, assuming that the rest of the stand-biomass continues to grow; and harvest utili

Fires. We compiled and analyzed municipal-level statistics on area burned by strata (trees/seedlings, scrubland, herbaceous/grasslands) from 1991 to 2016 (CONAFOR 2017). From the analysis of this historic record, most fire events were categorized as surface fires. Based on the analysis of the fire data corresponding to the two states, fires that affect the tree stratum are not as frequent as surface fires (predominantly due to human-caused ignition; Rodríguez 2008). Thus, all fire events were assumed as surface fires. The compiled information does not provide any explicit geographic location of the area burned so, for simplicity, we assumed that any forest stand could be affected by surface fires, but that these could only consume some small trees, foliage and surface litter.

Disturbance matrices

To represent the direct impacts of each disturbance type on carbon stocks and stock changes, the CBM-CFS3 uses disturbance matrices to quantify carbon transfers among carbon pools in the forest ecosystem, between these pools and the atmosphere, and transfers to the forest product sector (Kurz *et al*. 2009, Kull *et al*. 2011). These matrices contain information about each of the 22 ecosystem carbon pools included in the model to represent carbon transfers dynamics in more detail, though these can easily be grouped into the five IPCC carbon pools. Disturbance matrices for deforestation and forest recovery disturbance types were selected from default matrices available in the model and a new disturbance matrix was created to represent non-stand replacing fire face- trees, foliage and surface litter are consumed by the fire but overstory trees are not killed. An additional disturbance matrix representing crown fires could be added in the future to assess their relative contribution in terms of the total CO_2e emissions. However, this would require better data on the proportion of area burned by crown fires.

Table 4 shows the specific parameters corresponding to carbon transfers among pools or out of the ecosystem (to the atmosphere or to the forest products sector) corresponding to fires and deforestation.3 709.92 tirest ereres.s n

Table 4. Examples of disturbance matrices to account for carbon transfers among forest carbon pools and between these and the atmosphere due to: (a) surface fire events and (b) deforestation events which are assumed to consume 20% of the small trees and foliage, and transfer dead standing trees and their branches to the ground.

(a)

Surface fire

2.3. Simulation scenarios

cumulative emission reductions to 2030 and 2050. Finally, because BAU and all scenarios used the same historic information regarding forest characteristics (e.g. forest cover, age-class distribution and disturbances) and HWP assumptions (e.g. end-of-life treatment and decay), net emissions before 2018 were identical and thus their difference with BAU is zero (no-legacy effects).

Table 5. Summary of the four mitigation strategies and sub-scenarios (relative to business as usual BAU) for the forest ecosystem (FE), Harvested wood products (HWP) and Substitution benefit (SB) components, in Durango (DGO) and Quintana Roo (QROO).

Strategy name	Description	Parameter changed	Parameter value
M1. Net zero-deforestation	FE: Gradually reduce gross deforestation rate until in 2030 equals to gross recovery rate. It excludes forests within managed areas.	New gross deforestation rate (Kha yr^{-1}, % reduction from BAU)	
		DGO	3,746 (-49%)
		QROO	7,661 (-53%)
M2. Increased net forest recovery rate	FE: Same gross deforestation rate as in M1, but 10% more forest recovery rate from more intensified practices in non-forest lands.	New gross forest recovery rate (Kha yr^{-1}, % increased from BAU)	
		DGO	375 (+10%)
		QROO	766 (+10%)
M3. Better growth + more harvest + more HWPs with			

2.4. Land-Use Change (LUC) analysis

We compared the impacts of changes in deforestation with changes in forest recovery rates (holding other input variables constant), on the outcome and rank order of mitigation scenarios. The relatively coarse spatial and temporal resolution in the available land-use/land-cover maps (i.e. 4- to 9-year periods, 25 ha minimum mapping unit) could lead to the underestimation of gross deforestation rates. Moreover, reducing net deforestation is among Mexico´s stated forest strategies (UNFCCC 2015) and is expected to provide short-term benefits from national and international REDD+ programs. Thus, as a sensitivity analysis, gross deforestation rates were doubled and gross forest recovery rates increased such that the net deforestation rate remains the same in BAU and in mitigation scenarios to assess the possible impact of underestimating the conversion of forest land to other land uses.

-17.7 Tg CO_2e yr^{-}

For forest land converted to other land (FLOL) during the historic period, emissions vary with the gross deforestation rates. FLOL emissions throughout the historic and baseline periods in DGO are low (1.51 Tg CO_2

Table 6. Average

Figure 7. Cumulative mitigation for four scenarios (with sub-scenarios) in the states of DGO (left column) and QROO (right column) by component: (a) Forests, (b) HWP, (c) displacement and (d) the total cumulative mitigation.

