

Biogeographic divergence in mangrove resilience to accelerating sea-level rise

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71 **Abstract**

72 Mangrove forests raise their soil surface in response to relative sea-level rise (RSLR), a biogenic capacity that
73 underpins their value for coastal protection and blue-carbon storage. Whether this capacity is approaching its
74 upper limit, and whether that limit differs between the far-field Indo-West Pacific and intermediate-field
75 Atlantic-East Pacific settings distinguished by Holocene stratigraphy, has not been tested against contemporary
76 observations at a global scale. Here we synthesise for the first time the global mangrove surface elevation
77 table–marker horizon (SET-MH) record: 601 stations across 141 sites in 21 countries, of which 480 resolve an
78 elevation trend. Mangrove surface elevation gain ($3.59 \pm 9.51 \text{ mm yr}^{-1}$) lagged behind mean RSLR of $5.21 \pm$
79 3.42 mm yr^{-1} . The capacity to build elevation was constrained by a non-linear increase in shallow subsidence
80 with accretion. Structural equation modelling revealed tidal range as the dominant control on this constraint.
81 An elevation deficit becomes very likely ($P \geq 0.90$) at 8.1 mm yr^{-1} of RSLR in the Indo-West Pacific but at
82 6.3 mm yr^{-1} in the intermediate-field Atlantic-East Pacific sites sampled, and at only 2.4 mm yr^{-1} in reef
83 settings, mirroring the relative vulnerability to RSLR inferred from palaeo-stratigraphy. Elevation deficit,
84 rather than RSLR itself, predicts conversion to open water across the network of Surface Elevation Tables.
85 Mangrove resilience to sea-level rise is therefore bounded and regionally unequal, and in intermediate-field
86 Caribbean settings and on reef islands this limit is a present condition rather than a future projection.

87

88

89 Main text

90 Mangrove forests are a primary defence against shoreline erosion along tropical and warm-temperate coastlines
91 (Marois and Mitsch 2015), supporting fisheries, biodiversity and coastal livelihoods (Friess, Yando et al.
92 2020), and storing carbon at densities among the highest of any forest type (Sasmito, Sillanpää et al. 2020).
93 Recognition of these services has slowed clearance, mobilised restoration finance, and positioned mangroves
94 as a leading nature-based solution for climate mitigation and adaptation (Friess, Rogers et al. 2019). Recent
95 global assessments have documented a marked deceleration in mangrove loss and, in places, net gain; an
96 encouraging trajectory that has reframed mangroves as an ecosystem in recovery (Zhang, Murray et al. 2026).

97 That recovery, however, is conditional on the persistence of mangrove habitat under rising sea level. Because
98 mangroves occupy a narrow vertical range of the intertidal frame, they persist only by raising the forest
99 substrate elevations at a rate that matches RSLR, through the trapping of mineral and organic sediment and
100 the accumulation of root material (McKee, Cahoon et al. 2007) (Krauss, McKee et al. 2014). This capacity for
101 vertical adjustment has allowed mangroves to maintain an intertidal position over millennia of sea-level change
102 (Krauss, McKee et al. 2014), but it is not unbounded: a regional assessment across the Indo-Pacific found most
103 surveyed forests were not accreting fast enough to match projected rates of sea-level rise (Lovelock, Cahoon
104 et al. 2015), and beyond some rate of RSLR, vertical adjustment fails, the forest floor sinks within the tidal
105 frame (Schuerch, Spencer et al. 2018). Persistence depends on landward migration, an avenue increasingly
106 foreclosed by coastal development and hard defences (Schuerch, Spencer et al. 2018, Saintilan, Horton et al.
107 2023). Establishing where the upper bound of vertical adjustment lies is therefore central to any assessment of
108 future mangrove extent, and to the credibility of the carbon those forests are assumed to hold (Wu, Zhao et al.
109 2026).

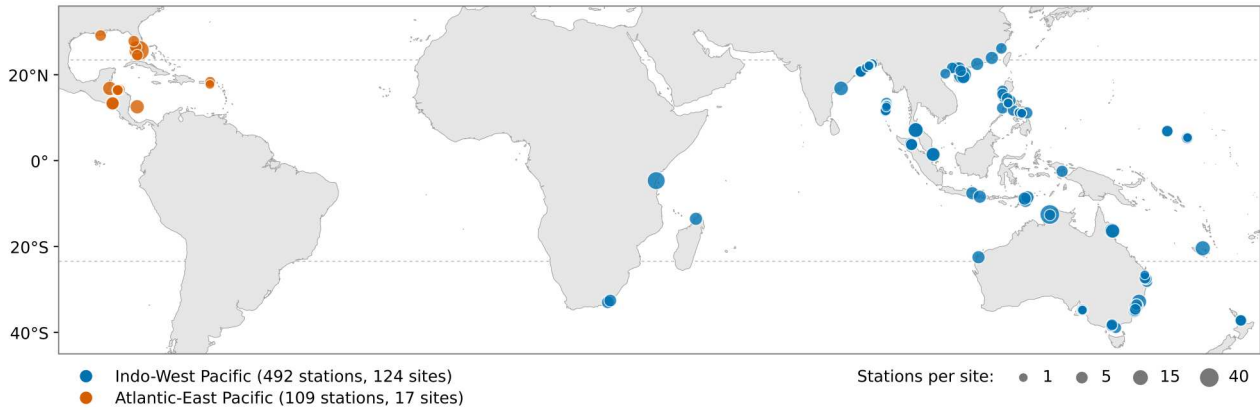
110 Mangroves are distributed across two biogeographic provinces that differ not only floristically but in their sea-
111 level and sedimentary histories (Duke, Ball et al. 1998). The Indo-West Pacific, largely far-field with respect
112 to former ice sheets, experienced a mid-Holocene highstand followed by relative stability (Li, Chua et al.
113 2023), and hosts the world's great sediment-rich deltaic and tide-dominated mangrove systems. The Atlantic-
114 East Pacific is more heterogeneous, spanning the macrotidal, sediment-rich coasts of northern South America
115 and West Africa as well as the microtidal carbonate and peat-forming systems of the Caribbean. The contrast
116 drawn from the Holocene record is therefore better framed by sea-level history than by province: intermediate-
117 field coasts of the western Atlantic and Caribbean have experienced continuous late-Holocene RSLR (Khan,
118 Ashe et al. 2017), and their mangroves occupy predominantly microtidal, sediment-poor, organic-rich
119 substrates. Palaeo-stratigraphy suggests that sustained mangrove vertical adjustment failed at lower rates of
120 RSLR in these intermediate-field settings than in the far-field Indo-West Pacific (Saintilan et al., 2020),
121 implying that vulnerability to sea-level rise is not globally uniform. Whether this divergence is expressed in
122 the contemporary record has not been tested, because instrumental observations have been too geographically
123 restricted.

