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Greenness trends and carbon stocks of mangroves across Mexico

To cite this article: Alma Vázquez-Lule *et al* 2019 *Environ. Res. Lett.* **14** 075010

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Environmental Research Letters



LETTER

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OPEN ACCESS

RECEIVED
20 June 2018REVISED
17 May 2019ACCEPTED FOR PUBLICATION
24 May 2019PUBLISHED
16 July 2019

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María Teresa Rodríguez-Zúñiga⁴, Isabel Cruz⁴, Rainer Ressler⁴ and Rodrigo Vargas^{1,5} ¹ Department of Plant and Soil Sciences, University of Delaware, Newark, DE, United States of America² Land Use and Finance for Innovation, Directorate General CLIMA, European Commission, Brussels, Belgium³ Centro de Investigación y de Estudios Avanzados, Unidad Mérida, Mérida, Yucatán, México⁴ Dirección General de Geomática, Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (CONABIO), Tlalpan, Ciudad de México, México⁵ Author to whom any correspondence should be addressed.E-mail: rvargas@udel.edu**Keywords:** temperature, precipitation, seasonality, mangrove forest, phenologySupplementary material for this article is available [online](#)**Abstract**

Mangroves cover less than 0.1% of Earth's surface, store large amounts of carbon per unit area, but are threatened by global environmental change. The capacity of mangroves productivity could be characterized by their canopy greenness, but this property has not been systematically tested across gradients of mangrove forests and national scales. Here, we analyzed time series of Normalized Difference Vegetation Index (NDVI), mean air temperature and total precipitation between 2001 and 2015 (14 years) to quantify greenness and climate variability trends for mangroves not directly influenced by land use/land cover change across Mexico. Between 2001 and 2015 persistent mangrove forests covered 432 800 ha, representing 57% of the total current mangrove area for Mexico. We found a temporal greenness increase between $0.003_{[0.001-0.004]}$ and $0.004_{[0.002-0.005]}$ yr⁻¹ (NDVI values \pm 95%CI) for mangroves located over the Gulf of California and the Pacific Coast, with many mangrove areas dominated by *Avicennia germinans*. Mangroves developed along the Gulf of Mexico and Caribbean Sea did not show significant greenness trends, but site-specific areas showed significant negative greenness trends. Mangroves with surface water input have above ground carbon stocks (AGC) between 37.7 and 221.9 Mg C ha⁻¹ and soil organic carbon density at 30 cm depth (SOCD) between 92.4 and 127.3 Mg C ha⁻¹. Mangroves with groundwater water input have AGC of 12.7 Mg C ha⁻¹ and SOCD of 219 Mg C ha⁻¹. Greenness and climate variability trends could not explain the spatial variability in carbon stocks for most mangrove forests across Mexico. Site-specific characteristics, including mangrove species dominance could have a major influence on greenness trends. Our findings provide a baseline for national-level monitoring programs, carbon accounting models, and insights for greenness trends that could be tested around the world.

Introduction

Mangroves cover 0.1% of the Earth's surface (Atwood *et al* 2017, Hamilton and Friess 2018), are within the most productive ecosystems of the world (average 1023 Mg of Carbon ha⁻¹; Donato *et al* 2011), and are highly vulnerable to global environmental change (Alongi 2015, Osland *et al* 2016). Previous studies have focused on the vulnerability of mangrove forests to sea level rise (SLR) and is expected that this environmental change will influence variables dependent to hydroperiods and salinity, that ultimately impact mangrove

forest structure and function (Woodroffe 1990, Mckee *et al* 2007, Lovelock *et al* 2015). Recently, there has been increasing attention on how climate variability could impact latitudinal migration of mangroves and their interactions with other coastal plant communities (Cavanaugh *et al* 2014, Saintilan *et al* 2014, Osland *et al* 2017). Climate variability, such as changes in air temperature and precipitation, influence the temporal and spatial patterns of ecosystems processes (e.g. photosynthesis, respiration, evapotranspiration) that control rates of mangroves growth and their geographical distribution (Twilley *et al* 1999,

Alongi 2015, Ward *et al* 2016, Cavanaugh *et al* 2018). Due to the relevance of mangrove forests for the global carbon cycle, it is critical to quantify the effects of climate variability on their ecosystem processes and carbon stocks around the world (Atwood *et al* 2017).

Greenness of vegetation around the world has been used as proxy for photosynthesis activity (Myneni *et al* 1997, Zhou *et al* 2014), net primary productivity (Park *et al* 2016) and water use efficiency (Zhang *et al* 2015). Studies at the global scale have shown positive greenness trends as consequence of CO₂ fertilization, nitrogen deposition, water availability, and climate variability (Forkel *et al* 2015, Zhu *et al* 2016). At the regional scale, studies have focused on quantifying greenness trends across the Northern hemisphere (Park *et al* 2016), tropical rain forests (i.e. Amazonas and Congo; Hilker *et al* 2014, Zhou *et al* 2014, Guan *et al* 2015) and grasslands (Trujillo *et al* 2012). Recently, the sensibility and range of mangroves distribution in the Americas were explained by greenness trends (Cavanaugh *et al* 2018). Other greenness studies on mangrove forests have been site-specific and they have identified land cover changes (Rahman *et al* 2013), mangrove degradation (Alatorre *et al* 2016, Ishtiaque *et al* 2016, Flores-Cárdenas *et al* 2017), disturbances by chilling events (Zhang *et al* 2016) and biomass change (Fuller and Wang 2014). Despite these efforts, there is still lacking information at country-specific scale to better understand the influence of climate variability on greenness trends of mangroves and to provide insights for changes in phenology, productivity, and ultimately carbon stocks.

Studies at global and continental scales have used coarse resolution data to predict potential climate variability effects over distribution, biodiversity (~50 km grids; Osland *et al* 2017), and spatial variability of above ground biomass in mangroves (~1 km grids; Hutchison *et al* 2014, Rovai *et al* 2016). Synthesis studies at the global scale have highlighted the role of mangrove forests for the Earth-system and the global carbon budget (Giri *et al* 2011, Hutchison *et al* 2014, Hamilton and Casey 2016, Ward *et al* 2016, Atwood *et al* 2017, Hamilton and Friess 2018), but country-specific information is needed to refine continental-to-global estimates and identify region-specific trends. Recent examples at the regional-scale and country-level include studies in the Indo Pacific Region (Donato *et al* 2011, Murdiyarso *et al* 2015, Richards and Friess 2016), Kenya (Gress *et al* 2017) and the United States (Hinson *et al* 2017). Despite these efforts it is important to provide and synthesize new information across other countries; especially, for those that have high country-specific carbon stocks and country-specific mangrove area such as Mexico (Atwood *et al* 2017, Hamilton and Friess 2018).

