LETTER
Greenness trends and carbon stocks of mangroves across Mexico

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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 hydro-periods 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 (Gavanaugh 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, 2011, 2014).
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, Ishbiaque 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; Oshland 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-Landelos 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)
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 (A Rwsw); (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 semi-diurnal tides. 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 72% 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 1S) 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 semi-diurnal (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 \cite{Los2013, Hilker2014} including mangrove forests \cite{Fuller2014, Alatorre2016, Flores-Cárdenas2017}.

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 (°C) and total monthly precipitation (mm) from Daymet at 1 km of spatial resolution from 2001 to 2015 \cite{Thornton2017}. 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 \cite{Cartus2014}. For SOCD, we used a product at 30 cm of depth \cite{Guevara2017} 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 \cite{Adame2013a, Ezcurra2016}. 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 \cite{Herrera-Silveira2016}; 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 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 low-
est (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 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 pre-
cipitation 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 max-
imum 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 precipita-
tion (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 (°C)  | Prcp (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 (±529.4)           | 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 (°C): Mean temperature from 2001 to 2015. Daymet data (Thornton et al. 2017).

Prcp (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.
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 hm³ year; CONAGUA 2016). Fifty-two percent of the ARsw rivers are dammed, and those dams could store ~84% of the total annual river discharge (~17 500 hm³ yr⁻¹; CONAGUA 2016). For HUsw-Pa, 28% of the rivers are dammed and dams can store ~26% of the total annual river discharge (15 240 hm³ 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 hm$^3$ 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 hm$^3$ yr$^{-1}$; CONAGUA 2016). There are not dams in HUgw but conservative estimates of groundwater extraction are ∼2400 hm$^3$ 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(i)). 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). HUgw-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 (~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

**Figure 4.** Greenness and climate variability trends across mangroves of Mexico. Mangroves over the Gulf of California and Pacific Coast (ARsw and HUsw-Pa) showed positive and significant greenness trends. Humid categories in the Gulf of Mexico and Caribbean Sea (HUsw-Gf and HUgw) showed positive and significant temperature trends. ARsw showed a negative precipitation trend.
in Mexico have experienced an average sea level rise >2.34 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 growth 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-Gardenas 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

**Figure 5.** Spatial variability of greenness trends across mangroves of Mexico. The central figure showed significant greenness trends (p < 0.05). red spots are negative greenness trend and green spots are positive greenness trend. Histograms showed the statistical distribution of the spatial variability of greenness trends for every mangrove category. Four representative mangrove areas are enhanced to show the percentage of greenness trend in every category.
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.

