Marine Pollution Bulletin 181 (2022) 113948

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Baseline

Carbon and nutrient burial within Peruvian coastal marsh driven by anthropogenic activities

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ARTICLE INFO

Keywords:
Peruvian coastal marsh
Carbon burial
Organic matter source
Urban expansion
Eutrophication

ABSTRACT

This research assessed carbon and nutrient burial during the past ~60 years within a Peruvian coastal marsh ecosystem affected by anthropogenic activities, by examining total organic carbon (TOC), total nitrogen (TN) and isotopes ($\delta^{13}C$ and $\delta^{15}N$) tracers in two dated sediment cores. Significantly higher TOC and TN burial, up to 416.4 ± 65.0 and 0.7 ± 0.1 g m^{-2} $year^{-1}$ respectively, were observed after an uncontrolled urban expansion starting in the early 1970's to the 1990's. The TOC and TN burial rates were up to twofold higher than those observed for preserved coastal marshes. Furthermore, the decreased $\delta^{13}C$ values (−16.1 ± 0.6 ‰) and increasing $\delta^{15}N$ values (+10.6 ± 2.6 ‰) indicate higher deposition of algal material and urban sewage during the same period. The higher burial rates during 1970's–1990's and reduced rates thereafter evidenced the role of coastal marsh ecosystems plays in sequestering carbon and nutrients.

There is a growing global interest in coastal wetland zones since they are recognized as highly productive ecosystems, as well as being able to support a vast biological diversity and provide important ecosystem services (Kathiresan and Alikunhi, 2011; Ouyang and Lee, 2014; Alongi, 2014). One of the most important ecosystem services of coastal wetlands is the sequestration of terrestrial, marine, and atmospheric carbon as biomass and within their sedimentary environments (Donato et al., 2011; Breithaupt et al., 2012; Pérez et al., 2017). Despite their high ecosystem value, coastal wetlands are threatened by anthropogenic pressures (e.g. urban expansion, industrial activities and land use) which may result in habitat degradation, eutrophication, increase in CO_2 emissions and general loss of ecosystem services (Pendleton et al., 2012; Luisetti et al., 2014; Pérez et al., 2018). Among coastal wetland zones, coastal marshes have a high carbon burial capacity, with a global average comparable with vegetated coastal forests such as mangrove ecosystems (Luisetti et al., 2013; Alongi, 2014; Wang et al., 2021). Also, due to their sedimentary characteristics and carbon burial capacity, salt marsh may mitigate local environmental contamination (e.g. sewage effluents, and eutrophication.) (Hughes et al., 2009; Livesley and Andrusiak, 2012; Lovelock et al., 2014). Anthropogenic impacts on coastal marsh may result in changes in primary production, organic matter sources and sediment accretion rates, and may modify significantly the carbon burial rates (Kristensen et al., 2008; Alongi, 2014; Pérez et al., 2018).

The coastal marsh ecosystem "Refugio de Vida Silvestre Pantanos de Villa" (PV) is a "wetland of international importance, as "waterfowl habitat". This location is considered as one of the most important wetland zones within the central Peruvian coast, being a biodiversity refuge along the South American Pacific desert and providing a variety of ecosystem services (e.g. supporting, provisioning, regulating and cultural services) (Lizarzaburu, 1992; INRENA, 1998; RAMSAR, 2019). During the colonial period this coastal marsh area was used for agricultural and livestock farming. In the early 1960's the area was designated for touristic recreation. In early 1970's, PV has been affected by