Our overarching goals were to quantify (a) greenness trends and their spatial variability, and their relationships with mean air temperature and total precipitation; and (b) the overall relationships

between greenness and carbon stocks (i.e. AGC and SOCD respectively) in mangrove forests across Mexico. Mexico is a megadiverse country and a global hotspot for conservation priorities (Myers *et al* 2000) with high potential for implementation of REDD + initiatives (Vargas *et al* 2017). It has 755 555 ha of mangroves (Valderrama-Landeros *et al* 2017) where trees can be taller than 35 m or smaller than 1 m as a consequence of gradients of local biophysical factors (i.e. hydroperiod, topography, salinity; López-Portillo and Ezcurra 2002, Ezcurra *et al* 2016). Furthermore, mangrove forests in Mexico have high country-specific carbon stocks and country-specific mangrove area, placing them as the top sixth of the world (Atwood *et al* 2017, Hamilton and Friess 2018). We based our analyses on unique country-specific mangrove cover maps between years 2001 and 2015 and we defined categories of mangroves considering their latitudinal distribution, mean air temperature, main input of freshwater and their location along the coast (i.e. Gulf of California, Pacific Coast, Gulf of Mexico, Caribbean Sea).

Here we asked three interrelated questions.

- (a) Are there greenness trends for mangrove forests across Mexico? We expected a greenness trend (positive trend) for all mangroves across Mexico, considering previous observations on the greening of global vegetation (Forkel *et al* 2015, Zhu *et al* 2016).
- (b) If there are greenness trends, how do they relate to air temperature or precipitation trends (i.e. climate variability)? We expected that positive greenness trends may be related to increases in air temperature (as main factor regulating canopy phenology and photosynthesis; Alongi 2015). Furthermore, changes in local precipitation may not explain greenness trends, as inland precipitation events (and consequently lateral freshwater inputs) could reduce salinity stress and increase local canopy photosynthesis.
- (c) Are carbon stocks (i.e. AGC and SOCD) related to trends of mangrove greenness or climate variables during the study period? We hypothesize that mangrove areas with significant greenness increase could have higher primary production and consequently have larger AGC and SOCD.

Materials and methods

Study area

Mangrove forest across Mexico are distributed between latitudes 27°50' to 14°30' N. The main mangrove species are: *Rhizophora mangle* L. (*red mangrove*), *Avicennia germinans* (L.) L. (*black mangrove*), *Laguncularia racemosa* (L.) C.F. Gaertn (*white*

mangrove) and *Conocarpus erectus* L. (buttonwood mangrove).

We defined four categories of mangroves considering: latitudinal distribution, mean air temperature, main input of freshwater (i.e. by rivers, with surface water as main input or groundwater as main input and due to karst topography), and their location throughout the coast (i.e. Gulf of California, Pacific Coast, Gulf of Mexico, Caribbean Sea). Defining mangrove categories across Mexico is relevant because the country has a large diversity of geomorphological features along its coast (Lankford 1977). Consequently, these characteristics influence local hydrology and define quality and quantity of freshwater, nutrients and sediments that influence mangroves' development and productivity (Twilley *et al* 1999). We considered as reference the categories developed by Lankford (1977) and the physiographic regions of Mexico (table 1S in supplemental material; Cervantes-Zamora *et al* 1990). Thus, we propose four general categories to summarize our analyzes: (a) Arid Mangroves with Surface Water Input over the Gulf of California and Pacific Coast (ARsw); (b) Humid Mangroves with Surface Water Input along the Pacific Coast (HUSw-Pa); (c) Humid Mangroves with Surface Water Input along the coast of the Gulf of Mexico (HUSw-Gf); (d) Humid Mangroves with Groundwater Input along the coast of the Gulf of Mexico and Caribbean Sea (HUGw) (figure 1).

Arid category includes all mangroves above the Tropic of Cancer (23°26' N) and mangroves in the Baja California Peninsula developed over six physiographic regions (see table 1S). These mangroves are usually located within narrow watersheds. Northern areas have small rivers and poor drainage, while southern areas have larger rivers with seasonal drainage. This category shows abrupt changes between mountain areas and coastal plains. Some areas are open and exposed to intermediate to high wave energy, with higher ebb velocity and predominantly semidiurnal tide. Surface water input is the main source of freshwater (Lankford 1977). Annual surface water discharge for this category is 20 838 hm³ yr⁻¹; representing nearly 7% of the total surface water discharge in Mexico (CONAGUA 2016; figure 1).

HUSw-Pa category includes all mangroves below the Tropic of Cancer (23° N Latitude) until the political limits of Mexico with Guatemala, along the Pacific Coast. This category includes mangroves over 6 physiographic regions along the central and south Pacific Coast (table 1S). Those mangroves are in narrow watersheds with abrupt changes between the land and coastal plains. This category has many rivers with small river basin and seasonal flow. All the coastal areas are open and exposed to high wave energy and high ebb velocity (Lankford 1977), where surface water input is the main source of freshwater. Annual surface water discharge for this category is 58 617 hm³ yr⁻¹; representing nearly 19% of the total

surface water discharge in Mexico (CONAGUA 2016; figure 1).

HUSw-Gf category includes all mangroves in the Gulf of Mexico, from the political limits of Mexico with United States until the last river founded in the Yucatan Peninsula (close to Campeche City). This category includes mangroves over 6 physiographic regions (table 1S). Those mangroves are in wide watersheds with many rivers with large drainage basins. The wave and tide energies are low, except during hurricanes or northern climatological events. Tides are predominantly diurnal, but rivers are the main source of freshwater (Lankford 1977). Annual surface water discharge is 224 032 hm³ yr⁻¹, representing nearly 72% of the total surface water discharge in Mexico (CONAGUA 2016; figure 1).

