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

by

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Abstract

Mexico was the first Non-Annex I country to submit its Intended Nationally Determined Contribution (INDC) and its Climate Change Mid-Century Strategy in accordance with the Paris Agreement of the United Nation Framework Convention on Climate Change (UNFCCC). Since 2012, the Mexican government through its National Forestry Commission (CONAFOR), with support from the North American Commission for Environmental Cooperation, the Forest Services of Canada and USA, the USA SilvaCarbon Program and research institutes in Mexico, has made important progress towards the use of carbon dynamics models to explore climate change mitigation options in the forest sector. Following a systems approach, here we assess the biophysical mitigation potential of forest ecosystems, harvested wood products and substitution benefits, for policy alternatives identified by the Mexican Government (e.g. net zero deforestation rate, sustainable forest management). We provide key messages and results derived from the use of available analytical frameworks (Carbon Budget Model of the Canadian Forest Sector and a harvested wood products model), parameterized with local input data in two contrasting states within Mexico. Using information from the National Forest Monitoring System (e.g. forest inventories, remote sensing, disturbance data), we demonstrate that activities aimed at reaching a net-zero deforestation rate can yield significant CO_2e mitigation benefits by 2030 and 2050 relative to a baseline scenario (“business as usual”), but, if combined with increasing forest harvest to produce long-lived products and substitute more energy-intensive materials, emissions reductions, could also provide other co-benefits (e.g. jobs, reduction in illegal logging). The relative impact of mitigation activities is locally dependent, suggesting that mitigation strategies should be designed and implemented at sub-national scales. Thus, the ultimate goal of this tri-national effort is to develop data and tools for carbon assessment in strategic landscapes in North America, emphasizing the need to include multiple sectors and types of collaborators (scientific and policy-maker communities) to design more comprehensive portfolios for climate change mitigation.

Keywords: Forest carbon; greenhouse gas; INDC; REDD+; forest management; Mexico; CBM-CFS3

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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 2012, Mexico was the first Non-Annex I country to establish a comprehensive General Climate Change Law (DOF 2012), which mandated the design and implementation of a national-scale measuring, reporting and verification (MRV) system. In 2015 Mexico submitted its Intended Nationally Determined Contribution (INDC) to reduce GHG and Short-Lived Climate Pollutant emissions 22% by 2030, and 50% by 2050 relative to its emissions in 2000 (UNFCCC 2015), and further detailed the forest sector's contribution in its mid-century strategy (SEMARNAT-INECC 2016). Mexico ranks twelfth in the world in forest cover (FAO 2015). The Land Use, Land-Use Change and Forestry (LULUCF) sector in Mexico is considered a net GHG sink of 140.6 Tg CO_2e (INECC-SEMARNAT 2015), compensating for one-fifth of the GHG emissions reported from all other sectors in 2013. Currently, Mexico reports GHG emissions for the LULUCF sector using methodology at an intermediate or Tier 2 level, using the stock-change approach with emissions factors estimated from country-specific forest-plot measurements (CONAFOR *et al.* 2014).

Changes in the carbon stocks in forest systems result from multiple dynamic processes (e.g. growth and mortality of biomass, litter production, decomposition of dead organic matter, natural and anthropogenic disturbances), which interact from the scale of a tree to the entire landscape (Nabuurs *et al.* 2007). Mexico recognizes the importance of advancing towards reporting levels with reduced uncertainty and is exploring more complex methodologies such as carbon dynamics models for measuring, monitoring and projecting future GHG emissions (PRONAFOR 2014, SEMARNAT-INECC 2016). Such models are powerful tools that allow the integration of information about land sector carbon dynamics and analysis at different spatial and temporal scales in a consistent manner (Kurz *et al.* 2009, Pilli *et al.* 2017). These models also improve the understanding of the mechanisms controlling carbon exchange between the atmosphere and vegetation (Birdsey *et al.* 2013). They can also be used to establish baselines and create scenarios for comparing and examining future impacts of different activities on carbon dynamics (e.g. management, land-use change, natural disturbances; Metsaranta *et al.* 2010, IPCC 2011, Smyth *et al.* 2014).

Since 2012, Mexico´s National Forestry Commission (CONAFOR), with financial and technical support from the Government of Norway, the United Nations Development Program, the Canadian Forest Service, the U.S. Forest Service, the USA SilvaCarbon Program, the U.S. Agency for International Development, and the North American Commission for Environmental Cooperation (CEC), started to modify and adapt available methods and modeling frameworks to estimate the role of Mexican forest ecosystems on GHG emissions/removals (Dai *et al.* 2015, Olguin *et al.* 2015, Mascorro *et al.* 2016, Kurz *et al.* 2016a). Building upon the work coordinated by the CEC, the Forest Services of the three countries have continued to advance the use of these analytical frameworks to evaluate the effects of human activities on future GHG emissions (e.g. in the US, Dugan *et al.* in review; in Mexico, Olguin *et al.* in review; and in Canada, Smyth *et al.* in review).

The primary objective of this project is to present an assessment of several forest policy alternatives identified by the Mexican Government that could contribute to meeting their GHG reductions goals, within two states identified as priority areas for the implementation of REDD+ activities (e.g. Reducing Emissions from Deforestation and forest Degradation, Smith *et al*. 2014) need to cite a reference for REDD – this is the first time you've mentioned it and you can't assume everyone will know what it is) and sustainable management practices in forests under social tenure (CONAFOR 2013, 2015).

Earlier studies have recognized that forest management practices and conservation can play a key role to mitigate climate change in Mexico (Masera 1995, de Jong *et al.* 1997, 2007, Olguin *et al.* 2011, 2016). Forest mitigation strategies should minimize net GHG emissions without compromising other societal needs (e.g. timber, fiber, energy, etc.) because changes in wood supply can affect the use of more emissions-intensive materials (e.g. fossil fuels, concrete, steel, Sathre and O'Connor 2010, Garcia *et al.* 2015, Smyth *et al.* 2016). Our second objective is thus to share lessons learned from the use of the analytical framework to assess and rank alternative mitigation options that can help the policy-making community in Mexico and other countries to prioritize mitigation actions. We use a systems-based approach which includes carbon dynamics 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 current MRV system.

Chapter 2. Methods

2.1. Study areas

In consultation with CONAFOR, we identified potential forest carbon mitigation scenarios and high-priority areas in which to evaluate them. CONAFOR selected the states of Durango (DGO) and Quintana Roo (QROO) due to their sound institutional coordination of forest policy implementation and the relevance of their forests for community-based management (Bray *et al.* 2003, Garcia-Lopez 2013, Ellis *et al.* 2015). These states provide contrasting biophysical characteristics, historic land-use changes, and contributions to national timber production (INEGI 2015a, 2015b).

The state of Durango (DGO) is located in the northwest of Mexico (Figure 1) with a total area of 12.3 M ha. The climate is very dry to dry/semi-dry in the eastern-central portion of the state (54% of land area), while in the western portion is mostly temperate sub-humid (34% of land area) and tropical sub-humid (11% of land area). Mean annual temperature (MAT) is 17°C, ranging from 1.7 °C in January to 31°C in May-June (García 1998). Mean annual precipitation (MAP) is 500 mm. DGO´s geography is complex, including vast deserts in the north, sierras and plains with extensive pastureland in the central and east, and parts of the Sierra Madre Occidental in the west. Soil types include Lithosols and Regosol, particularly in forest lands, and Phaeozems soils in grasslands and agricultural lands (INEGI 2014). Forest lands (based on forest classification used in the Biennial Update Report, INECC-SEMARNAT 2015) extend over an area of ~6 M ha. Of these, ~5 M ha contain coniferous and broadleaf species in pure or mixed stands (INEGI 2011) (Figure 1), which are mostly managed for timber extraction by more than 350 forest communities (Bray *et al*. 2003, García-López 2013). Losses to forest cover are primarily due to fires, particularly in areas near human activities (Avila-Flores *et al*. 2010). Other forest disturbances such as land-use change and pest events have relatively low impact on forest cover loss (INEGI 2015a). Since year 2000, the state of DGO has ranked first among Mexican states in national timber production, averaging 1.7 M m^3 yr^{-1} extracted (SEMARNAT 2014).

