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Ecological Estimation, Economic Valuation, and Policy Implications of Carbon Stocks and Sequestration in Mexican Mangroves

A thesis submitted in partial satisfaction of the requirements
of the degree of Master of Science

in

Marine Biology

by

Joy Alice Megumi Kumagai

Committee in charge:

Professor Octavio Aburto-Oropeza, Chair
Professor Mark Jacobsen
Professor Lisa Levin

2018

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Chair

University of California San Diego

2018

DEDICATION

To all the people who have constantly supported me, exemplified grace, and given me confidence, I dedicate this to you.

EPIGRAPH

"For I am the LORD your God who takes hold of your right hand and says to you, Do not fear; I will help you."

Isaiah 41:13

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ACKNOWLEDGMENTS

First and foremost, I want to thank and acknowledge God for giving me grace and mercy beyond comprehension, being my constant companion, and directing my life. You have supplied my every need and are my salvation. Thank you.

Secondly, I wish to express my sincere thanks to Octavio for trusting me with this opportunity and pushing me to go above and beyond what is expected. Also, for constantly supporting me and funding this research. I owe this project to you.

I wish to express my deepest appreciation to Matt for his constant guidance, patience, knowledge, and freely given time. You have developed me into a far better scientist and writer. This project would have not been able to come to fruition without you. Thank you.

Additionally, I want to thank my family, Joel, and Natalie for constantly supporting me not only in the process of starting, continuing, and finishing this thesis, but in the entirety of my life. You have been the bright spots in my life when frustration and doubt filled my brain and have been better friends and family than I would have every imagined. Thank you, Mom and Dad, for also helping to fund my education here at UCSD. I couldn't have done it without you. I love you all.

Finally, I acknowledge every person that has encouraged me along this path, whether it be directly or indirectly. I am made up of my identity in Christ and my experiences, which you have all helped mold. Thank you.

This thesis in part is currently being prepared for submission for publication of the material. Kumagai, J; Aburto-Oropeza, Octavio; Costa, M. The thesis author was the primary investigator and author of this material.

ABSTRACT OF THE THESIS

Ecological Estimation, Economic Valuation, and Policy Implications of Carbon Stocks and Sequestration in Mexican Mangroves

by

Joy Alice Megumi Kumagai

Master of Science in Marine Biology

University of California San Diego, 2018

Professor Octavio Aburto-Oropeza, Chair

Mexican mangroves are being deforested at an average rate of 1.15% per year, yet these essential ecosystems provide surrounding communities with increased fishery yields, protection from hurricanes, and run off filtration. Additionally, mangroves are well known for their ability to sequester and store carbon and have gained international recognition for this ecosystem service. The purpose of this study is to estimate current carbon stocks and sequestration rates and quantify their economic value at a local level throughout Mexico. We analyzed data from literature and calculated municipio-specific estimates of carbon. We found average carbon stocks of 519.3 MgC ha^{-1}, with sequestration rates between 0.63 to 3.46 MgC ha^{-1} yr^{-1}. Using the social cost of carbon, we estimated that the total carbon stocks in Mexican mangroves is worth 62 trillion US dollars. If baseline deforestation continues from 2016 to 2040, Mexico will lose more than 3 trillion dollars. Currently, each hectare of mangroves deforested costs an average of 42

thousand dollars between oxidation of carbon stocks and lost sequestration. In most places, the damages from deforestation outweigh the opportunity costs of cattle ranching and agriculture, which are common alternative land uses. In addition, the cost of investing in mangroves to meet Mexico's climate goals is less than the damages resulting from deforestation per area, although targeted management is necessary. The calculated value of carbon and cost of deforestation versus the price of investment in each municipio should be used to inform mangrove conservation policy in Mexico.

Introduction

Mangroves around the world are being actively destroyed at rates between one to three percent a year (Valiela et al. 2001). However, they are still greatly understudied due to physical impassibility and the perception of mangroves as wastelands (Gallatin et al. 1958). These ecosystems are one of the most economically and ecologically valuable forest environments on a per area basis (Kauffman et al. 2014). They provide abundant nursery habitats for juvenile fish, coastal protection from hurricanes, and create large carbon stores through long-term burial of detritus (Aburto-Oropeza et al. 2008; Ezcurra et al. 2016; Alongi 2012). The ability of mangroves to sequester and store carbon is becoming an increasingly relevant ecosystem service as the concentration of carbon dioxide in the atmosphere is rapidly rising (Solomon et al. 2008). Unfortunately, the importance of this system can be lost in communication to policy makers, governments, and communities as the carbon stores in mangroves have been difficult to quantify on regional scales (Jardine and Siikamäki 2014). Many countries are beginning to view the protection of natural carbon sinks as highly critical to combating climate change, yet few economic analyses have been completed at a scale that would allow the value of mangroves to be effectively used for policy. This project aims to estimate and compare the value of the carbon stocks and sequestration in mangroves to alternative land uses in the context of meeting Mexico's emission reduction goals.

Mangrove Carbon Stocks and Sequestration

Mexico has over 700 thousand hectares of mangroves, the fifth largest area of any country (Giri et al. 2010). This massive collection of mangrove forests is a valuable natural resource, given its ability to store and sequester carbon. Carbon storage can be divided into four

pools; aboveground biomass, belowground biomass, soil carbon, and litterfall. Soil carbon is the largest pool and contains three times the mass of carbon stored per area in mangroves compared to other types of forests (Donato et al. 2011). Mangroves not only store carbon but actively sequester it, qualifying them to be considered a blue carbon ecosystem (Nelleman et al. 2009). Blue carbon ecosystems are marine environments that capture and store organic carbon. Globally, mangroves account for only 0.4% of the area of forests, yet they contribute over 3% of the carbon burial in forests and 14% of carbon sequestration by the world's oceans (Alongi 2012; Makowski and Finkl 2018). Carbon sequestration in this study refers to the long-term burial of carbon, which cannot be equated to total wood production as we assume a steady state in aboveground biomass.

Mangrove Deforestation

Mangrove deforestation not only contributes to climate change by removing mangroves' ability to sequester carbon but also by releasing stored carbon dioxide into the atmosphere (Alongi 2012). It is widely accepted that 30-50% of global mangrove cover has been lost to human activity in the past century (Polidoro et al. 2010). This loss has deprived communities of coastal protection and significant profit in fisheries, and resulted in the emission of greenhouse gases (Alongi 2012). Mangrove deforestation also weakens coastal communities' resilience against the increasing hurricane activity, sea level rise, and other climate change impacts (Duarte et al. 2003; Emanuel 2005).

Valuation of Mangroves

Mangroves are important for society, but how do people ascribe economic value to this ecosystem? Many have sought to develop methods to do so for different habitats (Turner et al. 2010). This project utilizes three distinct ways to value mangrove habitats. First, one can simply sum the price of the components of a habitat. Secondly, the value could be equal to the amount of damage done if one destroys the ecosystem in question. Lastly, the price of performing the same functionality somewhere else could be used to associate value. In this study, we incorporate the first two methodologies to directly value or price mangroves, while the third is viewed as the minimum investment to conserve the habitat. To be able to do these evaluations a conversion factor to convert between carbon dioxide and a monetary price is needed.

Social Cost of Carbon

Carbon can be converted into dollars using the Social Cost of Carbon (SSC). The SCC is the marginal price of all future damage done by a pulse of one ton of carbon dioxide into the atmosphere (EPA 2016; Pearce 2003). This price is also equivalent to the value of damages avoided for the same reduction in carbon dioxide emissions. The SCC is especially useful as it allows economists to conduct cost benefit analyses to find which policies maximize utility or wellbeing for society. Unfortunately, due to simplifications in models and the challenges in attempting to comprehensively estimate potential future damages of climate change, the SCC is highly uncertain. Solicited expert economists and climate scientist opinions are extremely variable but average over $200 per ton of CO_2. If one only considers highly confident answers, the average is around $80 (Pindyck 2016). With the SCC, one is able to quantify the value of mangrove carbon stocks and sequestration and also how much damage is incurred from destroying them.

