Report

Current Biology

The novel mangrove environment and composition of the Amazon Delta

Highlights

- We describe a new forest structure for mangroves in the Amazon Delta
- Amazon Delta mangroves thrive in hyposaline and acidic soils
- We identified over 180 km^2 of previously unmapped forests in the Amazon Delta
- These mangroves may hold large coastal carbon stocks

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In brief

Bernardino et al. survey the Amazon Delta and find an unexpected structure and composition of mangroves, where they coexist with trees that are typical of freshwater wetlands. These mangroves were previously unmapped and will have an unprecedented value to climate mitigation and other ecosystem services on this region of the coast.

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Report

The novel mangrove environment and composition of the Amazon Delta

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SUMMARY

Both freshwater floodplain (*várzeas* and *igapós*) forests and brackish-saline mangroves are abundant and well-described ecosystems in Brazil.[1] However, an interesting and unique wetland forest exists in the Amazon Delta where extensive mangroves occur in essentially freshwater tidal environments. Unlike the floodplain forests found upriver, the hydrology of these ecosystems is driven largely by large macro-tides of 4–8 m coupled with the significant freshwater discharge from the Amazon River. We explored these mangroves on the Amazon Delta (00°52' N to 01°41' N) and found surface water salinity to be consistently <5; soil pore water salinity in these mangrove forests ranged from 0 nearest the Amazon mouth to only 5–11 at the coastal margins to the north (01°41′ N, 49°55′ W). We also recorded a unique mix of mangrove-obligate (*Avicennia* sp., *Rhizophora mangle*) and facultative-wetland species (*Mauritia flexuosa*, *Pterocarpus* sp.) dominating these forests. This unique mix of plant species and soil porewater chemistry exists even along the coastal strands and active coastlines of the Atlantic Ocean. Part of these unique mangroves have escaped current global satellite mapping efforts, and we estimate that they may add over 180 km^2 (20% increase in mangrove area) within the Amazon Delta. Despite having a unique structure and function, these freshwater-brackish ecosystems likely provide similar ecosystem services to most mangroves worldwide, such as sequestering large quantities of organic carbon, protection of shoreline ecosystems from erosion, and habitats to many terrestrial and aquatic species (monkeys, birds, crabs, and fish).

RESULTS AND DISCUSSION

The Amazon is home to diverse and complex wetland ecosystems, subject to variable hydrology, soil biogeochemistry, and vegetation cover.[1] A major hydrological distinction of Amazon tributaries are their different origin, chemistry, and color (e.g., whitewater and blackwater rivers). The freshwater non-tidal wetlands of the Amazon Basin are termed *igapós* (flooded by organic-rich blackwater rivers) or *várzea* (flooded by Andean sediment-rich whitewater rivers). On the Brazilian coast including the Amazon Delta, mangroves have been described as occurring along coastal fringes periodically inundated by macrotidal regimes (4–8 m) and under brackish to marine salinities. The Amazon region holds over 70% of Brazilian mangroves, and as such, it is of major importance for conservation, climate adaptation, and sustainable development. Brazilian mangroves have been typically recognized to be dominated by salt-tolerant mangrove species. The presence of other wetland obligate species typical of floodplain forests has rarely been described in these mangroves.[1,2] Mangroves of the legal Amazon living in mesohaline and polyhaline environments are dominated by well-developed trees (*Rhizophora mangle* and *Avicennia germinans*) under salinities of 17–23 PSU (practical salinity units).[3] However, we observed that the enormous freshwater volume transported along the coast in a NW direction (approx. 1.8×10^5 $m^3.s^{-1}$[4]) results in development of unique mangrove ecosystems. These conditions may reduce the differentiation in species composition between mangroves and tidal freshwater plant communities in the Amazon Delta, especially along the path of the Amazon freshwater plume (Figure 1). To further explore the nature of mangroves in the Amazon Delta in detail, we set on a 2-week expedition and found unique forests that are completely distinct from previous mangroves sampled along the Amazon coast and likely from any river delta in the world.