124 Here we assemble the global mangrove Surface Elevation Table- Marker Horizon (SET-MH) record to address
125 three questions. First, we quantify contemporary rates of mangrove surface elevation change relative to local
126 RSLR across the full network. Second, we identify the environmental controls on elevation change, and in
127 particular on the shallow subsidence that mediates the conversion of accreted sediment into elevation gain.
128 Third, we test whether the far-field/intermediate-field and geomorphic differences in threshold RSLR inferred
129 from palaeo-stratigraphy are expressed in the instrumental record, and whether the resulting elevation deficits
130 carry an observable signature of habitat loss.

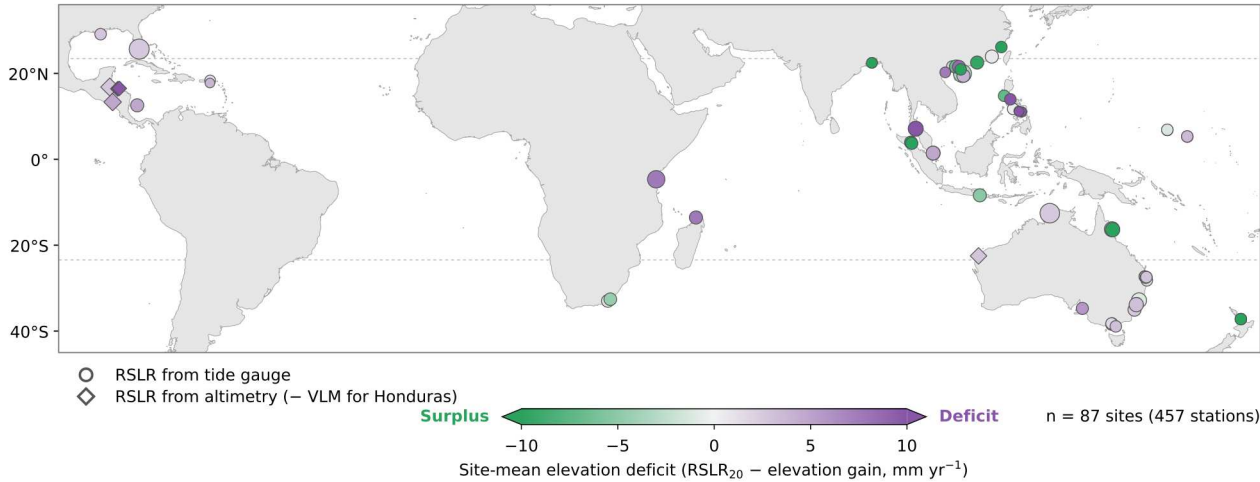
131 **The global mangrove SET-MH network**

132 The mangrove SET-MH network comprises 601 monitoring stations distributed across 141 sites in 21 countries
133 and on five continents, installed and read to a common protocol over the past three decades (Fig. 1a). Of these,
134 a surface elevation trend could be derived from 480 stations. Record lengths range from under one year to 24
135 years (median 5.1 yr); analyses of threshold behaviour are restricted to stations with more than eighteen months
136 of record. This is the first assembly and release of the global mangrove SET-MH dataset (Data S1).

a SET-MH distribution



b Elevation deficit relative to sea-level rise



137
138 **Fig. 1 | The global mangrove SET-MH network and site-level elevation deficit relative to sea-level rise.**

a, Distribution of mangrove Surface Elevation Table–Marker Horizon (SET-MH) stations: 601 stations at 141 sites in 21 countries. Each symbol is one site, placed at the mean position of its stations and sized by the number of stations. Colour shows biogeographic province: Indo-West Pacific (IWP; blue; 492 stations, 124 sites) and Atlantic–East Pacific (AEP; orange; 109 stations, 17 sites, all in the Gulf of Mexico, the Caribbean and Central America). b, Site-mean elevation deficit, defined as the 20-year relative sea-level rise (RSLR) minus the rate of surface elevation change, for the 87 sites (457 stations) with both an elevation trend and an RSLR estimate (73 IWP, 14 AEP). Positive values (purple) mean elevation gain is falling behind RSLR; negative values (green) mean elevation gain exceeds it. The colour scale is truncated at $\pm 10 \text{ mm yr}^{-1}$, and more extreme values take the end colours. Circles show sites whose RSLR comes from tide-gauge records, mostly from the Permanent Service for Mean Sea Level (PSMSL). Diamonds show sites without a suitable gauge, where RSLR is taken from satellite altimetry; for the Honduran sites, the altimetric rate is corrected for vertical land motion using Oelmann et al. (2024).

The SET-MH method (Cahoon 2024) resolves the components of surface elevation change that are otherwise conflated. A benchmark rod driven to the point of refusal provides a datum against which surface elevation change is measured, while an artificial marker horizon emplaced at installation records sediment accretion above it (Webb, Friess et al. 2013). The difference between the two isolates shallow subsidence (the compaction, decomposition and dewatering occurring between the surface and the base of the rod) which determines what fraction of accreted material is retained as elevation. Comparison of elevation change with RSLR at nearby tide gauges then yields the elevation surplus or deficit at each station (Extended Data Fig. 1).