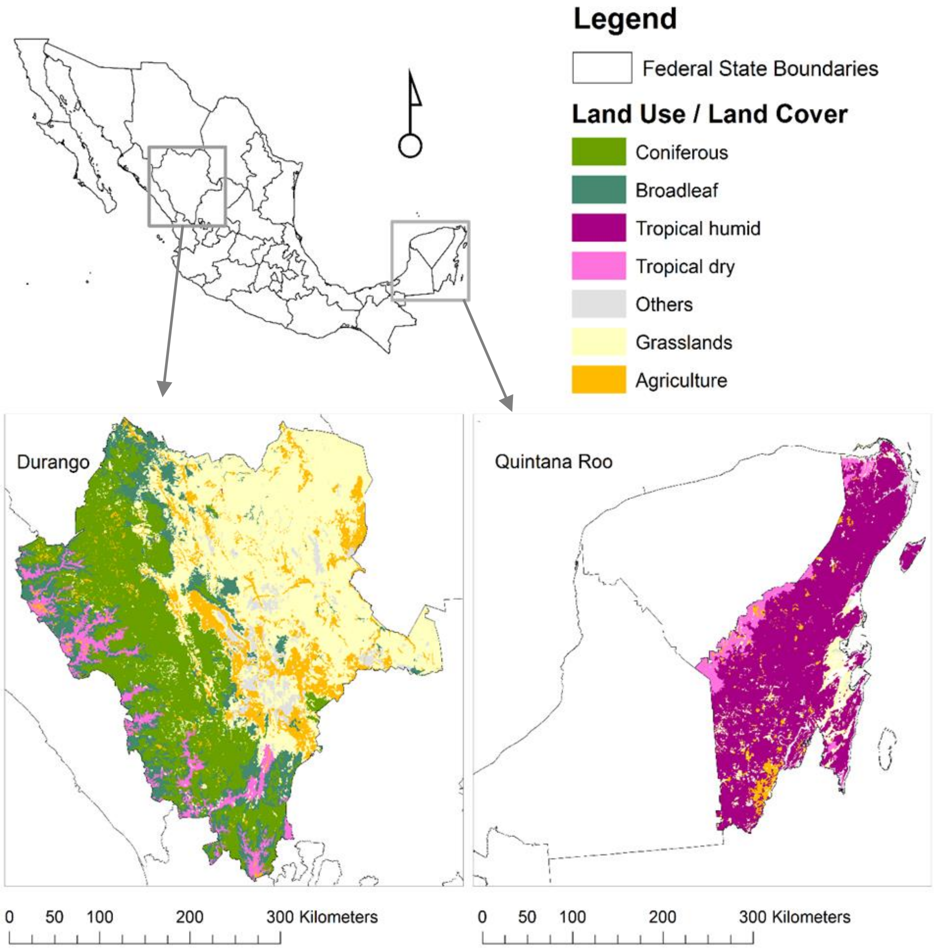


Figure 1.Durango (DGO) and Quintana Roo (QROO) study areas with main land-use/land-cover classes.

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-evergreen and semi-deciduous species (Figure 1). Timber extraction under sustainable management plans started in the early 1990s with a community-based forestry approach. Recently, timber production has been 40 K m^3 yr^{-1} on average, ranking first in production of tropical species in Mexico (SEMARNAT 2014). Forests in QROO have been subject to human activities (e.g. slash-and-burn agriculture and selective harvest) for thousands of years, with cycles of high density occupation and abandonment (Ford and Nigh 2009). Over the past decade, forest cover losses have been driven primarily by livestock and commercial maize production, and fires (Ellis *et al.* 2017). Currently QROO is part of Mexico´s strategy for REDD+ activities (CONAFOR 2015).

2.2. Modeling framework and data

We quantified the mitigation potential of the selected scenarios in the forest sector as the sum of the changes in net emissions, relative to a business as usual scenario. We used the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3; Kurz *et al.* 2009, Stinson *et al.* 2011) and the Carbon Budget Modelling Framework for Harvested Wood Products (CBM-FHWP; Smyth *et al.* 2014). Both models are consistent with IPCC Guidelines for national GHG reporting (IPCC 2006) and are used operationally by Canada for the annual production the National GHG Inventory Report (Environment Canada 2017). They have been adapted to represent Mexican conditions and are using data from Mexico. The scientific approach and necessary inputs for the parameterization of these models have been extensively documented (Kurz *et al.* 2009, Stinson *et al.* 2011, Kull *et al.* 2011, Pilli *et al.* 2013, Zamolodchikov *et al.* 2013, Smyth *et al.* 2014, Kim *et al.* 2016). The CBM-CFS3 implements the Gain-Loss method of the IPCC to estimate annual GHG emissions and removals in forest ecosystem. The CBM-FHWP model receives input from the CBM-CFS3 and tracks the fate of carbon in harvested biomass converted to wood products for various categories, uses, and landfills. Finally, we also estimate substitution benefits such as GHG emission reductions obtained from the use of wood products and biomass for energy (Smyth *et al.* 2016).

2.2.1. Spatial framework

In Mexico, past implementation of the Canadian Carbon Budget Model (CBM-CFS3) has used a national-scale framework of 94 spatial units (SPU) which results from the intersection of the 32 federal states and 7 ecoregions of the North American Ecoregions Level 1 (Olguín *et al.* 2011, 2015). This approach allows for the integration of inputs with different spatial resolutions within one assessment framework (Kurz *et al.* 2009) following the spatially-referenced approach (Reporting Method 1) of the IPCC (2006). In 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).

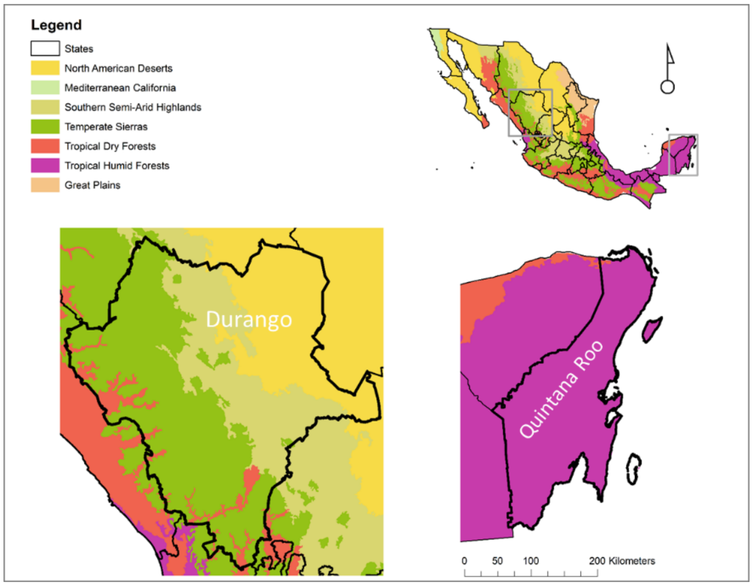


Figure 2. Distribution of the 6 Spatial Units resulted from the intersections of North American Ecoregions-Level I polygons (in colors) and Mexican states boundaries (in black) selected as pilot areas for Mexico: four in Durango and two in Quintana Roo.

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.

IPCC Land-Use categories	**This study (MAD-Mex labels, Gebhardt *et al.* 2014)**	**BUR classes (INECC-SEMARNAT 2015)**	**INEGI classification codes (INEGI 2015c)**
Forest lands	Coniferous	Coniferous forests	BA, BB, BJ, BP, BPQ, BS, MJ
	Broadleaf	Oak forest, cultivated forest, woody vegetation (special others)	BQ, BQP, BC, MK, BM
	Tropical Humid	Cloud forest, evergreen tropical forest, woody vegetation (hydric)	SAP, SAQ, SBP, SBQ, SBQP, SMP, SMQ, BG, SG, PT, VM
	Tropical Dry	Tropical deciduos/ semi-deciduos forest	MKE, MST, SBC, SBK, SMC, SBS, SMS
	Other vegetation	Woody vegetation (special others, xeric scrubs, and hydric)	BI, VPI, VPN, MC, MET, MKX, MRC, MSC, MSCC, MSN, ML, MSM, VG
Grasslands	Grasslands	Grasslands, non-woody vegetation (xeric scrubs, special others, and hydric)	PC, PH, PI, PN, PY, VS, VSI, VW, MDM, MDR, VD, VH, VY, VU, VHH, VA, VT
Agricultural lands	Agricultural lands	Agricultural lands	HA, HAP, HAS, HP, HS, HSP, RA, RAP, RAS, RP, RS, RSP, TA, TAP, TAS, TP, TS, TSP
Wetlands	Wetlands	Wetlands	ACUI, H20
Settlements	Settlements	Settlements	AH, ZU
Other lands	Other lands	Other lands	ADV, DV

2.2.2. Forest ecosystem dynamics for Mexico

The CBM-CFS3 combines information from forest inventories, growth and yield curves, and natural and/or anthropogenic disturbance events, to simulate carbon stocks and GHG fluxes associated with the IPCC´s five forest carbon pools (above and belowground biomass, dead wood, litter and soil), at both the stand and landscape level. For yield tables, we compiled and processed information from Mexico’s National Forest and Soil Inventory (INFYS) to define forest growth dynamics and the age class structure at the start of the simulation. The INFYS is comprised of a network of about 26,000 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).

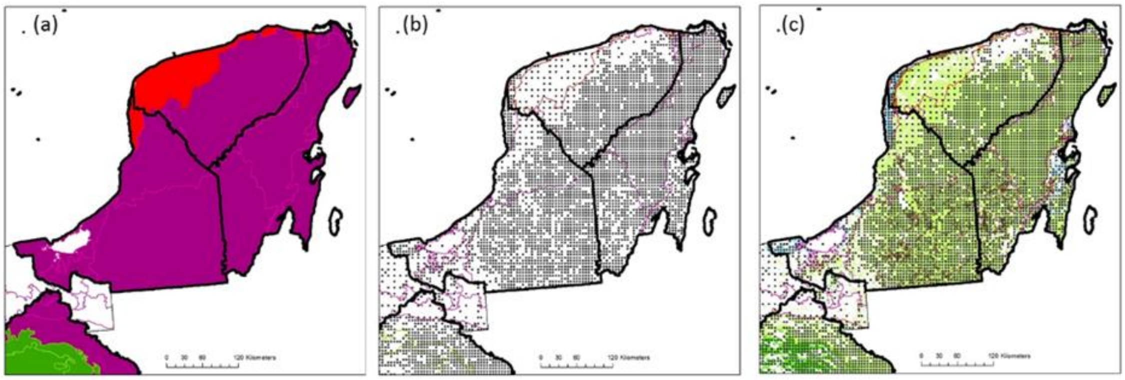


Figure 3. Example of INFYS plots selection for growth curves in QROO, using information on (a) ecoregion level IV (Tropical Dry in red, Tropical Humid in purple, Temperate Sierras in green), (b) plot locations (dots) and number of plots measured and re-measured, and (c) permanent forest cover (green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

A growth curve simulation routine was created by Gregorio Ángeles (*pers. comm*.) to use biomass or volume increment data and the time between INFYS plot measurements to estimate growth curves using a Maximum Likelihood Estimation routine. The simulation uses INFYS plot information at T1 and T2 for biomass/volume to calculate an increment and the time between measurements to place them along a growth curve of the form:

$$biomass = a(1 - e^{-b(age+c)}) \qquad \text{Equation 1}$$

Where parameters a, b, and c are scalars that define the shape of the curve.