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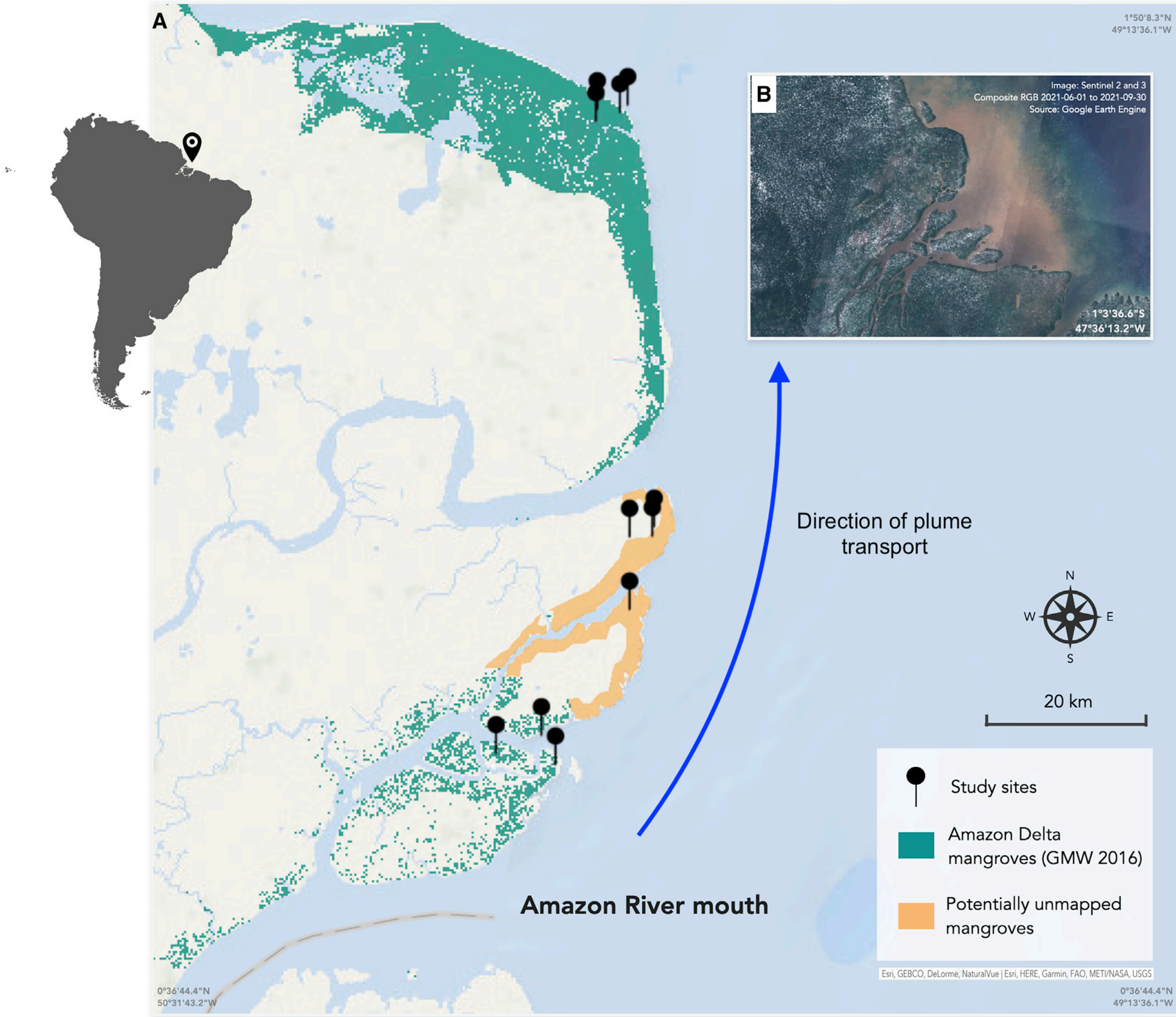

Figure 1. Mangrove distribution on the Amazon Delta

(A) Map showing the location and extent of a newly observed mangrove vegetation type (in orange) in the Amazon Delta. Global mapped mangrove vegetation (Global Mangrove Watch 2016) in the Amazon Delta in green. Study sites sampled in April 2022 indicated.

(B) Composite satellite image (Sentinel 2 and 3) of the Amazon River plume over the studied area from June to September 2021.

