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RESEARCH ARTICLE

Prioritizing mangrove conservation across Mexico to facilitate 2020 NDC ambition

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Abstract There is a scale mismatch between mangrove conservation and carbon emission mitigation policies despite mangroves contributing disproportionally to global carbon sequestration. Using Mexico as a case study in the integration of these scales, we estimate mangrove carbon value and deforestation rates at the *municipio* (local government) scale and develop a prioritization model that indicates where to focus conservation efforts. By using previously published global models of carbon stocks, Mexico-specific carbon sequestration data, and calculating gross deforestation, we found that the current rate of deforestation will result in a social cost of 392.0 (± 7.4) million US$ over the next 25 years. The prioritization model identified 26 *municipios* of 175, where if all mangroves are conserved, 50% of this cost could be avoided. Bridging the gap between research and governmental action using local initiatives will be paramount for the effective management of mangrove carbon.

Keywords Blue carbon · Carbon sequestration · Conservation · Ecosystem services · Mangroves · Mexico

INTRODUCTION

Mangroves make significant contributions to global carbon sequestration (Chmura et al. 2003; Nellemann and GRID-Arendal 2009). Although they comprise < 0.1% of Earth's surface (Atwood et al. 2017; Hamilton and Friess, 2018), mangroves sequester 13.5 Gt of carbon each year by converting CO_2 into organic carbon (Alongi 2012). A portion of this carbon is not decomposed and contributes to large organic carbon ("carbon" hereafter) stocks in mangroves. Mangroves contribute over 3% of global forest carbon sequestration (Alongi 2012), with soil carbon stocks triple than those in other forests (Donato et al. 2011). Clearing mangroves not only stops carbon sequestration but also exposes their large carbon stocks to be released into the atmosphere as CO_2 and CH_4 (Kauffman et al. 2016; Adame et al. 2018). Thus, deforestation increases carbon emissions and reduces mitigation capacity.

Despite this importance, mangroves are being deforested around the globe. Over the twentieth century, 30–50% of global mangrove cover has been destroyed (Gallatin et al. 1947; Polidoro et al. 2010). Drivers of deforestation are varied and nuanced. In Ecuador, large areas of mangrove have been converted into shrimp aquaculture ponds (Hamilton and Lovette 2015). In Indonesia, mangroves are converted into palm oil plantations (Richards and Friess 2016). Mangroves often experience pressures simultaneously including aquaculture, agriculture, coastal development, and pollution (Thomas et al. 2017).

Mexico provides a suitable case study in threats to mangroves due to its regional variation in deforestation drivers. Mexico has over 7 000 km^2 of mangroves, the fourth largest area of any country (Giri et al. 2011). In northwest Mexico, shrimp aquaculture has been a major cause of mangrove destruction since the 1980s (Páez-Osuna 2001). In addition, aquaculture changes hydrological patterns, increases salinity, and triggers eutrophication, which all impact mangrove health (Páez-Osuna et al. 2003). Further south along the Pacific coast, the expansion of agriculture, including oil palm plantations, has promoted the clearing of mangrove forests for cropland (Castellanos-

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Navarrete and Jansen 2015). On the Gulf of Mexico, oil spills and industrial pollution have had severe impacts on mangrove ecosystems (Botello et al. 1997). Finally, in the Mexican Caribbean, the tourism industry has stimulated the conversion of mangroves into coastal real estate (Hirales-Cota 2010).

A scale mismatch exists between local mangrove management and international carbon policies. Carbon policies often are implemented at country-wide scales, while deforestation and enforcement occur at the local scale (bottom-up). Broad national goals (top-down management) regarding mangrove conservation often lack specificity in implementation. Nationally Declared Contributions (NDCs) under the Paris Agreement are policy documents in which nations state their voluntary goals to mitigate and to adapt to climate change. In the ten countries with the greatest mangrove area, encompassing 63.9% of global mangrove cover, only four mention mangroves in their first NDCs (Giri et al. 2011; Gallo et al. 2017). Ideally, top-down management will meet with local conservation efforts, as they can be very effective (Theobald et al. 2000).

The purpose of this paper is to inform the implementation of top-down management so that it will meet with local-scale initiatives. We propose to bridge the gap between community-level mangrove conservation and national CO_2 mitigation by analyzing the value of carbon stocks at the *municipio* level and prioritizing conservation efforts based on the avoided social cost of deforestation. *Municipios* are territorial divisions of local government within each of the states in the Mexican Federation, and similar administratively and in size to the counties of many nations. First, we use previously published datasets to estimate *municipio*-level mangrove carbon stocks. Next, we estimate the damages from baseline mangrove deforestation over the next 25 years due to resultant carbon emissions and prevented sequestration. Finally, we produce a framework to inform where conservation efforts can be prioritized to address drivers of deforestation and to avoid significant climate-related damages. This scheme can be incorporated into Mexico's NDC and applied to other countries. Governments can use this prioritization scheme to inform top-down management that mesh with local-level initiatives to conserve mangrove ecosystems that bolster mitigation of and adaption to climate change.