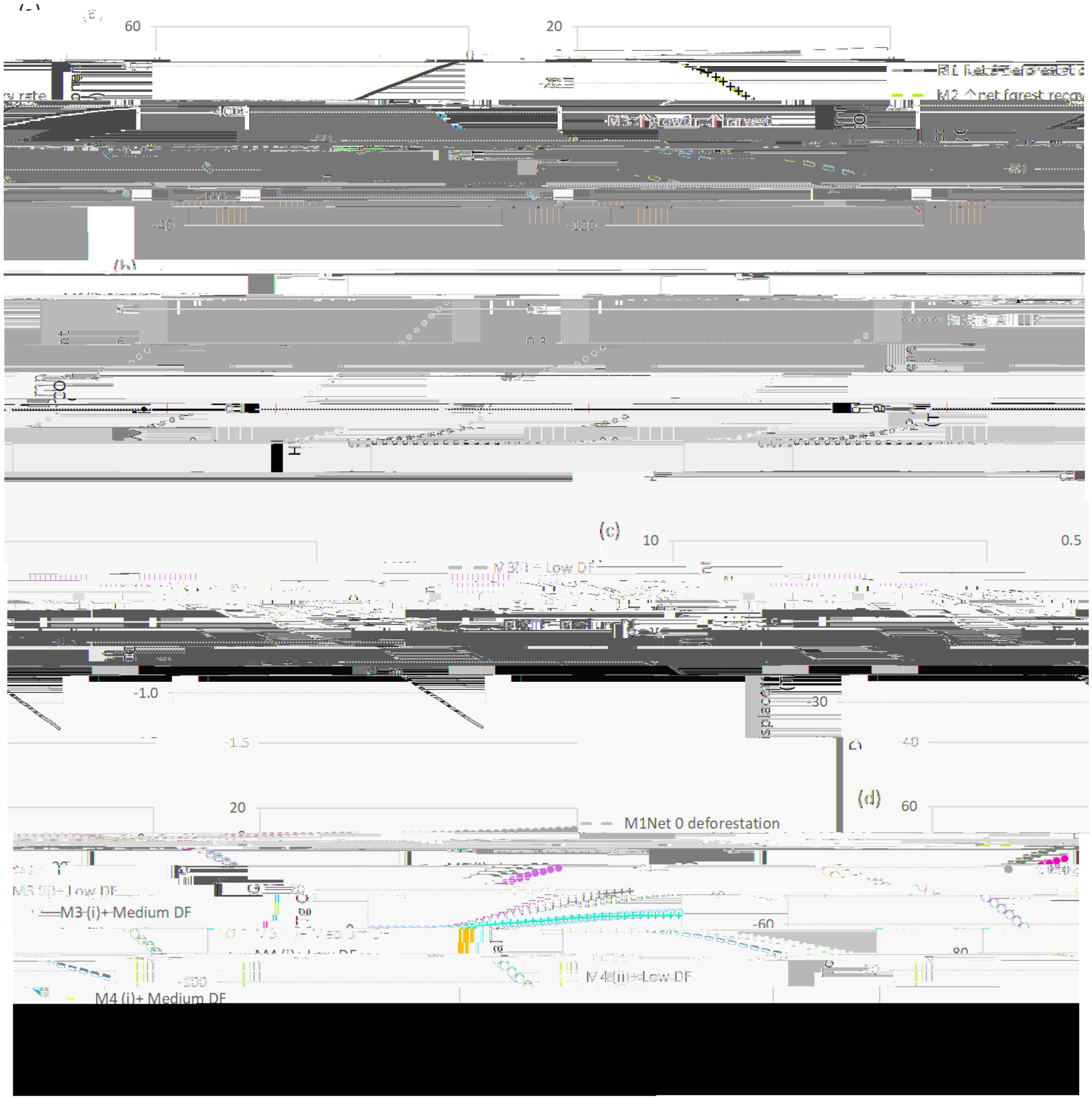
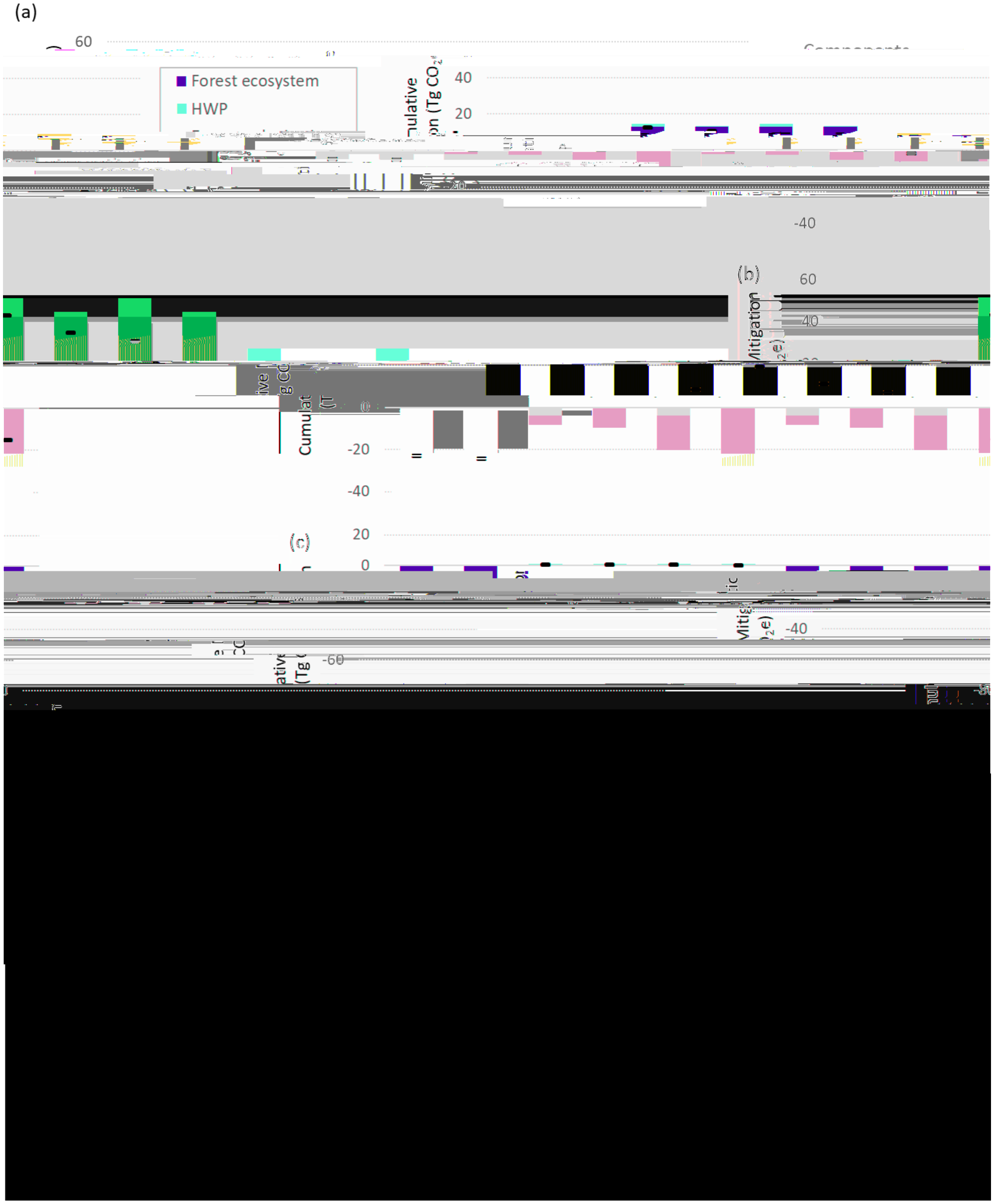


