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LETTER

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The undervalued contribution of mangrove protection in Mexico to carbon emission targets

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Abstract

Mangrove deforestation threatens to release large stores of carbon from soils that are vulnerable to oxidation. Carbon stored in deep soils is not measured in national carbon inventories. Thus, policies on emission reductions have likely underestimated the contribution of mangrove deforestation to national emissions. Here, we estimate that emissions from deforestation and degradation of mangroves in Mexico are 31 times greater than the values used to determine national emission reduction targets for the Paris Agreement. Thus, Mexico has vastly undervaluated the potential of mangrove protection to reduce its emissions. Accounting for carbon emissions from mangrove soils should greatly increase the priority of mangrove forests to receive funding for protection under carbon trading programs.

KEYWORDS
blue carbon, carbon markets, deforestation, degradation, Paris agreement

1 | INTRODUCTION

The International Paris Agreement (COP21) has been ratified by 147 nations that have committed to reduce their carbon emissions by 2030 (UNFCCC, 2015). According to the Intended Nationally Determined Contributions of each country (INDC), reductions will be partly achieved by decreasing emissions from land use, land use change, and forestry (LULUCF; Grassi et al., 2017; Le Quéré et al., 2015). Emissions from LULUCF are often estimated as the reduction in carbon stocks of woody vegetation. In forested wetlands such as mangroves, up to 95% of the carbon is stored in deep soils, not in the vegetation (Donato et al., 2011). Mangrove deforestation and degradation causes the release of large amounts of CO_2 (Lovelock, Fourqurean, & Morris, 2017) that has not been accounted in national emission programs. In this study, we compare historical and current emissions from mangrove deforestation in Mexico to its INDC committed in the Paris Agreement. Our goal was to provide a fair valuation of mangrove protection that includes emissions not only from the vegetation, but from their carbon-rich soils.

Emissions of CO_2 from Mexico represent 1.4% of global emissions, which places the country as the 13th largest emitter of greenhouse gasses in the world (UNFCCC, 2016). Mexico has committed to a 22% reduction in its annual greenhouse gas emissions by 2030 compared to those in 2013, including a target of net zero emissions from LULUCF (UNFCCC, 2016). To reach these ambitious emissions targets, Mexico will give priority to actions that have the "greatest and least-cost potential for reducing emissions, and that generate cobenefits in health and wellbeing for the population" including "conservation and recovery of coastal and marine ecosystems such as…mangroves" (UNFCCC, 2016). Mexico has 3.7% of the world´s mangroves (Hamilton & Casey, 2016), providing numerous ecosystem services, including biodiversity, protection from hurricanes, and nurseries for fish (Aburto-Oropeza et al., 2008; Adame, Hermoso, Perhans, Lovelock, & Herrera-Silveira, 2015a).

We combined a unique data set of mangrove ecosystem carbon stocks of Mexico (Adame et al., 2013, 2015a, b; Ezcurra, Ezcurra, Garcillán, Costa, & Aburto-Oropeza, 2016; Kauffman, Hernandez Trejo, del Carmen Jesus Garcia, Heider, & Contreras, 2015; and unpublished data from authors MFA, MB, JHS) with national-scale mapping of mangrove distribution, deforestation, and degradation (Valderrama-Landeros et al., 2017). First, we compared carbon stocks among climatic and geomorphologic settings. Second, we estimated past emissions (1970–2015) arising from deforestation and degradation of mangroves at a regional level. Finally, we created a predictive model to estimate carbon emissions from deforestation and degradation of mangroves, and compared them to the committed emission reduction targets in the Paris Agreement for 2030.

2 | METHODS

Mangroves in Mexico cover an area of 775,555 ha and occupy a range of geomorphological, hydrological, and climatic conditions (Valderrama-Landeros et al., 2017). On the North Pacific coast, the climate is arid and tidal amplitude ranges between 0.5 and 3.5 m. In the Central and South Pacific, the climate is warm subhumid and tidal amplitude ranges between 0.5 and 1.2 m. In the Gulf of Mexico, the climate is warm-humid, tidal amplitude is less than 0.5 m, and mangroves are mostly located in riverine settings. Finally, in the Yucatan Peninsula, the climate is warm subhumid, tidal amplitude is less than 0.5 m, and the substrate is karstic (carbonated). We compile a data set that covered the range of mangrove types and regions in the country (n = 276 sites in 8 locations; Figure 1, Table S1).