MATERIALS AND METHODS

Study areas

Only *municipios* that contained mangroves within their boundaries were included, comprising almost all coastal *municipios* of Mexico (Fig. 1). These 175 *municipios* were sorted into four regions according to climatic and geographic characteristics: Northwest Mexico, Mexican Pacific, Gulf of Mexico, and Mexican Caribbean (Vázquez-Lule et al. 2019). The percentage of mangroves protected in each *municipio* was calculated from the intersection of the mangrove and protected areas from UNEP August 2019 database (UNEP-WCMC & ICUN 2020).

Carbon stock and sequestration estimations

To estimate total mangrove ecosystem carbon stocks in each *municipio*, we summed estimates of the amount of carbon per unit area in aboveground biomass, belowground biomass, soil, and litter using ArcGIS Pro (detailed GIS methods are in SI). We retrieved data on mangrove area from 2005 and 2015 and all other spatial data from CONABIO's geoportal (https://www.conabio.gob.mx/informacion/gis/).

We calculated aboveground biomass from Simard et al. (2019) and used a carbon:biomass ratio of 0.48:1 to convert to carbon (Kauffman and Donato 2012). Soil carbon model predictions were obtained from Sanderman et al. (2018) at 30 m resolution using a soil depth of 1 m. Belowground biomass was estimated as 1.3 × aboveground biomass (Alongi 2012). Seven estimates of litter carbon stock from Mexican mangroves were obtained from the literature, averaging 1.21 Mg C ha^{-1} (Day et al. 1996; Utrera-López and Moreno-Casasola 2008; Coronado-Molina et al. 2012). Regional estimates of carbon sequestration were retrieved from published data (Gonneea et al. 2004; Adame et al. 2015; Ezcurra et al. 2016).

Valuation of mangroves and avoided damages

We value the carbon stocks and sequestration in mangroves at the *municipio* level using current estimates of the social cost of carbon (SCC). The SCC is the marginal cost of all future damage done by a pulse of one ton of carbon dioxide emitted into the atmosphere today (Pearce 2003). We performed two valuations. First, we simply multiplied carbon stock by the SCC to obtain an overall price. Second, we estimated the cost of the damages from deforestation (i.e., "avoided damages").

Mangrove carbon stocks were estimated by summing the four ecosystem carbon pools (aboveground biomass, belowground biomass, soil, and liter), converting to carbon dioxide equivalents (CO_2e), and multiplying the resulting CO_2e by the SCC. We used 40 US$ Mg^{-1} for the SCC in this study, based on a 3% discount rate to make the estimates of future benefits or avoidance of damages comparable with current costs of actions, a value regarded as conservative by the scientific community and actively used in carbon valuations (Polidoro et al. 2010; Pindyck 2019).

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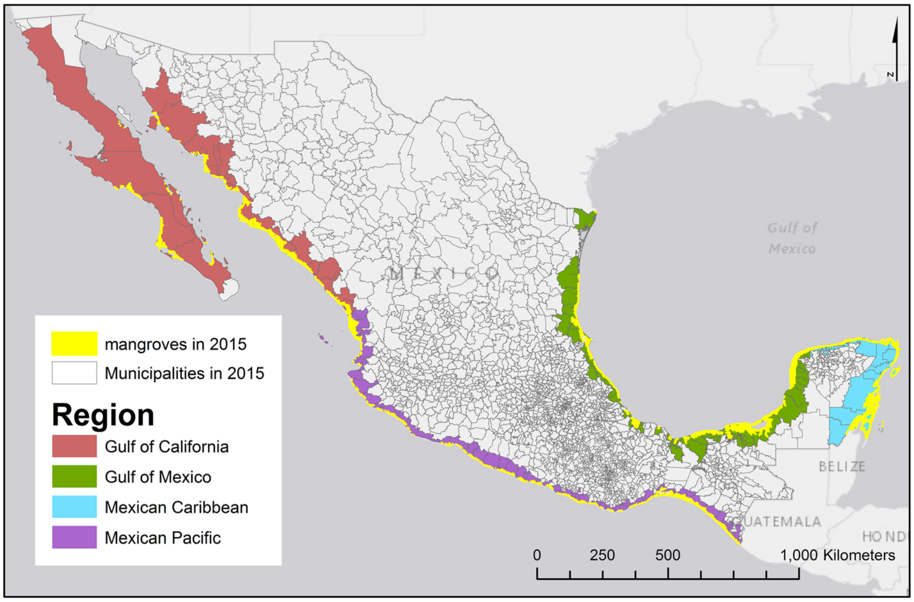

Fig. 1 Mexico's *municipios* containing mangroves divided into four geographic regions

Next, we calculated the damages from the emission of carbon stocks and the loss of future carbon sequestration to estimate avoided damages. We employed a baseline scenario of deforestation continuing at the current rate for 25 years. We calculated *municipio*-specific deforestation rates from government datasets detailing change between 2005 and 2015 (SI) and used these values to estimate baseline deforestation for 25 years. Apparent regrowth of mangroves was not included. Not all of the mangrove area loss accounted for stems from anthropogenic activity, but from natural events like hurricanes. Due to lack of data differentiating between anthropogenic and other damages, we assume that the carbon losses will be similar between these sources of degradation.