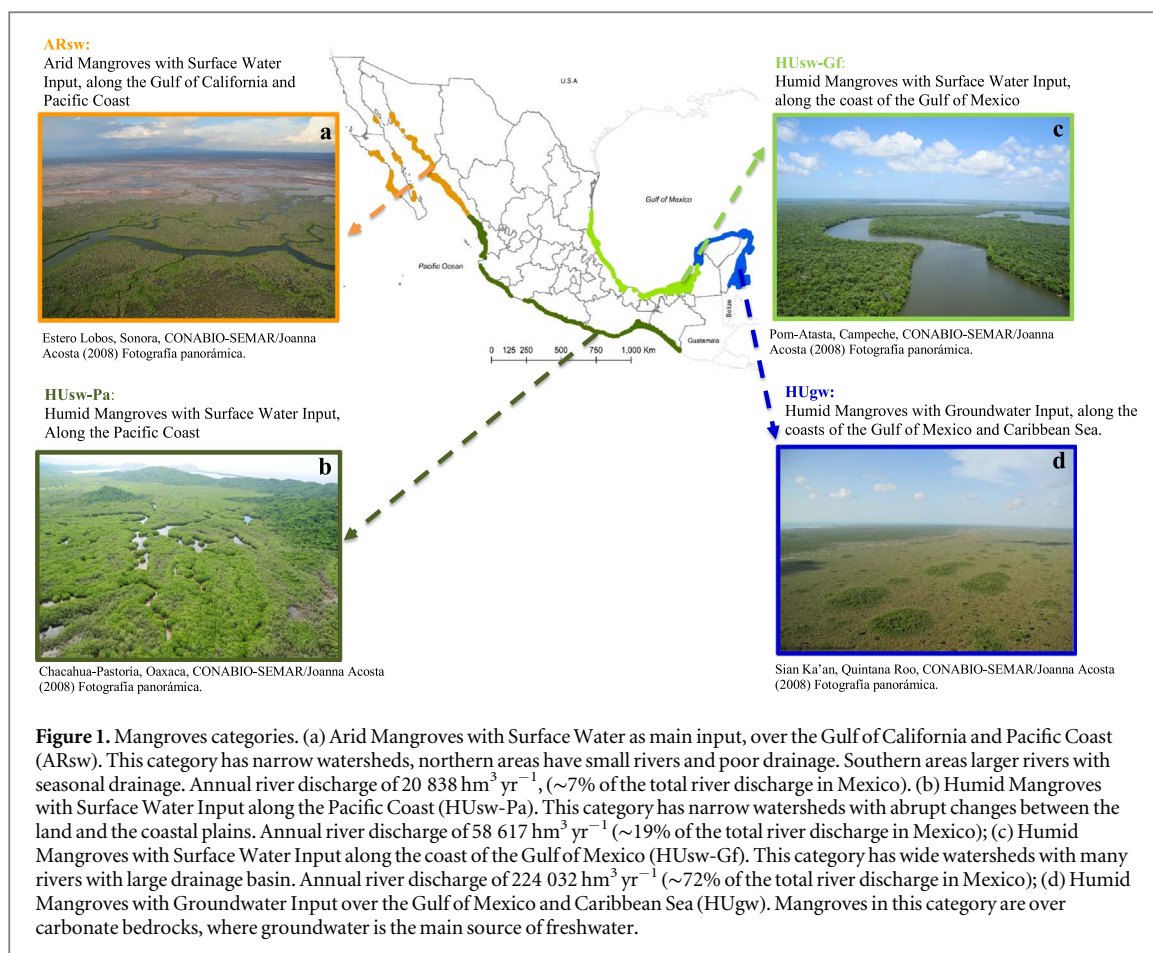
Humid mangroves with groundwater as main input of water (HUGw). This category includes mangroves of Yucatan Peninsula (YP) in two physiographic regions (table S1 is available online at stacks.iop.org/ERL/14/075010/mmedia). Those mangroves develop over carbonate platforms, where groundwater is the main source of freshwater. The wave and tide energies are low, except during hurricanes, northern climatological events, or areas on shelf margin reefs. Tides in this category can be diurnal or semidiurnal (Lankford 1977). Conservative estimates of groundwater outflow to the coastal areas are ~211 462 hm³ yr⁻¹ (Null *et al* 2014); this flow of freshwater is nearly similar to 70% of the total surface water discharge in the rest of the coastal areas in Mexico.

Persistent mangrove forest (PMF) coverage across Mexico

We aimed to quantify greenness trends for mangroves without a direct influence of land use/land cover change (LULCC) during the study period. Therefore, we identified PMF across Mexico between 2001 and 2015. Those mangrove areas were estimated from available cartographic sources for 2000 (Giri *et al* 2011), 2005, 2010 and 2015 from the Mexican Mangrove Monitoring System (Valderrama-Landeros *et al* 2017). We used fraction analysis to standardize all sources (i.e. maps) at 1 km of spatial resolution (S section 1). The PMF coverage was used to extract the Normalized Difference Vegetation Index (NDVI), climate variables (i.e. air temperature and precipitation) and carbon stocks (i.e. AGC and SOCD) for each mangrove category.

Detection of greenness of mangroves

We used monthly composites of NDVI from 2001 to 2015 at 1 km of spatial resolution of the MOD13A3 product from the Moderate Resolution Imaging Spectroradiometer (MODIS). Briefly, NDVI is the ratio between red and infrared wavelengths where values close to 1 represent higher greenness in vegetation, while values close to zero are degraded vegetation



or not vegetation. NDVI has been used to identify greenness of vegetation across multiple ecosystems around the world (Los 2013, Hilker *et al* 2014) including mangrove forests (Fuller and Wang 2014, Alatorre *et al* 2016, Flores-Cárdenas *et al* 2017).

We used 180 composites for each of the 9 tiles covering Mexico (h07v05, h07v06, h07v07, h08v05, h08v06, h08v07, h09v05, h09v06, j09v07; <https://reverb.echo.nasa.gov/>). These composites were resampled and mosaicked using the MODIS Reprojection Tool (<https://lpdaac.usgs.gov/tools>). We selected the best quality and reliability for the NDVI composites using the Time-series Generator Software (TiSeG; Colditz *et al* 2008) and applied a linear interpolation for gap filling (see S section 2). Finally, NDVI time series were independently analyzed for each mangrove category.

Climate variables

We used mean monthly air temperature ($^{\circ}\text{C}$) and total monthly precipitation (mm) from Daymet at 1 km of spatial resolution from 2001 to 2015 (Thornton *et al* 2017). Mean air temperature was estimated as the average of maximum and minimum air temperature for each pixel (thereafter referred as temperature). Temperature and precipitation data were projected at the same spatial features within persistent mangrove coverage and corresponding mangrove categories.

Above ground carbon and soil organic carbon density

We used country-specific information and extracted values for AGC (Cartus *et al* 2014). For SOCD, we used a product at 30 cm of depth (Guevara *et al* 2017) because we needed a comparable soil depth for all mangroves categories, and this is a recommended depth to compare different mangroves areas of the country (Adame *et al* 2013a, Ezcurra *et al* 2016). Both carbon products were one-time maps (i.e. AGC from 2007; SOCD from 1991–2010). Products were standardized per mangrove category according to results from a synthesis study (Herrera-Silveira *et al* 2016; see S section 2), and reprojected and resampled for the same spatial features within PMF coverage and corresponding categories.

Statistical analyses and annual mangrove greenness and climate variability

We used average monthly values during the study period to identify the annual mangrove greenness and climate variability for every mangrove category. We showed these results considering the greenness seasonality of mangroves. After that, we performed cross-correlation analysis to identify time-lags between the annual mangrove greenness peaks and climate variability peaks. We used the identified time-lags to adjust the annual greenness values with the climate variability

values. We did regression models between ‘adjusted’ greenness and climate variables to identify the main climate variable that controls the annual greenness for every mangrove category.