The process iteratively places these T1 to T2 biomass/volume increments and the time step between them, along the growth curve function to estimate the most likely parameters of the curve that fit the input data. We excluded from this analysis those forest plots that showed changes in carbon due to disturbances.

The process requires the estimation of the log-likelihood function that uses a generalized forest growth model determined from data in the United States Forest Inventory and Analysis program where the biomass/volume and age information is known (USDA Forest Service 2011). The input data are assumed to belong to a cohort of stands of the same forest type that grow similarly to forests of Mexico. The simulation routine does not explicitly output the values of the a, b and c parameters. It outputs age vs. biomass estimates at user-defined intervals (e.g. every 10 years) to a user-defined maximum age (e.g. 150 years). These output data pairs are then used as inputs to fit the growth curve equation above to obtain the values of the three parameters. Figure 4 shows the growth curves created to represent annual increments in merchantable volume (m^3 ha^{-1}) of the main forest types and ecoregions in DGO and QROO.

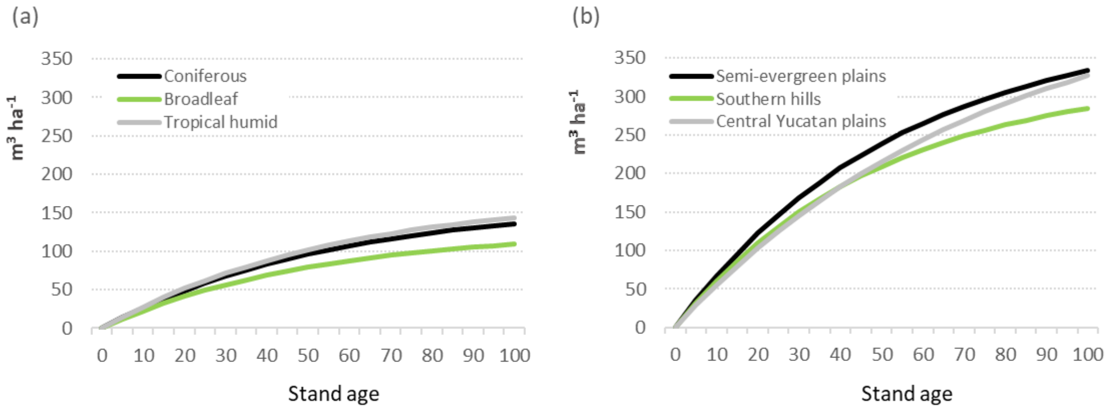


Figure 4. Examples of growth curves created to represent annual merchantable volume accumulation (m^3 ha^{-1}) of the main forest types and ecoregions in (a) DGO (i.e. ecoregion Level I “Temperate Sierras”) and (b) QROO (i.e. ecoregions Level IV in “Tropical Humid”).

Running this simulation requires an adequate number of data pairs to increase the likelihood of converging on a solution. In experimenting with numerous simulation runs it was established that at least 20 data pairs were needed for solution convergence on a model that was deemed realistic. We reviewed each forest type within an Ecoregion Level IV to determine if it had at least 20 data pairs. If one or more of the forest types had less than 20 pairs, then similar types were merged first across state boundaries and, if required, also across ecoregion Level IV boundaries to increase the number of data pairs. Because the information used to label the type of forest in each cluster is derived from map data with coarse spatial resolution and themes, it was determined to include data pairs with forest sublevels in an Ecoregion that correspond to spatially more distant sites. The implicit assumption is that forests within the same Ecoregion level IV grow similarly.

The INFYS was initially not implemented as a true permanent plot design, thus, data-pairs from T1 and T2 inventories do not necessarily measure the same trees, and some of the growth increments may be influenced by slight shifts in plot location. To filter out data-pairs where estimated biomass increment was likely attributable to plot shift and not growth, input data per growth curve set were examined for outliers. Biomass estimates from the input data were placed into one of three maturity classes, young, mature and old, based on biomass distributions. Once classified, data-pairs with increments within each maturity class above a certain threshold (i.e. greater than three standard deviations) were removed from the analysis.

Some plots with forest cover at T2 had lower biomass than at T1, which could be due to plot location shifts mentioned above, or due to disturbance losses from harvesting and degradation. Since forest disturbances are accounted for explicitly in the CBM-CFS3, it was important to filter the data-pairs where biomass decreases were greater than natural mortality rates. Therefore, decrements in biomass >2% annually were removed from the yield curve analysis as well.

To convert merchantable volume to total biomass data, we used default conversion parameters included in the CBM-CFS3. In the case of coniferous and oak species, we selected expansion factors that would fit best to local estimates (e.g. Vargas-Larreta *et al*. 2017). For the remaining species, we used default information included in the model (Boudewyn *et al.* 2007), as no information is available yet on biomass and volume components for Mexico. Thus, the proportion of branches, leaves and roots relative to the stem of the dominant species in tropical forests in Mexico, were assumed to be similar to generic oak.

The CBM-CFS3 requires an initial forest age-class structure for simulation. To estimate forest age distributions, Eq. 1 was inverted to produce Eq. 2. This process approximates time-since-a-stand-replacing-disturbance based on biomass values for each forest inventory plot. We recognize that this approach has many caveats. For example, forests are subject to gap dynamics disturbances that decrease the biomass content without resetting forest age to zero. The “age” distribution is applied to stands within each spatial unit and classifier set as:

$$age = -\frac{bc + \ln\left(\frac{-biomass + a}{a}\right)}{b} \qquad \text{Equation 2}$$

Figure 5 shows the estimated age distributions according to the estimated forest area of the two states in 2005 (the year when most of the forest inventory plots were established). From this figure, we can distinguish two main types of age class distributions: (a) relatively more even distribution of pine and broadleaf forests of DGO, and (b) a left-shifted distribution for semi evergreen tropical forest in QROO. In QROO, most forest stands are in the 0 to 30 year-old age class because forests are cleared relatively frequently under shifting cultivation systems or are affected frequently by other disturbances such as hurricanes and fires (Urquiza *et al*. 2007, Ellis *et al*. 2015).

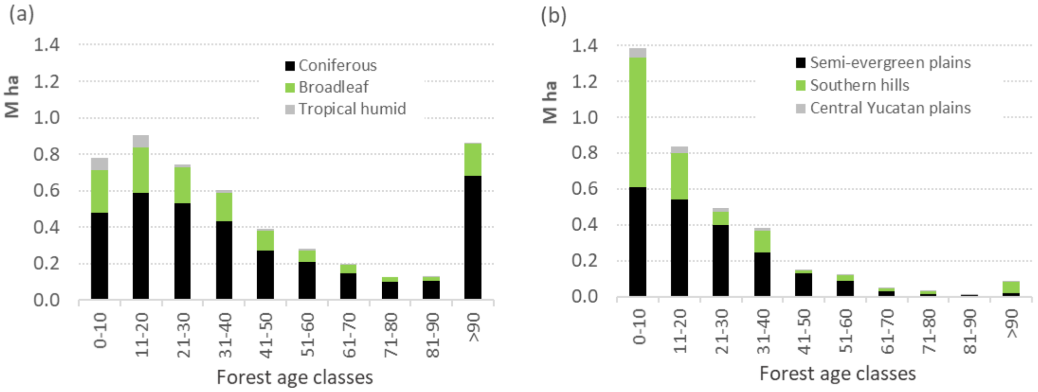


Figure 5**.** Estimated forest age classes distribution (in Mha) in the dominant forests in (a) DGO (i.e. ecoregion Level I Temperate Sierras) and (b) QROO (i.e. ecoregions Level IV in Tropical Humid).

Finally, in accordance with IPCC guidelines (IPCC 2006), the CBM-CFS3 represents carbon dynamics in dead organic matter (dead wood and litter) and soil carbon pools by explicitly linking these with changes in the above- and belowground biomass pools (e.g. transfers from annual processes such as litterfall and root turnover, natural mortality and disturbance events). In Mexico, analyses from INFYS plots provide estimates of the carbon content in each of the five pools, but there is little information on carbon transfers to dead organic matter and soil carbon. Thus, we used default values in the CBM-CFS3 on litterfall rates and base decomposition rates at a reference Mean Annual Temperature (MAT) of 10 °C, that were most appropriate for the selected forest types. Decomposition rates were then adjusted to actual MAT using the approach described in Kurz *et al*. (2009). Information from a national-scale mean annual temperature map (García 1998) was combined with the SPU map to estimate the dead organic matter decomposition rates used in the model with regional annual average temperature values.

Activity Data

Land-use/Land-cover (LULC) changes*.* We used national-scale land-cover and land-use maps for 1993, 2002, 2007 and 2011 from INEGI and intersected these maps to derive information on: deforestation (conversion of forest lands to other non-forest lands) and forest recovery events (conversion of non-forest land to forest land, mainly due to abandonment of agricultural lands). We divided total change over the observation period by the number of years in the interval to generate annualized land-use changes from 1993 to 2010. This method is currently used by CONAFOR to estimate LULC changes for GHG reporting, since there are no other national-scale products available to obtain land-use change estimates. We restricted deforestation and forest recovery events to areas outside of polygons associated with silvicultural activities.