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References
Adame M F, Kaufman J B, Medina I, Gamboa N J, Torres O, Caamal J P, Reza M and Herrera-Silveira J A 2013a Carbon stocks of tropical coastal wetlands within the karstic landscape of the Mexican Caribbean PLoS One 8 e56569
Adame M F, Zaldívar-Jiménez A, Teutli C, Caamal J P, Andueza M T, López-Adame H, Cano R, Hernández-Arapana H A, Torres-Lara R and Herrera-Silveira J A 2013b Drivers of mangrove litterfall within a karstic region affected by frequent hurricanes Biotropica 45 147–54
Alatorre L C et al 2016 Temporal changes of NDVI for qualitative environmental assessment of mangroves: shrimp farming impact on the health decline of the arid mangroves in the Gulf of California (1990–2010) J. Arid. Environ. 125 98–109
Alongi D M 2015 The impact of climate change on mangrove forests Curr. Clim. Change Rep. 1 30–9
Arreola-Lizárraga J A, Flores-Verdugo F J and Ortega-Rubio A 2004 Structure and litterfall of an arid mangrove stand on the Gulf of California, Mexico Aquat. Bot. 79 137–43
Atwood T B et al 2017 Global patterns in mangrove soil carbon stocks and losses Nat. Clim. Change 7 523–8
Bai J and Perron P 2003 Computation and analysis of multiple structural change models J. Appl. Econ. 18 1–22
Carslaw D C and Ropkins K 2012 Openair—an R package for air quality data analysis Environ. Model. Sofw. 27–28 52–61
Cartus O, Kellner dorfer J, Walker W, Franco C, Bishop J, Santos L and Fuentes J M M 2014 A national, detailed map of forest aboveground carbon stocks in Mexico Remote Sens. 6 5559–88
Castañeda-Moya E, Twilley R R and Rivera-Monroy V H 2013 Allocation of biomass and net primary productivity of mangrove forests along environmental gradients in the Florida Coastal Everglades, USA Forest Ecol. Manage. 307 226–41
Castañeda-Moya E, Twilley R R, Rivera-Monroy V H, Marx B D, Coronado-Molina C and Ewe S M L 2011 Patterns of root dynamics in mangrove forests along environmental gradients in the Florida Coastal Everglades, USA Ecosystems 14 1178–95
Cavanaugh K C, Kellner J R, Forde A J, Gruner D S, Parker J D, Rodríguez W and Feller I C 2014 Poleward expansion of mangroves is a threshold response to decreased frequency of extreme cold events Proc. Natl Acad. Sci. USA 111 723–7
Cavanaugh K C, Odland M J, Bardou R, Hinojosa-Arango G, López-Vivas J M, Parker J D and Rovai A S 2018 Sensitivity of mangrove range limits to climate variability Glob. Ecol. Biogeogr. 27 925–35
Cervantes-Zamora Y, Cornejo-Olgin S L, Lucero-Márquez R, Espinoza-Rodríguez J M, Miranda-Viquez E and Pineda-Vélazquez A 1990 Provincias biogeográficas de México Comisión Nacional para el Conocimiento y Uso de la Biodiversidad
Chan-Ke B A, Agraz-Hernández C M, Muñiz-Salazar R, Posada-Navegas G, Osti-Sáenz J, Castellano J E R, Conde-Medina K P and Vega-Serratos B E 2018 Ecophysiological response of Rhizophora mangle to the variation in hydrogen chemistry during five years along the Coast of Campeche, México Diversity 10 9
Chen Y and Ye Y 2014 Effects of salinity and nutrient addition on mangrove excoecaria agallocha PLoS One 9 e93337
Colditz R R, Conrad C, Wehrmann T, Schmidt M and Dech S 2016 pdf
Colditz R R, Conrad C, Wehrmann T, Schmidt M and Dech S 2008 TiSeG: a flexible software tool for time-series generation of MODIS data utilizing the quality assessment science data set IEEE Trans. Geosci. Remote Sens. 46 3296–308
CONAGUA 2016 Atlas del Agua en México Comisión Nacional del Agua México City, Mexico: Comisión Nacional del Agua (http://201.116.60.25/publicaciones/AAM_2016.pdf)
David I T and Kjerfve B 1998 Tides and currents in a two-inlet coastal lagoon: Laguna de Terminos, Mexico Cont. Shelf Res. 18 1057–79
Day J W, Conner W H, Ley-Lou F, Day R H and Navarro A M 1987 The productivity and composition of mangrove forests, Laguna de Términos, México Aquat. Bot. 27 267–84
Donato D C, Kaufman J B, Murdyvanyo D, Kurnianto S, Stidham M and Kanninen M 2011 Mangroves among the most carbon-rich forests in the tropics Nat. Geosci. 4 293–7