Greenness and climate variability trends and their spatial variability

We used monthly mean values of NDVI, temperature and precipitation to identify trends of greenness and climate variability. Trend detection analyses were performed using the non-parametric analysis Theil—Sen Regression, with 95% confidence intervals and deseasonalized data in ‘*openair*’ R package. Theil—Sen regression uses medians to calculate slopes between $n - 1$ point in the time series. Its robustness is based on bootstrap simulations to derive p -values, slope estimates and uncertainties (Wilcox 2004, Carslaw and Ropkins 2012). We show results of aggregated trends for greenness and climate variability per mangrove category.

We used the Annual Aggregated Time Series (AATS) method to identify the spatial variability of greenness trends (SVGT) and climate variables in ‘*greenbrown*’ R package, with 95% confidence interval. AATS aggregates seasonal time series values to annual values, and uses the sum of linear square residuals to estimate the breakpoints and the slopes in the time series (Bai and Perron 2003, Forkel *et al* 2013). AATS has a good performance for NDVI time series affected by seasonality, and is a conservative method for potential false positive or false negative trends (Forkel *et al* 2013). We report the SVGT per mangrove category. Spatial variability of climate variables trends are not shown, but we used them to identify linear relationships between SVGT and climate variables with carbon stocks.

We summarized the distribution of SVGT with histograms representing the percentage of significant greenness trends (GTP) for every category. We calculated the GTP by dividing the values of SVGT by the mean value of NDVI in each category.

Results

Greenness, climate and carbon stocks in mangroves

PMF between 2001 and 2015 across Mexico covered 432 800 ha. ARsw included 39 400 ha representing 9% of the PMF. The HUsw-Pa and HUsw-Gf included 82 300 ha and 123 500 ha, respectively. They represented 19% and 29% of the PMF, respectively. HUGw had 187 600 ha, it represented 43% of PMF (table 1).

Greenness, temperature, precipitation and carbon stocks showed significant differences across mangrove categories ($p < 0.05$), except for temperature in HUsw-Gf and HUGw, and precipitation in HUsw-Pa and HUsw-Gf (see results table S2). HUsw-Gf had the highest greenness with mean NDVI values of 0.77, while ARsw had the lowest greenness (19% lower than

HUsw-Gf). Temperature was higher and less variable for humid mangroves (HUsw-Pa, HUsw-Gf and HUGw; ~ 26 °C) than for those in arid regions (ARsw; 24.7 °C; ± 4.7). The HUsw-Gf showed the highest annual precipitation (1517 mm), while ARsw the lowest (413 mm). AGC was higher for HUsw-Gf (221.9 Mg C ha⁻¹) and lower for HUGw (12.7 Mg C ha⁻¹), while SOCD was higher for HUGw (219 Mg C ha⁻¹) and lower for ARsw (92.4 Mg C ha⁻¹; table 1).

Annual mangrove greenness and climate variability

Overall, lower greenness values were evident from April to May (range 0.53–0.72), while greenness peaked between October and January (range 0.67–0.80) (figure 2(a)). Temperature showed the higher values from April to October (figure 2(b)), while precipitation from July to October (figure 2(c)). We observed time-lags from two to five months between the highest values of temperature and precipitation with the highest values of greenness. In all cases, temperature and precipitation peaked before greenness (figures 3(a) and (b)). For ARsw, we found that temperature peaked three months before maximum greenness, while maximum precipitation peaked two months before maximum greenness. In contrast, for HUGw temperature peaked five months before than maximum greenness, while maximum precipitation peaked four months before maximum greenness (figures 3(a) and (b)). Overall, temperature was able to better represent the variability of greenness (ARsw $r^2 = 0.72$; HUsw-Pa and HUsw-Gf $r^2 = 0.74$; HUGw $r^2 = 0.69$; in all cases $p < 0.01$; figure 3(a)), than precipitation across categories (ARsw $r^2 = 0.30$; HUsw-Pa $r^2 = 0.40$; HUsw-Gf $r^2 = 0.44$; HUGw $r^2 = 0.41$; in all cases $p < 0.01$; figure 3(b)).

Greenness and climate variability trends and their spatial variability

Greenness trends had a significant increase for the mangrove categories developed over the Gulf of California and Pacific Coast. These categories are ARsw and HUsw-Pa (ARsw, $p < 0.001$, figure 4(a); HUsw-Pa, $p < 0.001$; figure 4(b)), with rates from 0.004 in ARsw to 0.003 in HUsw-Pa. We did not find significant greenness trends for the HUsw-Gf and HUGw developed over the Gulf of Mexico and Caribbean Sea (figures 4(c) and (d), respectively). However, these two categories were the only ones with a significant increase in temperature (figures 4(g) and (h)), with a range from 0.10 °C to 0.11 °C. ARsw was the only category with a significant decrease in precipitation (0.35 mm yr⁻¹; $p < 0.001$; figure 4(i)).

SVGTs showed that PMF areas over the Gulf of California and Pacific Coast (ARsw and HUsw-Pa) have a significant greenness increase (i.e. positive trend) during the study period, while areas in the Gulf of Mexico and Caribbean Sea (HUsw-Gf and HUGw) showed a mix of significant increase and decrease

Table 1. Greenness, climate variability and carbon stocks across mangroves of Mexico. The area represents persistent mangrove forest during 2001–2015 for each mangrove category. Mangrove categories show different area extent, temperature and precipitation values. Greenness is expressed as NDVI values. AGC and SOCD are expressed in Mg C ha^{-1} per category, as well the total amount of carbon stocks for the PMF area in each category.

Category	Area (ha)	NDVI	T ($^{\circ}\text{C}$)	Prpc (mm yr^{-1})	AGC (Mg C ha^{-1})	Total AGC (Tg)	SOCD (Mg C ha^{-1})	Total SOCD (Tg)	AGC + SOCD (Mg C ha^{-1})	Total Carbon (Tg)
ARsw	39 400	0.62 (± 0.06)	24.7 (± 4.7)	413 (± 147.4)	37.7 (± 8.2)	1.5 (± 0.3)	92.4 (± 6.3)	3.6 (± 0.3)	130.1 (± 14.5)	5.1 (± 0.6)
HUsw-Pa	82 300	0.70 (± 0.12)	26.8 (± 0.94)	1423 (± 536.1)	134.6 (± 8.2)	11.1 (± 0.7)	118.9 (± 43.3)	10.0 (± 3.5)	253.5 (± 51.5)	21.1 (± 4.2)
HUsw-Gf	123 500	0.77 (± 0.07)	26.3 (± 0.5)	1517 (± 329.4)	221.9 (± 93.0)	27.4 (± 11.5)	127.3 (± 44.7)	15.7 (± 5.4)	349.2 (± 137.7)	53.1 (± 16.9)
HUGw	187 600	0.64 (± 0.03)	26.2 (± 2.0)	1016 (± 182.8)	12.7 (± 3.7)	2.4 (± 0.7)	219.0 (± 84.9)	41.1 (± 15.9)	231.7 (± 88.5)	43.5 (± 16.6)

Category: (a) ARsw: Arid Mangroves with Surface Water Input, over the Gulf of California and Pacific Coast; (b) HUsw-Pa: Humid Mangroves with Surface Water Input, over the Pacific Coast; (c) HUsw-Gf: Humid Mangroves with Surface Water Input, over the Gulf of Mexico coast; (d) HUGw: Humid Mangroves with Groundwater Input, over the Gulf of Mexico and Caribbean Sea.