We sampled eleven mangrove forests along a gradient of the Amazon freshwater plume from the Amazon River mouth to the northern coast of Amapá state (Figure 1; Table 1). In the Amazon Delta, we found mangroves thriving in soils with porewater salinity from 0 to 11 PSU (mean 2 ± 3 PSU), whereas soil pH ranged from 4.65 to 7.25 (mean 6.33 ± 0.43) and redox potential (Eh) ranged from –220 to +194 mV (mean −44 ± 68 mV). Porewater salinities only increased to 5–10 in the farthest sites 100 km to the north (Table 1), suggesting that an extensive area of mangroves are thriving under the direct influence of the Amazon River plume. Although Brazilian mangrove soils are typically saline (porewater salinity > 15 PSU), and with higher pH (>6[5]), these Amazon mangrove soils have unique oligohaline and acidic soils. The acidic soils are likely related to the massive freshwater input from the Amazon River. The oligohaline soils in these Amazon mangroves are likely leading to lower sulfate reduction rates, inducing lower alkalinity export via sulfate reduction along with pyrite formation. Globally, very few mangroves have been found to thrive in soils with salinities below 5,[6,7] and only one site reported estuarine mangroves growing in freshwater conditions.[8] The lower salinity may influence soil functions including pollutant retention, carbon sequestration, and greenhouse gas emissions, since pyritization is directly linked to these functions.[9] For example, even mangrove systems with high salinities likely emit some level of methane,[10] emission rates in these low salinity forests may be expected to be even greater. The distinct soil properties of this coastal region further set the stage for the diverse plant species found in this atypical mangrove setting, of which has not yet been observed in any other region of the world.

Table 1. Transect metadata from sampled mangroves in the Amazon Delta

Region	Site name	Latitude	Longitude	Pore water salinity (PSU)/pH (min–max)	Tree density per ha	Top-ranked species
Amazon Delta	Bailique	N 00° 52′15.4″	W 50° 00′52.5″	0–2/5.4–6.5	12,748 (2,532)	*Avicennia* sp.
		N 00° 54′26.3″	W 50° 01′55.4″	0/5.5–7	9,289 (3,178)	*Pterocarpus* sp., *Rhizophora* sp., *Mauritia flexuosa*, *Avicennia* sp.
		N 01° 03′48.9″	W 49° 57′28.4″	0/4.2–4.8	10,859 (1,968)	*Pterocarpus* sp., *Mauritia flexuosa*, *Avicennia* sp.
		N 01° 09′13.5″	W 49° 55′21.5″	0–1/4.2–4.8	6,260 (1,254)	*Rhizophora* sp., *Avicennia* sp., *Montrichardia* sp.
		N 00° 53′06.5″	W 50° 05′18.1″	0/5.5–6.6	17,488 (4,367)	*Montrichardia* sp., *Pterocarpus* sp., *Mauritia flexuosa*, *Avicennia* sp., bamboos
	Araguari	N 01° 10′00.1″	W 49° 53′31.1″	5–8/5.5–5.8	4,945 (1,452)	*Rhizophora* sp., *Avicennia* sp., *Montrichardia linifera*
		N 01° 09′18.0″	W 49° 53′40.0″	3–7/6.5–6.9	9,579 (2,269)	*Pterocarpus* sp., *Avicennia* sp., *Rhizophora* sp.
	Sucuriju	N 01° 40′52.4″	W 49° 56′04.1″	7–11/5.1–6.0	2,079 (833)	*Rhizophora* sp., *Avicennia* sp., and understory ferns (*Acrostichum* sp.)
		N 01° 41′05.9″	W 49° 57′46.1″	0–2/4.7–5.2	533 (149)	*Rhizophora* sp., *Avicennia* sp., and understory ferns (*Acrostichum* sp.)
		N 01° 40′13.1″	W 49° 57′51.9″	0/4.8–5.2	2,276 (781)	*Rhizophora* sp., *Avicennia* sp., bamboos and understory ferns (*Acrostichum* sp.)
		N 01° 41′25.4″	W 49° 55′30.1″	0/6.3–6.5	4,016 (1,093)	*Rhizophora* sp., *Avicennia* sp., *Montrichardia* sp.

Location and detail of mangrove forests sampled along the Amazon Delta. Values expressed as range (min–max) or average (±SD).