Deforestation Damages and Investment into Mangroves

The damages associated with deforestation can be compared to the opportunity costs of alternative land uses. Aquaculture, agriculture, coastal development, and cattle farms are common examples of what land previously occupied with mangroves is used for (Alongi 2012; Giri et al. 2011, Kauffman et al. 2017). When making decisions about land use change, damages associated with deforestation of mangroves are often not considered and the ecosystem is undervalued (Clough 2013). If one considers just the benefit of increased fishery yields, $37,500 per hectare each year, mangroves are worth far more than previous estimates, such as the approximation of $10,000 per hectare annually (Aburto et al. 2008; Costanza et al. 1998). In 2007, the Mexican government stated that any destruction of mangrove trees is illegal (Article 60 TER 2007). Despite this law, exceptions and violations still occur.

Mexico has committed to reducing its greenhouse gas emissions by 22% before 2031, but has not addressed how stopping mangrove deforestation could be a part of that reduction in their NDC (Nationally Declared Contribution). The carbon sequestration by mangroves could be accounted as an additional pathway to lower emissions and meet Mexico's goal. We compare the cost of investing in mangroves for their ability to sequester carbon to the costs resulting from continued deforestation.

Research Objectives

The objectives of this study are three-fold, first to quantify the amount of carbon stored and sequestered in mangrove ecosystems in each municipio in Mexico. The second objective is to determine the per-hectare cost to society of mangrove deforestation and the rate of that deforestation in Mexico. Finally, we contextualize these results by comparing the avoided

damages of deforestation to the profits from alternative land uses in addition to estimating the cost of using mangroves to abate carbon emissions. This research addresses the need for more spatially explicit carbon estimates and will provide economic information critical to the conservation of mangroves and their role in meeting Mexico's climate goals.

Methods

Municipios in Mexico

The focus of this study was to develop estimates of carbon stocks and sequestration rates and their value at a scale that is relevant to policy makers throughout Mexico. The municipio level was chosen as conservation is most effectively performed at a local level (Theobald et al. 2000). Mexico's 32 states are divided into 2,457 municipios, analogous to counties in the U.S.A. Municipios range in area from 221 hectares in Natividad, Oaxaca, to over 5 million hectares in Ensenada, Baja California. For this study, only municipios that contained mangroves within their boundaries were included, comprising of almost all the coastal municipios of Mexico (Figure 1). These 172 municipios were divided into four geographic distinct regions, Gulf of California, Mexican Pacific, Gulf of Mexico, and Mexican Caribbean.

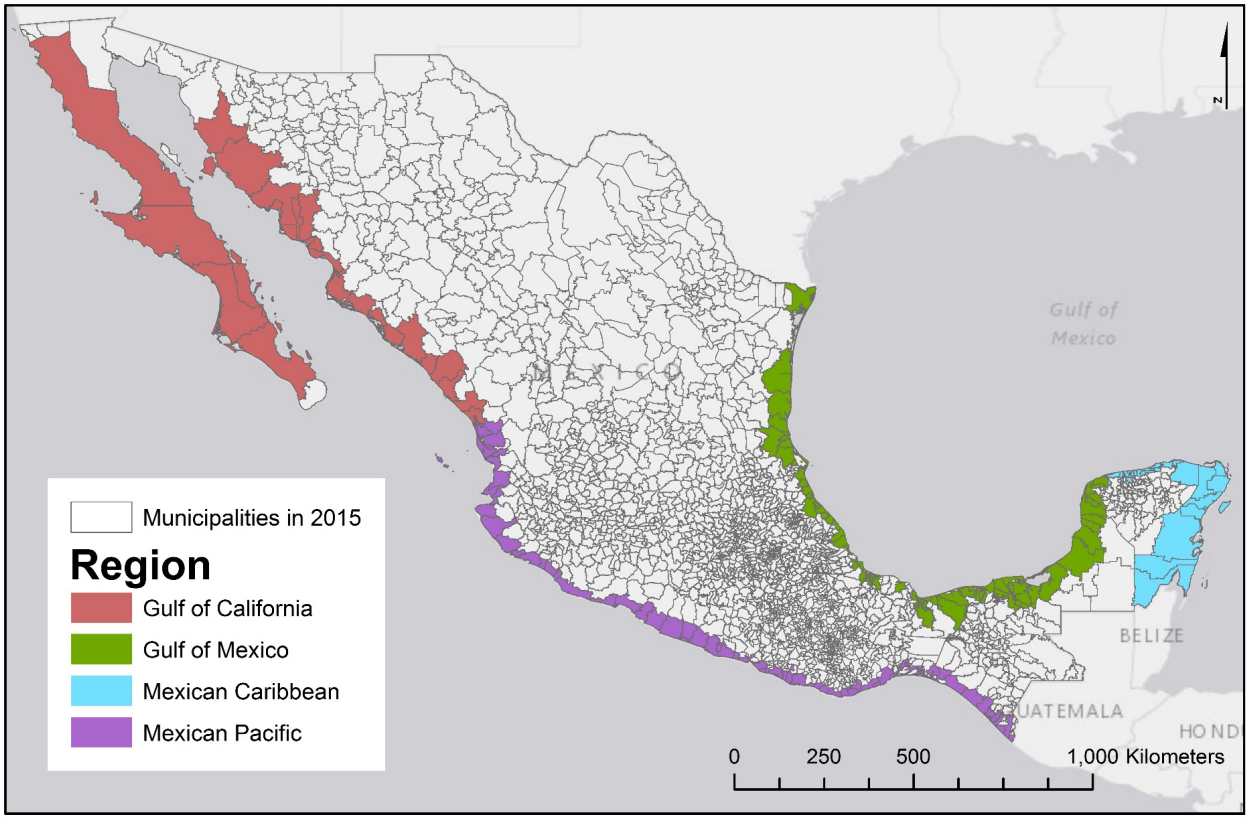

Figure 1: Mexico's municipios containing mangroves, divided into four geographic regions. Basemap sources: Esri, DeLorme, HERE, MapmyIndia.

Carbon Stock Estimates

To understand the amount of carbon stored in each municipio, total carbon was calculated by summing estimates of the amount of carbon in aboveground biomass, belowground biomass, soil, and standing litter using ArcGIS 10.5. Municipio boundaries and mangrove polygons representing coverage in 2005 and 2015 throughout Mexico were obtained from layers in CONABIO's geoportal (CONABIO 2005; CONABIO 2015).

Aboveground biomass was calculated with a published global equation which uses temperature and precipitation to calculate biomass using a regression (Hutchison et al. 2014; Equation 1). The data describing the mean temperature of warmest (BIO10) and coldest quarter (BIO11) as well as precipitation of wettest (BIO16) and driest (BIO17) quarter used in the equation were downloaded from BioClim at a spatial resolution of 30 arc seconds (Appendix IV). Detailed ArcGIS methods are noted in Appendix IV:A. Once the aboveground biomass was calculated, a ratio of 0.48 aboveground biomass to carbon was used (Kauffman and Donato, 2012).

Equation 1: Aboveground biomass equation from Hutchison et al. 2014. Temperature is in deci-degrees C.

$$(1) \qquad \mathrm{AGB}\ (\mathrm{t\ ha^{-1}}) = 0.295\mathrm{BIO10} + 0.658\mathrm{BIO11} + 0.0234\mathrm{BIO16} + 0.195\mathrm{BIO17} - 120.3$$

Soil carbon model predictions were obtained from Jardine and Siikamäki(2014) at a resolution of 5 arc minutes, and the mangrove polygons mapped onto this layer. Nine percent of the mangrove polygons did not overlap with the soil carbon data. To approximate these missing data, the original soil carbon dataset was interpolated using the Inverse Distance Weighted (IDW) method. IDW determines the value of cells in question by using a linear weighed

combination of surrounding raster cell values with nearer cells weighted more. The concentration of carbon in soil from Jardine and Siikamäki (2014), was transformed to carbon per area by integrating over a soil depth of 1m. Also, belowground biomass carbon was assumed to be equal to 1.3 times aboveground biomass carbon (Alongi 2012).

Eight estimates of standing litter carbon stock from Mexican mangroves were obtained from the literature (Day et al. 1996; Coronodo-Molina et al. 2012; Utrera-Lopez and Moreno-Casaola 2008). Out of these eight measurements, seven were chosen to calculate a representative average of 1.21MgC ha^{-1}. One value, 5.57MgC ha^{-1}, from the Riverine mangroves in Laguna de la Mancha reported in Utrera-Lopez and Moreno-Casaola (2008) was a major outlier and removed. Carbon was calculated from biomass once again using a ratio of 0.48.