Area (ha): Persistent mangrove forest from 2001 to 2015 at 1 km of spatial resolution.

NDVI: Mean NDVI from 2001 to 2015. MODIS product (MOD13A3).

T ($^{\circ}\text{C}$): Mean temperature from 2001 to 2015. Daymet data (Thornton *et al* 2017).

Prpc (mm yr^{-1}): Mean annual precipitation from 2001 to 2015 (Thornton *et al* 2017).

AGC (Mg C ha^{-1}): Above Ground Carbon at 1 km of spatial resolution. Product of Cartus *et al* (2014) corrected by estimations of Herrera-Silveira *et al* (2016).

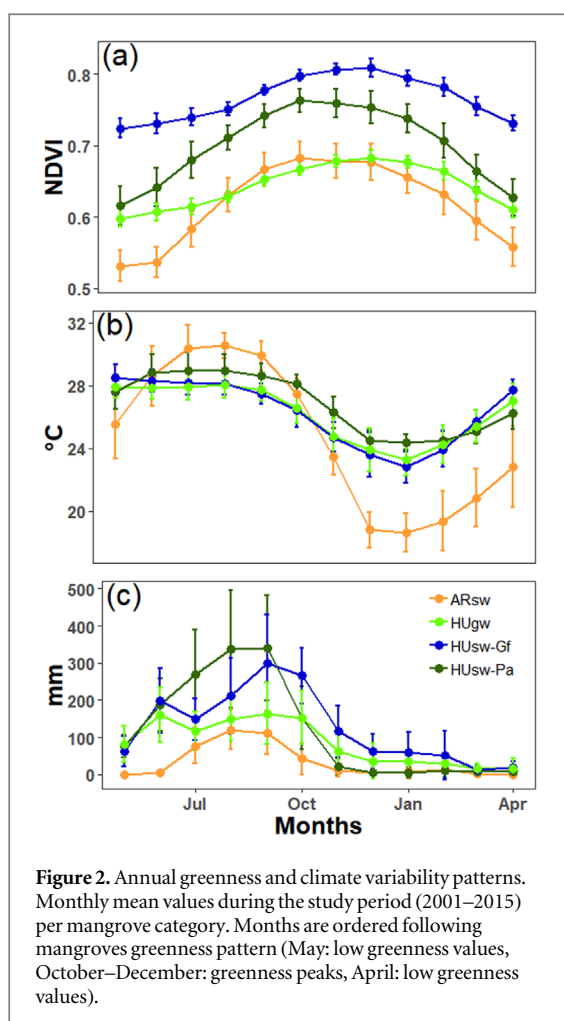
Total AGC (Tg): Total Above Ground Carbon per mangrove category.

SOCD (Mg C ha^{-1}): Soil Organic Carbon Density at the first 30 cm of depth at 1 km of spatial resolution. Product of Guevara *et al* (2017) corrected by estimations of Herrera-Silveira *et al* (2016).

Total SOCD (Tg): Soil Organic Carbon Density at the first 30 cm of depth per mangrove category.

AGC+SOCD (Mg C ha^{-1}): Total Above Ground Carbon and Soil Organic Carbon Density at 1 km of spatial resolution.

Total Carbon (Tg): Total Above Ground Carbon and Soil Organic Carbon Density per mangrove category.



(i.e. negative trend; figure 5(a)). More than 90% of the pixels in the ARsw showed greenness trends higher than zero (figure 5(b)), confirming the overall increase of greenness (figure 4(a)). Over 75% of the pixels in HUSw-Pa had greenness trends higher than zero (figure 5(d)).

GTP was different for every category. All categories, except the HUGw, showed GTP values between -2.65% and 2.28% (figures 5(c), (e) and (h)). HUGw showed the longer GTP range (-11.17% to 10.32% ; figure 5(f)). For example, Marismas Nacionales, part of the HUSw-Pa category (figure 5(e)), showed significant greenness trends in Southern areas (GTP >0 to 2.28%). In contrast, Pom-Atasta Lagoon in the Gulf of Mexico (figure 5(h)) and Sian Ka'an in the Caribbean Sea (figure 5(f)) showed significant negative greenness trends (GTP $< 0\%$).

We did not find significant relationships between the SVGT, climate variability and carbon stocks for most categories. HUSw-Gf was the only one with a negative relationship between negative greenness trends and AGC ($r^2 = 0.38$, $p > 0.01$); which was mainly observed for the Pom Atasta Lagoon (figure 5(h)). HUSw-Pa had a positive relationship between AGC and SOCD ($r^2 = 0.54$, $p > 0.01$).