Doyle T W, Smith T J and Robblee M B 1995 Wind damage effects of hurricane andrew on mangrove communities along the Southwest Coast of Florida, USA J. Coast. Res. 21 159–68
Ezcurra P, Ezcurra E, García-Peñalver P P, Costa M T and Aburto-Oropeza O 2016 Coastal landforms and accumulation of mangrove peat increase carbon sequestration and storage Proc. Natl Acad. Sci. 113 4404–9
Flores-Cárdenas F, Millán-Aguilar O, Díaz-Lara L, Rodríguez-Arredondo L, Hurtado-Oliva M A and Manzano-Sarabia M 2017 Trends in the normalized difference vegetation index for mangrove areas in northwestern Mexico J. Coast. Res. Res. accepted 34 877–82
Flores-Verdugo F, González-Farias F, Zamorano D S and Ramirez-García 1992 Mangrove ecosytems of the Pacific Coast of Mexico: distribution, litterfall, and detritus dynamics Coastal Plant Communities of Latin America ed U Seeliger (New York: Academic) pp 269–268
Forkel M, Carvalhais N, Verbesselt J, Mahecha M D, Neigh C S R and Reichstein M 2013 Trend change detection in NDVI time series: effects of inter-annual variability and methodology Remote Sens. 5 2113–14
Forkel M, Migliavacca M, Thonickie C, Reichstein M, Schaaf C, Weber U and Carvalhais N 2015 Codominant water control on global interannual variability and trends in land surface phenology and greeness Glob. Change Biol. 21 3414–35
Fuller D O and Wang Y 2014 Recent trends in satellite vegetation index observations indicate decreasing vegetation biomass in the southeastern saline everglades wetlands Wetlands 34 67–77
Giri C, Chichar, E, Tiesens I L, Zhu Z, Singh A, Loveland T, Masek J and Duke N 2011 Status and distribution of mangrove forests of the world using earth observation satellite data Glob. Ecol. Biogeogr. 20 154–9
Gress K S, Huxman M, Kairo J G, Mugi L M and Briers R A 2017 Evaluating, predicting and mapping belowground carbon stores in Kenyan mangroves Glob. Change Biol. 23 224–34
Guarnieri et al. 2015 Photosynthetic seasonality of global tropical forests constrained by hydroclimate Nat. Geosci. 8 284–9
Guevara M 2017 Coastal lagoons of Mexico their origin and classification Terra Latinoamericana New York: Academic 666p
Hernández C M A, Zaragoza C G, Iriarte-Vivar S, Hamilton S E and Friess D A 2018 Global carbon stocks and detritus dynamics Coastal Plant Communities of Latin America ed U Seeliger (New York: Academic) pp 269–268
Hinson A L, Feagin R A, Eriksson M, Najjar R G, Herrmann M, Bianchi T S, Kemp M, Hutchings J A, Crooks S and Boulton T 2017 The spatial distribution of soil organic carbon in tidal wetland soils of the continental United States Glob. Change Biol. 23 5468–80
Hutchinson J, Manica A, Swettenham R, Balmford A and Spalding M 2014 Predicting global patterns in mangrove forest biomass Conserv. Lett. 7 233–40
INEGII 2010 Censo de Población y Vivienda 2010 (Aguascalientes, Mexico: México Instituto Nacional de Estadística y Geografía)
Ishitake A, Miynt S W and Wang C 2016 Examining the ecosystem health and sustainability of the world’s largest mangrove forest using multi-temporal MODIS products Sci. Total Environ. 569–570 1241–54
Kaufman J B, Hernandez Trejo H, del Carmen Jesus Garcia M, Heider C and Contreras W M 2016 Carbon stocks of mangroves and losses arising from their conversion to cattle pastures in the Pantanos de Centla, Mexico Wetl. Ecol. Manage. 24 203–16
Kovtun M, Valdés I, Masek J and Blanco-Correa M 2001 Mapping disturbances in a mangrove forest using multi-date landsat TM imagery Environ. Manage. 27 763–76
Krass K W, Doyle T W, Twilley R R, Rivera-Monroy V H and Sullivan J K 2006 Evaluating the relative contributions of hydroperiod and soil fertility on growth of south Florida mangroves Hydrobiologia 569 311–24
Krass K W, Lovelock C E, McKee K L, López-Hoffman L, Ewe S M L and Sousa W P 2008 Environmental drivers in mangrove establishment and early development: a review Aquat. Bot. 89 105–27
Krass K W, McKee K L and Hester M W 2014a Water use characteristics of black mangrove (Avicennia germinans) communities along an ecotone with a northern geographical limit Geohydrology 7 354–65