Figure 8. Cumulative mitigation for all systems components and scenarios for the states of DGO (a: year 2030, b: year 2050) and QROO (c: year 2030, d: year 2050).



Chapter 4. Discussion

4.1. Mitigation potential by scenario

In both states, the best mitigation scenario by 2050 is increased net forest recovery rate (net zero deforestation plus 10% increase in recovery): the M2 scenario. This reduces cumulative emissions by -24 TgCO_2e in DGO26.49 5946 Tm[(D)5dETBT1 0 0 1 359.71 598359.71 (i10.)]TJ potential would have increased. These results show that the assumed increase in productivity that can be achieved does not offset potential C stock reductions resulting from increased harvest rates. While increases in forest productivity through forest management can be achieved, to maintain C stocks, the overall rates of harvests need to be selected carefully if increasing C stocks is also a goal.

4.2. LUC analysis

The land-use change maps used in this study are based on change assessment over multi-year periods. However, given the length of the observation period and the high rates of u ( )-4(o)13(f)-4at rowlt

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Figure 9. Comparison of BAU and scenarios M1 (net zero deforestation rate) and M2 (increased net forest recovery rate) in the forest ecosystem component of QROO, assuming gross deforestation rates were doubled and gross reforestation rates increased such that the net deforestation rate is the same in both scenarios.(a) Annual net GHG balance and (b) cumulative mitigation for M1 and M2 scenarios in the forest component.