Carbon Sequestration Estimates

While the previous section explains the calculation of the standing stock of carbon that if oxidized contribute to carbon dioxide emissions, here we estimate the potential for mangroves to be a pathway of reducing CO_2 emissions. Regional estimates of carbon sequestration were modeled using published data to convert litterfall to carbon sequestered. Lopez-Medellin and Ezcurra (2012) showed a significant relationship between latitude and litterfall, but a literature search did not reveal that this trend extends beyond the Gulf of California region (Figure 2). The data resulting from the search are listed in Appendix I, restricted to studies using a mesh size of 1 mm or less. The limited litterfall data was then divided into Pacific and Atlantic sides of Mexico, with the Gulf of California separated due to the established trend. In Baja, latitude was used to estimate litterfall allowing for municipio-specific estimates of carbon sequestration in this region. The litterfall values were then used to approximate carbon sequestration in the following

way. Two studies reported relationships between wood production and litterfall (Day et al. 1987; Day et al. 1996). Using these data, a ratio of 0.628 of litterfall to aboveground wood production was calculated. Next, aboveground wood production was assumed to be equivalent to belowground wood production, which is the pool most likely to be stored long term (Twilley, et al. 2017; Bouillon et al. Therefore, we estimated carbon sequestration from litterfall at a regional scale for all mangroves, and at a municipio level for the Gulf of California.

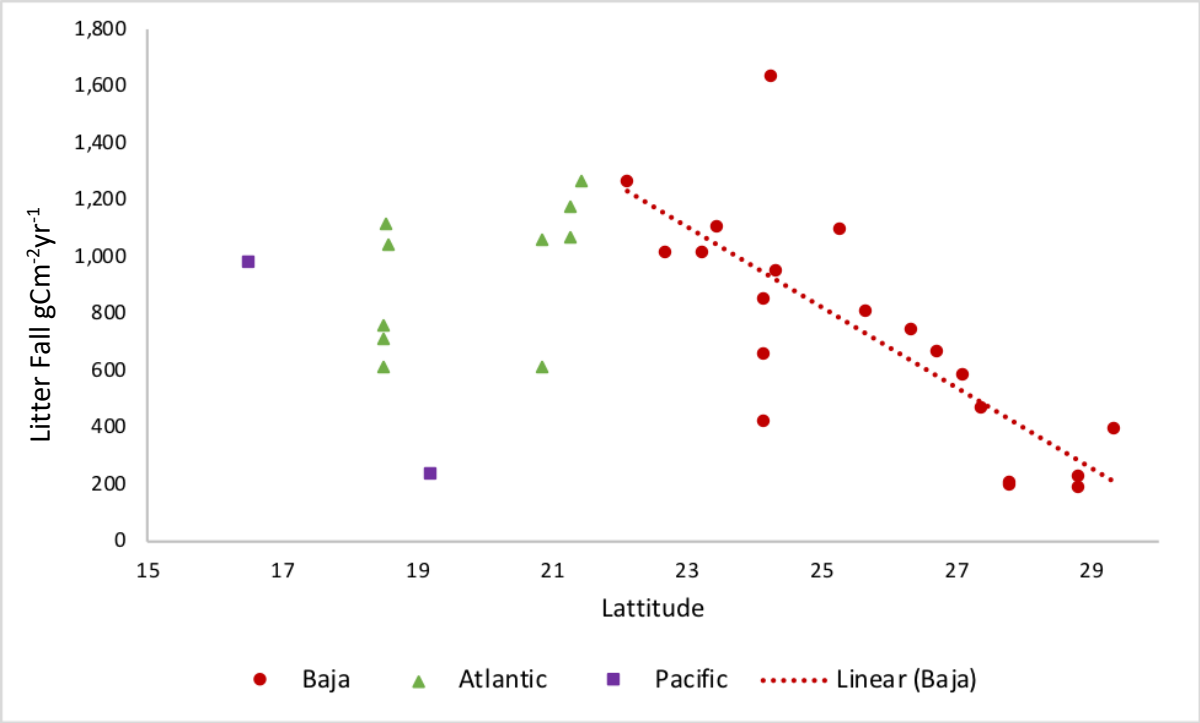

Figure 2: Relationship between litterfall and latitude data in the literature from Mexico. The linear trend line displayed on right is from Lopez-Medellin and Ezcurra, 2012.

Mangrove Deforestation

Baseline deforestation rates were estimated to understand the magnitude of damages from removing mangroves. Datasets from CONABIO were analyzed detailing the change in mangrove area to produce a yearly deforestation rate (CONABIO 2013; CONABIO 2016). The datasets were combined following methods explained in Appendix IV:B. To produce an accurate yearly deforestation rate between 2005 to 2015, mangrove deforestation was defined as areas larger

than 0.5 hectare that were converted from mangrove to non-mangrove. No polygons less than 0.5 hectares were considered as there were many small polygons (<0.1 ha) that resulted from errors in satellite classification of mangroves being propagated through multiple geoprocessing steps. Thus, only large areas of deforestation are used in the analysis due to the limit of the original spatial resolution of the satellite imagery. In addition, regrowth was also not considered. If we calculated the rate based on net deforestation, this method assumes that new growth in five years can cancel deforested area. This assumption is not accurate as destroying a mature mangrove ecosystem is not equivalent to newly expanded area of mangroves that registers the same spectral bands used in satellite classification (López-Medellín et al. 2011).

Value of Mangroves

The value of mangrove carbon stock was first estimated using the simplest evaluation method. This valuation consisted of summing the amount of carbon in the habitat, converting it into carbon dioxide equivalents (CO_2E), and multiplying the resulting CO_2E by the SCC. Forty dollars was used for the SCC in this study corresponding to a 3% discount rate (see discussion).

Avoided Damages Calculations

A baseline scenario of deforestation for 25 years was developed so the cost to society of deforesting mangroves between 2016 and 2040 could be computed. These damages include the release of carbon stocks and the loss of all future carbon sequestration. The amount of land deforested each year was determined by using the municipio-specific relative deforestation rate and multiplying that by the area of trees left in the previous year.

To value the carbon stocks, the amount of carbon released from aboveground biomass was computed by multiplying the aboveground carbon biomass and standing litter by 0.97%, This percentage is the proportion of aboveground biomass carbon that is released when a mangrove is deforested (Kauffman et al. 2016). These values originate from cattle pasture conversion, but are applied here to expected emissions from land use change in general. We assumed that 43% of belowground carbon would be released equally over the 25 years in consideration (Kauffman et al. 2016), which is an underestimation as soil carbon will decay exponentially (see discussion). For each year, the belowground biomass carbon and soil carbon in the area deforested were added together and multiplied by 0.43 (the proportion of carbon lost) and divided by 25 years. This value was then added to the release of carbon from previous years' deforestation. After 25 years, no new deforestation is considered, but carbon is still released from the previous mangrove removal until 2065. Release of aboveground and belowground carbon was converted into CO_2E, multiplied by the SCC, and then discounted to 2015 dollars using a 3% discount rate for each year unless stated otherwise.

All future lost carbon sequestration was accounted for in each municipio and added to the damages from the oxidation of carbon stocks. To estimate the value of foregone carbon sequestration, first the rate of sequestration was multiplied by the area of mangroves lost to deforestation. This yearly sequestration lost was then converted into CO_2E and multiplied by the SCC to represent the monetary annual damages. The net present value of the sum of the yearly damages was then computed using the R package "tvm" and a 3% discount rate unless stated otherwise (Truppia 2015). The resulting total avoided damages values represent the cost to society in releasing CO_2E and losing future carbon sequestration in mangroves following the baseline rate of deforestation between 2005 and 2015 for 25 years.

The per hectare avoided damages value used when comparing alternative land uses and investment costs was calculated in the same way as the total avoided damages, but just considering one hectare deforested in the present year.