Table 2 shows an example of a LULC change matrix for the states of QROO and DGO, for the intervals 2002 to 2007 and 2007 to 2011. The area in the matrices only shows the LULC change dynamics of the “Temperate Sierras” and “Tropical Dry Forests” ecoregions level 1 of DGO (together they contain 96% of the total forest land of the state). In QROO, all ecoregions level IV within “Tropical Humid Forests” were included in the analysis except “Wetlands” (mostly mangrove forests) because the model does not simulate carbon dynamics in wetlands.

Table 2. Example of a Land-Use/Land-Cover (LULC) change matrix for the States of (a) DGO (only Temperate Sierras and Tropical Dry Forests ecoregions) and (b) QROO (excluding Wetlands within Temperate Humid Forests ecoregion), using re-classified INEGI LULC maps for years 2002 to 2007 and 2007 to 2011. Cells in red represent forest land change to non-forest, in green color changes from a non-forest class to forest land, remaining cells total forest cover without change (e.g. transitions to other forest types or losses/gains of other vegetation types). All areas are in ha.

(a) DGO

From 2002	**To 2007**										**Sum**
	Coniferous	Broadleaf	Tropical humid	Tropical dry	Other vegetation	Grasslands	Agriculture	Human settlements	Other lands	Water bodies	
Coniferous	3,549,972	24,282		5,275		13,271	19,913	92			3,612,805
Broadleaf	17,164	1,323,563	41	44,520	3,923	11,805	5,669				1,406,685
Tropical humid			492								492
Tropical dry	2,461	3,613	5	548,544	907	735	6,310		153		562,728
Other vegetation					51,458	71	415	198			52,143
Grasslands	8,900	6,617		2,296	13	432,683	10,490	348			461,347
Agriculture	2,187	811	5	259	118	4,672	194,999	1,625			204,677
Human settlements							5	7,861			7,866
Water bodies										1,480	1,480
Sum	3,580,685	1,358,885	544	600,894	56,419	463,237	237,802	10,124	153	1,480	**6,310,223**

From 2007	**To 2011**										**Sum**
	Coniferous	Broadleaf	Tropical humid	Tropical dry	Other vegetation	Grasslands	Agriculture	Human settlements	Other lands	Water bodies	
Coniferous	3,568,223	9,405				1,165	1,868	24			3,580,685
Broadleaf	854	1,356,082		106		543	1,300				1,358,885
Tropical humid			544								544
Tropical dry		85		599,015		20	1,775				600,894
Other vegetation		4,775			51,644						56,419
Grasslands	2,060	419		16		456,450	3,861	37		394	463,237
Agriculture	198	1,083		277		84	236,148			13	237,802
Human settlements							20	10,104			10,124
Other lands									153		153
Water bodies										1,480	1,480
Sum	3,571,335	1,371,848	544	599,414	51,644	458,261	244,971	10,166	153	1,887	**6,310,223**

(b) QROO

From 2002	**To 2007**									**Sum**
	Broadleaf	Tropical Humid	Tropical Dry	Other vegetation	Grasslands	Agriculture	Human settlements	Other lands	Water bodies	
Broadleaf	457									457
Tropical Humid		2,905,387	4,489		29,374	33,977	15,756	68		2,989,051
Tropical Dry		1,026	261,623		1,828	6,007	266			270,750
Other vegetation				6,286		202				6,488
Grasslands		12,200	1,017		129,504	1,206	532	21		144,480
Agriculture		6,406	47		2,052	92,983	627			102,115
Human settlements		199					20,307			20,505
Other lands		202				87		2,521		2,810
Water bodies		20			22	57			9,832	9,931
Sum	457	2,925,440	267,176	6,286	162,779	134,520	37,487	2,610	9,832	**3,546,587**

From 2007	**To 2011**									**Sum**
	Broadleaf	Tropical Humid	Tropical Dry	Other vegetation	Grasslands	Agriculture	Human settlements	Other lands	Water bodies	
Broadleaf	180					277				457
Tropical Humid		2,869,007	2,580		25,784	19,618	7,882	467	101	2,925,440
Tropical Dry	78	12,645	243,727		1,253	8,781	692			267,176
Other vegetation		72		6,033		182				6,286
Grasslands		30,644	446	367	126,154	4,078	1,047	43		162,779
Agriculture		17,241	4,478	192	3,388	109,059	162			134,520
Human settlements		771	12			73	36,445	186		37,487
Other lands		102					85	2,423		2,610
Water bodies		27			9				9,796	9,832
Sum	258	2,930,509	251,242	6,593	156,587	142,068	46,313	3,120	9,897	**3,546,587**

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. Thus, we classified these as ‘unchanged’ and included them as part of the forestland 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 areas to delimit the forest areas eligible for harvest events (~850 K ha of forests in DGO and 500 K ha in QROO). However, there was no additional information on the areas by year which were affected by management practices (e.g. thinning, harvests). Forest management systems in most tropical and temperate forests in Mexico consist of selective cuts of uneven-aged forests (Torres-Rojo *et al.* 2016), thus we randomly selected forest stands of at least 25 years and removed biomass C using a percentage of harvest utilization reported for commercial species in Mexico (Fuentes *et al.* 2012).

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 utilization rates, which determine logging residues such as unused merchantable carbon, as well as tops, branches, foliage, etc., that are left on site to decompose. Information compiled on harvested wood products included mill efficiency rate (percentage of round wood to produce wood products) and mill residue treatment (Fuentes *et al.* 2012, Galicia *pers. comm.*). To ensure consistency between the state-level estimates and those generated by CBM-CFS3 and then transferred to CBM-FHWP, we converted to units of carbon the reported figures of merchantable harvests in m^3 and added a percentage (10-20%) for bark.

Table 3. Average values used to track carbon dynamics in forest ecosystem and harvested wood products components in the selected states by dominant commercial species type.

	DGO		**QROO**	
Average authorized round wood harvest, from 2005-2014 (1000 m^3)[a]	2,417		182	
Forest species types	**Coniferous**	**Broadleaf**	**High value**	**Common**
Average harvested round wood (without bark), from 2005-2014 (1000 m^3)[b]	1,532	188	6	34
Percentage bark (%)[c]	18	20	10	10
Volume to biomass conversion (g / cm^3)[d]	0.41	0.58	0.44	0.66
Carbon fraction	0.5	0.5	0.5	0.5
Eligible merchantable biomass to harvest per forest stand (%)[d]	90	73	77	77
Utilization rate (commercial harvest with salvage; %)[d]	82	65	56	49
Percentage of round wood to produce a product (%)[d]	59	47	51	47
Percentage of mill residues relative to sawdust in mill waste[d]	80	81	69	74
Percentage of mill residues burned relative to send to landfill (%)	50	50	50	50

[a] State-level reports (e.g. SEMARNAT 2014)
[b] Municipal-level reports (e.g. INEGI 2015a, 2015b)
[c] Kiernan and Freese 1997, Wehenkel *et al* 2012, O'Connell *et al* 2014
[d] Fuentes *et al.* 2012

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 events that resemble a “surface-fire” for which some small 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. For forest recovery events in which non-forest land converts back to forest land (not shown), the disturbance matrix does not redistribute carbon and only annual processes such as forest growth and natural mortality occur.

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	To						
	Remains in	Medium	AGF	Atmosphere			Sum
From	same C pool	DOM	DOM	CO_2	CH_4	CO	
SW/HW foliage	0.8			0.18	0.002	0.018	1
SW/HW other	0.8			0.18	0.002	0.018	1
AGVF DOM	0.2			0.72	0.008	0.072	1
AGF DOM	0.6			0.36	0.004	0.036	1
SW/HW branch snag	0.5	0.5					1
SW/HW stem snag	0.5		0.5				1

(b)

Deforestation	To								
	Remains in	Medium	AGF	BGF	Atmosphere			Products	Sum
From	same C pool	DOM	DOM	DOM	CO_2	CH_4	CO		
SW/HW merch		0.13			0.063	0.0007	0.0063	0.8	1
SW/HW foliage				0.6	0.36	0.004	0.036		1
SW/HW other			0.6		0.36	0.004	0.036		1
SW/HW submerch			0.75		0.225	0.0025	0.0225		1
SW/HW coarse roots			0.6		0.36	0.004	0.036		1
SW/HW fine roots				0.65	0.315	0.0035	0.0315		1
AGVF DOM				0.3	0.63	0.007	0.063		1
AGF DOM			0.3		0.63	0.007	0.063		1
BGF DOM	0.3				0.63	0.007	0.063		1
Medium DOM	0.65				0.315	0.0035	0.0315		1
SW/HW branch snag			0.3		0.63	0.007	0.063		1
SW/HW stem snag		0.65			0.315	0.0035	0.0315		1

*HW: Hardwood species; SW: Softwood species; Merch (live stemwood of merchantable size plus bark), DOM: Dead Organic Matter, Medium DOM (coarse woody debris on the ground), AGF: Aboveground Fast DOM (fine and small woody debris plus dead coarse roots in the forest floor, ca.≤ 5 mm and ¸75 mm diameter), Aboveground Very Fast DOM (foliar litter plus dead fine roots of ca. <5mm diameter), Belowground Very Fast DOM (dead fine roots in the mineral soil of ca.≤ 5 mm diameter). Source: modified after Kurz *et al*. (2009).