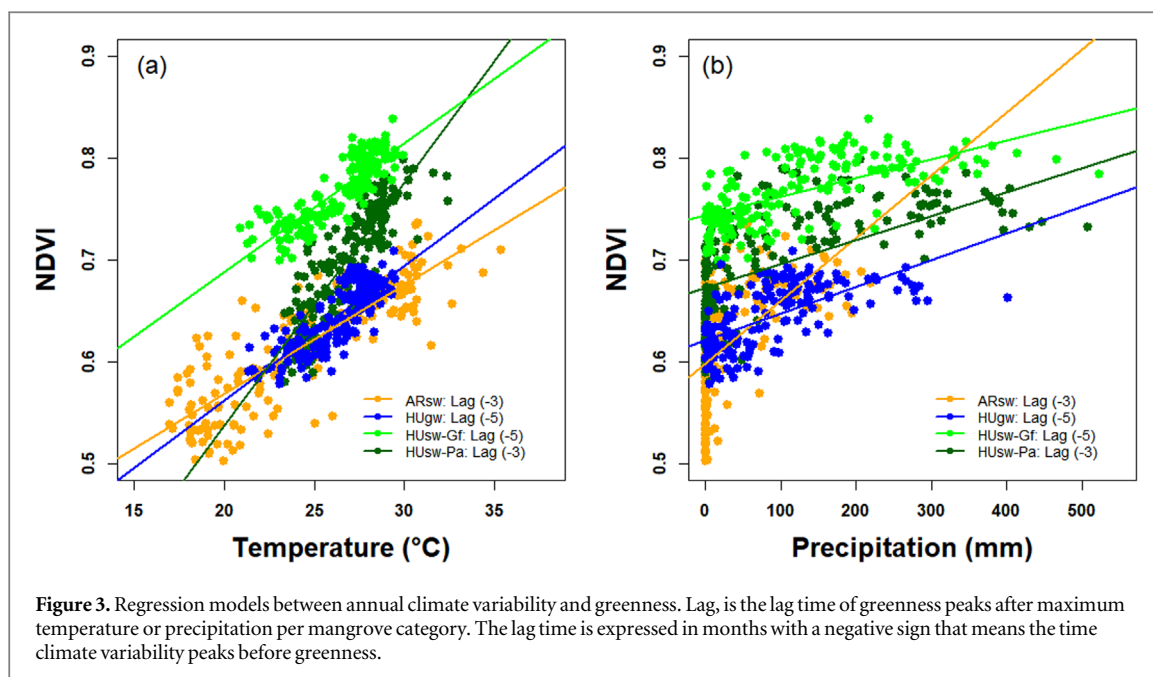
Discussion

Greenness and climate variability trends and their spatial variability

We found positive greenness trends for mangroves categories developed over the Gulf of California and Pacific Coast (ARsw and HUSw-Pa). Mangroves over the Gulf of Mexico and Caribbean Sea (HUSw-Gf and HUGw) did not show significant greenness trends; however, SVGTs were site-specific. Trends of climate variability were not consistent with greenness trends. These results suggest that the dominance of mangrove species could be one of the main factors on greenness trends, together with site-specific environmental factors such as quantity/quality of freshwater input, ocean water exchange, extreme events (i.e. frequency and magnitude of tropical storms and hurricanes) and human-induced changes (i.e. preferential flow paths of water).

ARsw and HUSw-Pa receive less than 30% of the total annual river discharge in Mexico ($79\,455\text{ hm}^3\text{ year}$; CONAGUA 2016). Fifty-two percent of the ARsw rivers are dammed, and those dams could store $\sim 84\%$ of the total annual river discharge ($\sim 17\,500\text{ hm}^3\text{ yr}^{-1}$; CONAGUA 2016). For HUSw-Pa, 28% of the rivers are dammed and dams can store $\sim 26\%$ of the total annual river discharge ($15\,240\text{ hm}^3\text{ yr}^{-1}$, CONAGUA 2016). These two categories are open to land-ocean exchanges influenced by medium to high wave energy (Lankford 1977). The combination of these factors could increase salt-water intake on mangrove soils and enhance the dominance of *Avicennia germinans*. This is the most tolerant mangrove species to higher salinities and extreme temperatures in the Americas (Krauss *et al* 2014a).

A. germinans dominate in almost all ARsw and some areas in HUSw-Pa (Flores-Verdugo *et al* 1992, Arreola-Lizárraga *et al* 2004, López-Medellín and Ezcurra 2012, Alatorre *et al* 2016, Mendoza-Morales *et al* 2016). Positive greenness trends on these categories could relate with physiological adaptations of *A. germinans*. It is known that *Avicennia* spp. can increase water retention and leaf thickness when salinity and aridity increase (Nguyen 2017). Therefore, this could have direct implications for the canopy reflectance and NDVI values. First, the infrared (IR) wavelength is sensitive to the water and air retained in the mesophyll structure of the leaves (Peñuelas and Filella 1998); consequently, higher water content in leaves (i.e. water retention) results in an increase of IR reflectance and higher greenness values. Second, *A. germinans* modifies leaf angles according to the sun conditions to reduce leaf temperature (i.e. heliotropism; Krauss *et al* 2008); consequently, this modification can increase overall canopy reflectance. Greenness trends could relate with physiological adaptations of dominant mangrove species, as well their canopy interaction at different wavelengths.