2.1 | Mangrove ecosystem carbon stocks

We quantified carbon stocks including living trees, downed wood, and soil up to at least 1 m in depth and in some locations up to 3 m. We compiled published and unpublished data obtained following the IPCC best practices for measuring carbon stocks in mangroves (Kauffman & Donato, 2012). Within each sampling site, we established transects perpendicular to the coastline with six plots established every 25 m. At each plot, carbon in trees, dead wood, and soil were sampled. For trees, measurements of diameter at breast height and allometric formulas were used to determine tree biomass (above ground and roots), which was converted to carbon by a factor of 0.48 (Kauffman & Donato, 2012). Deadwood was measured with the planar intersect technique (Van Wagner, 1968). Soil carbon was estimated to at least 1 m depth from cores sampled at depths 0–15; 15–30; 30–50; 50–100; and >100 cm. Samples were analyzed for bulk density and carbon content with an elemental analyzer. The soil carbon content was corrected for inorganic carbon through loss on ignition (Heiri, Lotter, & Lemcke, 2001) or acidification of samples with hydrochloric acid before analyses.

Mean carbon stocks were compared among different types of mangroves (Lugo and Snedaker, 1974). Hammock forests are slightly elevated relative to surrounded areas and associated with freshwater springs; fringe forests are those at the edge of rivers or estuaries; basin forests are located inland along drainage depressions, and scrub forests are composed of trees <1.5 m in height. The mean mangrove carbon stock for each region within Mexico was estimated from the mangrove area (Valderrama-Landeros et al., 2017) and the mean carbon stock of mangroves within the region. In the Central Pacific and northern Gulf of Mexico, where data were not available, the carbon stock of mangroves was obtained from a zone with similar climatic and geomorphological characteristics (warm-subhumid mesotidal from the state of Oaxaca, and warm-humid microtidal from the state of Tabasco, respectively).

2.2 | CO_{2e} emissions from mangrove deforestation and degradation

Emissions from past deforestation and degradation were estimated from the carbon content of vegetation, downed wood, and soil (1 m-depth) per hectare times the difference in mangrove area over the periods 1981–2005, 2005–2010, and 2010–2015 (Valderrama-Landeros et al., 2017). We defined deforestation as a change from mangrove to nonmangrove area, and degradation as the loss of carbon in a forest that is not deforested following the Golden Observation of Forest Cover and Land Cover Dynamics Guidelines (GOFC-GOLD, 2015).

Mangrove loss in the North and Central Pacific is mostly a result of conversion to shrimp ponds, while mangrove loss in the rest of the country is mainly due to changes in the hydrology, land use change for cattle, and tourist developments. Losses of carbon were considered to be 80% of the total ecosystem carbon stock when mangroves were converted to shrimp ponds (Kauffman, Heider, Norfolk, & Payton, 2014);