We found a unique structure and composition of the mangrove forests of the Amazon Delta. As typical of mangroves, they occur on river and coastal fringes that are periodically inundated by tides and supported mature mangrove-obligate trees including *Rhizophora* and *Avicennia*. However, the low porewater salinities suggest a strong influence of the freshwater output of the Amazon River. In addition to mangrove species, we found a co-dominance with woody species typical of freshwater wetlands such as Buritis palm (*Mauritia flexuosa*), Açaí (*Euterpe oleracea*), Cortiça (*Pterocarpus* sp.), and a rich understory dominated by bamboos (*Guadua glomerata*), lianas (*Rhabdadenia biflora*, *Entada polyphylla*), aningas (*Montrichardia* sp.), and ferns (*Acrostichum aureum*; Figure 2). Contrary to mangrove forests worldwide, the understory vegetation was abundant at the fringing areas in the mouth and over to the north, suggesting that the Amazon River plume and the high rainfall at the river mouth (>3,400 mm year^{-1} [11]) facilitate a unique assemblage of plant species.[6] Our data give support to the importance of rainfall and freshwater river input to mangrove stand richness globally.[12] Within the river mouth, mangroves had a higher density of trees (11,328 ± 1,871 individuals per ha). The tree density within the mangroves in the delta is similar to the ones in mesohaline Amazon mangroves on the coast of Pará to the east (range of 3,377–27,640 ind. per ha[3]). Estuarine and coastal mangroves to the north of the Amazon plume were also composed of a mix of freshwater and mangrove plants (3,904 ± 1,299 ind. per ha) and a distinct understory vegetation with ferns, lianas, bamboos, and aningas. Such mangrove structure has never previously been documented on deltas or coastal fringing mangroves of the world. They are also strikingly distinct from floodplain forests in the Eastern Amazon, which have a distinct tree composition and richer biodiversity.[13]

Our survey expands the existing mapped area of mangroves in the Amazon River mouth by nearly 20% with a potential addition of 180 km^2 of forests, increasing recent remote sensing estimates in Brazil with an updated area of 11,252 km^2 of mangroves.[14,15] Our exploration suggests that over 1,713 km^2 or 15.2% of Brazilian mangroves are directly influenced by the Amazon River plume within the Amazon Delta. Satellite data indicate that the previously recognized area of mangroves in the Amazon Delta has remained relatively stable from 2010 to 2016 win a net loss of 12.85 km^2 (decrease of 0.8%), indicating minor net effects of natural processes (erosion) on mangrove coverage of this region.[16] Given their atypical aboveground structure and soil biogeochemistry, it is yet premature to estimate with any accuracy their total ecosystem carbon stocks. However, considering that those mangroves have a unique mixture of well-developed trees, occur where freshwater is not limiting, and receive vast quantities of suspended sediments from the Amazon River plume, we predict that these forests

Figure 2. Mangrove stands in the Amazon Delta

(A) View of the forest fringe of estuarine mangroves in the Amazon Delta.

(B) Detail of the root system of a mature *Rhizophora mangle* alongside with the understory vegetation.

(C) Mixed plant composition of palms, *Rhizophora mangle* and *Avicennia* sp. in the Amazon Delta.

may hold among the largest global carbon stocks of coastal oceans.[7] As a result of their exceptional structure, these mangrove forests will likely provide distinct ecosystem functioning and support for unique related animal and plant species over their large expanse. The novel structure of these mangroves will also likely offer new opportunities to study unrecognized ecological and biogeochemical processes next to the largest river delta in the world, which will need to be investigated in detail.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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- QUANTIFICATION AND STATISTICAL ANALYSIS

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.cub.2022.06.071.

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AUTHOR CONTRIBUTIONS

A.F.B., J.B.K., C.J.S., T.O.F., and G.N.N. designed research; A.C.A.M., F.M.S., T.M.T.S., C.G.M., R.F.C., A.E.B.S., and T.S.F.S. performed research; A.F.B., A.C.A.M., F.M.S., T.S.F.S., R.F.C., T.O.F., and J.B.K. analyzed data; and A.F.B., A.C.A.M., J.B.K., C.J.S., G.N.N., T.S.F.S., and T.O.F. wrote the paper.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Software and algorithms		
Google Earth Engine	https://earthengine.google.com	Gorelick et al.[17]
Sentinel satellite images	https://www.eumetsat.int/our-satellites/sentinel-series	Drusch et al.[18]
Global mangrove extent UN	https://data.unep-wcmc.org/datasets/45	Bunting et al.[19]

RESOURCE AVAILABILITY

Lead contact

Further information and requests should be directed to and will be fulfilled by the lead contact, Angelo Bernardino (angelo.bernardino@ufes.br).