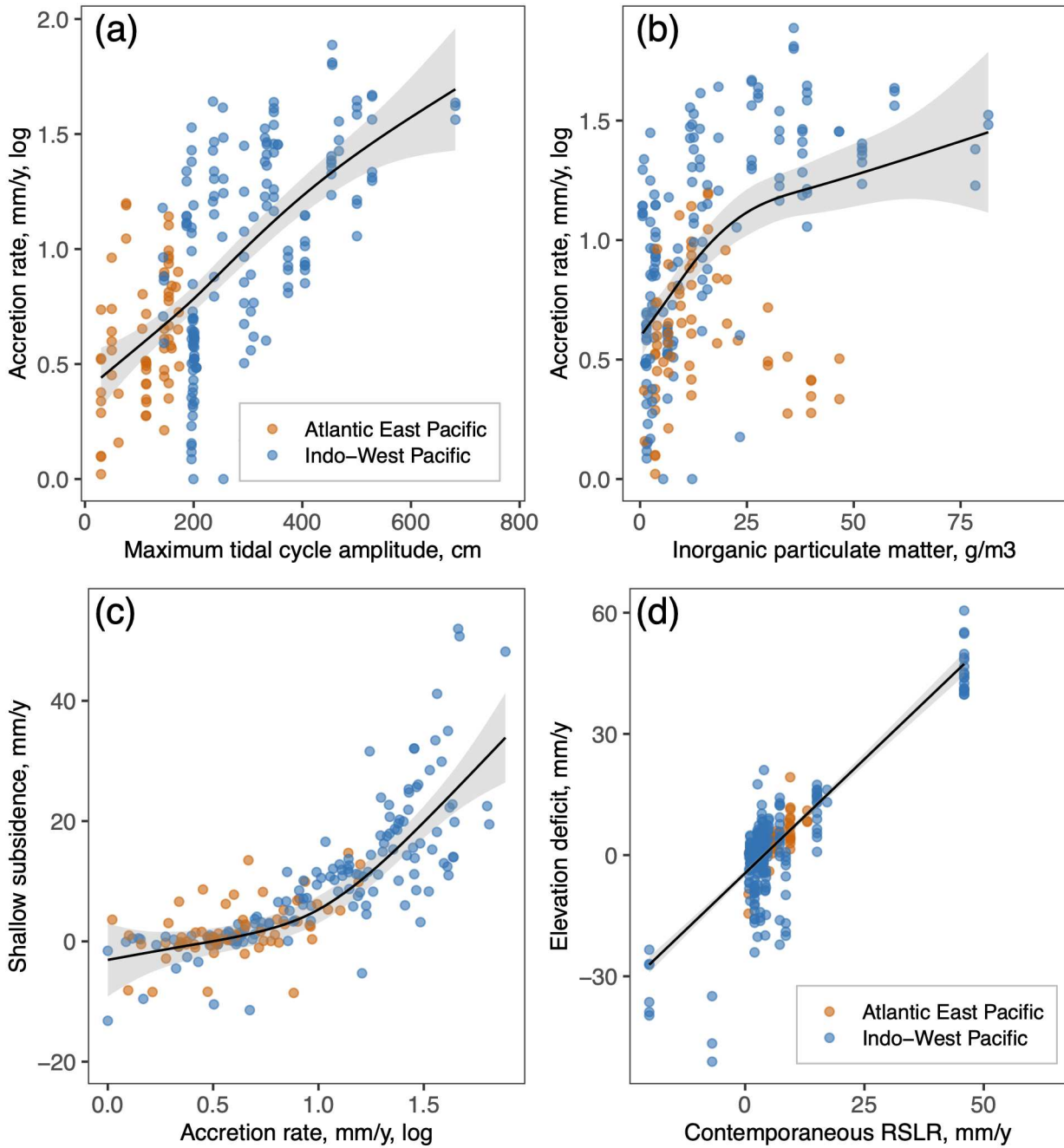
The network is not a random sample of global mangrove area. Relative to the mangrove estate as a whole, which is predominantly tropical, meso- to macrotidal and sediment-rich, the SET-MH network over-represents subtropical, lower-tidal-range and lower-suspended-sediment settings and under-represents the great deltaic systems of Southeast Asia and South America. We account for this bias when generalising and note that its direction is conservative with respect to our central finding: the settings that are under-sampled are those in which accretion, and therefore vertical adjustment, is most rapid. The bias is sharpest in the Atlantic-East Pacific, where all 109 stations lie in the Gulf of Mexico, the Caribbean and Central America, and none on the Atlantic coasts of South America or Africa. Following Saintilan et al. (2020), we therefore use ‘Atlantic-East Pacific’ (AEP) and ‘Indo-West Pacific’ (IWP) as labels for the intermediate-field and far-field settings represented in the network; our AEP results characterise microtidal, organic-rich intermediate-field mangroves, not the Atlantic-East Pacific province as a whole.

Contemporary elevation change and its controls

Across the network, mangroves gained surface elevation at a globally averaged rate of $3.59 \pm 9.51 \text{ mm yr}^{-1}$, compared with a mean RSLR of $5.21 \pm 3.42 \text{ mm yr}^{-1}$ recorded at nearby tide gauges over the preceding 20

173 years. Mangroves are therefore raising their surface at rates approaching, but on average below, contemporary
174 RSLR. Elevation change was best predicted by vertical accretion, but only a fraction of accreted material was
175 expressed as elevation gain (slope 0.35, $r^2 = 0.18$, $n = 233$; slope 0.45, $r^2 = 0.38$ for records exceeding three
176 years). The reason is that shallow subsidence increased steeply with accretion rate ($r^2 = 0.43$, $n = 230$: Fig 2c),
177 and did so non-linearly, with the shallow subsidence rate of increase inflecting between approximately 5 and
178 10 mm yr⁻¹ of accretion (Fig. 2c). Above this range, higher accretion rate yields progressively less additional
179 elevation. This same negative feedback previously documented for tidal marshes (Saintilan et al., 2022), is
180 here confirmed in mangroves across a substantially wider range of accretion rates, establishing that high
181 accretion alone is not evidence of resilience. The same pattern was evident in an earlier synthesis of 44
182 mangrove SET-MH records, in which mineral accretion was found to be a poor predictor of vulnerability and
183 high-accretion minerogenic systems were not better buffered against sea-level rise because of correspondingly
184 high subsidence (McKee, Krauss et al. 2021). Our network-scale analysis confirms this relationship across an
185 order of magnitude more stations.

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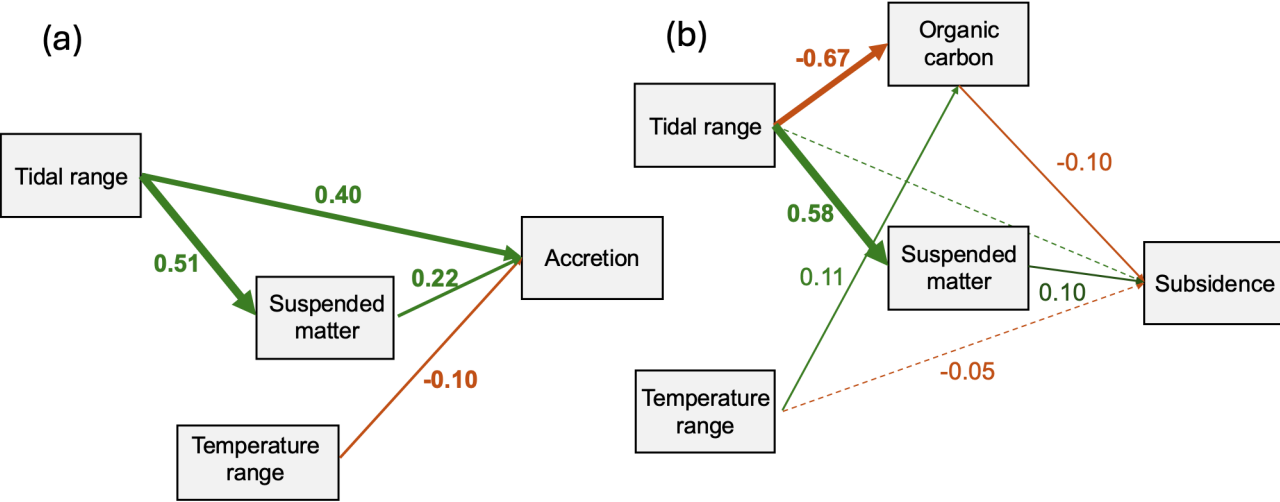