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https://doi.org/10.1016/j.marpolbul.2022.113948
Received 10 March 2021; Received in revised form 7 July 2022; Accepted 9 July 2022
Available online 18 July 2022
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several anthropogenic activities (e.g. uncontrolled urban expansion, increased sewage loading, and oxidation ponds discharge) resulting in higher inputs of nutrients and organic matter into the sedimentary environments (FOVIDA, 2006; Aponte et al., 2018; Pulido and Bermudez, 2018). In 1989 this coastal area was designated as a reserved area (Aponte et al., 2018). Studies of the PV ecosystem have evaluated the carbon content in marsh vegetation (Aldave and Aponte, 2019), the carbon burial capacity of aquatic plants (Aponte, 2017), carbon stock losses within areas affected by fires (e.g. ~210.40 Mg ha^{-1}) (Ramirez et al., 2022) as well as carbon stocks in natural wetland reserves (e.g. 2,21 × 10^6 MgC for Los Pantanos de Villa wetland reserve) (Aponte et al., 2021). However, the sediment burial rates and the recent geochemical evolution of this coastal marsh ecosystem were previously unknown. Understanding carbon dynamics within eutrophic systems in coastal zones is a worldwide concern (Alongi, 2014; Peng et al., 2018; Pérez et al., 2020a). This study aims to evaluate anthropogenic impacts on carbon and nitrogen burial within sedimentary environments of the PV coastal marsh ecosystem.

The PV coastal marsh ecosystem (Fig. 1) is located within the densely urbanized Lima region on the central coast of Peru, where approximately 10 million people live (Aponte and Ramírez, 2011; Aponte et al., 2018). This ecosystem presents enclosed geomorphology as it is not connected directly to the ocean, and characterized by a1–5% slope topography and contains approximately 276 ha of marsh vegetation dominated by *Distichlis spicata*, *Salicornia fruticosa* and *Schoenoplectus americanus* (Ramírez and Cano, 2010). The waterbodies located within this ecosystem ranged between 1 and 2 m in depth and exhibited water temperature of 25.5 ± 1.2 °C, pH values of 8.3 ± 0.3 and dissolved oxygen values of 13.4 ± 4.1 mg L^{-1} (Huaman-Vilca et al., 2020). Also, during the past few decades, this coastal marsh zone has been affected by different types of anthropogenic disturbances (e.g., uncontrolled urban expansion, land use, extractive activities and sewage releases) (Lizarzaburu, 1992; Aponte and Ramírez, 2011; Aponte et al., 2018).

In 2019, two 30 cm-depth sediment cores were collected 70 m apart in PV (Fig. 1). Sediment compaction during the collection was minimized by using 10 cm inner diameter PVC tubes. The coring sites were selected avoiding plant roots to minimize the sediment mixture (Pérez et al., 2020a). After collection, each sediment column was sectioned on site in 1-cm intervals from the top to the base. Subsamples were stored at 4 °C before being air dried at 40 °C. Triplicate samples of *Distichis spicata*, *Salicornia fructicosa, Schoenoplectus americanus* were collected in the study area. In addition, three samples of phytoplankton-derived organic matter were collected from near water bodies using a phytoplankton net (Ingebrigtsen et al., 2017).

The dry bulk sediment density was determined by dividing the dry sediment weight over the initial sediment volume for each subsample (Ravichandran et al., 1995; Pérez et al., 2020). The determination of ^{210}Pb activity in sediments was performed by direct measurement of 46.5 KeV gamma-ray peaks, whereas ^{226}Ra activity was calculated averaging its daughters' peaks ^{214}Pb and ^{214}Bi (295.2 KeV) (351.9 KeV) (609.3 KeV); finally, the ^{210}Pb-ex activity was estimated by subtracting the ^{226}Ra from the total ^{210}Pb activity (Moore, 1984; Sanders et al., 2010; Pérez et al., 2020a). These measurements were made in a semi-planar intrinsic germanium high purity coaxial detector coupled to a multichannel analyzer (Sanders et al., 2010; Pérez et al., 2020a). The sediment accumulation rates (SAR) were calculated using the constant initial concentration (CIC) method (Appleby and Oldfield, 1992). The sediment age was calculated using the equation: Sediment age = [Year of sampling] − [Average depth of sediment interval / SAR] (Pérez et al., 2020b; Conrad et al., 2019). Sediment sub-samples were decarbonated for each interval to measure total organic carbon content (TOC) and carbon isotopic ratio (δ^{13}C), while non-decarbonated sub-samples were used to measure total nitrogen content (TN) and nitrogen isotopic ratio (δ^{15}N) (Kennedy et al., 2005; Schlacher et al., 2014; Peng et al., 2018). These analyses were performed using an elemental analyzer coupled to an isotope ratio mass spectrometer Thermo Finnigan Model Delta Plus XP (Naidu et al., 2000; Sanders et al., 2014; Pérez et al., 2020b). The TOC and TN burial rates were estimated following the equations: Burial rates (g m^{-2} $year^{-1}$) = [SAR; cm yr^{-1}] × [DBD; g cm^{-3}] × [TOC or TN; g g^{-1}] (Sanders et al., 2014; Pérez et al., 2020b). According to the American Society for Testing Materials (1963), the textural composition of sediments was determined using sieves. Sedimentary phases were compared using arithmetic means for each geochemical variable. Statistical differences were determined by the post hoc Tukey's Honestly Significant Difference test (ANOVA + Tukey HSD) (α = 0.05) with the previous testing of data normality by a Shapiro–Wilk analysis.