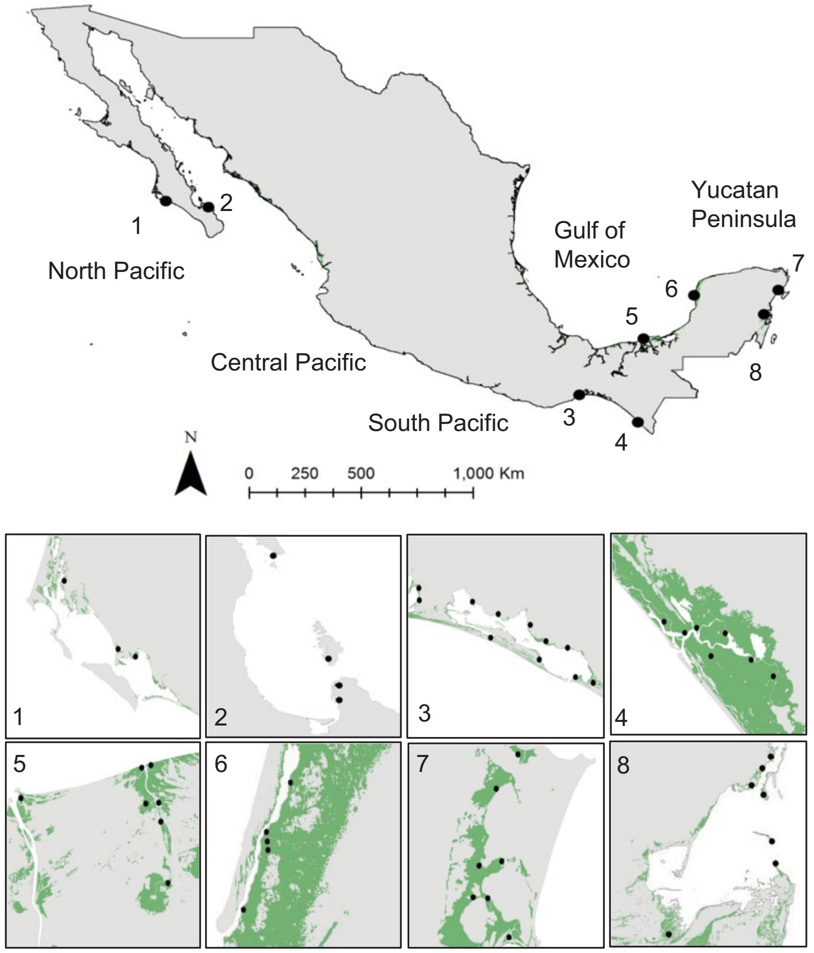

FIGURE 1 Mangrove distribution in Mexico (Valderrama-Landeros et al., 2017) CONABIO 2015 and locations where carbon stocks were quantified. Boxes show detailed distribution of mangrove forests for the eight key locations: (1) Bahia Magdalena, (2) La Paz, (3) Oaxaca Coast, (4) La Encrucijada Biosphere Reserve, (5) Pantanos de Centla Biosphere Reserve, (6) Celestun Biosphere Reserve, (7) Nichupte National Park, (8) Sian Ka'an Biosphere Reserve (Adame et al., 2013, 2015a, b; Caamal-Sosa et al., 2012; Gutiérrez-Mendoza & Herrera-Silveira, 2015; Kauffman et al., 2015)

and 66% when mangroves were converted to cattle pasture (Kauffman et al., 2015, 2017). These values were based on in situ measurements of carbon loss in the region and by models of organic carbon decomposition after mangrove disturbance (Lovelock et al., 2017). Emissions from degradation were determined similarly to deforestation, except losses were capped at 20% of the total carbon stock (Lovelock, Ruess, & Feller, 2011).

The CO_2 emissions arising from mangrove deforestation and degradation were determined by multiplying the loss in carbon stocks by a conversion factor of 3.67. The losses of carbon from mangrove forests will be mostly through CO_2 emissions directly from the forest floor and from dissolved inorganic carbon that is released to adjacent creeks (Borges et al., 2003; Chen et al., 2017; Lovelock et al., 2011) Emissions of CO_2 stabilize after 5 years and are expected to continue for at least 20 years (Lovelock et al. 2011, 2017)

2.3 | Projections of carbon emissions and contribution to Mexico's emission targets

The Paris Agreement considers 2013 as the baseline from which future emissions need to be assessed (INDC; UNFCCC, 2016). The Forest Reference Emission Level of Mexico has been constructed from the historical period of 2000 to 2010 (CONAFOR-SEMARNAT, 2015), thus, we used deforestation rates from 2005 to 2010 for our model. Deforestation rates were higher from 1981 to 2005 and lowest from 2010–2015, thus the estimated emissions vary depending on the reference level selected. We projected future carbon emissions from deforestation and degradation by developing a model of mangrove area and carbon emissions for each of the five regions (R code stored in: https://github.com/cbrown5/MangroveCarbon). The area of mangroves was modeled with constant loss rates from deforestation and degradation