Harvested wood products and displacement factors

We used state-level statistics on the production of broad categories of wood commodities that are used in the CBM-FHWP model. These categories include sawn wood production ("*escuadría y durmientes*"), wood panels ("*chapa y triplay*"), paper, pulp and particleboard ("*celulósicos y tableros*"), and other industrial roundwood ("*postes, pilotes y morillos*"). Following the production approach for GHG emissions reporting (IPCC 2006), we compiled information from annual exports of wood commodities at the country level from SEMARNAT (there are no official data published at municipal or state-level). In the case of product and landfill half-life values, we used Tier 1 IPCC values (IPCC 2003) as described by Smyth *et al*. 2014. For example, for sawn wood and other solid wood we used 35 years, for panels 25 years, and for pulp and paper 2 years. We assumed that 50% of the product-end-of-life was directed to landfills and 50% burned (Germánico Galicia *pers. comm*.). Landfill half-lives were estimated also as described in Smyth *et al*. 2014.

To estimate the potential mitigation benefit from the use of forest biomass in the energy and product sectors, we applied published displacement factors and multiplied these by the change in the amount of biomass used. A displacement factor indicates the number of units of carbon emissions reduced per unit of wood carbon used. Thus, the resulting efficiency in avoided emissions (substitution benefit) depends on the reference system where wood will be utilized (e.g. construction, housing, energy). For example, we used the following displacement factors in our simulation scenarios: 0.89 MgC/MgC for bioenergy (e.g. from mill residue), 0.54 or 2 MgC/MgC for sawn wood and 0.45 or 2 for wood panels (Sathre and O'Connor 2010; Smyth *et al.* 2014, 2016). The values for wood products are conservative, considering the results from a meta-analysis conducted by Sathre and O'Connor (2010) based on 21 studies over a range of product substitutions (metals, minerals and plastics), reported that on average one Mg C of wood product substitutes 2.1 Mg C of non-wood products. Most of the values for displacement factors ranged between 1 to 3 MgC/MgC.

2.3. Simulation scenarios

We constructed a business as usual (BAU) baseline scenario and 4 mitigation scenarios (with 2 sub-scenarios). The BAU baseline scenario estimates the GHG fluxes if forest management and disturbance rates observed in the past continue into the future (2018 to 2050). We use the average annual gross rates from the last 10-year period of available activity data for land-use change (LUC) (2000-2010), harvests (2005-2014) and area burned (2007-2016). Net ecosystem CO_2e balances for the two states were generated as the sum of all GHG emissions and removals corresponding to carbon transfers in above- and belowground biomass, dead wood, litter and mineral soil forest carbon pools. We also estimated the net emissions from Harvested Wood Products (HWP) production and use under a BAU scenario. We assumed that, in the BAU, changes in policies will not occur and changes in forest carbon cycling due to climate change will be negligible.

We modeled four forest carbon mitigation scenarios, and combined these with two sub-scenarios for the HWP and substitution components (Table 5). Specifically, we estimated the biophysical mitigation potential (relative to BAU) if, by 2030, the following activities are implemented: (M1) net zero deforestation rate (conversion of forest lands to other non-forest lands equals to conversion from non-forest lands to forest lands), (M2) M1 plus increased net forest recovery rate, and (M3) increased forest productivity and timber production. For M3, we examined four sub-scenarios resulting from changes in the HWP component if (i) forest commodity proportions are the same as in BAU or (ii) the increased harvest volume goes entirely to long-lived products (LLP). We analyzed the effect of avoiding GHG emissions from more emissions-intensive materials (substitution benefit) using low (iii) and medium (iv) displacement factor values published in the literature (Sathre and O’Connor 2010; Smyth *et al.* 2014). The last scenario (M4), combines all the activities (M2 and M3, including sub-scenarios). In all cases, we simulated a linear transition from BAU in 2018 to the full implementation of the mitigation actions in 2030.

Net GHG emissions in all scenarios were calculated as the net sum of the GHG fluxes in the forest ecosystem, HWPs and substitution benefit components. To assess the mitigation potential of the proposed strategies, we subtracted from each mitigation scenario the net GHG emissions of BAU at the state level, and report both annual and 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 substitution benefits *(4 sub-scenarios)*	FE: Increased productivity and production in forests over a 50-years rotation cycle, from improved thinnings, road infrastructure, fire and pest controls, within managed areas.	Forest area affected (ha)[a]	
		DGO	3,576,086
		QROO	507,429
		Additional annual harvest (t C yr^{-1}, %)	
		DGO	218,025 (+50%)
		QROO	6,788 (+50%)
	HWP: (*i*) More carbon transferred but same proportion of commodities as in BAU or (*ii*) 100% of increased harvest goes to longer-lived products (LLP)	Additional growth (m^{3}ha^{-1}yr^{-1})[b]	2.7
		In sub-scenario (*ii*), sawn wood component changes in percentages points relative to BAU:	
		DGO	+9%
		QROO	+7%
	SB: (*iii*) Low substitution benefit for wood products or (*iv*) medium substitution benefit	Displacement factor for sawn wood – panels:	
		Low (t C avoided / t C used)	0.54-0.45
		Medium (t C avoided / t C used)	2
M4. All forest strategies + more HWPs with substitution benefits	M2 and M3 combined (including sub-scenarios)	M2 and M3 combined (including sub-scenarios)	

[a] Managed areas map provided by CONAFOR and intersected with INEGI´s Land-use/Land-cover map, year 2011, reclassified into broad forest categories harmonized with Mexico´s Biennial Update Report (see SI).
[b] Increased growth was modeled from two measurement cycles from National Forest Inventory.

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.

Chapter 3. Results

3.1. Historic and baseline emissions

3.1.1. Activity data

Land Use Change (LUC). The historic and projected deforestation and forest recovery areas for the period 2000 to 2050 are shown in Figure 6a for DGO (left) and QROO (right). In the historic period, rates of deforestation in DGO are low but variable, while forest recovery remained at a relatively stable rate. In QROO, the deforestation rate was relatively constant while forest recovery was more variable and both rates were much higher than in DGO.

Fires. The municipal level data on area burned are highly variable in both states. DGO has a minimum annual area burned of 615 ha yr^{-1} and a maximum of 51,755 ha yr^{-1}. The mean of 18,711 ha yr^{-1} is projected into the future for the baseline, despite the high standard deviation (±17,230 ha yr^{-1}). QROO had corresponding values for a minimum of 447 ha yr^{-1}, a maximum of 79,161 ha yr^{-1}, a mean of 18,083 ha yr^{-1}, with a standard deviation of ±22,077 ha yr^{-1} (Figure 6a).

Harvests. Harvest rates in DGO are almost an order of magnitude greater than in QROO (Figure 6a). DGO produces nearly 1/3 of all harvested wood (mean 436,051 Mg C yr^{-1}) recorded in Mexico's national statistics with the variability in production driven by economic conditions (SEMARNAT 2014).

3.1.2. Emissions

Both states were net carbon sinks throughout the period of analysis (Figure 6b): 2000 to 2050. QROO was a sink of -14.1 Tg CO_2e yr^{-1} compared to -7.96 Tg CO_2e yr^{-1} for DGO. The contribution of different land categories varies with the strongest sink in forest land which remains as forest land (FLFL).

Net GHG emissions in FLFL respond to 1) forest age structure, which drives overall uptake rates by forest type, 2) emissions from forest fires and harvests, and 3) changes in forest area. Both states are strong sinks in the historic period (2000 to 2016), -9.7 and

-17.7 Tg CO_2e yr^{-1} in DGO and QROO, respectively. The sink strength in both states decreases over time in the baseline estimates (2017 to 2050) due to forest ageing and continuous reduction in forest area; in DGO from -8.7 Tg CO_2e in 2017 to -6.1Tg CO_2e in 2050 and QROO from -15.9 Tg CO_2e in 2017 to -8.0 Tg CO_2e in 2050. The faster growing, relatively younger forests of QROO are a stronger sink during the historic period and at the beginning of the baseline, but they decrease to the sink strength of the forests in DGO by 2050. The variability seen in the historic period arises from variable incidence of disturbances, with troughs in sink strength corresponding to years with high incidence of fires and harvests. This variability is removed in the projections because we use average annual fire and harvest rates in the BAU scenario (Figure 6b).