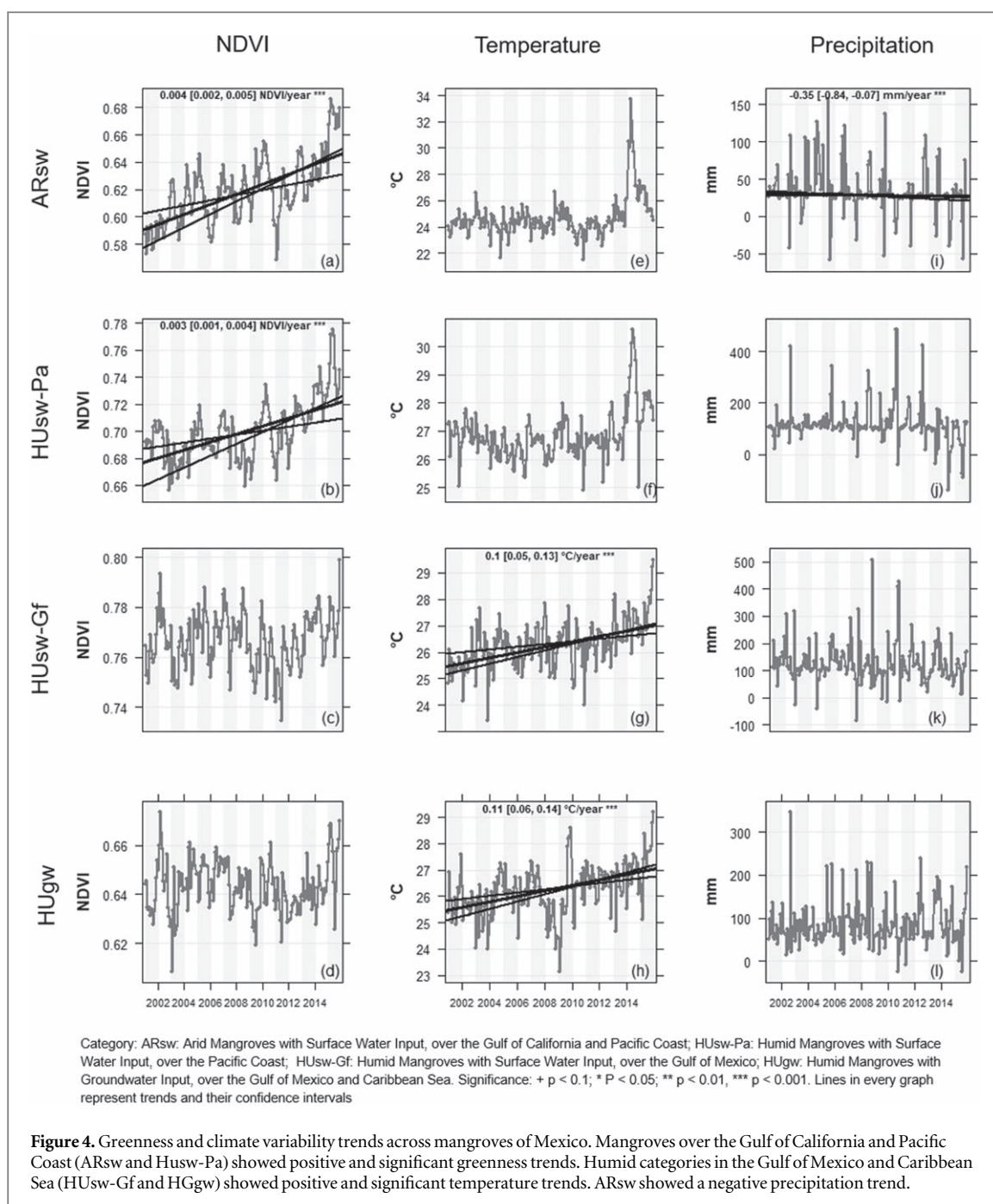


Resilience of mangrove species to environmental conditions and human impacts could also enhance greenness trends. *A. germinans* is one of the most resilient species to recent climate variability with the ability to expand its global distribution to the Poles and to encroach over temperate coastal saltmarshes (Cavanaugh *et al* 2014, Madrid *et al* 2014, Saintilan *et al* 2014, Krauss *et al* 2014a). Its expansion should relate with potential greenness increase, as consequence of trees recruitment and canopy growth. Human-induced changes could drive differential impacts on the mangrove community that eventually may enhance greenness trends. For example, Marismas Nacionales part of HUSw-Pa category (figure 5(e)), has experienced a differential impact on its mangrove community, losing nearly 8000 ha of mangrove in the last 30 years (mainly *Laguncularia racemosa*; Kovacs *et al* 2001, Valderrama *et al* 2014) and potentially enhancing the presence and development of *A. germinans*. Those impacts are a consequence of human-induced preferential flow paths of water from the ocean to the land (i.e. Cuatlá Channel opened in the 1970s with an average opening of ~50 m, but currently the opening has ~800 m; Google Earth). This preferential flow path increased the salinity on the mangrove soils and could enhanced the differential impacts on the mangrove community (Kovacs *et al* 2001). Our results showed that positive greenness trends in mangroves over the Gulf of California and Pacific Coast may relate with mangrove species composition and differential impacts of site-specific characteristics and human-induced changes.

HUSw-Gf and HUGw did not show significant greenness trends. These categories receive the major amount of freshwater in the country (~200 000 hm³ yr⁻¹ per category); where HUSw-Gf is influenced by rivers and HUGw by groundwater. Forty-four percent

of the HUSw-Gf rivers are dammed with a capacity to store ~13% of the total annual river discharge (~29 500 hm³ yr⁻¹; CONAGUA 2016). There are not dams in HUGw but conservative estimates of groundwater extraction are ~2400 hm³ yr⁻¹; representing nearly ~1% of the potential water outflow to the coastal zone (INEGI 2010, Null *et al* 2014). Sediments and nutrient inputs are the main difference between both categories. HUSw-Gf have the major river discharge across Mexico and likely increase the inputs of sediments, nutrients and particulate matter (Rivera-Monroy *et al* 1995, David and Kjerfve 1998, Morán-Silva *et al* 2005), while HUGw category is composed by mesotrophic or oligotrophic systems, with a medium to poor nutrient concentrations (Herrera-Silveira *et al* 2002, Lagomasino *et al* 2015). These differences have an influence on the mangrove's structure and composition (Adame *et al* 2013a, Kauffman *et al* 2016). Mangrove dominance in HUSw-Gf and HUGw is variable (Day *et al* 1987, Hernández *et al* 2011, Adame *et al* 2013a, 2013b, Kauffman *et al* 2016, Chan-Keb *et al* 2018, López-Portillo *et al* 2018). Here, we postulate that this mangrove variability is the reason for the lack of temporal greenness trends on the Gulf of Mexico and Caribbean Sea.

Site-specific SVGTs were more evident on HUSw-Gf and HUGw than in ARsw and HUSw-Pa. Two examples are Pom Atasta Lagoon in HUSw-Gf (figure 5(h)) and Sian Ka'an in HUGw (figure 5(f)). Those areas showed negative SVGTs. This could be related to the dominance of the species, where Pom Atasta Lagoon has a species composition of *Rhizophora mangle*, *Laguncularia racemosa* and different rainforest species (Vázquez-Lule *et al* 2012), while Sian Ka'an is mainly dominated by *R. mangle* (figure 5(f); (Adame *et al* 2013a). These negative greenness trends could also related to the negative effects of chronic

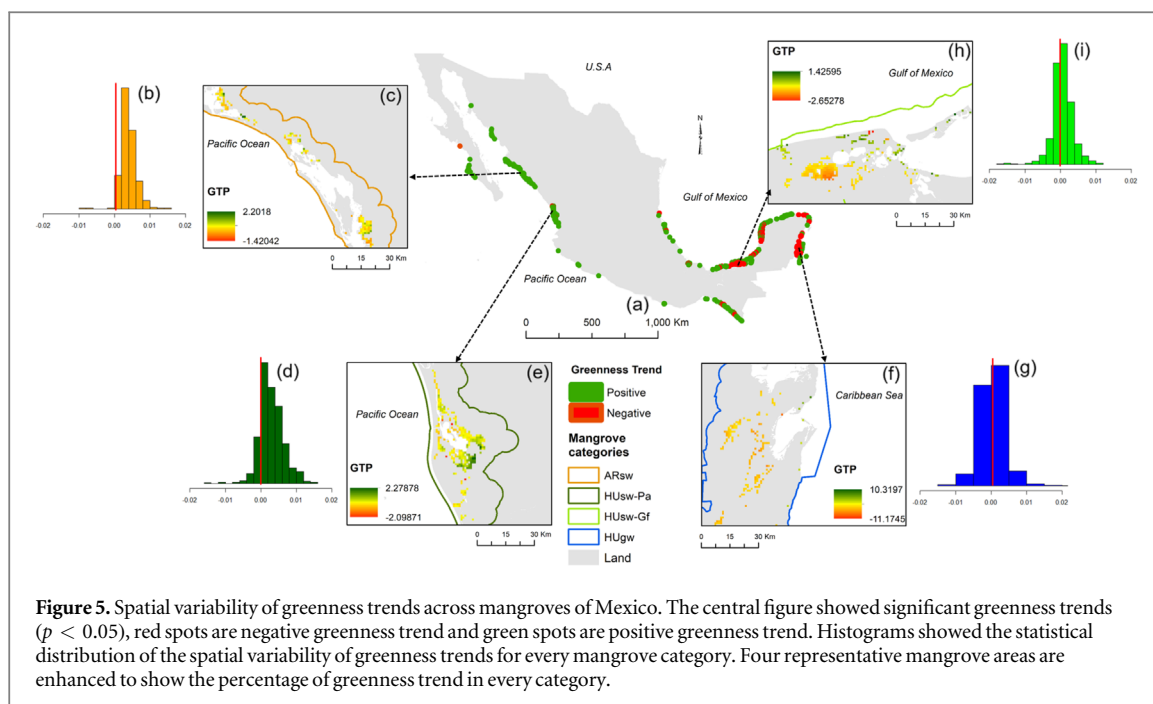


environmental and anthropogenic disturbances (e.g. hurricanes, SLR, reduction of freshwater, pollution in sediments or water, etc) that could influence a decrease in forest grow and productivity.