$$A_{t,j} = A_{1,j}e^{t(d+g)}$$

where $A_{t,j}$ is mangrove area (hectare) at time t in region j, d_j is the rate of deforestation in a region and g_j is the rate of degradation in a region. Emissions from deforested mangroves occurred continuously at a rate r_d

$$E^d_{j,t} = \int_0^B D_{b,j,t} C^d_j r_d e^{-br_d} db$$

where $E^d{}_{j,t}$ are emissions from deforestation at time t, $D_{b,j,t}$ is the area of mangroves logged b years ago, the integral is over mangroves deforested at different times (b up to a maximum of B) and $C^d{}_j$ is the maximum potential for carbon emissions from deforested mangroves. We set $B = t$ so that we only accounted carbon emissions from mangroves deforested since 2013, the year considered as baseline for emissions. Emissions from degradation were calculated similarly, except that potential emissions were lower. By integrating over time since deforestation and degradation, we estimate cumulative carbon emissions to a given year. Mexico's carbon emissions reduction targets were estimated on an annual basis assuming constant annual emissions from land use change in the business as usual scenario (UNFCCC, 2016) In our model emissions vary over time. Therefore, we calculated the contribution of mangrove deforestation and degradation toward the 2030 target to the cumulative emissions over 2013 to the end of 2030. We designed the model to be conservative in that it provides a lower-bound estimate on cumulative emissions. The model is conservative in four ways: (1) We account for the time-lag between deforestation and degradation and the emission of carbon; (2) potential emissions are a fraction of total soil and tree carbon; (3) we do not account for deforestation of degraded forests, which may release additional carbon emissions; and (4) we do not account for carbon that would have been sequestered by deforested and degraded mangroves.

2.4 | Error

Our estimates of cumulative emissions accounted for uncertainty in measurements of carbon stocks following the GOFC-GOLD (2015) Mean carbon stocks are shown with their respective propagated error from all the measurements involved in carbon stock estimations. For the carbon emissions model, we ran Monte-Carlo simulations where we drew carbon stock values from normal distributions. For each Monte-Carlo draw, the carbon stock values were drawn from normal distributions that were centered on the mean value across cores for all regions and the standard deviation was given by the standard error of samples.

3 | RESULTS

Mangrove carbon stocks including soils to 1 m deep had a mean value of 442 ± 89 Mg C ha^{-1} (mean ± propagated error; range from 77 to 948 Mg C $ha^{-}1$; Figure 2A). When considering soil carbon deeper than 1 m, the mean ecosystem carbon stock was 890.1 ± 321 Mg C ha^{-1} (range of 77 to 2,099 Mg C ha^{-1}). On average, only 18% of the organic carbon was stored in the trees. Across climatic regions (Figure 2A), the lowest carbon stocks including soil up to 1 m were found in warm-arid climate with 265 ± 34 Mg C ha^{-1}; mangroves from warm-humid and warm-subhumid climates have similar carbon stocks with 521 ± 47 and 541 ± 85 Mg C ha^{-1}, respectively. Among forest type, highest carbon stocks (trees, down wood, and soils to 1 m deep) were found in hammock mangroves with 1,015 ± 11 Mg C ha^{-1} (Figure 2B). The lowest carbon stocks were found in scrub mangroves with 263 ± 63 Mg C ha^{-1}. Fringe-riverine, fringe-estuarine, and basin mangroves had carbon stocks of 557 ± 17 Mg C ha^{-1}, 491 ± 39 Mg C ha^{-1}, and 524 ± 53 Mg C ha^{-1}, respectively.

Regional carbon stocks estimated for 2015 (Table 1) were largest in the Yucatan Peninsula with 221.2 Tg C (421,926 ha; 524 ± 176 Mg C ha^{-1}), followed by Northern Pacific with 48.9 C (187,383 ha; 261 ± 39 Mg C ha^{-1}), Gulf of Mexico with 45.3 Tg C (87,048 ha; 521 ± 47 Mg C ha^{-1}), Southern Pacific with 32.1 Tg C (72,187 ha; 441 ± 47 Mg C ha^{-1}), and Central Pacific with 1.8 Tg C (7,011 ha; 254 ± 5 Mg C ha^{-1}). The total carbon stock of mangroves of the country are conservatively estimated to be 349 ± 6 Tg, if including soils deeper than 1 m, the stock is estimated to be 543 Tg C.