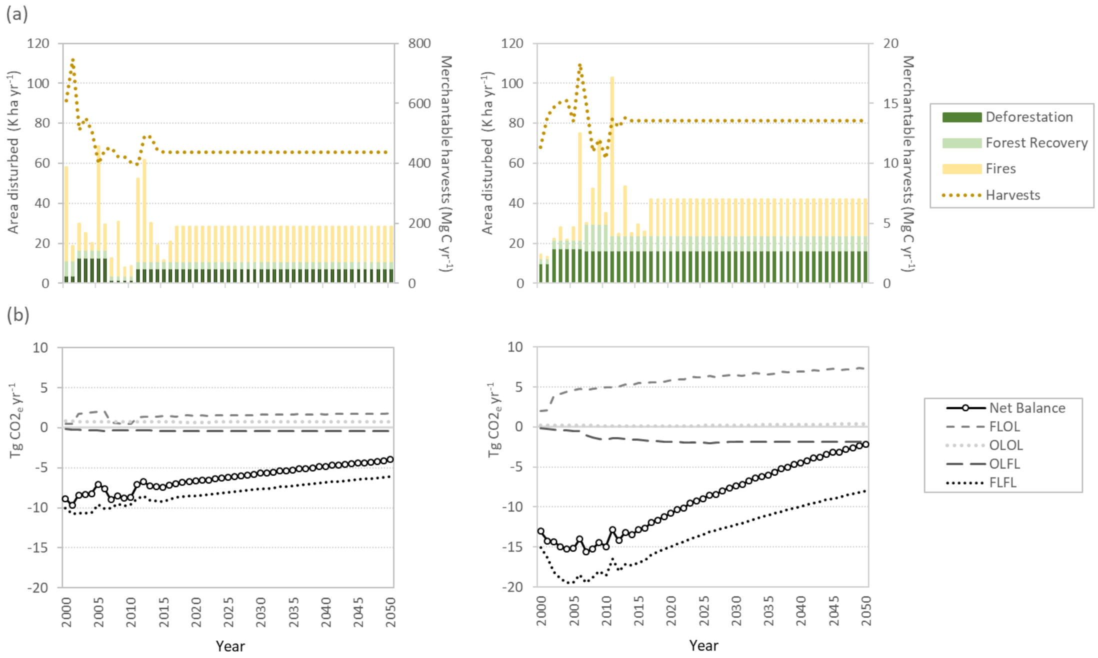


Figure 6. Annual CO_2e balance in the states of DGO (left column) and QROO (right column) for the historic (2000-2017) and Business as Usual (2018-2050) periods. Panel (a) shows by land-use category GHG emissions and removals, which are affected by disturbance events shown in panel (b). Note that the scale of the Y axis for merchantable harvest in panel (b) is different for both states. FLFL: Forest land remaining Forest land, OLOL: Non-forest lands remaining non-forest lands, FLOL: Forest land converted to non-forest lands, OLFL: Non-forest lands converted to forest land.

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_2e yr^{-1}) compared to QROO (5.91 Tg CO_2e yr^{-1}). Both states show increasing emissions as more lands are deforested towards the end of the BAU period. The CBM-CFS3 simulates decay of wood residues over time and thus emissions increase as cumulative FLOL area increases. Forest recovery (OLFL) contributes a weak sink in DGO (-0.381 Tg CO_2e yr^{-1}) and QROO (-1.57 Tg CO_2e yr^{-1}) strengthening slightly over time as recovered forest area is added. Non-forest land (OLOL) emissions are shown here for completeness and represent small emissions on lands deforested more than 20 years ago. This analysis does not include emissions from management of non-forest lands.

3.2. Mitigation

The cumulative mitigation benefits are summarized for forest, HWP and substitution (Figure 7). Negative values represent an actual mitigation benefit, while positive numbers represent an increase in emissions, or “negative mitigation benefit” with respect to the BAU scenario. In both states scenario M2 (net zero deforestation rate plus a 10% increase in net forest recovery rate by 2030) achieves the greatest emissions reductions in 2050 with a cumulative mitigation benefit of -24.4 Tg CO_2e in DGO and -110.9 Tg CO_2e in QROO. The average annual benefit varies by decade for the different mitigation scenarios (Table 6). For both states, scenario M2 continues to provide the most benefit in terms of emissions reductions, however the rankings of other scenarios vary over time.

The relative contribution of each component in the systems approach varies among scenarios and in 2030 and 2050 (Figure 8). Reduction in deforestation rates has the greatest impact on forest ecosystems, with much larger impacts in QROO than DGO. In the two states, increases in harvest rates by 50% (half the national goal) reduce forest carbon stocks and the resulting emissions are only partly off-set by carbon storage in HWP or substitution benefits from energy and product substitution, thus leading to net increases in emissions.

Table 6. Average annual mitigation (TgCO$_2$e yr^{-1}) by decadal range: 2021-2030 (A), 2031-2040 (B), and 2041-2050 (C), for each scenario and sub-scenario.

Mitigation strategies		Durango			Quintana Roo		
		A	B	C	A	B	C
M1. Net 0 deforestation rate		-0.46	-0.85	-0.98	-2.14	-3.88	-4.55
M2. ↑net forest recovery rate		-0.48	-0.88	-1.03	-2.24	-4.03	-4.75
M3. ↑growth and ↑harvest	(i) + Low DF	1.12	1.62	1.49	-0.001	0.19	0.23
	(ii) + Low DF	0.95	1.31	1.16	-0.01	0.18	0.22
	(i) + Medium DF	0.83	1.16	1.03	-0.01	0.17	0.21
	(ii) + Medium DF	0.31	0.33	0.18	-0.03	0.14	0.18
M4. All forest strategies	(i) + Low DF	0.67	0.72	0.49	-2.13	-3.87	-4.52
	(ii) + Low DF	0.50	0.42	0.17	-2.14	-3.88	-4.53
	(i) + Medium DF	0.38	0.27	0.04	-2.14	-3.89	-4.53
	(ii) + Medium DF	-0.14	-0.56	-0.81	-2.16	-3.92	-4.57

Notes: (i) More carbon transferred but same proportion of commodities as in BAU, (ii) 100% of increased harvest goes to longer-lived products (LLP)

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.

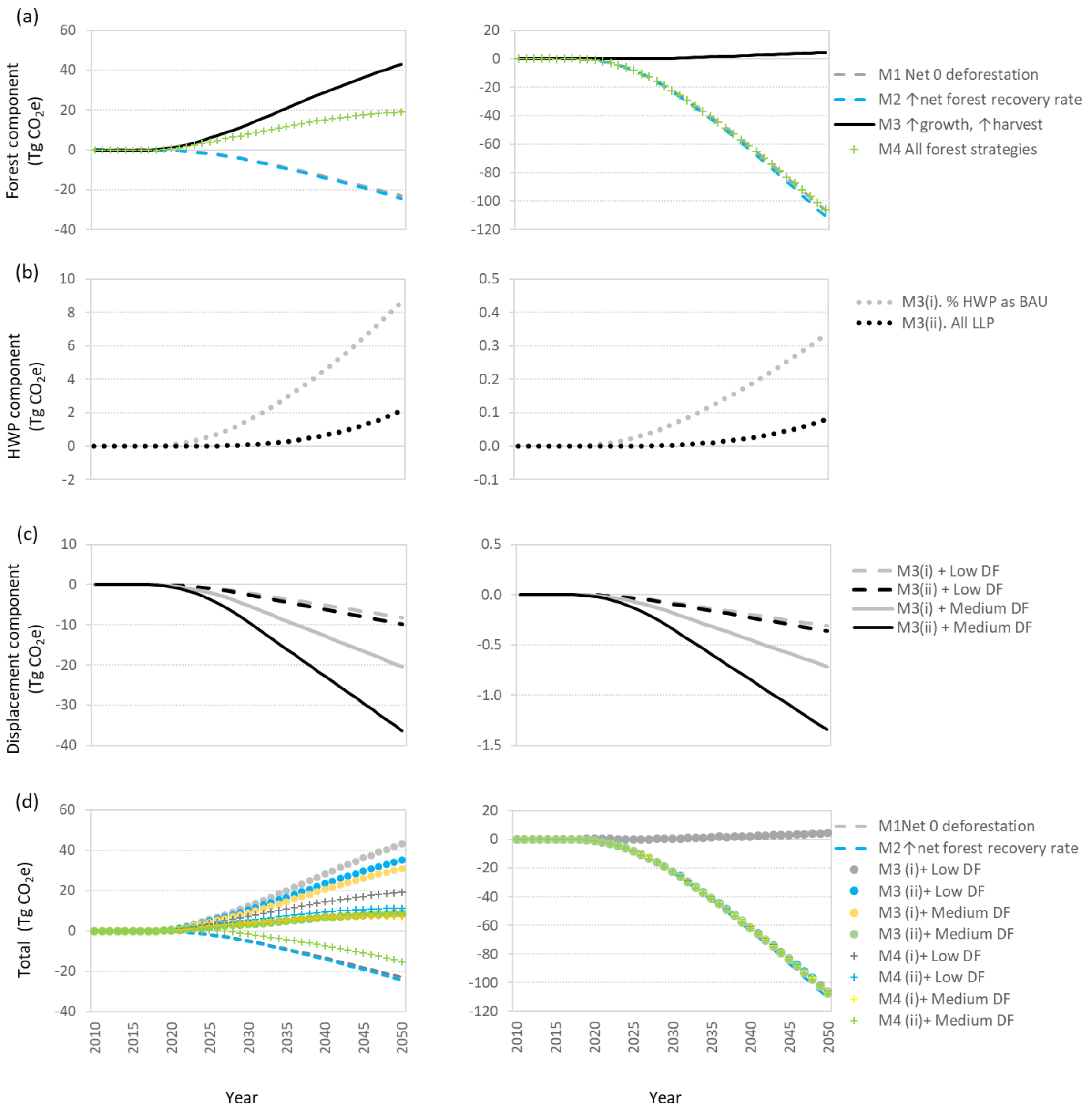
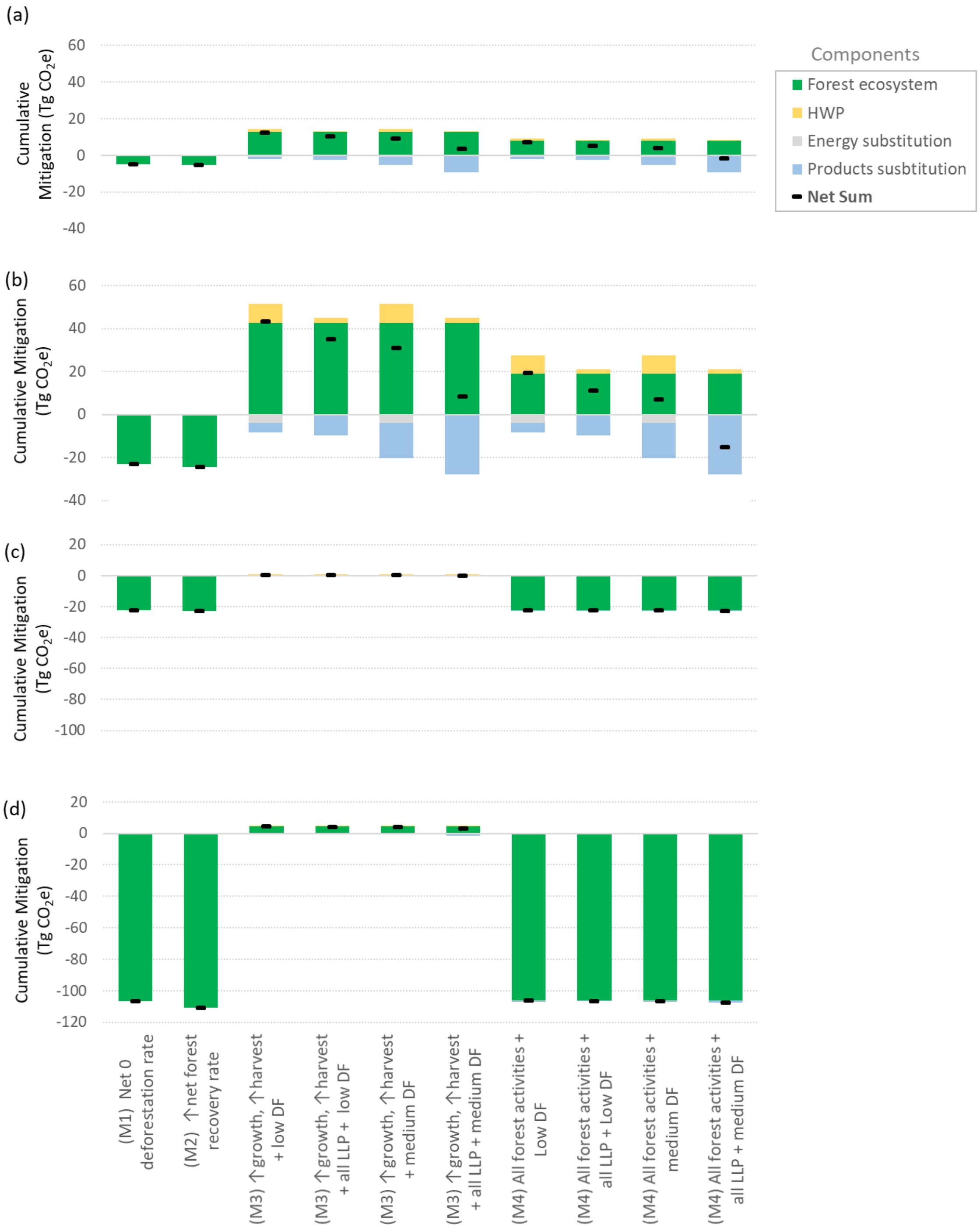