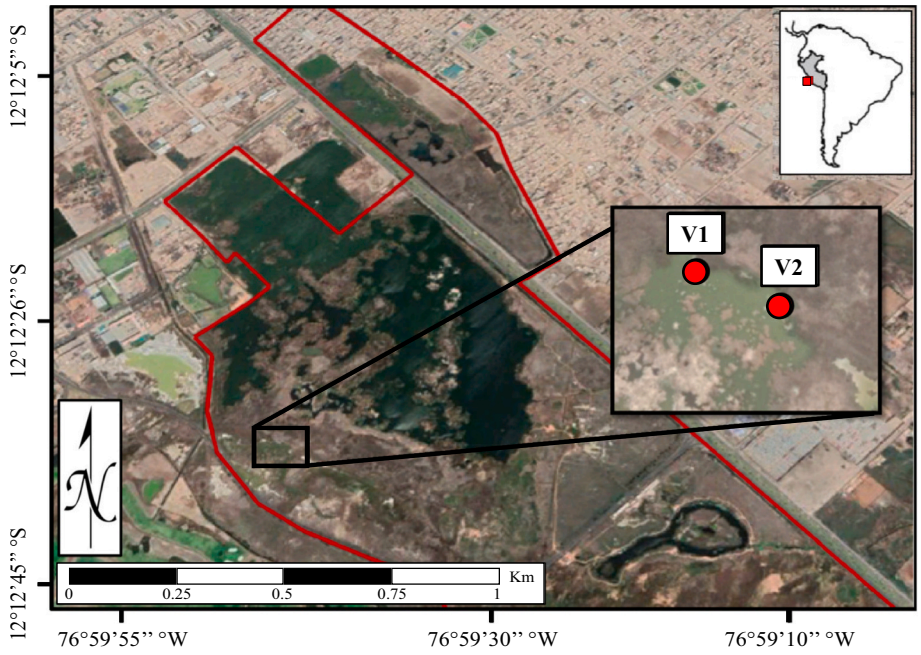


Fig. 1. Map of the sampling stations within the "RVSPV" saltmarsh ecosystem (Red circles). Saltmarsh bounds are outlined in red. *Satellite image from US Department of State Geographer. Data SIO, NOAA, U.S. Navy, NGA, GEBCO and published by Google Earth 2019.* (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The decline of the ^{210}Pb-ex activity as a function of depth for cores V1 and V2 reflected a consistent SAR (ESM-Fig. 1), whereas the textural composition of both cores presented <50 % of sand content along with the sediment profile (ESM-Fig. 2), suggesting that significant disturbance or mixing did not occur along with the sediment profile (Nittrouer et al., 1984; Appleby and Oldfield, 1992). The similarity between ^{210}Pb-ex activity profiles in the replicate cores support the reliability of our SAR estimates (ESM-Fig. 1). The SAR values obtained in this study are 0.51 and 0.58 cm yr^{-1} for V1 and V2 (ESM-Fig. 1), resulting in an average SAR of 0.55 ± 0.04 cm yr^{-1} for this study area, which was used to calculate TOC and TN burial rates in both sediment cores. These results are in agreement with the global mean determined for coastal marsh ecosystems (0.6 cm yr^{-1}), including both preserved and impacted ecosystems (Chmura et al., 2003; Ouyang and Lee, 2014). Studies have described that coastal marsh ecosystems affected by anthropogenic activities (e.g. urban expansion, land use and industrial purposes) may present SAR values up to 0.90 cm yr^{-1}, whereas preserved marshes values may reach 0.4 cm yr^{-1} (Cahoon, 1994; Callaway et al., 1997; Dittmann et al., 2016). These higher SAR values within impacted systems may result from the input derived from anthropogenic wastes (e.g. sediments, organic matter and nutrients) (Anisfeld et al., 1999; Atwood et al., 2017; Pérez et al., 2018). Higher SAR values may also be observed near the water source (e.g. ocean, creeks, or rivers), which may increase the probability of sediment and particulate material input into the sedimentary environments (Oenema and Delaune, 1988; Chmura and Hung, 2004; Zhou et al., 2007). Under this context, our results for the PV coastal marsh area (0.55 cm yr^{-1}) are higher than the range of previous studies in preserved systems (0.3 cm yr^{-1}) (Chmura et al., 2003) and