From 1981 to 2005, Mexico emitted an annual average of 3.9 ± 1.8 Tg CO_{2e} yr^{-1} due to mangrove deforestation and 0.09 ± 0.04 Tg CO_{2e} yr^{-1} due to mangrove degradation. From 2005 to 2010, the annually mean emissions decreased to 2.7 ± 1.2 Tg CO_{2e} yr^{-1} from deforestation, but emissions from degradation increased to 0.34 ± 0.15 Tg CO_{2e} yr^{-1}. From 2010 to 2015, emissions from deforestation decreased to 0.21 ± 0.10 Tg CO_{2e} yr^{-1} and emissions from degradation continued at 0.29 ± 0.13 Tg CO_{2e} yr^{-1} (Table 2).

We predict that avoiding deforestation and degradation of mangroves from 2013 to 2030 will reduce cumulative emissions by 32.8 Tg CO_{2e} (Figure 3A). If including the carbon in soil deeper than 1 m, the cumulative emissions are 54.4 Tg CO_{2e}. Alternatively, if we attribute the emissions to the year that deforestation or degradation occurred, the estimated emissions from mangroves up to 1 m in soil are 51.5 Tg CO_{2e}. The highest emissions occurred in the Yucatan Peninsula and North Pacific; the lowest emissions were measured in the Central Pacific, mainly due to a small mangrove area (Figure 3B). Overall, we found that avoiding mangrove deforestation and degradation corresponds to