The oxidized carbon and the carbon sequestration prevented by the deforestation of mangroves each year in the scenario were used to calculate avoided damages. Aboveground biomass loss was estimated by multiplying aboveground biomass carbon and standing litter by 97%, the proportion of aboveground biomass carbon that is released when a mangrove is deforested (Kauffman et al. 2016). We assumed that 43% of belowground carbon would be released at a constant rate over 25 years, a conservative estimate as soil carbon likely decays exponentially (Kauffman et al. 2016; Lovelock et al. 2017). To estimate the value of foregone carbon sequestration, first the sequestration rate was multiplied by the mangrove area lost to deforestation. This yearly sequestration lost was then converted into CO_2e and multiplied by the SCC to estimate annual damages. The net present value of the sum of the yearly damages was then computed in R using the package "tvm" and a 3% discount rate (Truppia 2015). The resulting total avoided damages represent the cost to society of emitting carbon and losing future carbon sequestration in mangroves following the baseline rate of deforestation between 2005 and 2015 for 25 years. Per-hectare avoided damages were calculated in the same way as the total avoided damages except that the deforestation of only one hectare in the current year was considered.

Uncertainty analysis

Uncertainty for the municipio carbon estimations was accounted for by calculating the variance of the error from the aboveground biomass regression model from Simard et al. (2019) and using the variance of error reported in Sanderman et al. (2018) for the soil carbon data. The variance of the biomass and soil carbon estimates were used in Monte Carlo simulations to randomize each *municipio* carbon values (all four carbon pools) by generating 100 randomized numbers with a gamma error distribution, with the *municipio* expected value for biomass and soil carbon, and the calculated variance of the estimate. Statistics within parentheses are standard deviations unless stated otherwise. To characterize their variance, ranges of carbon stock and avoided damages values were calculated based on the varying carbon estimates.

Investment in mangrove conservation and prioritization

One component of a strategy for Mexico to meet its emissions reduction goals by 2030 as stated in their NDC (https://www4.unfccc.int/sites/ndcstaging/Pages/Home.

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aspx) is to reduce mangrove deforestation and to account for the carbon sequestration associated with this intervention. Given mounting investment in carbon capture technology, some of this funding could be used to conserve mangroves for their ability to capture carbon.

To estimate a reasonable level of investment, we used the estimated Marginal Cost of Abatement (MCA), a dollar value which represents the marginal cost of reducing net emissions by one ton of CO_2, not a direct market price. MCA curves are a tool used to analyze mitigation policies and to estimate the price of CO_2 required to achieve a specified level of abatement (Yang et al. 2018). The MCA is applicable only to the carbon sequestration provided by mangroves (not the storage value). We recommend the lower bound of MCA estimates as a reasonable level of investment to devote to mangrove conservation for carbon sequestered. Climate change mitigation funds can be invested into mangrove conservation, and the returns will include all the services that mangroves provide beyond carbon sequestration. High and low bounds for the MCA for Mexico were found in Clarke et al. (2016). The GCAM and TIAM-ECN models of MCA were chosen for low and high bounds, respectively, because they addressed Mexico specifically and included land use change as a mitigation method. These models produced \$20 and \$120 as estimates of the MCA for a goal of a 22% reduction in carbon emissions. Annual sequestration estimates were multiplied by the MCA to produce bounds for the potential investment in protecting mangroves. The potential investment in mangroves for 25 years was calculated as well using the MCA at a 3% discount rate.

To estimate the impact on the economy of paying for all the carbon sequestered by mangrove ecosystems, we calculated a variable named Carbon Sequestration Economic Impact for each *municipio*. The value of carbon sequestration in mangrove ecosystems each year (the 20\$ MCA value multiplied by the total CO_2 sequestered per *municipio*) was divided by the GDP (gross domestic product). *Total ingresos* (Total Income) per *municipio* was used as a proxy for GDP from the 2017 INEGI government dataset (INEGI 2018). Values from the last year with data were used if no data were available for 2017. Pesos were then converted into US\$ with a conversion factor of 18.92:1 US\$. This variable was included in the prioritization schemes to assess the local benefit of the government payments for conservation programs to promote carbon sequestration. To define prioritization schemes, we plotted for all *municipios* the yearly deforestation rate against the economic impact of carbon sequestration. The conservation priority was defined simply as the product of the deforestation rate (a measure of threat) and the economic impact of sequestering carbon (a measure of benefit). Other prioritization schemes were developed based on the simple rules of either putting economic impact as a first priority and deforestation as the second or, alternatively, prioritizing areas of high deforestation threat over those with high economic impact (see Supplementary Material S1). The projected results of these alternative schemes did not improve the predicted avoided damages of the rate × impact product scheme, which represents the idea that that conservation priorities should be directed towards *municipios* that are under high threat and where, simultaneously, the economic impact of conservation would be highest.