Alternative Land Use Comparison

To compare the damages and opportunity costs of alternative land uses, the average profits per area in each municipio for agriculture and cattle were determined. The profits were then subtracted from the avoided damages value for mangroves. A government dataset, describing profits and area seeded in winter and summer seasons in 2016 was downloaded off the Servicio de Información Agroalimentaria y Pesquera website (SIAP, Anuario Estadístico de la Producción Agrícola 2016). Pesos were converted into US dollars using a ratio of 0.053526 dollars to one peso; the average rate from February 2017 to January 2018. The agriculture land use value was then calculated as the profit from agriculture for 2016 divided by the area seeded over the year, repeated yearly until 2040 and then discounted back to 2015 and summed. The average area and profits from agriculture over the next 25 years was assumed to be constant. The land use value for cattle raising was calculated in the same manner, with information extracted from a dataset on profits for producers supplied by SIAP for 2016 (SIAP, SAGARAPA 2016). Profits were the combined pesos between the value of cattle alive and sacrificed. The area was then gathered for large, medium, and small cattle producers from the Instituto Nacional de Estadística y Geografía (INEGI, Actualización del marco censal agropecuraio 2016). These results were analyzed using different discount rates, 2.5%, 3.0% to 5.0%, with corresponding SCC of 59, 40, and 11.50 dollars, to test the sensitivity of these results to discount rates (Interagency Working Group on Social Cost of Greenhouse Gasses, 2016).

Potential Investment into Mangroves

If Mexico is going to invest in both emissions abatement for mitigation of climate change and adaptation to meet their climate goals, mangroves offer a low-cost method and will also perform multiple ecosystem services. Thus, the money used to abate can be used to invest in mangroves and the returns will include all the services mangroves provide, not only carbon sequestration. The Marginal Cost of Abatement (MCA) can then be used as an estimate of the amount one could potentially invest in mangroves to sequester carbon on a per hectare basis. High and low bounds for the Marginal Cost of Abatement for Mexico representing the marginal cost of reducing one metric ton of carbon dioxide emissions were found in Clarke et al. 2016. The GCAM and TIAM-ECN models were chosen for the low and high bounds out of the Latin American models where Mexico was a unique region and land use change as a method of abatement. These models produced $20 and $120 for the Marginal Cost of Abatement to meet a 22% reduction in carbon emissions. The amount of sequestered carbon per year was multiplied by $20 and $120 to produce the potential investment to protect mangroves as a source of carbon dioxide removal. The amount for twenty five years was calculated as well using a three percent discount rate.

Results

Carbon Stock and Sequestration Estimates

A total of 425.7 TgC carbon was estimated to be in the mangroves throughout Mexico, with an average of 519.3 MgC in each hectare. The min and max of carbon per hectare in the municipalities were 429.6 and 631.7 MgC ha^{-1} (Figure 3). For an average hectare in Mexico, the carbon stock was made of 71.9% soil, 12.1% above ground, 15.7% below ground, and 0.2% standing litter carbon. The second appendix can be referenced for the carbon in each municipio, divided by carbon pool. The aboveground biomass contained a strong latitudinal gradient (r^2 = 0.74, $p < 0.001$), while the soil carbon lacked a significant latitudinal trend ($p = 0.62$). The total carbon that each municipio contained was highly variable as the area of mangroves varied (Figure 4). The Mexican Pacific region had the most carbon per municipio while the Mexican Caribbean region had the highest average carbon per area in mangroves.

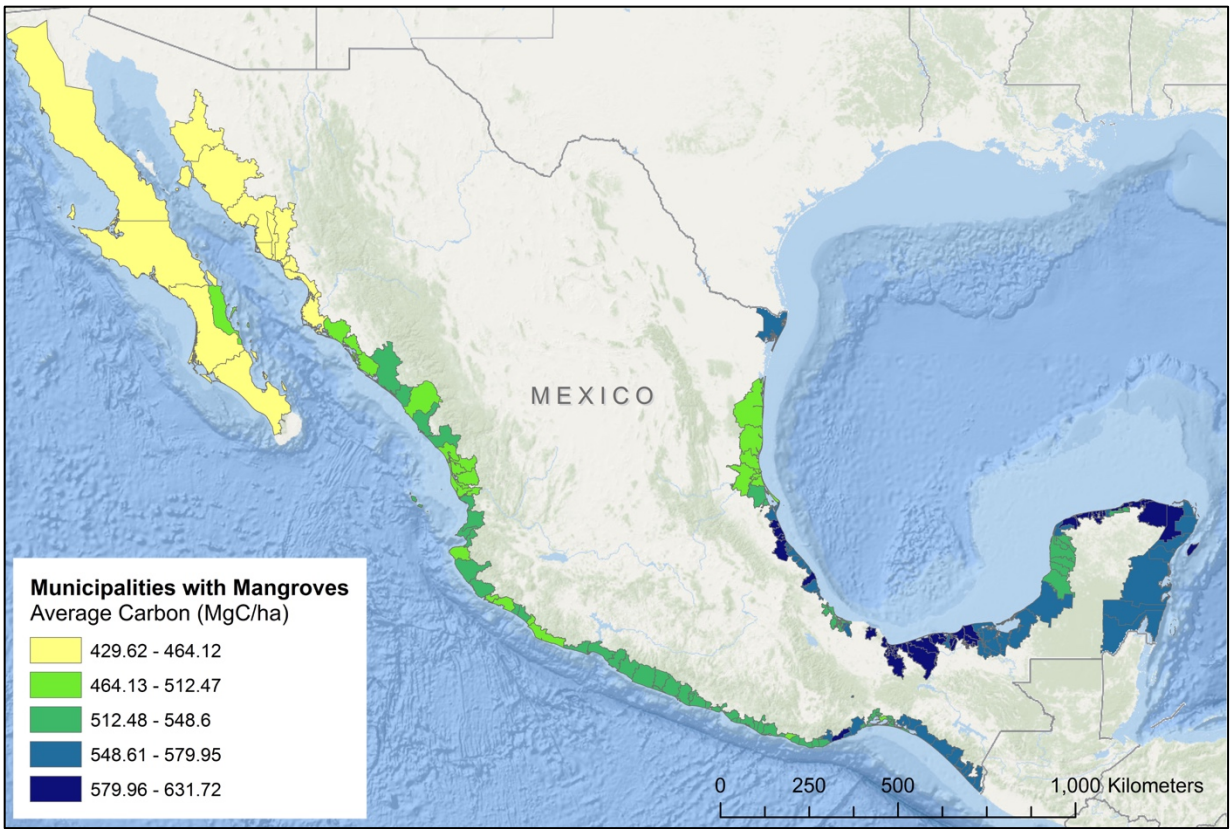

Figure 3: Average carbon per hectare in each municipio throughout Mexico that contains mangroves. The Mexican Pacific and Yucatan contain the highest carbon intensity, while more northern municipios, especially the Baja California region, have less carbon per area. Basemap sources: Esri, GEBCO, NOAA, National Geographic, DeLorme, HERE, Geonames.org, and other contributors.