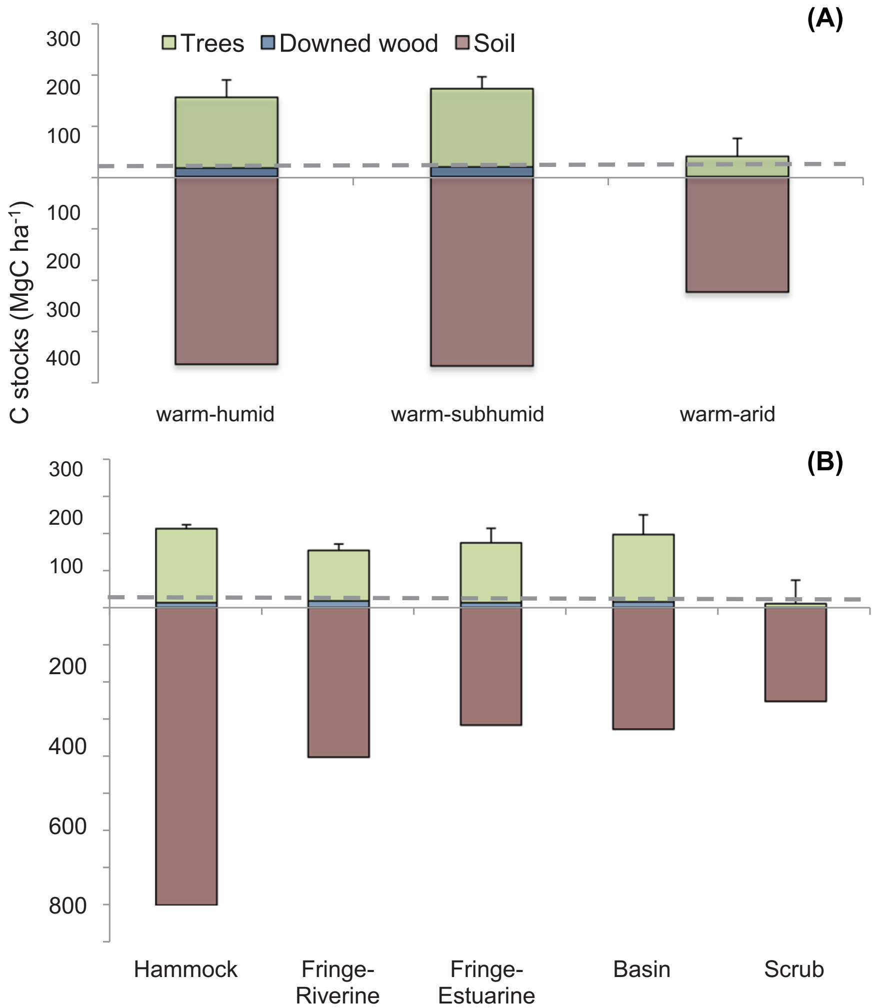

FIGURE 2 Mangrove ecosystem carbon stocks: Trees, roots, soils to 1 m depth, and downed wood (Mg C ha^{-1}) across (A) climates and (B) geomorphological settings of Mexico. Bars represent error in the total carbon stock, where error has been propagated from measurements of each component: trees, downed wood, and soil. Downed wood data from warm-arid climate are not available. The dashed line represents the officially reported value of carbon stocks of mangroves in Mexico (CONAFOR-SEMARNAT, 2015), which is the baseline considered for the Paris Agreement and carbon trading programs

6–10% of Mexico's target emissions from LULUC in the Paris Agreement.

4 | DISCUSSION

Our mean carbon stock measured for mangroves in Mexico is 22 times larger than the officially reported and used to estimate the Nationally Determined Contributions of Mexico (10–16 Mg C ha^{-1}; CONAFOR-SEMARNAT, 2015). When considering soil carbon deeper than 1 m, the mean ecosystem carbon stock is 57 times larger than the official reported value. The mismatch between measured and officially reported carbons stock has implications for mangrove conservation in Mexico. For example, the first carbon trading program in Mexico is being carried out along the South Pacific coast from 2017 to 2022 (CONAFOR, 2016). In the agreement, the carbon stock baseline for mangroves was considered to be 22 Mg C ha^{-1}, a value greatly underestimated when compared to our direct measurements of 785 Mg C ha^{-1}. Our analysis is a step towards a fair valuation of mangrove forests that could help Mexico participate in voluntary and regulatory carbon markets.

Carbon emissions from mangrove deforestation were undervalued in the INDC of Mexico because the protocol used estimate carbon stocks was designed for terrestrial forests. In Mexico, mangroves were grouped in the category “hydrophilous vegetation” which includes freshwater and saline wetlands. The protocol for “hydrophilous vegetation” only considers carbon in trees with a diameter larger than 7.5 cm and does not distinguish among mangrove species. Our estimates of avoided emissions are much

TABLE 1 Regional and national carbon stocks and deforestation and degradation rates (%) from 1981 to 2005, from 2005 to 2010 and 2010 to 2015 estimated from mangrove areas from Valderrama et al. (2017). Values are means ± propagated errors for carbon stocks, and mean ± SE for deforestation/degradation rates within regions. Negative deforestation rates are mangrove area gains and negative deforestation rates are mangrove condition improvement

	Carbon stocks (Tg C)	Deforestation rate (%)			Degradation rate (%)		
Region	2015	1981–2005	2005–2010	2010–2015	1981–2005	2005–2010	2010–2015
North Pacific	48.9 ± 11.6	0.22 ± 0.07	0.49 ± 0.23	−0.57 ± 0.30	0.11 ± 0.03	0.29 ± 0.09	−0.07 ± 0.03
Central Pacific	1.8 ± 0.3	4.12 ± 2.25	0.38 ± 0.65	−0.44 ± 0.10	−0.07 ± 0.05	0.13 ± 0.06	0.18 ± 0.19
South Pacific	32.1 ± 2.1	1.52 ± 0.84	−0.40 ± 0.43	0.23 ± 1.48	0.01 ± 0.01	0.13 ± 0.15	0.58 ± 0.94
Gulf of Mexico	45.3 ± 3.3	0.08 ± 0.29	0.46 ± 0.30	−0.35 ± 0.37	−0.00 ± 0.00	0.07 ± 0.04	0.42 ± 0.17
Yucatan Peninsula	221.2 ± 27.1	0.31 ± 0.03	0.22 ± 0.08	−0.23 ± 0.08	0.02 ± 0.03	0.11 ± 0.09	0.01 ± 0.05
Total	348.5 ± 107.1						