Materials availability

This study did not generate new unique reagents

Data and code availability

- Data reported in this paper will be shared by the lead contact upon request
- This paper does not report original code
- Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request

METHOD DETAILS

In April 2022 we carried out a 15-day expedition and sampled eleven mangrove sites across the Amazon delta and to the north of the Amazon coast. Five mangrove sites were sampled within the Bailique archipelago and two mangrove sites were sampled near the Araguari region (Amazon delta and coastal fringe areas; Longitude 50°32'29.4''to 49°51'20.1''W, Latitude 0°37'47.9''to 1°14'6.1''N, Data S1). Four mangrove sites were sampled in the Sucuriju river (named Northern coast mangroves; Longitude 50°28'48.2''to 49°51'0.6''W, Latitude 1°14'18.2" to 1°49'20.5" N) including three estuarine and one coastal fringe sites (Table 1). Our sampling protocol closely followed global methods used to assess mangrove forest structure.[20] At each mangrove site, six sub-plots were established 20 m apart along a 100 m transect positioned in a perpendicular direction from the mangrove/estuary ecotone. In each sampled mangrove site, we established six subplots and results are the means of these subplots. Composition and tree density of the mangroves were quantified through identification of the species and measurements of diameter at breast height (1.3m, hereafter dbh) of all trees rooted within each sub-plot of each transect. Plot size for tree measurements was 154 m^2 (7 m radius) for trees >5 cm dbh and a nested plot with a radius of 2 m for trees with a dbh of <5 cm. In mangroves this consisted of standing live and dead tree biomass (above and belowground), and soils to the depth of an indurated horizon composed of marine sands. The indurated horizon was considered the depth where we could not penetrate the soil auger further. At all sites, we sampled soils down to 2 meters depth, except in Araguari sites that had marine sands at approximately 100 cm depth.

We sampled soil pore water interstitial salinity and pH of the groundwater collected in the boreholes using methods described in Kauffman and Donato.[20] A portable handheld refractometer (VEE GEE STX-3, range 0-100 parts per thousand) and pH meter (Milwaukee Instruments, pH56, pH -Temperature meter) was used for measuring the salinity and pH of the soil pore water. Care was taken to ensure that no surface water mixed with the sampled soil pore water as surface water was usually lower in salinity. Pore water was sampled at each soil sampling plot (n = 6 in each sampled transect). The soil pH and the redox potential (Eh) values were determined obtained during soil sampling. The pH readings were obtained with a glass electrode calibrated with pH = 4.0 and 7.0 standard solutions and the Eh values were obtained using a calomel electrode (Hanna Instruments, model HI991003).

We applied georeferenced shapefiles of satellite remote sensing from the Global Mangrove Watch dataset[19] to obtain regional estimates of the mangrove areas in the delta, using ArcGIS software measuring tool. The extent of Amazon delta mangroves were considered the entire region under the direct or indirect influence of the Amazon river plume and high rainfall of the region (Figure 1). The area of mangroves in the delta were then measured manually based on our *in situ* observations, by contouring the coastal mangroves with a polygon from the datasets from 2010 and 2016. The new potential mangrove forests were identified and area calculated by extrapolating the forest cover from the average range from shore using cartographic coastline features from ARCGIS Ocean basemap extended 1.3 to 4.0 km inland according to mapped mangroves and our field observations.[19] The Amazon plume extent was identified using ESA/EUMETSAT Sentinel 2 and 3 satellite image composite,[18,21] processed in Google Earth Engine.[17]

QUANTIFICATION AND STATISTICAL ANALYSIS

Soil data (salinity, pH) was sampled in each plot (n=6 per site, Data S1) and reported as average (1 standard deviation) per site. Tree density were counted in each plot, and averaged across 6 plots in each site. Calculations were made in Microsoft Excel. No statistical tests were made.