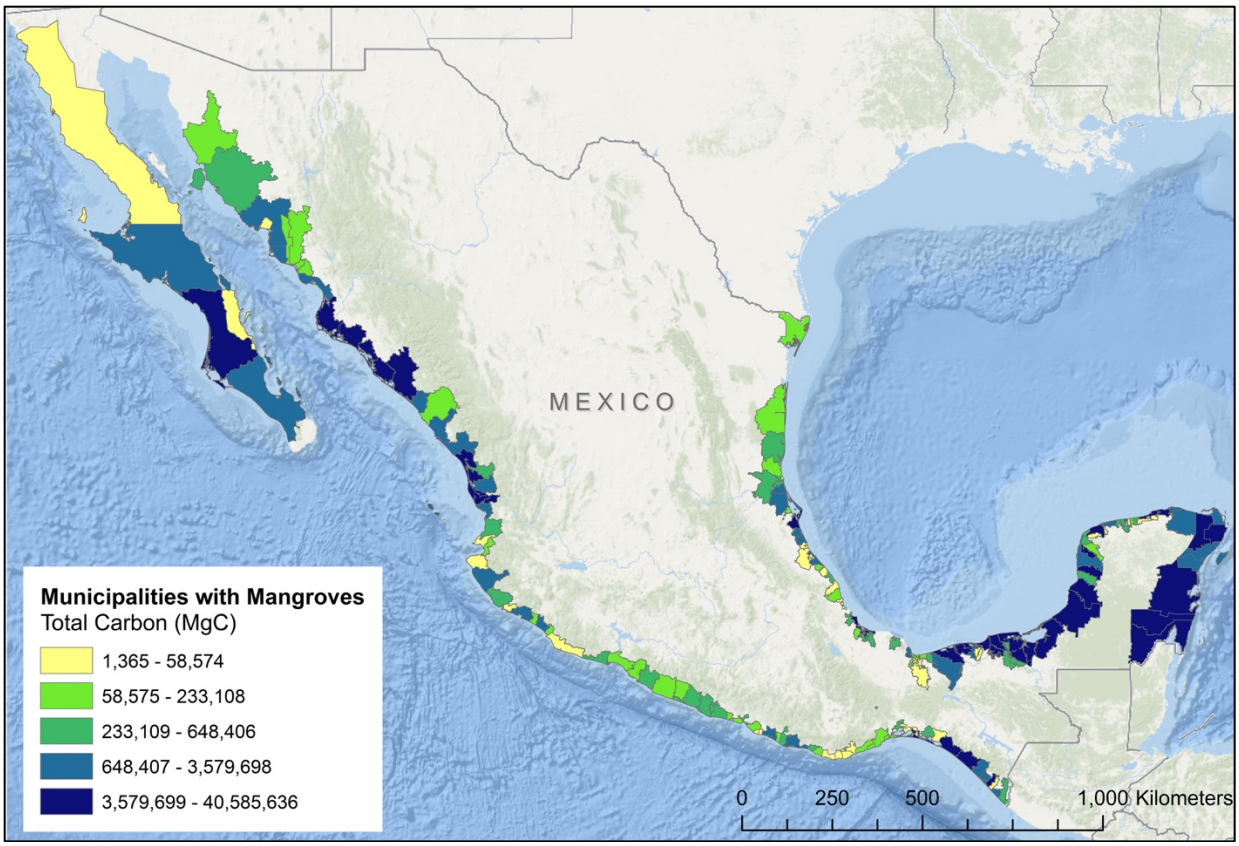

Figure 4: Total carbon in mangroves for each municipio in Mexico. Trend observed with latitude previously in average carbon per area is not observed in total carbon. Basemap sources: Esri, GEBCO, NOAA, National Geographic, DeLorme, HERE, Geonames.org, and other contributors.

Carbon sequestration was estimated for three distinct regions in Mexico. The sequestration rate for Baja California region ranged between 0.61 and 3.46 MgC ha^{-1} yr^{-1} depending on latitude. The rest of Mexico was divided between Atlantic and Pacific due to data limitations. For the Atlantic mangroves, the carbon sequestration rate was 2.74 MgC ha^{-1} yr^{-1}, higher than the Pacific mangroves at 1.80 MgC ha^{-1} yr^{-1}. These results are similar to previous estimates of an average global carbon burial rate of 1.67 MgC ha^{-1} yr^{-1} (Alongi 2012).

Mangrove Deforestation

The average yearly deforestation rate in Mexico was 1.15% for the period of 2005-2015. The Gulf of Mexico showed the highest deforestation for both total area and relative to 2005 area

destroyed, with 12,522 ha destroyed in ten years, representing 13% of mangroves deforested between 2005 to 2015 (Figure 5). The Mexican Caribbean had the least mangroves destroyed, although 4,425 ha of their forests were lost with 0.81% yearly deforestation. The yearly deforestation rate for NW Mexico and the Mexican Pacific was 0.97% and 1.18%, respectively. Seven municipios (4%) had no deforestation registered. Appendix III reports the deforestation rate for each municipio.

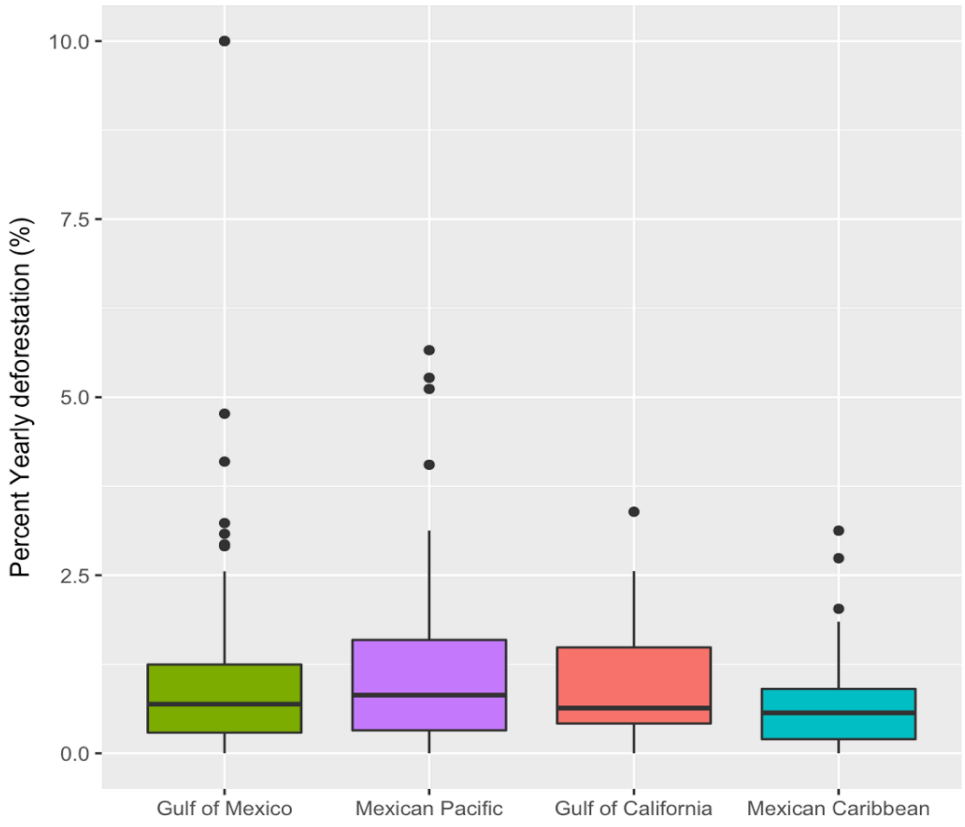

Figure 5: Average yearly deforestation rate between 2005 to 2015 in each region in Mexico.

Economic Value and Avoided Damages

Considering just the value of carbon in the mangroves, the value of mangroves per hectare in the municipios ranged between $63,221 and $92,591 (Appendix III). The total value of the carbon stocks was 62.39 trillion dollars. Kauffman recently estimated that it takes 182

years to sequester the same amount of carbon released from the conversion of land to shrimp farms (Kauffman et al. 2018), while rebuilding the entire stock of carbon would take much longer. Thus, this large and high-priced resource is thousands of years old and cannot be readily replaced with planting new mangroves.

Calculations to estimate the cost to society of destroying mangroves in Mexico resulted in a range between $25,341 and $49,825 with an average of $42,037 for a single hectare. If baseline deforestation continues for 25 years, total avoided damages to society would be 3.18 trillion dollars. Per municipality total damage would be between 0 and 297 million dollars with an average of 18.5 million dollars (Appendix III). This range is dependent on the baseline deforestation rate, the average amount of carbon in each municipio, and the sequestration rate. Valuing mangroves based on the damages done by deforestation results in about half of the price of their carbon stock per area (Figure 6).