TABLE 2 Regional and national carbon emissions from deforestation and degradation rates from 1981 to 2005, from 2005 to 2010 and 2010 to 2015 estimated from mangrove area loss (Valderrama et al. 2017) and ecosystem carbon stocks. Values are means ± propagated errors from carbon stocks and mangrove area. Annual emissions were considered to be zero when there was no net loss of mangrove area or no net gain in degraded mangrove area

	Annual emissions from deforestation (Tg CO_{2e})			Annual emissions from degradation (× 10^6 Mg CO_{2e})		
Region	1981–2005	2005–2010	2010–2015	1981–2005	2005–2010	2010–2015
North Pacific	0.32 ± 0.06	0.68 ± 0.12	0	0.04 ± 0.01	0.10 ± 0.02	0
Central Pacific	0.21 ± 0.02	0.02 ± 0.00	0	0	0.002 ± 0.00	0.002 ± 0.00
South Pacific	1.24 ± 0.18	0	0.21 ± 0.03	0.003 ± 0.00	0.03 ± 0.00	0.14 ± 0.02
Gulf of Mexico	0.11 ± 0.01	0.60 ± 0.08	0	0.002 ± 0.01	0.02 ± 0.02	0.14 ± 0.00
Yucatan Peninsula	2.00 ± 0.70	1.40 ± 0.49	0	0.04 ± 0.03	0.18 ± 0.11	0.01 ± 0.06
Total	3.88 ± 1.76	2.69 ± 1.22	0.21 ± 0.10	0.09 ± 0.04	0.34 ± 0.15	0.29 ± 0.13

higher than the INDC for Mexico because we included carbon stored in soils and downed wood, and because we accounted for variation in carbon stocks among mangrove species. Currently, official reference values for Mexico report annual emissions from LULUCF are 32 Tg CO_{2e}, with emissions for mangroves (grouped within primary and secondary hydrophilous vegetation) estimated to be about 0.07 Tg CO_{2e} yr^{-1} (CONAFOR-SEMARNAT, 2015), an underestimation by 2.2 Tg CO_{2e} or a factor of 31.

Our estimates of carbon emissions from mangrove forests are conservative; however, they have some caveats. First, our data set has some gaps, importantly, the states of Veracruz, in the Gulf of Mexico, and the states of Sinaloa and Nayarit in the Northern Pacific. These states have 24.1% of the mangroves of the country. Thus, field sampling in these locations will improve our final estimations. Nevertheless, the variation between carbon stocks within climatic regions was consistent and unlikely to change national estimations drastically (Figure 2). Second, some mangroves may naturally emit methane and nitrous oxide and these emissions have not been considered in this study. However, methane and nitrous oxide emissions in mangroves are usually very low (<1% of emissions), and they are lower in natural compared to deforested mangroves (Kristensen et al., 2008; Siikamaki, Sanchirico, & Jardine, 2012). In locations where salinity is high, such as Northwest Mexico, methane emissions are too low to be detected (Giani, Bashan, Holguin, & Strangmann, 1996). Third, after deforestation, some carbon is emitted from the soil to the atmosphere and some is exported to adjacent water where it can be later emitted as CO_2 (Borges et al., 2003; Sidik & Lovelock, 2013). However, there is potential for a small fraction of recalcitrant carbon not emitted, but transported and stored elsewhere (Adame & Lovelock 2011; Chen et al., 2017). To date, there is no information to account for this small fraction of missing carbon in national emission budgets. And finally, carbon sequestration rates from standing mangroves were not taken into account, thus the contribution of mangroves to reduce carbon emissions is underestimated. Mangroves in Mexico sequester between 1.2 and 7.0 Mg C ha^{-1} yr^{-1} in their soil (Adame et al., 2015b; Ezcurra et al., 2016), and approximately 18.4 Mg C ha^{-1} yr^{-1} as wood and roots (Alongi, 2014). Thus, every year, mangroves may sequester an additional 19.6 Tg CO_2, the equivalent to 46% of the committed reductions from land use sector. In all, our analyses provide the best account so far of the contribution of avoiding mangrove deforestation and degradation to national emissions.