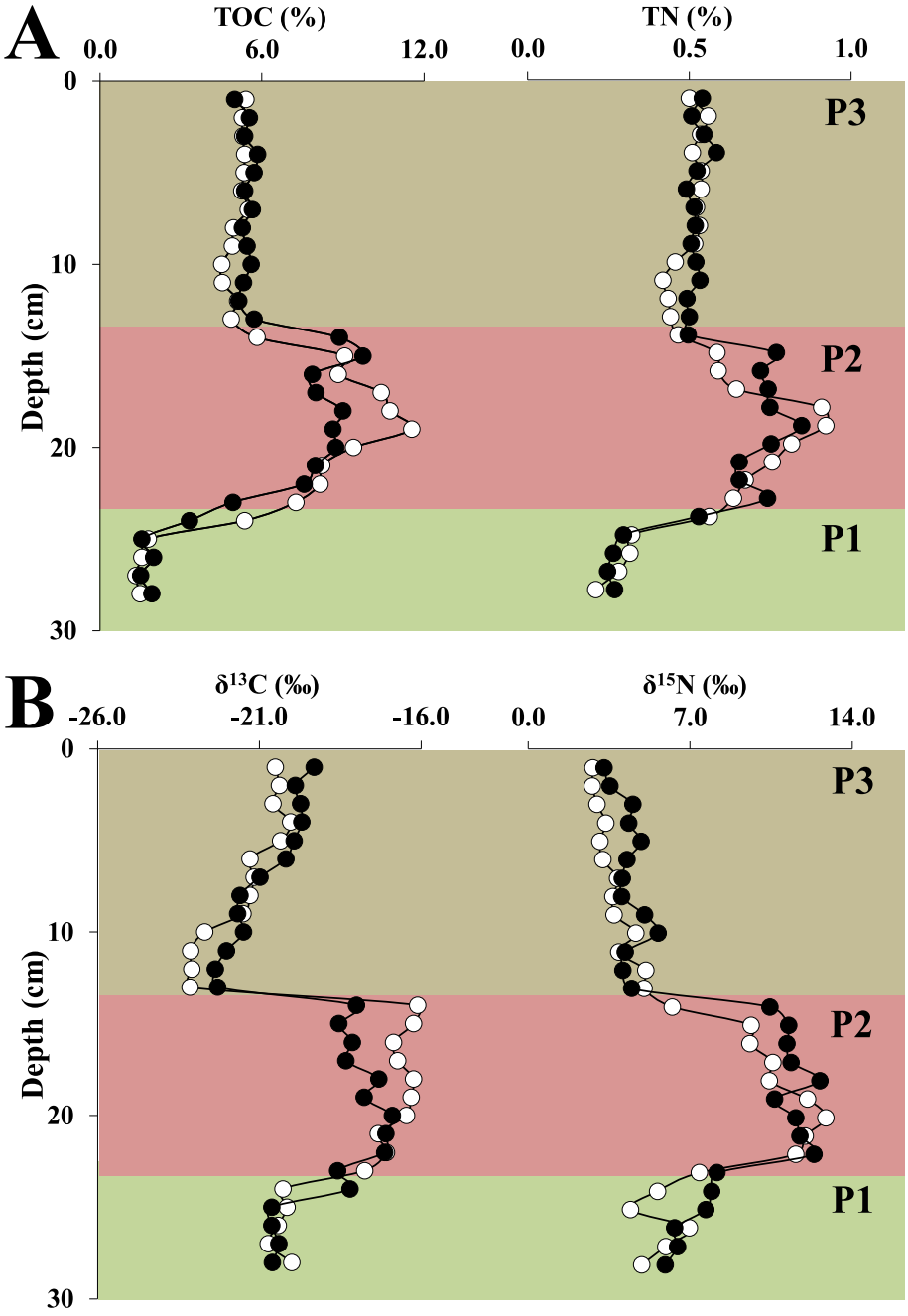


Fig. 2. (A) Percentage content of total organic carbon (TOC) and total nitrogen (TN) (B) Isotopic signatures of δ^{13}C and δ^{15}N. Different phases are presented: P1 (Green shaded area), during 1960's–1970's; P2 (Red shaded area), during 1970's – late 1990's; and P3 (Brown shaded area), during 1990's – 2010's. White circles (Core V1), Black Circles (Core V2). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

local sea level rise (0.2 cm yr^{-1}) (Takahashi et al., 2014). These higher rates could be related to the sewage releases derived from the nearby urban area, and to the enclosed geomorphology which protects the system from ocean erosion (Aponte et al., 2018; Pulido and Bermudez, 2018).

Variations of TOC, TN, $\delta^{13}C$ and $\delta^{15}N$ are strongly correlated and remarkably similar in both cores, confirming the reliability of the records (Fig. 2). From these well-defined records, three sedimentary phases, P1 to P3, were determined based on these records (P1: 1960's–1970's; P2: 1970's–1990's and P3:1990's–2010's). The TOC and TN contents were significantly higher in P2 in comparison with P3, whereas the lowest values were observed during P1 (Fig. 2A), also trends in terms of burial rates were similar (Fig. 3). These observations suggest that a higher organic matter burial started during the1970's as a result of intensified fertilization of primary production driven by the beginning of an uncontrolled urban expansion near to this coastal marsh area (Aponte et al., 2018; Pulido and Bermudez, 2018). The transition from higher carbon and nutrient burial rates during P2 to lower rates during P3 (Fig. 3A–B) agrees with this area's environmental history. During the early 1970's a large and uncontrolled urban expansion occurred near to