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188 **Fig. 2 | Controls on accretion, subsidence and elevation deficit.** Vertical accretion above the feldspar
 189 horizon correlates with maximum tidal amplitude (a) and inorganic particulate sediment concentration of
 190 adjacent waters (b), both variables being lower in the Atlantic-East Pacific (intermediate field) mangroves
 191 sampled by the SET-MH network. The translation of accretion into elevation gain is limited by shallow
 192 subsidence, in the upper levels of the sediment profile (called shallow subsidence) which increases with the
 193 rate of accretion, consistent with but over a greater range than that encountered in the tidal marsh SET-MH
 194 dataset (c). Thus, shallow subsidence at elevated levels of accretion is the primary reason an elevation deficit
 195 (RSLR-elevation change rate) (d). Grey shading indicates the confidence interval for the generalised additive
 196 model fit lines.

197

198 To identify what governs the elevation constraint imposed despite additional accretion of sediments, we used
199 structural equation modelling to partition the direct and indirect effects of tidal range, temperature range, soil
200 organic carbon and inorganic suspended sediment on shallow subsidence (n = 150; Fig. 3). The model
201 reproduced the observed covariance structure well (CFI = 0.983, TLI = 0.922, SRMR = 0.037); although the
202 test of close fit was inconclusive (RMSEA $\leq$ 0.05, P = 0.07).



203

204 **Fig. 3 | Structural equation models of the controls on surface accretion and shallow subsidence.** Path
205 diagrams identifying the drivers of (a) surface accretion (CFI = 1.00, TLI = 1.02, SRMR = 0.0180) and (b)
206 shallow subsidence (CFI = 1.00, TLI = 1.00, SRMR = 0.019) across SET-MH stations. Boxes denote measured
207 variables: tidal range, mean annual temperature range, suspended sediment concentration and soil organic
208 carbon. Arrows denote directed paths, with values giving standardised path coefficients; green indicates a
209 positive and orange a negative effect, arrow width is scaled to the magnitude of the coefficient, and dashed
210 arrows indicate paths retained in the model that were not statistically significant.

211

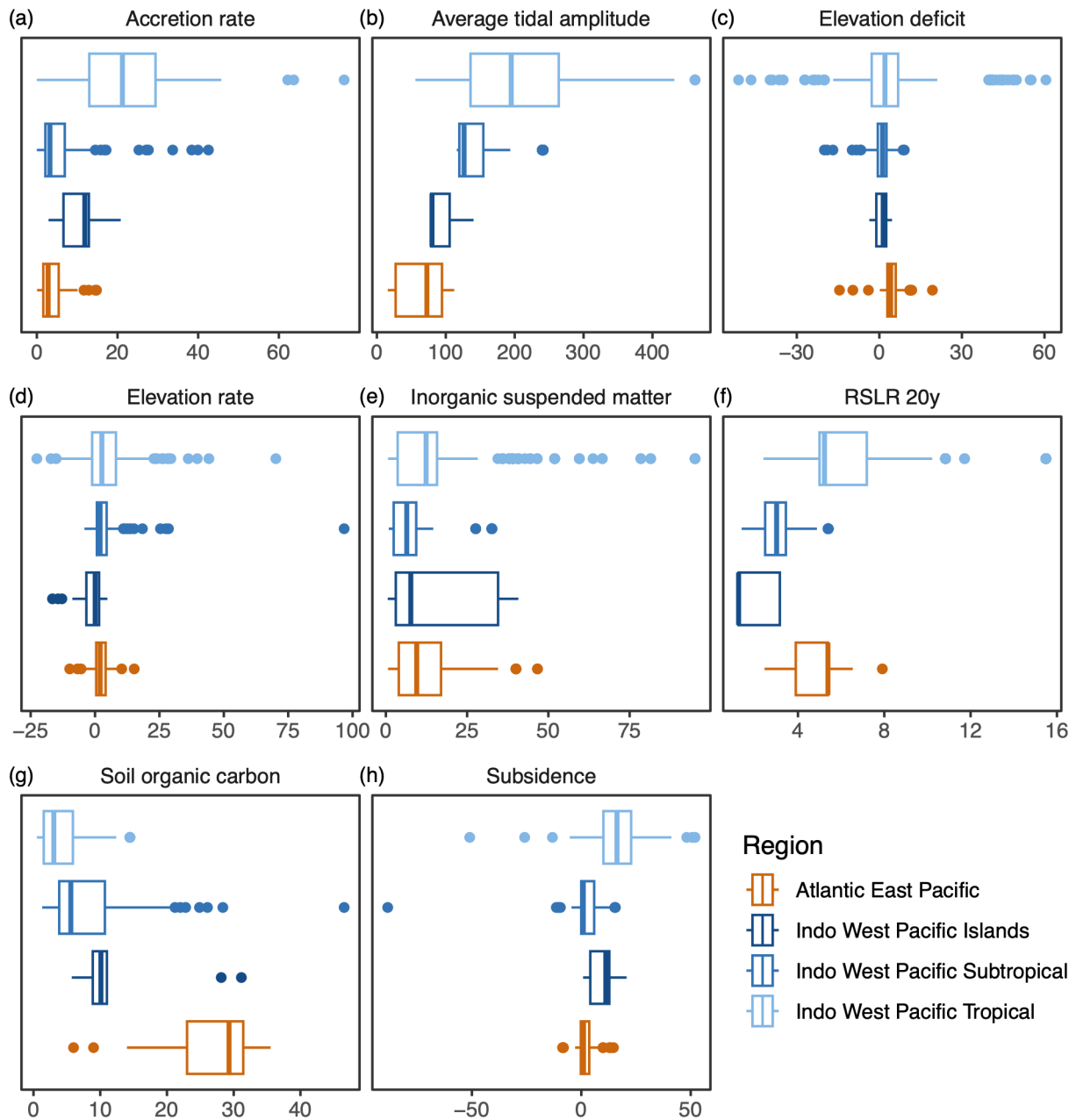
212 Tidal range emerged as the dominant control on both surface accretion and shallow subsidence (Fig.3). It
213 exerted the strongest direct effect on shallow subsidence (standardised coefficient +0.40, P < 0.001) and
214 simultaneously structured the substrate, decreasing the concentration of soil organic carbon (-0.62, P < 0.001)
215 and increasing inorganic suspended matter (+0.70, P < 0.001). Likely processes include the tidal pumping of
216 mineral sediment on to mangrove platforms on the high tide (diluting soil organic carbon concentration),
217 followed by low tide phases promoting dewatering and the exposure of organic carbon to mineralisation.