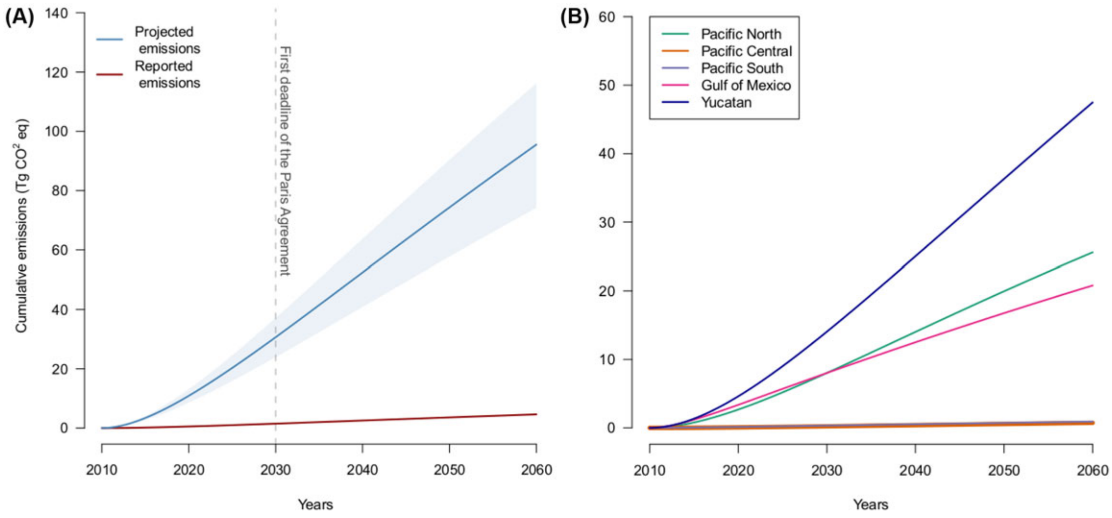

FIGURE 3 Cumulative emissions (Tg CO_{2e}) from mangrove deforestation and degradation since 2013 (national baseline) and projected to 2060 for (A) the whole country and (B) for regions of Mexico. In panel (A), the shaded area represents the 25% and 75% quartile of the mean distribution. The dashed line represents the cumulative emissions (35 Tg CO_{2e}) for avoiding mangrove deforestation and degradation for emission commitments for 2030. The model accounts for lag in emissions of carbon, so that deforestation in a given year continues to contribute to emissions in the following years

Similar to Mexico, many countries with large areas of mangroves and high rates of deforestation, such as Brazil, Colombia, and Costa Rica, did not account for soil carbon in their Forest Reference Emissions levels. Thus, their national policy could also be underrepresenting the importance of mangroves in mitigating carbon emissions. For example, mangrove deforestation in the Dominican Republic, mainly due to the conversion of mangroves to shrimp farms, results in mean instantaneous annual emissions of 0.7 Tg CO_{2e}, (Kauffman et al., 2014) or about 14% of their INDC. The potential for mangroves to mitigate national carbon emissions needs to be assessed for individual countries based on field measurements and accurate mangrove areas (e.g., Atwood et al., 2017; Kauffman, Heider, Cole, Dwire, & Donato, 2011; Schile et al., 2016). The example of Mexico in this study suggests that other countries could reach their committed targets in the Paris Agreement partly by conserving mangroves.

In conclusion, mangroves occupy a relatively small area, but their protection affords nationally significant reductions in carbon emissions. Currently, emissions from mangrove deforestation and degradation are underestimated, thus they are undervalued in carbon mitigation programs. In this study, with our improved data set that includes deep soils, and our predictive model, we provide the most complete account so far for the contribution of mangroves to mitigate emissions at a national level. In Mexico, avoiding deforestation and degradation of mangroves will account for a cumulative 32.8–54.4 Tg CO_{2e}, (2013–2030) which corresponds to 6–10% of their target emissions from LULUC in the Paris Agreement, a value that is 31 times larger than officially reported.

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SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

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