the PV coastal marsh area, resulting in the input of higher nutrients and organic matter contents. Then, in the early 1990's, the urban expansion was controlled and its impacts were mitigated by the construction of a sewage system which resulted in a likely decrease of these loads into the coastal marsh environments (FOVIDA, 2006; Aponte et al., 2018). The TOC burial rates reached 400 g m^{-2} yr^{-1} during P2 (Fig. 3A), which is about twofold higher than the global average described for preserved coastal marsh ecosystems (240 g m^{-2} yr^{-1}) (Chmura et al., 2003; Ouyang and Lee, 2014; Wang et al., 2021), and threefold higher than the burial rates registered for preserved mangrove forests (Alongi, 2014; Pérez et al., 2018). However, this is consistent with higher values observed in coastal marsh ecosystems affected by natural (e.g. storms and flooding) and anthropogenic factors (e.g. urban expansion, industrial activities and land use), which may present carbon burial rates between 500 and 1000 g m^{-2} yr^{-1} (Andrews et al., 2008; Palomo and Niell, 2009; Day et al., 2011). It is also comparable to burial rates measured in mangroves impacted by anthropogenic factors (e.g. sewage releases, aquaculture, and urban expansion) (Pérez et al., 2018; Pérez et al., 2020a; Pérez et al., 2020b). The TN burial rates during P2 were comparable to that observed in preserved mangrove forest and sixfold lower than that observed within impacted mangroves (Pérez et al., 2020a; Pérez et al., 2020b). This comparison suggests that coastal marshes may be able to burial carbon within sedimentary environments at comparable rates to mangrove ecosystems although the nutrient filtering capability may be lower than that observed within mangrove forests due to difference in these vegetation types (Alongi, 2014).