Figure 8. Cumulative mitigation for all systems components and scenarios for the states of DGO (a: year 2030, b: year 2050) and QROO (c: year 2030, d: year 2050).



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 DGO and -111 $TgCO_2e$ in QROO. The greatest contribution within this scenario is achieved through a ~50% reduction in gross deforestation rates relative to BAU, the same annual reduction reached in the net zero deforestation rate (M1 scenario). Thus, both M1 and M2 scenarios gave DGO a cumulative net emissions reduction of 2% in 2030 and 7% and 8%, respectively in 2050 (Figure 8(b)). In QROO, the emissions reduction was 6% in M1 and M2 scenarios in 2030, and 23% and 24% respectively in 2050 (Figure 8(d)). The more than threefold mitigation potential in 2050 of QROO compared to DGO is because of QROO's higher baseline rates of gross deforestation and forest recovery (Table 2), the more rapid carbon accumulation rates and higher forest carbon density (Figure 4, Table 8).

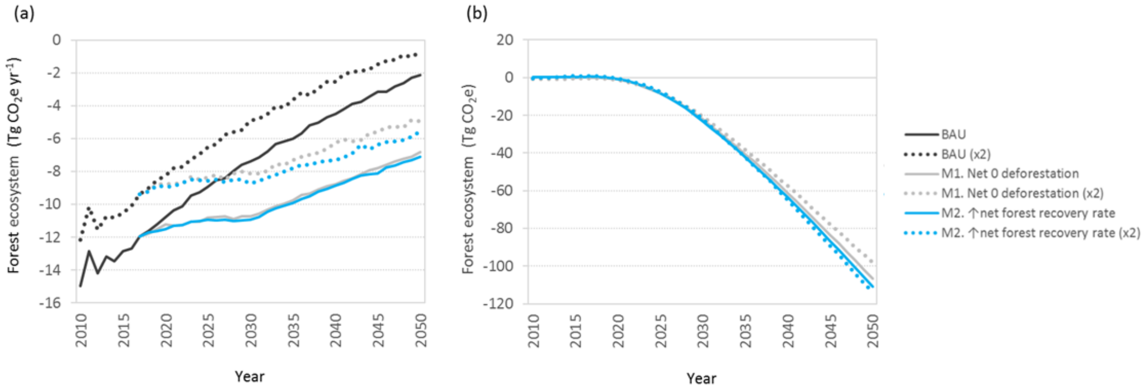
Increasing forest productivity combined with increasing harvest rates always yields a negative mitigation outcome in the forest component because the increased C uptake is more than offset by more significant increase in harvest of C relative to BAU (Figure 7b). Despite the long history of silvicultural activities in both states, managed forest area in QROO is relatively small and contributes only 0.6% to Mexico's annual harvest. Thus, the carbon loss from increasing harvest rates is quite small in the M3 and M4 scenarios (Figure 8d). In contrast in DGO, where more than half of the forest area is under silvicultural management, the carbon loss from harvesting 50% more and using the lower displacement factor (0.5 MgC/ MgC), generates 14% more CO_2e emissions by 2050 relative to BAU (Figure 8b). The cumulative mitigation benefit becomes positive only when the increased harvest rate is combined with higher forest recovery rates as in M4 scenario, and all the extra carbon transferred to HWPs goes to sawn wood and we assume a displacement factor of 2 MgC/ MgC. This results in the second-best mitigation strategy for DGO, with a 4% emissions reduction relative to BAU (Figure 8b). Finally, the carbon losses in the M3 scenario decreases towards the end of the simulation (Table 6). Had we assumed a full implementation of this strategy earlier in the simulation cycle (increasing the number of harvest cycles of relatively fast-growing forest) the mitigation 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 forest growth, some areas may have been subject to forest cover loss and regrowth between observations. For example, Urquiza *et a*l. (2007) and Lawrence and Foster (2002) report that basal area of secondary forest stands (~25 years old) in QROO, already had reached 40% of that of old-growth (>50 years old). If such disturbance/regrowth events did occur between observations, then the gross rates of land-use changes are higher than those assumed in our analyses.

New annual land-use/land-cover maps are being produced at various spatial and temporal resolutions (e.g. Hansen *et al.* 2013, Gebhardt *et al.* 2014 / MAD-Mex system) and these could be used in the future to derive better estimates of annual rates of LU/LC change. This could provide more accurate estimates of gross deforestation and forest recovery rates. Re-running the analyses for QROO using the higher gross LUC rates (but same net deforestation rate) increased the GHG emissions, reduced the size of the sink in the later years of the BAU and mitigation simulations (Figure 9a) as expected. In BAU between 2000 and 2017 the cumulative reduction in the CO_2e sink is 23 % (-46.7 TgCO_2e). However, the differences in the cumulative mitigation benefits are quite small (Figure 9b). While the available activity data (derived from relatively coarse spatial and temporal resolution) might be underestimating gross rates of LUC and therefore net CO_2 emissions, the rank order of the mitigation strategies remains unchanged. The net difference between gross deforestation rate and gross recovery rate is still 0 % in the M1 scenario, but the mitigation benefit is reduced as there are more emissions in the new BAU (e.g. -98.2 TgCO_2e in 2050). In contrast, under the M2 scenario, a 10% increase in the forest recovery rate yields a 33% mitigation benefit relative to the new BAU by 2050.

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 2005-2008 and 2005-2010 respectively. Our estimates for DGO showed a net sink (-6.5 Tg CO_2e yr^{-1}) while López *et al*. (2012) reported a relatively small source (0.2 Tg CO_2e yr^{-1}) for the same reporting period. For QROO, both estimates were a net CO_2 sink, but the size of the sink reported by Pereira *et al.* (-43.6 Tg CO_2e yr^{-1}) was three times our value (-14.9 Tg CO_2e yr^{-1}). Unfortunately, due to lack of information on how those numbers were derived, we cannot determine the causes of these differences.

Growth dynamics are one of the most important drivers of overall emissions estimates within the CBM-CFS3. According to our analysis of growth rates at the ecoregion-level, current annual increment in the Temperate Sierra of DGO averaged 0.65 Mg C ha^{-1} yr^{-1}. This average was very close to the 0.66 Mg C ha^{-1} yr^{-1} reported for coniferous and broadleaf forests in the National GHG Inventory of 1990-2002 (de Jong *et al.* 2010), higher than the national averages reported in BUR (INECC-SEMARNAT 2015) or in the DGO´s Strategic Forest Plan (SRNyMA 2006), which varied from 0.3 to 0.56 Mg C ha^{-1}

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} for ≤ 20 years and 0.5 Mg C ha^{-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 consistent with Mexico's goal under the National strategy on sustainable forest 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.