Hurricanes affect the canopy of mangroves (Doyle *et al* 1995, Adame *et al* 2013b, Zhang *et al* 2016). During the study period there were 17 tropical storms and hurricanes (TS-H) affected HUGw mangroves (24% of them were major, category 3 or more in Saffir–Simpson scale). HUsW-Gf mangroves were impacted by 24 TS-H, with no major hurricanes. There were 23 TS-H for ARsw (less than 5% were major) and 17 for HUsW-Pa (12% were major; NOAA 2018a). All categories, except HUsW-Pa, had an increase $> 4\%$ on the TS-Hs frequency between 2001 and 2015, compared to the

period of 1980–2000. HUGw had the higher frequency increase (9%), while the HUsW-Pa the lower decrease ($\sim 18\%$). Therefore, we propose that hurricane impacts could cancel out any potential greenness increase over the Gulf of Mexico and Caribbean Sea, mainly via the negative effect of canopy defoliation during storm events (Doyle *et al* 1995, Zhang *et al* 2016).

We highlight that other factors could also influence greenness trends. For example, SLR and its effect on phosphorus (P) availability may have a differential effect on the mangroves productivity and carbon stocks based on site-specific characteristics (Krauss *et al* 2006, 2008, 2014b, Castañeda-Moya *et al* 2011, 2013, Rovai *et al* 2018). All mangrove categories



in Mexico have experienced an average sea level rise $>2.34 \text{ mm yr}^{-1}$ (NOAA 2018b) that may enhance soils fertility by increasing P availability (Krauss *et al* 2006, Castañeda-Moya *et al* 2011) and intensify the positive greenness trends detected for ARsw and HUsw-Pa. However, other mangrove areas (e.g. HUgw) could experience canceling effects by SLR and P availability, and could explain the slow root and leaf turnover rates experienced by those mangroves (Castañeda-Moya *et al* 2011, 2013). We conclude that SLR and P availability could enhance grow and be reflected on greenness, but the timing of the response will depend on site-specific characteristics.

Annual variability of greenness and climate drivers and their relationship

Our results show that mangroves across Mexico have a seasonal cycle with higher greenness during winter months, as seen across North America (Zhang *et al* 2016) and at the local scale in mangroves of Mexico (Pastor-Guzman *et al* 2015, Flores-Cárdenas *et al* 2017). Furthermore, we found that annual greenness peaks have a time-lag of two to five months after the peak of temperature and precipitation, respectively. This time-lag may be related to higher stress conditions for mangroves during warmer months (Chen and Ye 2014). Mangroves are tropical and subtropical vegetation stressed by constant water salinity inputs, this could limit the photosynthesis activity during warmer months that may delay the greenness increase. The time-lag effect of precipitation may be related to the time that water requires to move from high watershed areas to the coast, and the time involved in dissolving nutrients before they are available to mangroves. We propose that global-scale studies of greenness (Forkel *et al* 2015, Zhu *et al* 2016) should

consider that greenness patterns of mangroves may be decoupled from patterns of terrestrial ecosystems as they can be influenced by regional (i.e. teleconnections) or local factors inherent to coastal wetlands.

Carbon stocks and greenness

Our analyses show that the spatial variability of greenness and climate trends are not related to carbon stocks in almost all mangroves of Mexico. AGC and SOCD did not show significant spatial relationships for almost all categories. Globally, SOCD patterns in mangroves do not overlap with AGC patterns (Atwood *et al* 2017), likely as a consequence of site-specific factors for the origin of soil organic carbon (Ezcurra *et al* 2016). HUsw-Gf mangroves have more than 40% of AGC than other categories, likely because HUsw-Gf represent the most developed and structured mangroves across Mexico (Day *et al* 1987, Kauffman *et al* 2016). HUgw showed the highest amount of SOCD with 58% more than the other categories, possible because this category is less influenced by spring water pulses (i.e. large river discharge). We postulate that in HUgw the surface SOCD could have lower lateral transport rates to the coastal ocean than in the other categories, and consequently it could have a longer residence time at the 0–30 cm depth. Many mangrove areas in this category are P limited that could increase the SOCD (Castañeda-Moya *et al* 2011, Rovai *et al* 2018, Twilley *et al* 2018). These results are consistent with recent studies at global scale (Rovai *et al* 2018, Twilley *et al* 2018). Positive greenness trends on mangroves could increase AGC stocks, but their effect on SOCD may depend on site-specific factors (Twilley *et al* 1999, Sanders *et al* 2016, Osland *et al* 2017). Our results imply that carbon stocks (in some mangrove categories of Mexico, mainly dominated by *A. germinans*) could

increase in the future, but some other areas could experience a decrease (e.g. Gulf of Mexico and Caribbean Sea). Consequently, there is a need to develop reference frameworks for long-term monitoring projects of carbon stocks in mangroves of Mexico and implementation of REDD+ initiatives (Vargas *et al* 2017).

Conclusion

Our results quantified greenness trends and their spatial variability across PMF without direct influence of LULCC. Our results showed a greenness increase for mangroves developed over the Gulf of California and Pacific Coast, mainly dominated by *A. germinans*. In contrast, site-specific biophysical factors could influence the response of mangroves across the Gulf of Mexico and Caribbean Sea. Overall, greenness trends were not consistently influenced by trends in temperature or precipitation. We propose that the combination of environmental factors such as quantity/quality of freshwater input, storms, anthropogenic influence, and site-specific characteristics could have more influence on greenness trends than climate variability alone. Finally, greenness and climate variability trends are not directly related to carbon stocks for most mangrove areas of Mexico. Our findings provide a baseline to develop regional monitoring programs, carbon accounting models, and could be tested across other mangrove forests around the world.

Acknowledgments

AVL and MG acknowledge support from CONACyT doctoral fellowships. RV acknowledges support from NASA Carbon Monitoring Systems (80NSSC18K0173) and the National Science Foundation (1652594).

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