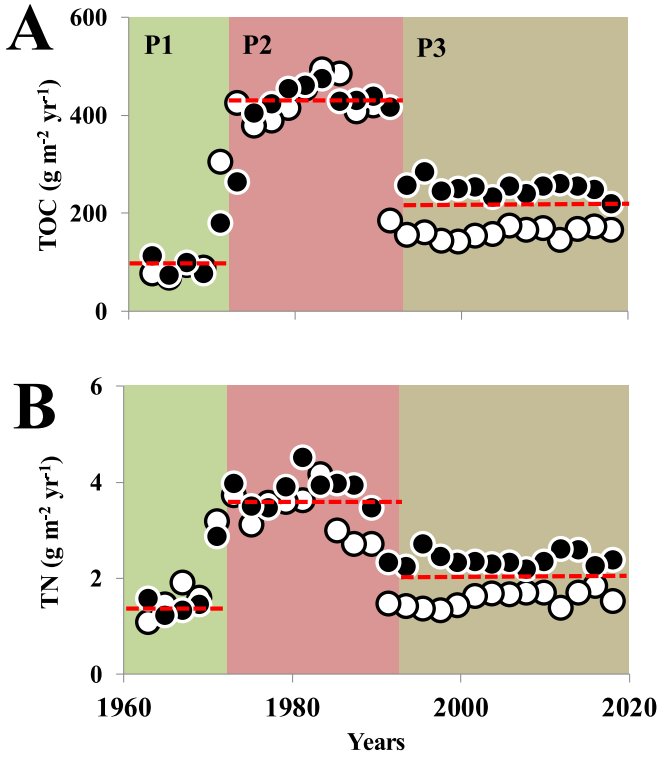


Fig. 3. (A) Burial rates of total organic carbon (TOC) (B) Fluxes of total nitrogen (TN). Different phases are presented: P1 (Green shaded area), during 1960's–1970's; P2 (Red shaded area), during 1970's – late 1990's; and P3 (Brown shaded area), during 1990's – 2010's. White circles (Core V1), Black Circles (Core V2). Dashed red lines represent average burial rates. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

During P1, the $\delta^{13}C$ and $\delta^{15}N$ values (Fig. 2B) are close to those obtained from fresh marsh vegetation (ESM-Table 1). These values suggest that terrestrial organic matter (e.g. local marsh vegetation) was the dominant source of organic matter and nutrients during this period (Peterson et al., 1985; Meyers, 2003; Hewitt et al., 2020). The significantly lower TOC and TN percentage contents during this sedimentary phase in comparison with the other phases (Table 1) may reflect that lower productivity due to high organic matter remineralization rates of which could have been occurring within the sedimentary environments (Alongi et al., 2005; Pérez et al., 2020a). During P2, $\delta^{13}C$ and $\delta^{15}N$ exhibit higher values than P1 (Fig. 2B), comparable with the values derived from phytoplankton material (ESM-Table 1). This result evidenced a higher contribution of algal material deposition within the sedimentary environments (e.g. phytoplankton, cyanobacteria-derived organic matter) (Meyers, 2003; Chappuis et al., 2017; Hewitt et al., 2020) and likely reflects the beginning of isotopically heavy nitrogen influx derived from anthropogenic activities during early 1970's (Aponte et al., 2018). The high nutrient influx likely triggered the dominance of phytoplankton and cyanobacteria material during this period, derived from the sewage release due to the urban expansion near to the study area (Diebel and Vander Zanden, 2012; Paredes et al., 2019; Pérez et al., 2020a). Finally, during P3, the $\delta^{13}C$ values are higher in comparison with P2 (Fig. 2B), and again consistent with the $\delta^{13}C$ values obtained from fresh marsh vegetation (ESM-Table 1), which suggests the deposition of higher proportions of terrestrial or saltmarsh organic matter (Peterson et al., 1985; Hewitt et al., 2020). These results may reflect the expansion or greater contribution of saltmarsh vegetation (Sanders et al., 2014; Pérez et al., 2020a). The $\delta^{15}N$ values reflect the deposition of significantly lighter nitrogen in sediments (Table 1), suggesting the decrease in the influx of heavy anthropogenic nitrogen during P3 (Dawson et al., 2002; Kendall et al., 2008; Paredes et al., 2019). The lighter $\delta^{13}C$ and $\delta^{15}N$ values were associated during this phase to lower percentage contents and burial rates of TOC and TN in comparison with P2 (ESM-Fig. 3), which may reflect the decrease in production and deposition of algal organic matter (e.g. phytoplankton and cyanobacteria) (Chappuis et al., 2017; Hewitt et al., 2020; Pérez et al., 2020a). These changes occurred when public policies were established to regulate urbanization during the early 1990's. Sewage systems and sanitary controls were established, mitigating the discharge of nutrients and organic material into the sedimentary environments of PV coastal marsh area (INRENA, 1998; FOVIDA, 2006; Aponte et al., 2018).