RESULTS

Carbon stocks

A total of 216.3 (± 4.2) Tg C carbon are contained in mangroves ecosystems throughout Mexico, with an average of 259.9 (± 2.2) Mg C ha^{-1} estimated from global models in the literature. The minimum and maximum carbon stocks calculated for *municipios* are 117.7 and 486.7 Mg C ha^{-1}. These values are likely underestimates as they do not include soil carbon deeper than 1 m, although Kauffman et al. (2014) and Ezcurra et al. (2016) report depths greater than 1 m. Adame et al. (2018) found a national average of 349 Tg C which includes direct measurements of carbon stocks. The average carbon stock distribution is 80.5% soil, 10.8% belowground biomass, 8.3% aboveground biomass, and 0.2% standing litter carbon. (See Associated Data for carbon data in each *municipio*. S1) The total area of mangroves each *municipio* contains is highly variable, and therefore the total carbon of each *municipio* varies substantially (Fig. 2). The Mexican Caribbean region has the most carbon per *municipio*, while the Gulf of Mexico has the highest average carbon per area.

Deforestation and damages

The average yearly deforestation rate in Mexico was 0.43% for the period of 2005–2015. We calculated deforestation over these ten years at the *municipio* level, and it ranged from 0% (12 *municipios*) to 100% (1 *municipio*: Ciudad Madero, Tamaulipas). The Gulf of Mexico showed the highest deforestation for both total area and relative to 2005 area loss, with 5 272 ha destroyed in ten years, an average of 0.615% per year (Fig. 3). The Mexican Caribbean had the lowest area of mangroves deforested, with 945 ha lost at a rate of 0.227% per year. The yearly deforestation rates for the Gulf of California and Mexican Pacific were 0.205% and 0.419%, respectively.

Considering just the value of carbon stocks, the average value of mangroves per hectare was 38 100 (± 4 030) US\$ with a range across *municipios* between 17 224 US\$ and 71

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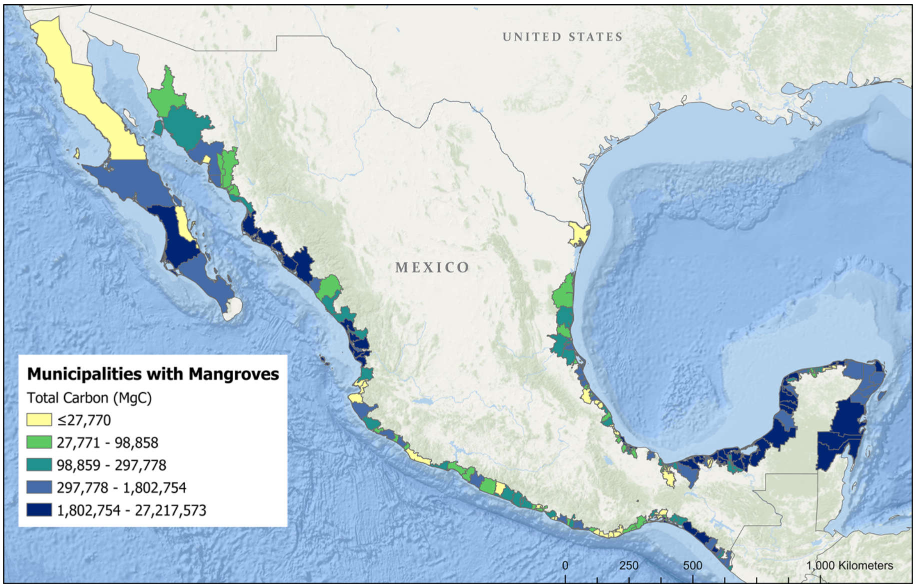

Fig. 2 The total amount of organic carbon in mangroves for each *municipio* in Mexico