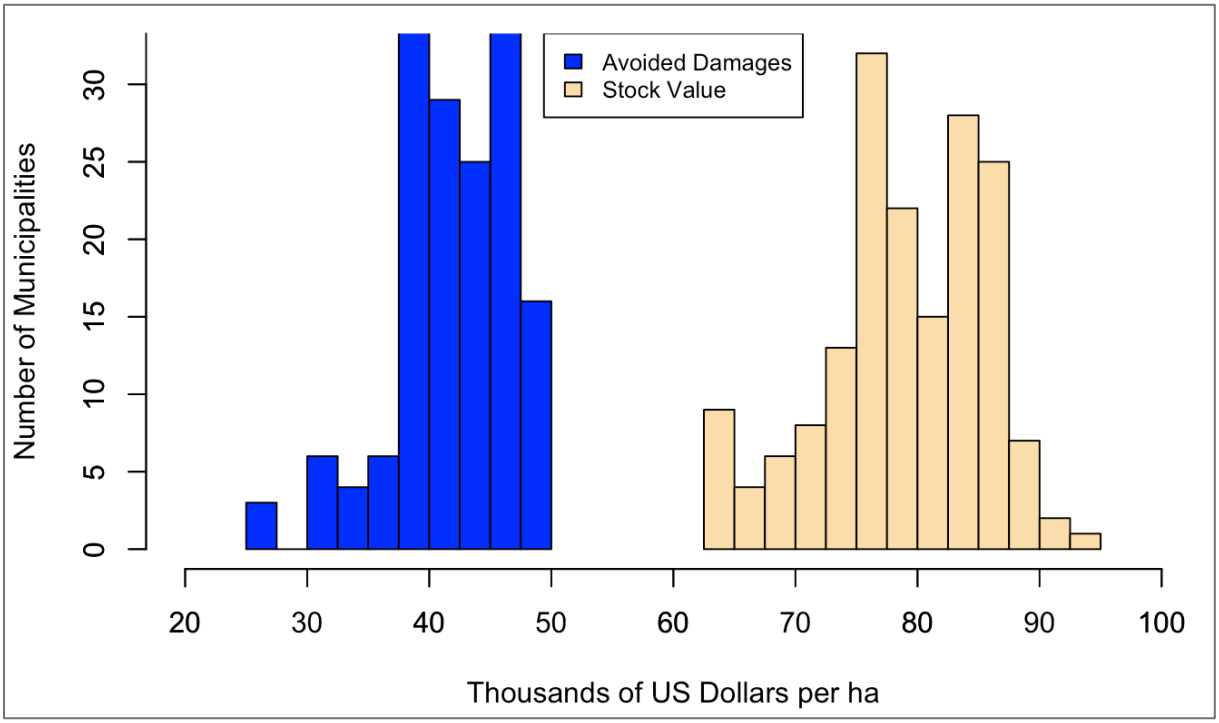

Figure 6: Comparison of two different methods to value mangroves. Avoided damages refers to the price to society of deforesting one hectare of mangroves. Stock value is the total value of the carbon stores in mangroves.

Alternative Land Uses

To understand how the benefits from preventing mangrove deforestation compare to alternative land uses, the profits from agriculture and cattle ranching were subtracted from the damages from deforestation per hectare for a 25-year time period (Figure 7). MAP is the difference between Mangrove Avoided damages and the Profit of an alternative land use (Equation 2).

Equation 2: Definition of MAP

$$(2) \qquad MAP = \boldsymbol{M}angrove\ \boldsymbol{A}voided\ damages - \boldsymbol{P}rofit\ of\ Alternative\ land\ use$$

If MAP is positive, the benefit of avoiding deforestation is higher than the average profit of the alternative land use. If MAP is negative, the opposite is true, which indicates that those municipios potentially are at a higher risk of deforestation since the alternative land use is larger than the cost to society for deforestation.

For agriculture, MAP is positive in 90% of the municipios, which demonstrates that conserving mangroves for just their ability to sequester and store carbon is profitable. For cattle, MAP was positive in 94% of the municipios (Table 1). Cattle was less sensitive to varying the discount rates as the average profit was less than agriculture. Using the highest discount rate, 5%, MAP was still positive in 85% of the municipios. For cattle, if one changes the discount rate from 0.025 to 0.05, eleven percent of municipalities switched between positive to negative MAP, while sixty percent changed in agriculture.

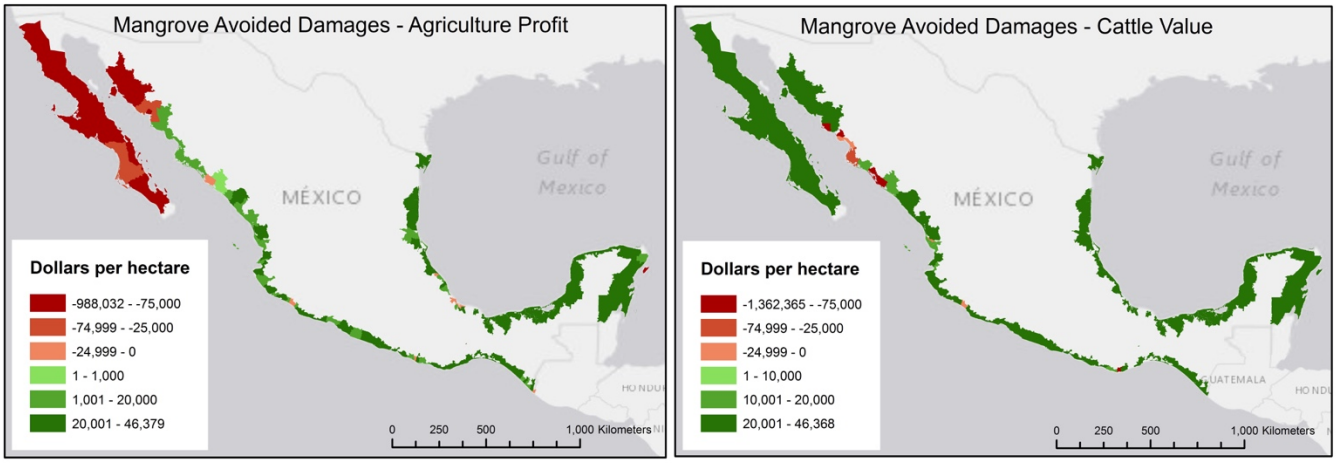

Figure 7: MAP for each municipo for agriculture (A) or cattle (B) on a per hectare basis. Green municipios represent municipios where MAP is positive. Red municipios represent municipos where MAP is negative. Calculation in figure was done with a 0.03 discount rate for both mangroves and the alternative land use. Basemap sources: Esri, DeLorme, HERE, MapmyIndia.

Table 1: Outcomes of the sensitivity of the results in Figure 7 from the discount rate. The table is the comparison between agriculture/cattle profit and avoided damages from mangrove deforestation with three different discount rates.

	DISCOUNT RATE (%)	CARBON PRICE ($)	POSITIVE MAP MUNICIPIOS (%)
AGRICULTURE	2.5	59	93
	3	40	90
	5	11.50	33
CATTLE	2.5	59	96
	3	40	94
	5	11.50	85

NDC Goals and Investment into Mangroves

Mexico's Nationally Determined Contribution (NDC), which is their voluntary commitment to reducing greenhouse gas emissions, does not explicitly include mangroves even in their land use change statements. Mexico's goal is to reduce emissions of greenhouse gasses by 22% (UNFCCC, 2015) from 973 to 762 $MtCO_2E$, the latter number including a negative 14 $MtCO_2E$ sequestered by LULUCF (Land Use, Land Use Change and Forestry). The estimated

carbon sequestration from all of Mexico's mangroves each year is 7.77 $MtCO_2E$, which is a large natural resource that could be used to adapt to climate change.

The high and low bound on the Marginal Cost of Abatement (MCA) was chosen to be $20 and $120, thus results are presented as ranges using these values. If one is to invest in meeting the goal of 22% reduction in greenhouse gases by 2030, they could account for the carbon sequestered by mangroves that were going to be deforested. Governments are investing in carbon capture technology, such as the Sleipner Project, although it is expensive and natural ecosystems can perform the same function (Herzog 2001). Thus, countries could direct some of this funding towards protecting mangroves for their ability to capture carbon. The potential investment per hectare could be set equal to the MCA as mangroves sequester carbon and provide additional ecosystem services. Following this logic, on a per hectare basis the potential investment was calculated to be between $250 and $6,342 per year, depending on MCA value used and carbon sequestration rate. For each municipio, the potential investment to protect the mangrove forest for 25 years was less than the cost to society from damages resulting from deforestation and much smaller than the whole stock value, saving on average between 24 and 39 thousand dollars in avoided damages per hectare (Figure 8).