218 Temperature range exerted a weaker negative direct effect on subsidence (-0.35 , $P < 0.001$), suggesting that
219 consistently warm tropical conditions may promote organic carbon decomposition (as demonstrated in
220 incubation experiments: (Zhu and Cheng 2011),(Xiao, Zhang et al. 2025) thereby exerting a minor influence
221 on shallow subsidence. Neither soil organic carbon (-0.08) nor inorganic suspended matter ($+0.03$) had a
222 significant direct effect on subsidence. The organic-rich substrates characteristic of the intermediate-field
223 Atlantic-East Pacific sites are therefore a correlate of a low-tidal-range regime and karstic geomorphic setting
224 rather than the mechanical cause of vulnerability.

225 **Biogeographic divergence in vulnerability**

226 The two groups differ systematically across every variable implicated by the structural model (Fig. 3). Atlantic-
227 East Pacific stations are microtidal (mean maximum tidal amplitude 138 cm against 332 cm in the Indo-West
228 Pacific), sediment-poor and highly organic (median soil organic carbon 27.8% against 3.9%), and accrete and
229 gain elevation more slowly (4.0 against 13.9, and 1.54 against 4.04 mm yr⁻¹). A greater proportion of Atlantic-
230 East Pacific SET-MH stations are in elevation deficit relative to 20-year RSLR (84% of 58 stations against
231 67% of 375).

232 Disaggregated by region (Fig 4; Extended Data Table 1), the pattern is more textured than a simple two-
233 province contrast. Indo-West Pacific tropical sites combine the highest accretion in the network (19.7 mm yr⁻¹)
234 with the highest shallow subsidence (14.0 mm yr⁻¹, Fig 4a), so that abundant sediment supply yields only
235 moderate net elevation gain (3.96 mm yr⁻¹). Temperate Southern Hemisphere sites in Australia, New Zealand
236 and South Africa experience low RSLR (3.19 mm yr⁻¹, Fig 4f) but also low accretion (7.10 mm yr⁻¹, Fig 4a),
237 and a majority nonetheless sit in elevation deficit (62%) with the notable exception of the Firth of Thames,
238 New Zealand, subject to high sedimentation rates following land clearance from the mid-1800 (Swales,
239 Bentley Sr et al. 2015). Pacific island sites record some of the lowest elevation gain in the network (~ 1.23 mm
240 yr⁻¹) and are subject to the lowest RSLR (2.13 mm yr⁻¹).



241

242 **Fig 4: Differences in accretion, elevation, and key predictive variables among mangrove regions.** In this
 243 network the Atlantic-East Pacific group comprises intermediate-field sites in the Gulf of Mexico, the Caribbean
 244 and Central America, and does not represent the province as a whole; these sites show higher organic carbon
 245 concentrations, lower rates of vertical accretion, lower rates of subsidence, and lower tide range and higher
 246 rates of RSLR than settings in the Indo-West Pacific.

247

248 Deltaic settings illustrate why sediment supply alone is a poor predictor of vertical adjustment. Of eleven
 249 deltaic sites with records exceeding three years, seven were in elevation surplus and four in deficit, and the

250 division does not follow accretion rate. In the Bangladesh Sundarbans, accretion of 30.9 mm yr⁻¹ against
251 shallow subsidence of 12.3 mm yr⁻¹ produced a net elevation gain of 18.6 mm yr⁻¹ and a surplus of 13.7 mm
252 yr⁻¹ over local RSLR. However, in the Red River delta at Xuan Thuy, Vietnam, comparable accretion of 27.5
253 mm yr⁻¹ was more than offset by shallow subsidence of 32.1 mm yr⁻¹, so that the forest floor lost elevation at
254 4.6 mm yr⁻¹ and fell behind a relatively modest RSLR of 2.97 mm yr⁻¹ by 7.6 mm yr⁻¹. Chinese deltaic and
255 open-coast sites occupy the intervening ground, with subsidence consuming most of a comparable sediment
256 load to leave marginal deficits at Yunxiao (accretion 21.4, subsidence 17.2 mm yr⁻¹) and Wenchang (accretion
257 18.8 and subsidence 17.5 mm yr⁻¹). What separates surplus from deficit is therefore the fraction of accreted
258 sediment retained as elevation, not the sediment load itself: high accretion cannot be read as evidence of
259 resilience.

260 These deltaic deficits are likely to be conservative. The tide-gauge and vertical-land-motion estimates from
261 which we derive RSLR are anchored to gauge and GNSS locations that may not be situated on the actively
262 compacting delta plain, and the vertical land motion recorded at our Asian deltaic sites (−1.1 to +1.2 mm yr⁻¹)
263 is accordingly much smaller than published rates of subsidence for the same delta systems, where withdrawal
264 of groundwater and hydrocarbons drives subsidence at rates of several millimetres per year (Nicholls, Lincke
265 et al. 2021). Deep subsidence of this kind lies below the base of the SET benchmark and is therefore invisible
266 to our measurements, entering the elevation budget only through the RSLR term. Where deep subsidence is
267 under-represented, the true elevation deficit at deltaic sites will exceed the values reported here (Swales, Denys
268 et al. 2016).