Aquatic or terrestrial environments able to sequester terrestrial, marine and atmospheric carbon, accumulating it as biomass or within soils, sediments and the water column, are sometimes referred to as "blue carbon ecosystems" (Donato et al., 2011; Breithaupt et al., 2012; Alongi, 2014). Due to the current global environmental context, many non-governmental organizations and governments are funding activities focused on conservation, expansion and restoration of blue carbon ecosystems to enhance the carbon burial capacity of these areas to mitigate climate change (Alongi, 2014; Dittmann et al., 2016; Hiederer

Table 1
Post-hoc Tukey's Honestly Significant Difference test (ANOVA + Tukey HSD) results for the temporal variations of the geochemical proxies between sedimentary phases within the "RVSPV" saltmarsh ecosystem. Three sedimentary phases were delineated by considering the main temporal changes in the carbon nutrient burial trends for both sediment cores: Phase 1 (P1), during 1960's–1970's ($n = 10$); Phase 2 (P2), during 1970's – 1990's ($n = 20$); and Phase 3 (P3), during 1990's – 2010's ($n = 26$). "X" symbol represents arithmetic mean for the whole sediment column. * $p < 0.05$. *Underlined acronyms present non-statistical differences among them.*

Variables	n	Average ± SE	Interactions
TOC (%)	10	P1: 2.1 ± 1.1	
	20	P2: 8.3 ± 1.3	
	26	P3: 5.2 ± 0.5	* P1 < P3 < P2
	56	X: 5.8 ± 2.2	
TN (%)	10	P1: 0.4 ± 0.1	
	20	P2: 0.8 ± 0.1	* P1 < P3 < P2
	26	P3: 0.5 ± 0.1	
	56	X: 0.5 ± 0.2	
TOC (g m^{-2} yr^{-1})	10	P1: 117.6 ± 63.2	
	20	P2: 406.5 ± 61.0	* P1 P3< P2
	26	P3: 225.4 ± 22.3	
	56	X: 263.2 ± 137.7	
TN (g m^{-2} yr^{-1})	10	P1: 1.7 ± 0.3	
	20	P2: 3.8 ± 0.6	* P1 P3 < P2
	26	P3: 2.1 ± 0.4	
	56	X: 2.6 ± 1.0	
TOC (g m^{-2})	10	P1: 237.3 ± 133.2	
	20	P2: 852.5 ± 130.3	* P1 < P3 < P2
	26	P3: 464.4 ± 107.0	
	56	X: 562.1 ± 260.8	
TN (g m^{-2})	10	P1: 34.3 ± 11.2	
	20	P2: 74.2 ± 12.4	* P1 P3 < P2
	26	P3: 42.19 ± 8.4	
	56	X: 52.2 ± 19.8	
$\delta^{13}C$ (‰)	10	P1: −21.3 ± 0.4	
	20	P2: −16.1 ± 0.6	* P3 P1 < P2
	26	P3: −21.1 ± 1.1	
	56	X: −19.6 ± 2.0	
$\delta^{15}N$ (‰)	10	P1: +5.4 ± 2.3	
	20	P2: +10.6 ± 2.6	* P3 P1 < P2
	26	P3: +3.8 ± 0.6	
	56	X: +6.4 ± 3.2	