Krass K W, McKee K L, Lovelock C E, Cahoon D R, Saintilan N, Reef R and Chen I 2014b How mangrove forests adjust to rising sea level New Phytol. 202 19–34
Lagomasino D, Price R M, Herrera-Silveira J, Miralles-Wilhelm F, Meredz-Antonio González-Álvarez Y H 2015 Connecting groundwater and surface water sources in groundwater dependent coastal wetlands and estuaries: Sian Ka’an biosphere reserve, quintana roo, Mexico Estuaries Coasts 38 1744–63
Lankford R R 1977 Coastal lagoons of Mexico their origin and classification Estuarine Processes (Amsterdam: Elsevier) pp 182–213
Los S O 2013 Analysis of trends in fused AVHRR and MODIS NDVI data for 1982-2006: indication for a CO2 fertilization effect in global vegetation Glob. Biogeochem. Cycles 27 318–30
Lovelock C E et al. 2015 The vulnerability of Indo-Pacific mangrove forests to sea-level rise Nature 526 559–63
López-Medellín X and Escarré E 2012 The productivity of mangroves in northwestern Mexico: a meta-analysis of current data J. Coast. Conserv. 16 399–403
López-Portillo J and Escarré E 2002 Los manglares de México: una revisión Maderas y Bosques 8 27–31
López-Portillo J, Lara-Dominguez A L, Vásquez G and Aké-castillo J A 2018 Water quality and mangrove-derived tannins in four coastal lagoons from the Gulf of Mexico with variable hydrologic dynamics J. Coast. Res. 34 77–88
Madrid E N, Armitage A R and López-Portillo J 2014 Avicennia germinans (black mangrove) vessel architecture is linked to chilling and salinity tolerance in the Gulf of Mexico Front. Plant Sci. 5 503
McKee K L, Cahoon D R and Feller I C 2007 Caribbean mangroves adjust to rising sea level through biotic controls on change in soil elevation Glob. Ecol. Biogeogr. 16 545–56
Mendoza-Morales A J, González-Sansón G and Aubinet-Bécaud 2016 Producción espacial y temporal de hozarasca del manglar en la laguna Barra de Navidad, Jalisco, México Rev. Biol. Trop. 64 259–73
Morán-Silva A, Antonio L, Franco M, Chávez-López R, Franco-López J, Bedia-Sánchez C M, Contreras F, Mendiesta F G, Brown-Peterson N J and Peterson S M 2005 Seasonal and spatial patterns in salinity, nutrients and chlorophyll a in the Alvarado Lagoonal system Veracruz, Mexico Gulf Caribb. Res. 17 133–43
Mundiar Y, D’Purushothpino J, Kaufmann J B, Warren M W, Samsitdo S D, Donato D C, Manuri S, Krisnawati H, Taberima S and Kurnianto S 2015 The potential of Indonesian mangrove forests for global climate change mitigation Nat. Clim. Change 5 1089–92
Myers N, Mittermeier R A, Mittermeier C G, da Fonseca G A B and Kent J 2000 Biodiversity hotspots for conservation priorities Nature 403 853–8
Myneni R B, Keeling C D, Tucker C J, Asrar G and Nemani R R 1997 Increased plant growth in the northern high latitudes from 1981 to 1991 Nature 386 796–792
Nguyen H T 2017 Leaf water storage increases with salinity and aridity in the mangrove Avicennia marina: integration of leaf structure, osmotic adjustment and access to multiple water sources Plant Cell Environ. 40 1576–91
NOAA 2018a Historical Hurricane Tracks (https://doi.org/10.25921/82hy-9e16)
NOAA 2018b Sea Levels Online: Sea Level Variations of the United States Derived from National Water Level Observation Network Stations (Silver Spring, MD: NOAA’s Ocean Service, Center for Operational Oceanographic Products and Services (CO-OPS))
Null K A, Knee K L, Crook E D, de Sieyes N R, Rebolloledo-Vieyra M, Hernández-Terrones L and Paytan A 2014 Composition and fluxes of submari ne groundwater along the Caribbean coast of the Yucatan Peninsula Cont. Shelf Res. 77 38–50
Otsland M J, Enwright N M, Day R H, Gabler C A, Stagg C L and Grace J B 2016 Beyond just sea-level rise: considering macroclimatic drivers within coastal water vulnerability assessments to climate change Glob. Change Biol. 22 1–11
Otsland M J et al 2017 Climatic controls on the global distribution, abundance, and species richness of mangrove forests Ecol. Monogr. 87 341–59
Park T, Ganguly S, Tammervik H, Euskirchen E S, Hogda K-A, Karlsen S R, Brovkov V, Nemani R R and Myneni R B 2016 Changes in growing season duration and productivity of northern vegetation inferred from long-term remote sensing data Environ. Res. Lett. 11 84001