269 The provinces therefore arrive at elevation deficit by mechanistically distinct routes. In the Atlantic-East
270 Pacific sites, deficit arises from insufficient accretion: low tidal range and limited mineral supply provide little
271 material with which to build, and subsidence is correspondingly low (1.69 mm yr⁻¹) but so is elevation gain.
272 In saturated peats, low compaction combined with root-driven subsurface expansion can itself sustain
273 elevation, as documented for Caribbean peat systems that kept pace with sea-level rise through below-ground
274 production rather than mineral input (McKee et al., 2021). Mineral input in these settings is primarily derived
275 from episodic tropical cyclones transporting sediment during storm surges (Castañeda-Moya, Rivera-Monroy
276 et al. 2020, Feher, Osland et al. 2020). In the Indo-West Pacific, deficit arises despite abundant accretion,
277 because a large fraction is consumed by shallow subsidence. The distinction implies different modes of
278 sensitivity to further acceleration in RSLR: intermediate-field Atlantic-East Pacific mangroves of the kind
279 sampled here are supply-limited and cannot readily increase elevation gain, whereas Indo-West Pacific
280 mangroves retain accretionary capacity but face diminishing returns as shallow subsidence increases.

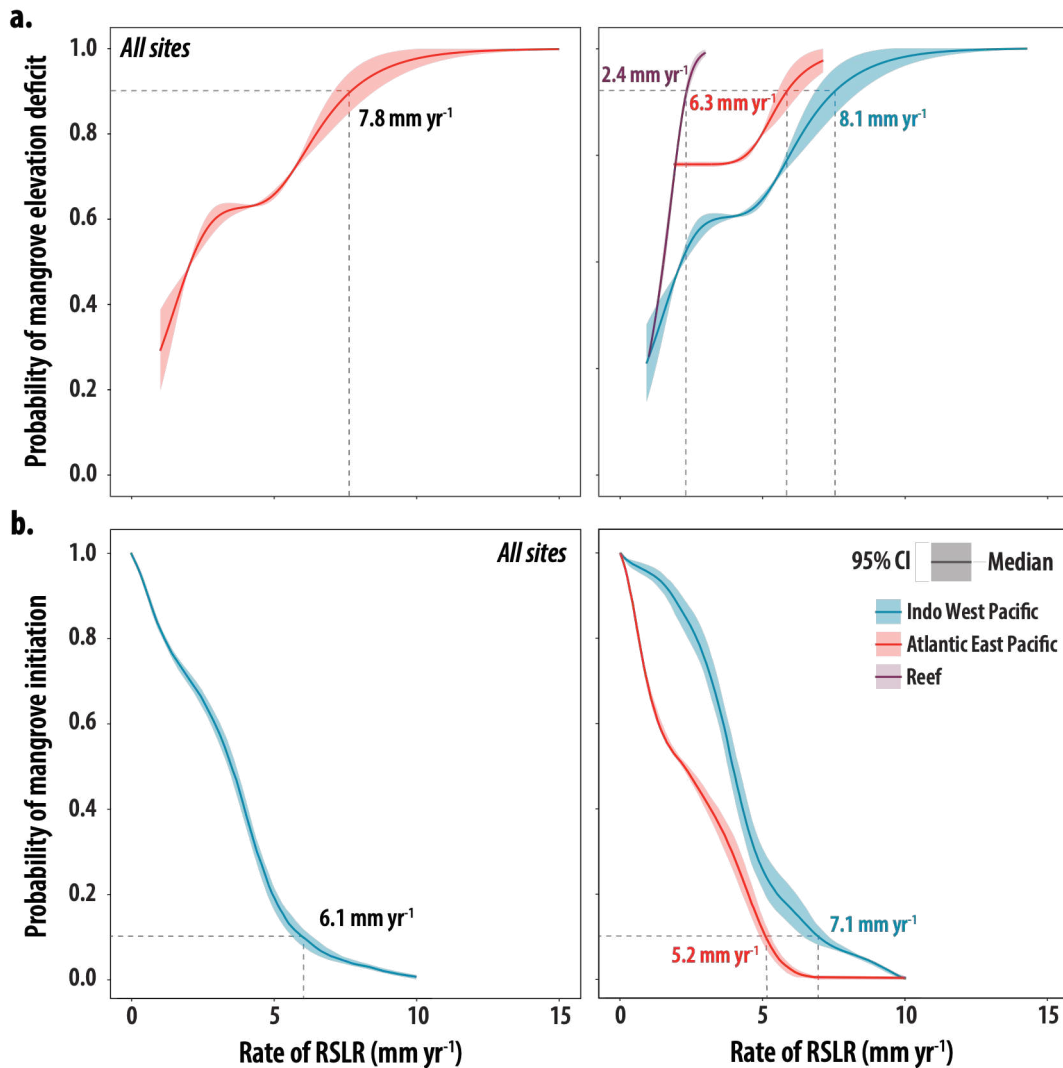
281 The six- to seven-fold higher organic content in the intermediate-field Atlantic-East Pacific soils sampled here
282 reflects the millennial legacy of sustained RSLR, which promotes below-ground production and organic
283 preservation, and corresponds to the low-tidal-range, low-mineral regime that the structural model identifies
284 as the operative control. The same contrast has been reported for tidal marshes in the same far-field and

intermediate-field settings (Rogers, Kelleway et al. 2019), reinforcing the interpretation that coastal geomorphic setting and sea-level history structure substrate composition, which in turn co-varies with, but does not directly drive, vulnerability.

Thresholds align with the palaeo record

Modelling the probability of an elevation deficit as a function of 20-year RSLR across stations with more than three years of record, deficit becomes very likely ($P \geq 0.90$) at 7.8 mm yr^{-1} globally ($n = 366$; Fig 5). Disaggregated by province, the threshold is 8.1 mm yr^{-1} in the Indo-West Pacific ($n = 308$) and 6.3 mm yr^{-1} in the Atlantic-East Pacific ($n = 58$) (Fig. 5). Thresholds also differ markedly by geomorphic setting: tide-dominated settings sustain vertical adjustment to 8.6 mm yr^{-1} and terrigenous estuaries to 7.3 mm yr^{-1} , whereas mangroves on reef substrates reach very likely deficit at only 2.4 mm yr^{-1} ($n = 25$), a rate already exceeded across most of the tropical ocean.

These contemporary thresholds correspond in rank and approximate magnitude to those inferred independently from Holocene stratigraphy, in which sustained mangrove initiation becomes unlikely above approximately 7.1 mm yr^{-1} in far-field Indo-West Pacific settings and approximately 5.2 mm yr^{-1} in intermediate-field Atlantic-East Pacific settings (Saintilan, Khan et al. 2020); Fig 5). The two records are methodologically unrelated, one derived from radiocarbon-dated sediment archives spanning millennia, the other from benchmark surveys spanning years to decades and they are subject to different sources of error. That they converge on the same ordering, and on thresholds separated by a comparable margin, provides cross-timescale corroboration that the divergence is real rather than an artefact of either method. The contemporary thresholds sit systematically $\sim 1\text{-}1.5 \text{ mm yr}^{-1}$ above the palaeo estimates, plausibly because the instrumental record captures a transient response to recent acceleration that has not yet worked through to the stratigraphic outcome.