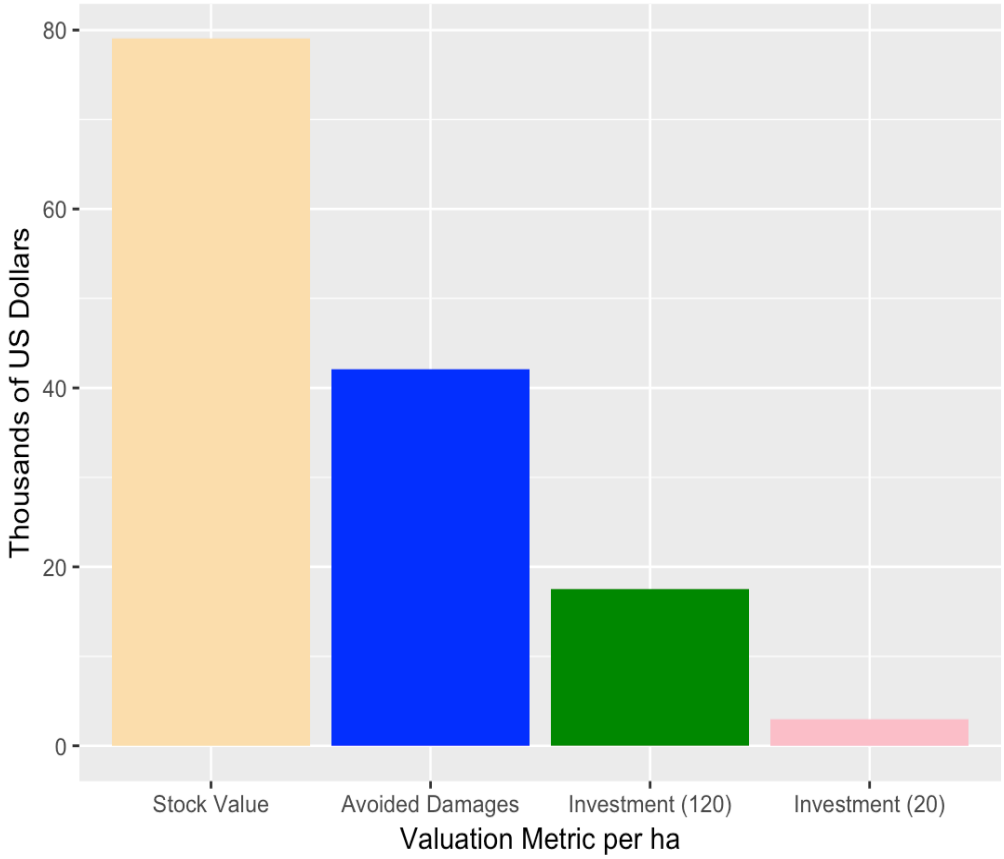

Figure 8: Comparison between stock value, avoided damages, and needed investment towards mangroves for both $120 and $20 marginal cost of abatement prices for 25 years. On a per area basis, the value of mangroves and cost of deforestation is much higher than the investment to conserve mangroves.

Investing to protect all the mangroves in Mexico for a year at $20 MCA would cost up to 2.6 billion dollars, which is 0.014% of the GDP in 2018. The baseline deforestation rate extrapolated out 25 years would cause damages that exceed the needed investment to protect all mangroves in 67% of municipios, assuming using $20 for MCA. This indicates that the investment costs are less than the damages wrought by deforestation in more than half of the municipos. It is more expensive to invest in the protection of all mangroves in one out of four regions than to continue baseline deforestation, if only considering ecosystem services of holding and sequestering carbon (Figure 9). The average area of mangroves per municipio is higher in

the Mexican Caribbean compared to other regions, therefore the average investment costs are also higher.

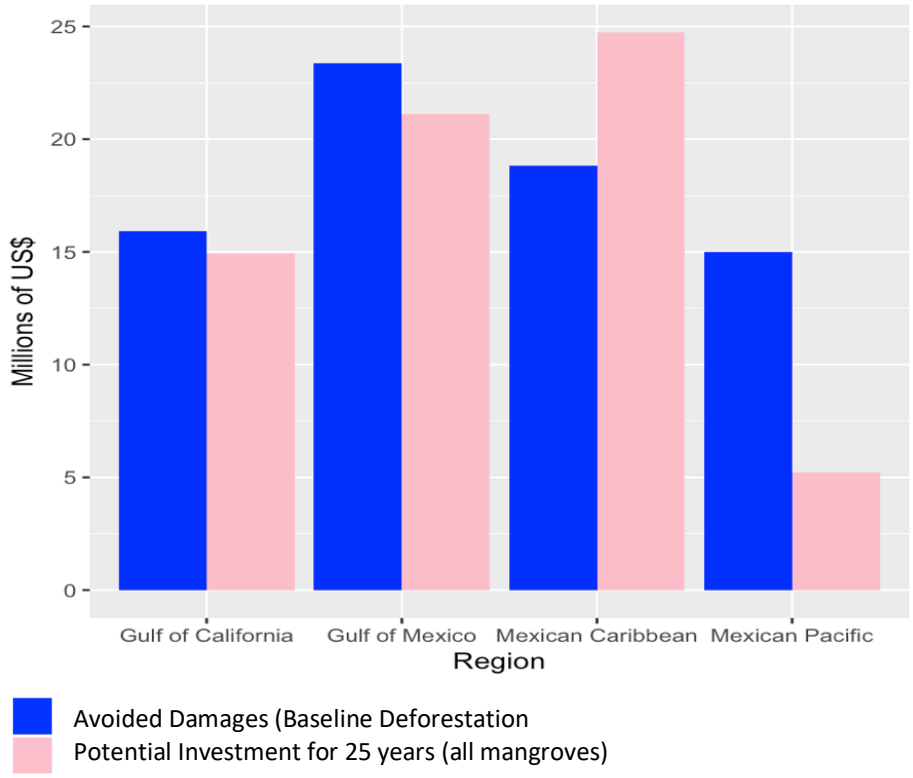

Figure 9: Comparison between avoided damages and investment on average for each region. Blue indicates the average avoided damages based on baseline deforestation rates in each municipio for 25 years. Pink bars are the average needed investment to protect all mangroves.

This thesis in part is currently being prepared for submission for publication of the material. Kumagai, J; Aburto-Oropeza, Octavio; Costa, M. The thesis author was the primary investigator and author of this material.

Discussion

Sources of Error and Assumptions

Due to the interdisciplinary nature of this research, the study has tremendous uncertainty in two forms. First there is uncertainty in the land use value that could be addressed with more measurements of carbon, species composition, and high resolution economic data for various land uses. Secondly, uncertainty due to the missing conceptual links, especially translating ecological values to monetary amounts, create the need to implement analytical assumptions introducing error. The process of combining these estimated carbon estimates for economic analyses, amplifies the uncertainties and requires making assumptions with limited data. The analysis has the potential to be as a framework which will hopefully be published and built upon by other scientists to reduce uncertainty and expand the research to other countries.

Carbon Stock, Sequestration, and Emission Estimates

For the carbon estimates most of the uncertainty comes from applying global carbon datasets and models to the municipio level and from the lack of data in litter rates reported in Mexico. The total carbon calculated in this study does not reflect the natural variability of ecosystem carbon that has been observed in actual measurements. The stability in the calculated estimates is most likely due to analytical error in global models and the ratios used. Although more specific carbon stock measurements from Mexico for each pool would have been ideal, the use of global models and conversion factors was sufficient to meet the goal of informing policy-makers of the value mangroves have.

In addition, the original belowground carbon data from Jardine and Siikamäki (2014) had to be interpolated so that 9% of municipios have an estimate of soil carbon. These municipios

therefore do not have their values taken directly from published material, although this method is often used and accepted. Not including these municipios would diminish the studies' applicability to municipios in Mexico. Further, the depth of soils was assumed to be 1 m as standard in the literature, but this generic metric creates a large limitation to soil carbon estimates. The depth of the soil can be less than 100 centimeters to more than a few meters deep, resulting in large ranges of the below ground carbon stock in mangroves (Ezcurra et al. 2016).

A ratio of 1.3 was used to convert aboveground biomass to belowground biomass as reported in Alongi D. This ratio is not always appropriate and is an active area of research, but due to data limitation the ratio was used (Ezcurra, et al. 2016).

The regional carbon sequestration estimates calculated in this study fall within the range of carbon sequestration rates in the literature obtained by different methods despite having less data. There were only two study sites from the Pacific side of Mexico, and 10 from the Atlantic side. Latitude could not be used as a proxy so we used these published values despite the few study sites. If we opted to use the global average 1.67 MgC ha^{-1} yr^{-1}, this would result in lower avoided damage estimates but also lower investment costs as one would be accounting for less carbon sequestration capability (Alongi 2012). Thus, using this rate would result in a similar amount of savings but contribute less to the climate solution. In addition, methane is a potent greenhouse gas and is released from mangroves (Rosentreter et al. 2018), but this study does not subtract the methane release from carbon sequestration because this discharge of gas occurs before as well as after deforestation (Kristensen et al. 2008).

Carbon emission values were taken from a paper comparing carbon emission release from converted cattle pastures. In this study we applied these values to both cattle and agriculture, which was deemed appropriate due to agriculture production penetrating soil more

deeply than cattle. One assumption implemented was a steady release of the belowground carbon pool throughout 25 years, instead of a more realistic negative exponential release with more carbon emitted initially and emissions extending further into the future (Lovelock et al. 2017). The negative exponential release of CO_2 would increase the damages from deforesting mangroves as costs occurring soon are valued more than if they occurred later. In addition, there is very minimal release of CO_2 occurring after thirty years. Due to the uncertainty in release, the emissions were modeled as flat to ensure an underestimation.