and Viñas, 2018). The coastal marsh ecosystems cover an area of approximately 6 million hectares at a global scale presenting a carbon burial rate of 240 g m−2 yr−1, including impacted and preserved systems (Chmura et al., 2003; Ouyang and Lee, 2014; Dittmann et al., 2016). It is important to consider that within these coastal marsh ecosystems, >70 % of the carbon is retained in form of sedimentary organic matter (Batjes, 1996; Murray et al., 2011; Alongi, 2014). We extrapolate the average carbon burial rates obtained in the sediment cores to the complete PV coastal marsh surface area of 276 ha to estimate the total carbon burial and CO_2 equivalents of the ecosystem (Aponte et al., 2018; Pulido and Bermudez, 2018). Thus, using the average carbon burial rate of 275 g m^2 yr^{-1} obtained in this study and, 276 ha from PV coastal marsh ecosystems sequester approximately 759 tons of organic carbon per year in sediments which may represent about 70 % of the total amount (Batjes, 1996; Murray et al., 2011; Alongi, 2014). Then, converting the calculated organic carbon to CO_2 equivalents by using the converting factor of 3.67 (Dittmann et al., 2016; Hiederer and Viñas, 2018) results in an estimation of 2790 tons of CO_2 buried per year within PV coastal marsh. If a value of USD 30 per ton of CO_2 is used for carbon credits calculation (Garnaut, 2008; Dittmann et al., 2016; Hiederer and Viñas, 2018), the carbon burial of the whole PV coastal marsh area represents approximately USD 83600 per year in carbon credits or USD 300 per hectare. Our study demonstrates the value of the PV coastal marsh systems to reduce net anthropogenic carbon emissions.

In conclusion, two sediment cores analyzed from the PV coastal marsh wetland located within the densely urbanized area of Lima - Peru show how the evolution of the urbanization conditions since the 1960's has impacted the sedimentary environment and carbon burial within this important ecosystem. During 1960's, the lower TOC and TN contents reflected conditions prior to anthropogenic activities, while the isotopic values evidenced the deposition of terrestrial organic matter. Starting in the early 1970's, the urban expansion and the associated sewage discharge caused the eutrophication of the coastal wetland, strong algal productivity, and an increases in TOC and TN burial rates. In the early 1990's, public policies on urbanization, sewage, and sanitary system were introduced, inducing a decrease in algal production in PV, accompanied by lower TOC and TN contents and burial rates. We show that the PV coastal marsh presents a high capacity for carbon and nutrient burial, and should therefore be considered as an important blue carbon sink. This study provides the first evaluation of carbon burial in Peruvian coastal marshes in relation to their environmental condition and site specific history. Further studies in preserved and impacted coastal marshes are necessary for a better understanding of the dynamics of carbon and nutrient burial capacity within these blue carbon systems.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2022.113948.

Research involving human participants and/or animals

Non-applicable.

Informed consent

Non-applicable.

CRediT authorship contribution statement

AP: Conceptualization, writing – original draft.
RE, RC, RJ, JC: Sampling campaigns and samples pretreatment.
PER, RSG, DO: Review & editing.
HA, CJS, MC: Conceptualization, methodology, review & editing.
AP, HA, CJS and MC designed the study and all co-authors approved the final version of the manuscript and agree to be accountable for all aspects of this document.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This research was supported by the "Fondo Nacional de Desarrollo Científico Tecnológico y de Innovación Tecnológica" (FONDECYT - PERU) thought the Magnet program (Grant n° 007-2017-FONDECYT), the "Incorporación de Investigadores" program (Grant n° E034-2019-02-FONDECYT-BM) and the "Fondo Nacional de Desarrollo Científico Tecnológico y de Innovación Tecnológica" (FONDECYT - PERU) thought the "Proyecto de Investigación Aplicada y Desarrollo Tecnológico 2018-1" (Grant n° 087-2018-FONDECYT BM-IADT-AV). This research received also support from the Brazilian Research Council (CNPq), (CAPES/PRINT/UFF proc. n° 88881.310184/2018-01) and the Australian Research Council (DE160100443, DP150103286 and LE140100083).

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