4.3. Comparisons of model predictions and published estimates

In Mexico, state-level studies of GHG fluxes are available for the forest ecosystem component for DGO (López *et al.* 2012) and QROO (Pereira *et al.* 2010) for the periods yr^{-1}, but were within reported range of the IPCC (2003) values of 1.5 (0.25 to 3) Mg C ha^{-1} yr^{-1} for coniferous and 2 (0.25 to 4) Mg C ha^{-1} yr^{-1} for broadleaf. Our growth rate estimate for the Tropical Humid Forests ecoregion in QROO of 1.6 Mg C ha^{-1} yr^{-1}, also fell within the values reported for semi-evergreen forests in the Yucatan peninsula of 1.1 to 13.0 Mg C ha^{-1} yr^{-1} (Read and Lawrence 2003, Urquiza *et al*. 2007, Aryal *et al*. 2014), was the same value reported for these forests at the national level by de Jong *et al*. (2010), and within the reported range of 2 Mg C ha^{-1} yr^{-1} $^{-1}$ yr^{-1} for > 20 years for moist forests in America (~1000 mm) by the IPCC (2003).

In general, the estimates for growth increment are within the range of reported values for these forest types in Mexico. However, for scenario M3 we assumed a 2.7 m^3 yr^{-1} average increase over 50 years, in addition to current average annual increment, to be

management to increase production and productivity (ENAIPROS in Spanish, CONAFOR 2013). We also assumed that the maximum volume attainable for a stand was unchanged (Germánico Galicia *pers. comm.*) Table 7 shows that over a 50-year rotation cycle, all selected forest types present in both states could increase in their growth rates. With the assumptions above, all growth curves in DGO with the proposed rate increase reached the maximum volume allowed before 50 years. Since an overall increase in volume was not allowed, the average rate over 50 years was less than proposed rate.

Table 7**.** Comparison of average values of current growth rate, proposed increased rate and possible increased rate (in Mg C ha^{-1} yr^{-1}), by main ecoregions-forest types in both states, over a 50-years rotation cycle.

Temperate Sierras

Model estimates of C stocks were compared to published estimates of aboveground biomass and soil C pools. Table 8 shows that in general, our values for these two C pools in the selected forests were also consistent with available data for coniferous, broadleaf and semi-evergreen forests in Mexico. For example, from the analysis of the frequency distribution of biomass estimates derived from the two cycles of plot-level measurements of INFyS (2004-7, 2009-13) we estimated that the forests in the state of QROO were concentrated in younger age classes (Figure 5). This assumption corresponded well with the aboveground biomass values reported in this study when compared against values for secondary forests of the Yucatan peninsula and northern Chiapas (e.g. <35 years old, Urquiza *et al*. 2007, Orihuela *et al*. 2013, Aryal *et al.* 2014), but was almost twice the national average reported in BUR (INECC-SEMARNAT 2015). In contrast, we assumed a relatively even age-class distribution at the start of the simulation for DGO (Figure 5). Here, our state-level estimate for aboveground biomass fell within the reported values between secondary and mature forests for coniferous and broadleaf forests.

In general, reported values for soil did not vary much among successional stages of the forests. However, our estimate for QROO differs between 0% and 12% compared to studies in the Yucatan peninsula, and by up to 25% at the national level. To our knowledge, there are no scientific publications examining soil carbon at the local or state level in DGO. Thus, we compared our estimate against values reported -4(an)3()14(s,)6( )-4(9-4(pa)3(r))]TJ

Finally, interactions among mitigation activities can affect the sign of the benefits over time. In our analysis for the M4 scenario (where all forest strategies are combined), adding more LLP and changing the displacement factor from a low to a medium value in DGO, changed the negative mitigation benefit to a positive one and became the second-best mitigation strategy for that state. Although more local data on displacement factors are required, this example shows the role that HWPs can play in achieving forest carbon mitigation targets and highlights the importance of including them in national GHG inventories.

INEGI 2003 *Conjunto de datos vectoriales de la carta de uso del suelo y vegetación, escala 1:250,000, Serie III* (Aguascalientes, Mexico: Instituto Nacional de Estadística y Geografía (INEGI))

INEGI 2007 *Conjunto de datos vectoriales de la carta de uso del suelo y vegetación, escala 1:250,000, Serie IV* (Aguascalientes, Mexico: Instituto Nacional de Estadística y Geografía (INEGI))

INEGI 2011 *Conjunto de datos vectoriales de la carta de uso del suelo y vegetación, escala 1:250,000, Serie V* (Aguascalientes, Mexico: Instituto Nacional de Estadística y Geografía (INEGI))

INEG 2014 *Conjunto de datos vectoriales edafológico, escala 1:250000, Serie II*

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