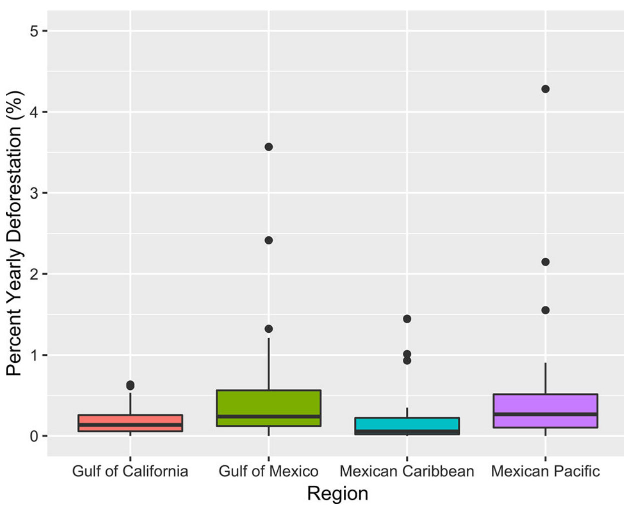

Fig. 3 Average yearly deforestation rate between 2005 and 2015 in each region in Mexico, with one outlier removed from Gulf of Mexico (a *municipio*, Ciudad Madero, Tamaulipas), with a yearly deforestation rate of 10%). These rates were calculated by comparing the amount of mangrove area that changed from mangrove to non-mangrove. The mean deforestation rate for each region is represented by the thick center black line

342 US$. The total value of the carbon stocks was 31.70 (± 0.61) thousand million US$.

The average estimated climate-related cost of destroying mangroves in Mexico is 21 000 (± 1 800) US$ for a single hectare, with values ranging between 8600 US$ and 39 500 US$ per hectare. If the baseline deforestation rate continues for 25 years, total damages to society would be 392.0 (± 7.4) million US$. Per *municipio* total damage would range from 0 to 81.5 million US$ with an average of 2.2 million US$.

Investment in mangroves

Using the MCA, we calculated potential investment in Mexico to be between 44.7 US$ and 182.5 US$ per hectare per year. For every *municipio* on a per-hectare basis, the investment to protect mangrove forests for 25 years was less than the cost to society from deforestation damages and smaller than the stock value, saving on average between $10 800 and $31 900 in avoided damages per

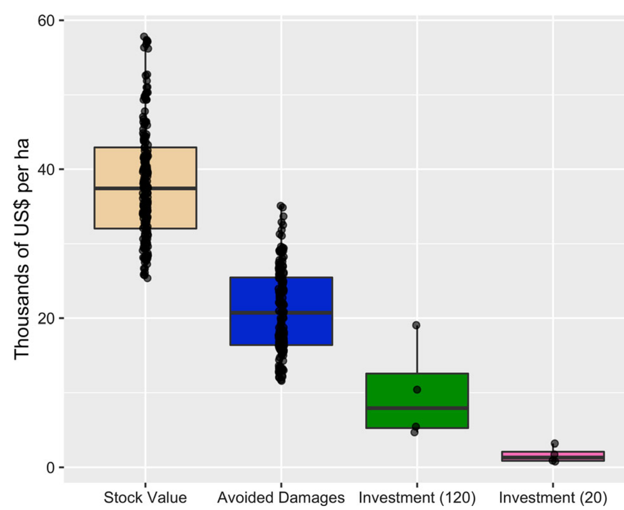

Fig. 4 Comparison of different valuation metrics displaying between *municipio* variance, including stock value, avoided damages, and investment in mangroves, using a $120 and a $20 marginal cost of abatement prices, over 25 years on a per hectare basis. The black points represent each *municipio* value that was used to estimate the mean per hectare value. The stock and damages values were estimated for each of 175 *municipios*, while the investment values are based on four regional carbon sequestration estimates

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hectare (Fig. 4). Across Mexico, 605 000 ha of mangroves fall into protected areas. 85% of *municipios* protect either less than 25% of their mangrove area or more than 75%. The median percentage of mangrove area under protection by *municipio* is 47.7%.

Prioritization Schemes

Ranking *municipios* for priority solely based on avoided damages, 11 and 39 municipios would have to half mangrove deforestation to avoid 50% and 80% of damages, respectively. Alternatively, an approach to ranking *municipios* that takes into account local variables is to rank by the simple product of deforestation percentage and carbon sequestration economic impact (Fig. 5). In this scheme, between 24 and 29 *municipios* out of 175 would have to halt deforestation to avoid 50% of the damages from baseline deforestation (Fig. 6). Two other schemes had similar damage avoidance trajectories but required a larger number of *municipios* to reach either the 50 or 80% threshold (see Supplementary Information S2). To avoid 50% of the predicted damages, between 62 and 64 *municipios* would need to stop all deforestation under the preferred scheme.