306

307 **Fig. 5 | Probability of elevation deficit as a function of RSLR, by province.** Bayesian modelled
 308 probability that a station is in elevation deficit against 20-year RSLR, for stations with records exceeding
 309 eighteen months (a). Dashed line marks the $P = 0.90$ (very likely) threshold; droplines mark the
 310 corresponding rate of RSLR for each province. Modelled probability of the initiation of vertical mangrove
 311 accretion during the Holocene postglacial marine transgression at rates of RSLR modelled by glacio-isostatic
 312 adjustment (b) from (Saintilan, Khan et al. 2020).

313 The two records are not measured over comparable intervals. Our SET-MH observations have a median
 314 duration of 5.1 yr, whereas the stratigraphic thresholds integrate accretion over centuries to millennia, and rates
 315 measured over these different windows are known to differ systematically (Breithaupt, Smoak et al. 2018). It
 316 has been argued that short SET-MH records (typically sub-decadal) overstate resilience relative to longer-term
 317 radiometric estimates (Parkinson, Craft et al. 2017), although comparisons in mangroves have generally found
 318 short and longer SET records, and SET and radiometric rates, to be similar ((Lovelock, Cahoon et al. 2015);
 319 (Breithaupt, Smoak et al. 2018). To the extent that a short-record bias exists, the regional thresholds reported

here would be upper bounds on sustained capacity, and the agreement with the palaeo record correspondingly conservative.

The practical significance of these probabilities depends on the rates of RSLR presently experienced. Mean 20-year RSLR across Atlantic-East Pacific stations is 4.89 mm yr^{-1} , below the 6.3 mm yr^{-1} at which deficit becomes very likely ($P \geq 0.90$); but individual stations within the region already exceed that rate, contemporaneous rates measured over the period of SET operation are higher still, and 84% of the Atlantic-East Pacific stations in the network are presently in elevation deficit. For mangroves on reef substrates the position is more acute: deficit becomes very likely at only 2.4 mm yr^{-1} , a rate now exceeded across essentially the entire tropical ocean. In these settings, the rates associated with very likely deficit have already been realised.

Elevation deficit manifests as open-water conversion

Elevation deficits should ultimately influence habitat condition, though considerable lag times may exist corresponding to the rate of elevation capital drawdown. Using satellite-derived open-water occurrence around SET-MH stations, comparing the two decades before and after 2000, we found no relationship between change in open-water signature (representing a change in mangrove vegetation cover) and the rate of RSLR ($r^2 = 0.001$, $P = 0.50$, $n = 410$). There was, however, a weak but highly significant positive relationship with elevation deficit ($r^2 = 0.030$, $P = 0.0004$; Extended Data Fig 3). To test whether this association survives adjustment for the covariates that also structure open-water change, we fitted random forest models to site-mean normalised surface-water change using 31 environmental and 5 categorical predictors, with skill assessed by site-blocked cross-validation (Methods). The models explained a modest but stable fraction of variance among sites ($R^2 = 0.21$, SD 0.15; $n = 146$), and both SET-derived elevation terms (elevation deficit relative to 20-year RSLR, and the elevation trend itself) were retained among the leading predictors, alongside potential evapotranspiration, vertical land motion and suspended sediment concentration. The presence or absence of coastal wetland loss and gain within the 5 km^2 buffer was better resolved (AUC = 0.82 and 0.85 respectively), whereas the magnitude of area lost, among sites recording any loss, was not predictable ($R^2 = 0.16$, SD 0.21; $n = 53$). Elevation deficit therefore carries information about open-water conversion that is not reducible to the climatic and geophysical setting, although the models locate this signal in whether a site converts rather than in how much area it loses.

Implications

Our observations show that mangroves are, at present, raising their surface at rates approaching contemporary RSLR, and doing so at rates well above those that prevailed through the stable late Holocene. In that narrow sense the recent optimism about mangrove trajectories (Zhang, Murray et al. 2026) is well founded: these are responsive systems, and their biogenic feedbacks are demonstrably engaged. That capacity is unevenly

distributed. Intermediate-field Atlantic-East Pacific mangroves become very likely to enter deficit at a lower rate of rise than those of the Indo-West Pacific (6.3 against 8.1 mm yr⁻¹) because low tidal range limits the mineral sediment available to build with, while carbonate reef settings (where that supply is largely absent) record the lowest elevation gain in the network (1.23 mm yr⁻¹) despite its lowest rates of relative sea-level rise (2.13 mm yr⁻¹).

Centuries of accretion under conditions of relative sea-level stability have accumulated substantial elevation capital in mangrove systems, such that an elevation deficit does not result in immediate habitat loss. Rather than drowning instantaneously, mangroves in deficit draw down this accumulated buffer, and the time to buffer exhaustion may range from decades to centuries, contingent on buffer magnitude and the severity of the deficit (Krauss 2021, Rogers 2021). This distinction is an important consideration for how the permanence of mangrove blue carbon is evaluated: a forest presently in deficit is storing carbon on a commitment that has already been made, and in the most vulnerable settings the assumption of indefinite persistence is not supported by the elevation record.

The divergence we document between biogeographic settings has direct consequences for where conservation and management efforts are best placed. Monitoring, restoration investment and the crediting of blue-carbon permanence should be weighted by the vulnerability of the setting rather than applied uniformly. Microtidal, sediment-poor intermediate-field systems such as those of the Caribbean, and mangroves occupying reef substrates, where very likely deficit arises at rates of RSLR already surpassed almost everywhere warrant particular caution, and are the settings in which landward retreat pathways are the most consequential interventions available. Conversely, the high-tidal-range, sediment-rich systems of the Indo-West Pacific retain strong accretionary capacity, and protecting the sediment supply on which that capacity depends is the corresponding priority. However, on subsiding Asian deltas, where mangroves already sustain among the highest accretion rates in our network, the binding constraint may not be sediment supply but the rate of relative sea-level rise itself, with a substantial share of that rate a consequence of decisions about subsurface fluid extraction (Nicholls, Lincke et al. 2021). Reducing anthropogenic subsidence is, on this evidence, among the more immediately actionable measures available for sustaining mangrove forests in the deltaic settings that hold much of the world's mangrove carbon.