Ecoregions L1	Forest types or Ecoreg. Level IV	Available INFYS plots	Current Rate	Proposed Rate	Possible Rate
DGO					
Temperate Sierras	Coniferous	1,119	0.69	1.36	1.15
	Broadleaf	713	0.57	1.24	0.88
	Tropical humid	87	0.73	1.40	1.22
QROO					
Tropical Humid Forests	Central Yucatan plains	1,176	1.54	2.21	2.21
	Semi-evergreen plains	806	1.71	2.38	2.38
	Southern hills	1,404	1.49	2.17	2.17

Notes: CurrentRate= average rate of growth from 0 to 50 years in m^3 ha^{-1} yr^{-1}; ProposedRate=CurrentRate+2.7 m^3 ha^{-1} yr^{-1}; PossibleRate=Due to maximum volumes possible, this is the rate where the either 1) CONAFOR goal can be met (ProposedRate=PossibleRate) or 2) Used the maximum volume for a species and it will be attained in 50 years at the rate shown here (PossibleRate<ProposedRate). Conversion from volume to Mg C assumed a simple $2.7m^3*0.5*0.5$

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 in the BUR and in a study at the regional level in Western Sierra Madre. Here, our values were between 8% and 17% lower than the national values for coniferous forests or the regional study, but 43% higher than the estimate for broadleaf mature forests reported in the BUR (INECC-SEMARNAT 2015).

Table 8. Comparisons of reported average estimates on carbon stocks for aboveground biomass (AGBiom) and soil organic carbon (SOC) in DGO and QROO.

	AGBiom (MgC ha^{-1})	**SOC (MgC ha^{-1})**
DGO (Coniferous and broadleaf forests)		
Silva-Arrendondo and Návar-Cháidez 2009	57 (0.24 CI)	
López-Serrano *et al.* 2016	44 (22 SD)	
López *et al.* 2012		
Coniferous	46	
Broadleaf	31	
Balbontín *et al.* 2009 – Western Sierra Madre		58 (44 SD)
de Jong *et al.* 2010 – National		
Coniferous secondary forests	15 (23%U)**	58 (41%U)
Coniferous mature forest	47 (11%U)**	63 (23%U)
CONAFOR 2014 – National		
Coniferous secondary forests	22 (5%U)	49 (66%U)
Coniferous mature forest	37 (2%U)	44 (66%U)
Broadleaf secondary forests	15 (5%U)	35 (54%U)
Broadleaf mature forest	21 (5%U)	30 (68%U)
IPCC 2003, 2006, Temperate forests - America		
Coniferous ≤20 years	25 (10-55)	38
Coniferous >20 years	65 (20-140)	
This study*	**35 (1 SD)**	**53 (0.1 SD)**
QROO (semi-evergreen tropical humid forests)		
Urquiza *et al.* 2007		
30-50 yr-old forest	53 (2 SE)	
Old-growth forest (>50 yrs)	103 (4 SE)	
Orihuela *et al.* 2013		
Secondary forests	59 (±9 CI)	75 (+10;-9 CI)
Undisturbed forest	104 (±15 CI)	75 (+12;-10 CI)
Aryal *et al.* 2014		
20 yr-old forests	41 (12 SD)	50 (33 SD)
35 yr-old forest	55 (2 SD)	68 (30 SD)
Mature forest (> 35 yrs)	99 (24 SD)	67 (35 SD)
Sánchez *et al.* 2015	112 (8%U)	69 (13%U)
CONAFOR 2014 – National		
Evergreen secondary forests	20(9%U)	84 (59%U)
Evergreen mature forest	40 (3%U)	61 (94%U)
IPCC 2003, 2006 Tropical forests (2000-1000 mm of mean annual precipitation) - America	105 (100-210)	38-65
This study*	**59 (4 SD)**	**67 (0.03 SD)**

Notes: *Average values for the period 2001-2010; SD=Standard Deviation; SE=Standard Error; CI=95% Confidence Interval; %U= percentage of uncertainty. **These values include live aboveground and belowground biomass.

4.4. Considerations for implementation of scenarios

Although future analyses should also address economic and social elements for the full implementation assessment of mitigation activities (e.g. Lemprière *et al.* 2017, Xu *et al.* 2017), our study provides assessments of the potential GHG impacts of the mitigation strategies outlined in Mexico´s NDC. A mitigation target based on a change of activity data (e.g. net zero deforestation rate) may yield similar types of benefits, but at very different magnitudes depending on where it is implemented. National policies have different effects on actual emissions reductions depending on local forest characteristics and historic rates of LUC and it is therefore important to consider different policies at the state or even municipal levels when designing mitigation strategies.

Avoiding deforestation has significant mitigation benefits in QROO and much less so in DGO, because of the different deforestation rates in the baseline case and differences in forest carbon density at maturity (higher in QROO and lower in DGO). In QROO, in addition to reducing the deforestation pressure (e.g. cattle ranching, fire events, etc.; Ellis *et al.* 2015), we estimate that the avoided deforestation will require the equivalent to increasing the current network of conservation areas by 30% by 2030 (if they work properly and there is no leakage). Another potential way to achieve this goal in QROO is by expanding the area under regulated forest practices. Forest management currently has little impact on emissions in this state. If the area under management is increased greatly, the benefit would be twofold; it would help to reduce the overall rate of deforestation and avoid forest degradation through illegal logging practices (the last two not considered in this analysis). It would also increase the number of policy actions and co-benefits (Kapos *et al.* 2012, Skutsch *et al.* 2017) and still maintain the positive mitigation benefits within the state.

The timing of policy implementation matters. In the case of DGO, if harvest is increased by 50%, it will generate higher CO_2e emissions relative to BAU. However, implementing forest management actions sooner (e.g. transitioning sooner to higher productivity and harvest cycles) can ameliorate the increase in CO_2e emissions in M3 scenario by 2050 and provide other co-benefits in terms of contributing to revenues from LLP, diversified job options, etc. In addition, timing is also relevant for enhancing the mitigation potential of other strategies, such as increasing benefits from enhanced forest recovery (the earlier the better) or the duration of carbon stored in HWPs.

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.

Chapter 5. Conclusion

Mexico has a national forest inventory that allows for reporting changes in all carbon pools every five years as part of its MRV system. With the collaboration of the three forest services of North America, CEC and other government partners, progress has also been made to assess the impacts of the main drivers (forest growth, harvest, fire and land-use changes) of past and projected emissions as well as assess mitigation activity scenarios. This information can support the design of low-cost, high-benefit, forest sector interventions (Aguillón *et al.* 2009) to help achieve mitigation and adaptation goals (e.g. NDC).

Here we assessed the impacts of possible national forest mitigation strategies on net GHG emissions in two contrasting states. Using a consistent and transparent systems approach for the forest sector, we parameterized available tools with information from Mexico (e.g. forest inventory, activity data, HWP) to quantify the biophysical mitigation potential of specific actions that the government has identified as priorities to reach emission reduction goals, while co-existing with other forest management policies (e.g. increasing national-scale timber supply and productivity – ENAIPROS).

The results show clearly that if reducing GHG emissions is the main goal, avoiding deforestation (M1 and M2 scenarios) is the principle strategy to do so. In both states, the greatest reduction came from reducing gross deforestation rates by 2030, but the magnitudes were very different due to differences in the baseline rates of deforestation as well as differences in carbon density. Because GHG reduction goals interact with other socio-economic aspects (e.g. the need for employment, timber, etc.), the results from this analysis shows a variety of policy actions available to meet societal needs and still reduce GHG emissions (e.g. increase harvest for manufacturing of long-lived products, use of mill residues for bioenergy, use of wood products instead of steel or concrete). The possible actions taken together will never maximize the benefit from any one goal, however the approach used here can help identify the most optimal compromise for the forest sector.

In Mexico, the systems approach has not previously been used, but this study demonstrates the utility of existing modelling frameworks, parameterized with local data, for both monitoring and projections. Few studies are available that have examined the mitigation potential of the forest sector in Mexico (Masera *et al.* 1997, Aguillón *et al.* 2009, Garcia *et al.* 2015). This study provides some important insights since it: 1) identifies and assesses the main drivers of GHG emissions (e.g. land-use changes), 2) does not assume a fixed mitigation potential (recognizes changes over time in this type of system), 3) uses the same data that are used for national official reporting to the UNFCCC, 4) tracks carbon in HWP (currently assumed in Mexico´s official reporting as instantly oxidized after harvest), 4) assesses the potential interaction with other sectors to reduce emissions, 5) provides specific information related to Mexico´s NDC and Mid-Century plans for 2030 and 2050 and 6) exemplifies the implication of non-carbon objectives (e.g. increasing timber production) on the forest sector that may affect the success of reaching mitigation targets (e.g. NDC).

While the estimates of emissions and removals can be improved (e.g. when more detailed information becomes available on land-use change, forest degradation rates, displacement factors, etc.), this framework can already be expanded to other regions of Mexico and other more complex scenarios can now be implemented (e.g. forest degradation reduction, sustainable forest management), analyzed and ranked against alternative management policies. This work provides a solid foundation for the continued evolution and improvement for implementing the systems approach to mitigation by the forest sector in Mexico.

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