DISCUSSION

Mangroves are a significant resource for communities around the world, providing the services of fisheries habitat, storm protection, and climate change mitigation, yet these ecosystems continue to be degraded (Valiela et al. 2001; Aburto-Oropeza et al. 2008; Ezcurra et al. 2016). In this study, we evaluated damages from deforestation and attempted to bridge management efforts and current mangrove carbon stock research. To do so, we focused on two carbon research questions using a sound scale for

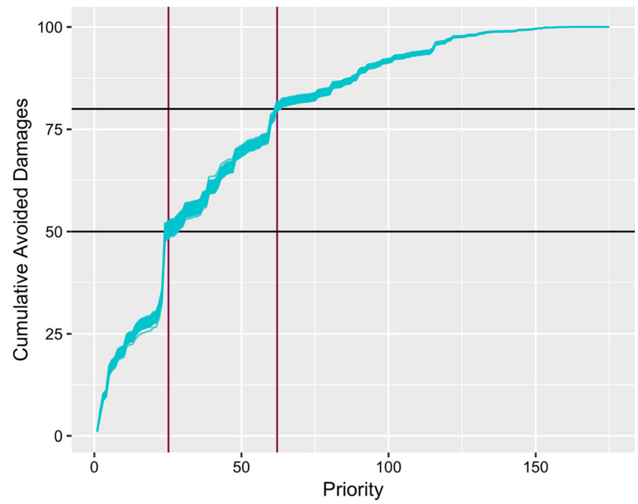

Fig. 6 Cumulative avoided damage curves for the prioritization scheme incorporating deforestation and economic benefit. The vertical width of the curve represents the 95th confidence intervals. The *x*-coordinates of the intersections of the curve and the black lines (50 and 80% thresholds), indicated by the purple lines, reveal the numbers of *municipios* where all deforestation needs to be halted to avoid 50 and 80% of baseline damages

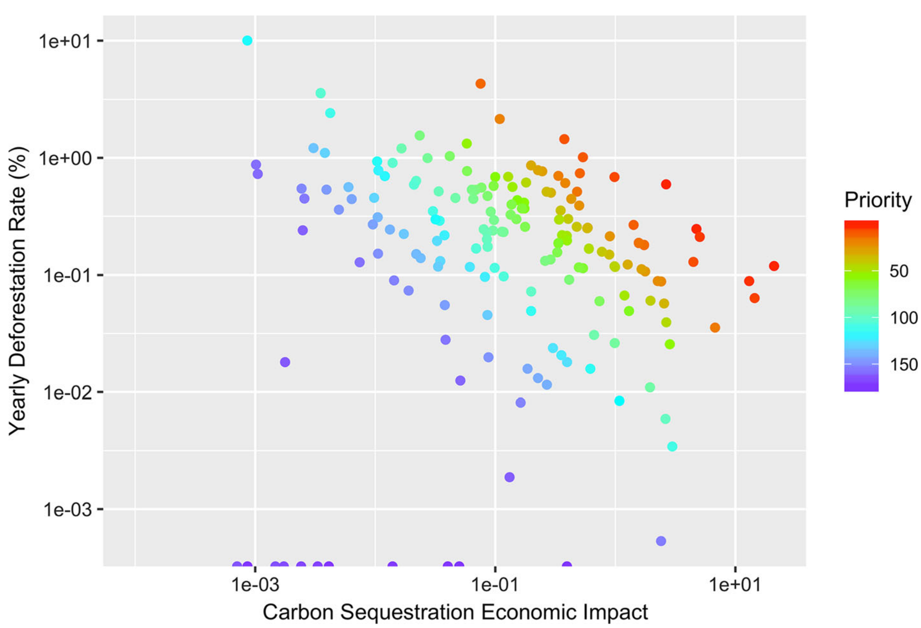

Fig. 5 A *municipio* conservation prioritization scheme where priority is assigned according to the product of yearly deforestation rate and carbon sequestration economic impact. Each point represents a ranked *municipio* and the color corresponds to conservation importance. Axes are displayed on a log scale and Veracruz de Ignacio de la Llave, Veracruz was removed as an outlier

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Table 1 List of the *municipios*, identified by the prioritization scheme taking into account deforestation and local economic impact, where conserving all mangroves can avoid 50% of carbon emissions damages from deforestation compared to baseline deforestation over the next 25 years