Pastor-Guzman J, Atkinson P M, Dash J and Rioja-Nieto R 2015 Spatiotemporal variation in mangrove chlorophyll concentration using Landsat 8 Remote Sens. 7 1433–50
Peñuelas J and Filella L 1998 Visible and near-infrared反射ance of high-mangroves to aquaculture with change point and mixed-pixel analyses of high-fidelity MODIS data Remote Sens. Environ. 130 96–107
Richards D R and Friess D A 2016 Rates and drivers of mangrove deforestation in Southeast Asia, 2000–2012 Proc. Natl Acad. Sci. 113 344–9
Rivera-Monroy V H, Day J W, Twilley R R, Vera-Herrera F and Coronado-Molina C 1995 Flux of nitrogen and sediment in a fringe mangrove forest in terminos lagoon, Mexico Estuar. Coast. Shelf Sci. 40 139–60
Rovai A S et al 2016 Scaling mangrove aboveground biomass from site-level to continental-scale Glob. Ecol. Biogeogr. 25 286–98
Rovai A S, Twilley R R, Castañeda-Moya E, Rial P, Cifuentes-Jara M, Manroy-Villalobos M, Horta P A, Simonassi J C, Fonseca A L and Pagliosa P R 2018 Global controls on carbon storage in mangrove soils Nat. Clim. Change 8 534–8
Saintilan N, Wilson V C, Rogers K, Rajkaran A and Krauss K W 2014 Mangrove expansion and salt marsh decline at mangrove poleward limits Glob. Change Biol. 20 147–57
Sanders C J, Maher D T, Tait D R, Williams D, Holloway C, Sippo J Z and Santos I R 2016 Are global mangrove carbon stocks driven by rainfall? J. Geophys. Res. Geol. 121 2600–9
Thornton P E, Thornton M M, Mayer P W, Wei Y, Devarakonda R, Vose R S and Cook R B 2017 Daymet: Daily Surface Weather Data on a 1-km Grid for North America Version 3 (Oak Ridge, TN: ORNL DAAC)
Trujillo E, Moleotch N P, Goul don M L, Kelly A E and Bales R C 2012 Elevation-dependent influence of snow accumulation on forest greening Nat. Geosci. 5 705–9
Twilley R R, Rivera-Monroy V H, Chen R and Botero L 1999 Adapting an ecological mangrove model to simulate trajectories in restoration ecology Mar. Pollut. Bull. 37 404–19
Twilley R R, Rovai A S and Rial P 2018 Coastal morphology explains global blue carbon distributions Front. Ecol. Environ. 16 503–8
Valderrama L, Troche C, Rodriguez M T, Marquez D, Vázquez B, Velázquez S, Vázquez A, Cruz M I and Resil R 2014 Evaluation of mangrove cover changes in Mexico during the 1970–2005 period Wetlands 34 747–58
Valderrama-Landeros I H, Rodriguez-Zúñiga M T, Troche-Souza C, Velázquez-Salazar S, Villeda-Chávez E, Alcántara-Maya J A, Vázquez-Baldarás B, Cruz-López M I and Resil R 2017 Manglares de México: actualización y exploración de los datos del sistema de monitoreo 1970/1980–2015 Comision Nacional para el Conocimiento y Uso de la Biodiversidad. Ciudad del México p 128
Vargas R et al 2017 Enhancing interoperability to facilitate implementation of REDD+: case study of Mexico Carbon Manage. 8 57–65
Vázquez-Lule A D, Couturier S, Schmidt M, Colditz R, Silván-Cárdenas J L and Llamas Barba R 2012 The estimation of aerial biomass and structural parameters of mangroves in laguna pom atasta, capeche and laguna agua brava, Nayarit, Mexico, using ALOS PALSAR radar images (Brazil: Selper Brasil) (www.selperbrasil.org.br/selper2012/PDF/FP_SELPER-087.pdf)
Ward R D, Fries R A, Day R H and MacKenzie R A 2016 Impacts of climate change on mangrove ecosystems: a region by region overview Ecosyst. Heal. Sustain. 2 1
Wilcox R R 2004 Some results on extensions and modifications of the Theil–Sen regression estimator Br. J. Math. Stat. Psychol. 57 265–80
Woodroffe C D 1990 The impact of sea-level rise on mangrove shorelines Prog. Phys. Geogr. 14 483–520
Zhang K, Kimball J S, Nemani R R, Running S W, Hong Y, Gourley J and Yu Z 2013 Vegetation greening and climate change promote multidecadal rises of global land evapotranspiration Sci. Rep. 3 1–9
Zhang K, Ross M and Gann D 2016 Remote sensing of seasonal changes and disturbances in mangrove forest : a case study from South Florida Ecosphere 7 1–23
Zhou L et al 2014 Widespread decline of Congo rainforest greenness in the past decade Nature 508 86–90
Zhu Z et al 2016 Greening of the earth and its drivers Nat. Clim. Change 6 791–5