Economics and Investment

The chosen social cost of carbon, discount rate, and time horizon are variables requiring decisions that heavily influence the results. The very existence and use of a number to describe the social cost of carbon dioxide is controversial due to the difficulty in quantifying all the impacts of climate change. Although the SCC is controversial, the usability and convenience of having a marginal cost associated with carbon dioxide emissions is important when addressing the magnitude of abatement and adaptation towards climate change. SCC values range between just a few dollars to a thousand per ton of CO_2 entering the atmosphere. Forty dollars was chosen as it is viewed as an underestimate to the scientific community while being actively used to value carbon (Pindyck 2016, IPCC). Forty dollars was extrapolated using integrated assessment models, which attempt to model all the impacts of climate change, and are the primary tool to estimate damages wrought by climate change (Metcalf and Stock 2017). The SCC was used to translate carbon emissions to dollars to understand the value of mangroves, as well as compare alternative land uses to the damages from deforestation.

The 2.5, 3, and 5 percent discount rates this study utilized can be regarded as conservatively high compared to discount rates used for societal problems such as climate change where the goal of helping the next generation is held in high regard. The Stern Review uses a discount rate of 1%, stating that it would be unethical to have a higher discount rate in light of our obligation to future generations. If we employed a 1% discount rate with SCC equal to $59 (the same as 2.5%), the avoided damages would be three times as large (Stern 2007). A three percent discount rate was selected as we are considering the investment into mangroves compatible with other land uses in economic analyses. Therefore, the future is viewed from the perspective of people making land use decisions rather than those concerned with climate change.

Twenty-five years was the chosen time frame to consider for yearly deforestation as it is within a human life span and thus politically relevant, and because disturbed mangrove soils release only minimal amounts of CO_2 30-40 years after disturbance (Lovelock et al. 2017). One might expect that the next 25 years will not reflect similar amounts of mangrove deforestation due to inaccessibility of mangrove habitat, advancement in monitoring, and implementing legal protections. Although this is plausible, a growing population demands more food supplies from agriculture, cattle, and aquaculture production which are some of the major pressures for mangrove conversion. In addition, developments in technology combined with dropping prices for electronics will grant people increased access to pristine environments, including mangroves. Considering these options, the deforestation rate between 2005 to 2015 was used for a baseline as it is a middle of the line estimate.

The effects of this deforestation are further reaching than just the years when deforestation occurs. Belowground carbon is released for many years following disturbance and

all future carbon sequestration is forfeited. In effect, the avoided damages calculation assumes that future carbon sequestration will continue without reaching a maximum capacity. In the Caribbean, research has demonstrated that mangroves have kept accumulating carbon without stopping throughout the Holocene, if the sea level did not rise too quickly (McKee 2007) Instead of assuming carbon sequestration occurs indefinitely, one could assume that the maximum sequestration in the future is equal to the belowground carbon stock. In most municipios the avoided damages would decrease by <1%, with the highest being a difference of 4%. Thus, this choice has relatively little influence on the results as it impacts the values hundreds of years into the future where the discount factor is near zero.

The low and high range for the marginal cost of abatement was the outcome of a large research effort to quantify how much abatement will cost around the world (Van der Zwann et al. 2016). There was over an order of magnitude of difference in estimates in Latin American countries (Clarke et al. 2016). I opted to use $20 and $120 for MCA to estimate the potential investment for mangroves since each municipio will have differences in economic conditions.

Implications of Results

While only considering mangrove ecosystem services related to carbon, on a per area basis it is more economically viable to invest in protecting mangroves than allowing deforestation to continue. In addition, for most municipios just the cost of the impact from releasing carbon stocks and losing sequestration from deforestation outweighs the profits from agriculture and cattle. If other ecosystem services were included such as coastal protection from wave energy and fisheries, the number of municipios where the alternative use is more profitable would drastically decrease. Constanza et al. 2008 values coastal wetlands at 8,240 ha^{-1} yr^{-1} for

hurricane protection, while mangroves contribute \$37,500 ha^{-1} yr^{-1} in increased yields in blue crab and fisheries (Aburto-Oropeza et al. 2008).

Creating agricultural lands and cattle farms can be done alongside conserving mangroves as these activities do not have to occur in the same location. In the data presented, there were no significant correlations between mangrove deforestation, agriculture, or cattle profit to indicate that these activities must occur on the same land. In the municipios where the alternative land use is more profitable, the mangroves are at a higher risk of deforestation.

The marginal cost of abatement was extrapolated to produce estimates of the amount of investment for mangrove protection. On an average hectare, between 22 and 39 thousand dollars is saved in damages over 25 years, yet protecting all mangroves at a \$20 per ton of CO_2 in Mexico to prevent baseline deforestation in every municipio is not profitable. In the municipios where protecting all mangroves is more expensive than damages from deforestation, the loss is larger than the savings occurring in municipios where protecting all mangroves is profitable. These results suggest that targeted protection would be ideal. How one accomplishes this would need to be specific for each municipio depending on market forces and economic conditions for the population impacted. For subsistence farmers, potentially being compensated for the conservation of mangroves might prevent deforestation. Although, large companies may still deforest even if they sacrifice the compensation and are fined. Policy options for each municipio will need to be developed with locals and enforced.

There are many developers who suggest that one could offset forest deforestation impacts on a country by planting the same amount of forests in a different location. This transfer of environmental goods will not work well with mangroves due to the time it takes to rebuild large carbon stores (Kauffman et al. 2018). Replacing a well-developed mangrove ecosystem would

take hundreds of years to build up the same carbons stocks and associated value (Appendix II). Protection of mangroves ensures that carbon stores remain intact, allows Mexico to count the carbon sequestration towards their climate goals, and preserves an ecosystem that continues to provide several services for the surrounding communities.

At a municipio level, local governors could request financial assistance in the range of potential investment included in Appendix III from the Mexican government to protect mangroves. The Mexican government could fund this protection with support from the Green Climate Fund and other resources as this money would be used to directly prevent baseline deforestation. Including clear statements about mangrove deforestation goals and accounting for mangroves as part of abatement plans would transform Mexico's next NDC to take advantage of their natural resources in mangroves. With this two-pronged approach, Mexico could effectively prevent mangrove deforestation at a municipio level and help to secure mangroves as a national resource today and for future generations.

Next Steps for Research

Specific carbon maps of both stocks and sequestration supported by on-the-ground measurements will help countries further develop climate abatement plans that include mangroves. These carbon maps or databases could be used for understanding and protecting priority areas of mangrove ecosystems, especially when combined with documenting other ecosystem services. Specifically, research on the depth of peat in mangrove ecosystems will create more accurate data, erasing the need to assume a one-meter depth. Additionally, developments in monitoring mangrove deforestation will also help with these goals as continuous data can provide insight into drivers and magnitude of deforestation as well as

management plans. With a more in-depth analysis of deforestation and carbon sequestration, one could apply the research presented here to other countries to support the inclusion of mangroves in climate change abatement plans.

This research was limited by the availability of data for palm oil, aquaculture, and revenue data in general. If one were able to find the revenue from alternative land uses where there originally were mangroves, the analysis could be taken much further looking at opportunity costs. Palm oil and aquaculture are two common alternative land uses for mangroves globally but little to no accurate data can be found on these industries in Mexico (Siikamäki et al. 2012). In addition, land value could be used in other studies as a general number to compare to the damages from deforestation as it represents what the land could be potentially used for instead of mangroves. While research in these areas is important and will help to optimize land management, science communication is essential for change to happen. Policy makers will need to be exposed to this information and other research in formats easily understood to help create a world without unnecessary environmental degradation, excess warming, and unchecked exploitation.

Conclusion

Through coupled biological and economic analyses, this study demonstrates that the carbon stocks and sequestration in Mexico's mangroves are a national resource that should not be lost. Municipio-specific carbon store information is made available with this analysis alongside the value of these stores and the rates at which mangroves sequester carbon. Avoiding deforestation damages is important as the continuation of current trends will cost society millions of dollars per each municipio. To be able to maximize effectiveness of investment, targeting deforestation is necessary and will need to be locally flexible. If municipio-specific estimates are used, and local policy is created in line with national goals, this study could produce an example to other countries on how to stop deforestation to protect mangroves and prevent increased emissions.

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