Priority	State	Municipality	Area (ha)	Region	Total carbon (MgC)	Yearly deforestation (%)	Avoided damages	Protected area (%)
1	Oaxaca	San Francisco del Mar	9178	Mexican Pacific	1 919 723	0.12	4 434 636	0.04
2	Nayarit	San Blas	6558	Mexican Pacific	1 816 584	0.59	17 503 001	97.73
3	Nayarit	Rosamorada	13 830	Mexican Pacific	3 808 643	0.25	14 884 106	99.68
4	Yucatán	Dzilam de Bravo	11 951	Mexican Caribbean	3 330 107	0.09	3 301 225	99.51
5	Nayarit	Santiago Ixcuintla	24 815	Mexican Pacific	6 235 666	0.21	21,964,959	99.60
6	Yucatán	Celestún	28 304	Gulf of Mexico	8 204 843	0.06	5 555 838	84.64
7	Guerrero	Benito Juárez	839	Mexican Pacific	221 339	0.69	2 491 843	0.00
8	Chiapas	Pijijiapan	12 018	Mexican Pacific	4 065 443	0.13	8 313 637	59.17
9	Yucatán	Telchac Puerto	599	Mexican Caribbean	127 095	1.45	1 861 310	99.44
10	Yucatán	Ixil	675	Mexican Caribbean	127 788	1.01	1 359 871	99.87
11	Chiapas	Tonalá	8 301	Mexican Pacific	2 569 362	0.27	10 798 151	88.92
12	Oaxaca	Santiago Jamiltepec	643	Mexican Pacific	193 054	0.74	2 224 58	0.02
13	Oaxaca	Santa María Xadani	29	Mexican Pacific	6350	4.28	343 711	0.00
14	Sinaloa	Escuinapa	10 839	Gulf of California	2 517789	0.18	5 944 087	99.64
15	Oaxaca	Villa de Tututepec de Melchor Ocampo	3 711	Mexican Pacific	1 173 824	0.19	3 496 134	49.21
16	Nayarit	Acaponeta	1 243	Mexican Pacific	248795	0.51	2 293 164	100.00
17	Yucatán	San Felipe	7 703	Mexican Caribbean	2 182 960	0.04	862 129	99.78
18	Guerrero	Marquelia	349	Mexican Pacific	94 883	0.70	1 102 556	0.00
19	Oaxaca	San Dionisio del Mar	40	Mexican Pacific	8659	2.15	283 673	0.00
20	Guerrero	Petatlán	1 122	Mexican Pacific	341 110	0.61	3 304 511	0.00
21	Yucatán	Río Lagartos	3152	Mexican Caribbean	891 560	0.09	857 309	99.74
22	Campeche	Palizada	23 114	Gulf of Mexico	7 871 650	0.09	7 750 171	100.00
23	Campeche	Champotón	13 413	Gulf of Mexico	3 364 964	0.39	13 312 782	11.16
24	Campeche	Carmen	90 910	Gulf of Mexico	27 217 573	0.21	60,955,846	94.24
25	Veracruz	Tampico Alto	2 017	Gulf of Mexico	413 919	0.45	1 994 949	17.25
26	Chiapas	Mapastepec	3 870	Mexican Pacific	1 346 652	0.11	2 325 471	100.00

management (*municipios*): (i) what is the cost of deforesting mangroves, and (ii) where are the priority areas for mangrove conservation? We found that deforestation continues to occur in Mexico despite top-down policy. Yet, the value of mangroves or the cost incurred from their deforestation is much higher than proposed levels of investment based on carbon abatement costs per area.

Prioritization schemes

This study provides a prioritization scheme that guides where to prioritize the establishment of bottom-up initiatives to achieve national goals assuming that conservation priority should be given to *municipios* where the risk of losing mangroves and the local economic impact from government-funded conservation are both high. The scheme is simple and efficient in terms of the number of *municipios* required to reduce 50% of potential damages. Mexico can achieve this goal by investing in 26 *municipios* (Table 1), which in average have 61.52% of mangroves in protected areas and 0.6% deforestation rates.

Governance

Land tenure system in Mexico is diverse. Mangroves themselves are owned by the federal government but exist on land that is owned publicly (state parks/national reserves), privately (businesses/individuals), or socially (*ejidos/tierras communes*). Property owners and users need to be aware and participate in reaching national goals about mangroves on their land. The value of carbon for each *municipio* can motivate the level of government that works directly with the owners of the land (*ejidos*, *comuneros*,

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local, and federal protected areas), to work to create systems that effectively protect these areas.

Despite Mexico establishing over 50 protected areas that contain mangroves covering 605 thousand hectares of mangrove and passing legislation that states that the actively disturbing disturbance mangroves or changing the hydrological system is illegal, deforestation still occurs (Diario Oficial de la Federación 2007; Cissell et al. 2018; UNEP-WCMC & ICUN 2020). The primarily top-down policies used in the past have not prevented deforestation. Mexico's 2015 NDC dedicates one sentence to mangroves when discussing plans for conservation. Mexico has one of the best long-term national monitoring systems for mangroves producing distribution datasets every five years, and mentions mangroves in its NDC, but clear guidelines on mangrove management need to be set within their NDC.

Nationally declared contribution (NDC) suggestions

An improved NDC in 2020 with a focus on mangrove conservation will help establish top-down legislation to integrate national goals and local initiatives surrounding blue carbon. The international research community has compiled guidance on how to incorporate wetland management into greenhouse gas inventories (Blain et al. 2013). Based on this case study, we also have three suggestions for material to be included in Mexico's NDC from a top-down perspective:

(1) The federal government should set a clear national blue carbon public policy and set a standard SCC to standardize analyses of CO_2 abatement programs.
(2) A system for frequent monitoring of mangrove growth and deforestation (< 5 years) should be implemented and additional information collected on carbon sequestration and emissions from land use change.
(3) A Payment for Ecosystem Services (PES) program should be implemented in which the data produced from suggestion 2 are sent to the federal government and local communities are reimbursed, based on the set SCC, for carbon sequestered by mangrove ecosystems.

We suggest that a robust payment for ecosystem services (PES) scheme be implemented in the communities that takes into account deforestation and local economic benefit. We provide a prioritization scheme to identify *municipios* in which a PES scheme could be implemented. PES schemes are agreements where landowners are paid for managing an ecosystem that provides benefits. Current PES programs in Mexico include a hydrological services program, *Pago por Servicios Ambientales-Hidrológico,* which pays land owners for forest conservation (Alix-Garcia et al. 2012) but does not include mangroves, and REDD+, which only considers trees > 4 m. If communities agree to a PES to conserve and to monitor these habitats, mangroves will continue to provide valuable ecosystem services and ensure the resilience of Mexico's coastlines.

The results from this study provide an important requisite to meet national goals: the accurate quantification of the economic value of mangrove carbon to help negotiate between stakeholders and competing land uses. For NDC suggestion 2 to be effective, carbon conservation subsidies should be employed for the development and dissemination of tools to monitor mangrove carbon stocks. Also, resolving competing incentives, such as subsidies for agriculture, between government ministries is necessary to meet national goals efficiently. If the costs of these programs are less than the damages, the benefits far outweigh the investment costs, as mangroves provide other numerous and valuable ecosystem services. While we address top-down management, bottom-up and top-down initiatives need to meet for blue carbon to play a role in reaching abatement goals.

Challenges for the future

In large-scale research, there are always tradeoffs between local precision and regional cover. Thus, it was necessary to make assumptions to answer the research questions. The assumptions made that have the highest influence on the results are the use of global models, the conversion factors used in the estimation of carbon stocks and sequestration, and the value for the SCC and associated discount rate.

One improvement in future studies would be to develop a Mexico-specific carbon stock model at 30 m resolution to capture the variability observed in actual measurements (Costa et al. 2019). The homogeneity between municipalities is due to averaging over large areas, reducing local-scale variability in estimates. The use of a general conversion factor to estimate belowground biomass from aboveground biomass and to estimate the fraction of carbon lost under a disturbance scenario contribute to the loss of finer variation. Additional studies are needed to develop an understanding of how aboveground biomass is related to belowground biomass as current conversion ratios used are vastly different, ranging from 0.49 to 1.3 (Alongi 2012; Blain et al. 2013).

An important economic assumption we made is to use \$40 for the SCC and a 3% discount rate. We assumed that there is a steady release of carbon from oxidizing carbon stocks post-deforestation. These assumptions contribute to conservative estimations of avoided damages and of the value of mangroves for their carbon stocks and sequestration.

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The SCC and discount rate also heavily influence the results. Although the SCC is controversial, the utility of having a marginal cost for CO_2 emissions is important when addressing the magnitude of abatement. SCC estimates range between negative values to hundreds of dollars per ton of CO_2 (Ricke et al. 2018). The 3% discount rate used here is conservatively high when considering discount rates used for other societal problems. The Stern Review uses a rate of 1%, stating that it would be unethical to have a higher discount rate in light of our obligation to future generations (Godard 2008). A 3% discount rate was selected as we matched the discount rate often used to value land for other uses. If we employed a 1% discount rate with a SCC of $59, the avoided damages would be three times as large. Matching the discount rate ensures that this analysis is relevant from the perspective of real-world land use decisions, not just that of climate change, perceived by many as a long-term concern.

Oxidation of carbon stocks was modeled as a steady-rate process over 25 years to ensure a conservative estimate of avoided damages. A more realistic negative exponential model, with more carbon emitted initially and emissions extending father into the future would increase the damages experienced sooner, which are more highly valued (Lovelock et al. 2017). We modeled the oxidation of carbon stocks under land use change using data from mangroves converted into cattle pastures (Kauffman et al. 2016). The use of these percent oxidation estimates from conversion to cattle pastures was deemed conservative as common alternative land uses such as conversion to aquaculture or urban sprawl that excavate the ground have high emissions (Kauffman et al. 2014) and likely disturb the soil more than conversion to pasture. Improvements in quantifying the SCC and emissions released due to ecosystem degradation will help solidify the economic cost of mangrove deforestation.

CONCLUSION

The results of this study can be used to develop many strategies to account for mangrove carbon in Mexico. Beyond Mexico, this research approach can be applied to other countries that possess mangroves, allowing for the integration of national goals, ecosystems, and economies. The value of mangrove carbon stocks and sequestration should be accounted for and compared to potential investment and costs of conservation for each country. Although each country would require additional analysis, in many cases mangroves have the potential to be accounted for and integrated into national carbon mitigation goals. Growing international consciousness in recent decades of the need to meet goals for reducing carbon emissions has led to a pivotal opportunity. Countries will be able to utilize their natural ecosystems to mitigate emissions while increasing adaptation capacity and securing a sustainable future. To seize this pivotal moment, research will need to take spatial scale into account to generate information that is accurate, and useful to scientists, policy makers, and local stakeholders.

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