Author contributions:

Conceptualization NS, AR, NK, DC; Data curation; NS, KR, CEL, DAF, KWK, RMacK, MG, LH, AJ, JJK, KMcK, LC, AK, JAC, FS, AS, PH, GRG, KW, SA, JR, JA, DM, SS, JR, MW, RKB; VB, CW, MR, ANH, NC, FHS, JR, KKL, LM, EJB, NP, SS, JC, MJO, LCF, JCL, CC, LM, YG, JK. Formal analysis NS, KEK, JZ, NK, AR, JW, KR, NM, BH, NM, XL; Project administration and supervision NS; Writing - original draft NS; Writing -

review and editing NS, CEL, DAF, AR, KWK, LM, LZ, JAC, NC, DM, KKL, RKB, BPH,
KMcK

Competing Interests Statement

The authors declare no competing interests.

Figure legends

Fig. 1 | The global mangrove SET-MH network and site-level elevation deficit relative to sea-level rise.

a, Distribution of mangrove Surface Elevation Table–Marker Horizon (SET-MH) stations: 601 stations at 141 sites in 21 countries. Each symbol is one site, placed at the mean position of its stations and sized by the number of stations. Colour shows biogeographic province: Indo-West Pacific (IWP; blue; 492 stations, 124 sites) and Atlantic–East Pacific (AEP; orange; 109 stations, 17 sites, all in the Gulf of Mexico, the Caribbean and Central America). b, Site-mean elevation deficit, defined as the 20-year relative sea-level rise (RSLR) minus the rate of surface elevation change, for the 87 sites (457 stations) with both an elevation trend and an RSLR estimate (73 IWP, 14 AEP). Positive values (purple) mean elevation gain is falling behind RSLR; negative values (green) mean elevation gain exceeds it. The colour scale is truncated at $\pm 10 \text{ mm yr}^{-1}$, and more extreme values take the end colours. Circles show sites whose RSLR comes from tide-gauge records, mostly from the Permanent Service for Mean Sea Level (PSMSL). Diamonds show sites without a suitable gauge, where RSLR is taken from satellite altimetry; for the Honduran sites, the altimetric rate is corrected for vertical land motion using Oelmann et al. (2024).

Fig. 2 | Controls on accretion, subsidence and elevation deficit. Vertical accretion above the feldspar horizon correlates with maximum tidal amplitude (a) and inorganic particulate sediment concentration of adjacent waters (b), both variables being lower in the Atlantic-East Pacific (intermediate field) mangroves sampled by the SET-MH network. The translation of accretion into elevation gain is limited by shallow subsidence, in the upper levels of the sediment profile (called shallow subsidence) which increases with the rate of accretion, consistent with but over a greater range than that encountered in the tidal marsh SET-MH dataset (c). Thus, shallow subsidence at elevated levels of accretion is the primary reason an elevation deficit (RSLR-elevation change rate) can occur in mangroves as well as in tidal marshes (d). Grey shading indicates the confidence interval for the generalised additive model fit lines.

Fig. 3 | Structural equation models of the controls on surface accretion and shallow subsidence. Path diagrams identifying the drivers of (a) surface accretion (CFI = 0.98, TLI = 0.92, SRMR = 0.037, $\chi^2 = 4.26$, $P = 0.039$) and (b) shallow subsidence (CFI = 0.98, TLI = 0.92, SRMR = 0.037, $\chi^2 = 7.17$, $P = 0.028$) across SET-MH stations. Boxes denote measured variables: tidal range, mean annual temperature range, suspended inorganic matter concentration and soil organic carbon. Arrows denote directed paths, with values giving

standardised path coefficients; green indicates a positive and orange a negative effect, arrow width is scaled to the magnitude of the coefficient, and dashed arrows indicate paths retained in the model that were not statistically significant.

Fig 4: Differences in accretion, elevation, and key predictive variables among mangrove regions. In this network the Atlantic-East Pacific group comprises intermediate-field sites in the Gulf of Mexico, the Caribbean and Central America, and does not represent the province as a whole; these sites show higher organic carbon concentrations, lower rates of vertical accretion, lower rates of subsidence, and lower tide range and higher rates of RSLR than settings in the Indo-West Pacific.

Fig. 5 | Probability of elevation deficit as a function of RSLR, by province. Bayesian modelled probability that a station is in elevation deficit against 20-year RSLR, for stations with records exceeding eighteen months (a). Dashed line marks the $P = 0.90$ (very likely) threshold; droplines mark the corresponding rate of RSLR for each province. Modelled probability of the initiation of vertical mangrove accretion during the Holocene postglacial marine transgression at rates of RSLR modelled by glacio-isostatic adjustment (b) from (Saintilan, Khan et al. 2020).

Methods

1. Conceptual Model

We conceptualise surface elevation trends as a function of elevation gains (through mineral and organic matter accumulation and soil volume expansion, including root mass gain) and losses (through sediment erosion, and soil volume losses associated with subsidence, auto-compaction and decomposition of organic matter). These processes are driven by hydrological, geomorphological and biological contributions (Extended data Fig. 1). Hydrological processes influence the accumulation of sediment through the mechanism of tidal inundation. Tides determine the space available for accumulation of both mineral and organic matter (accommodation space), and accumulation of tidally borne matter on mangrove surfaces is also a function of inundation depth and duration. Sea-level rise alters the depth of tidal inundation and consequently influences both accommodation space (the space into which intertidal wetlands can accrete) and the rate of vertical accretion occurring in mangroves. Geomorphological processes influence the suspended sediment supply, sediment characteristics and the rate of shallow subsidence. Biological processes include the influence of vegetation on sediment trapping and below-ground root production, and the influence of microbial decomposition on soil organic matter concentrations and volumes (Krauss, McKee et al. 2014). Climate (temperature and precipitation) influences biological processes including plant productivity, microbiological activity

451 and root mass decomposition. Identifiers and variables used in the analysis are provided in Extended
452 Data Table 1.

453

454 2. SET-MH network and installation

455 The Surface Elevation Table-Marker Horizon (SET-MH (Lynch, Hensel et al. 2026) technique
456 is the global standard for measuring contemporary movement of wetland surfaces for comparison to
457 changes in sea-level (Webb, Friess et al. 2013). The SET-MH installation combines a benchmark rod
458 and detachable arm against which wetland elevation change is repeatedly measured (the SET) with
459 an artificial marker horizon against which wetland vertical accretion is measured (the MH) (Cahoon,
460 Reed et al. 1995) (Extended Data Fig. 1). Two types of benchmark rod are used: the “original” SET
461 design consisting of a hollow aluminium tube (~ 7.5 cm dia.) up to 8 m in length, and an “rSET”
462 design, or rod SET, consisting of a stainless-steel rod (~ 1.5 cm dia.) capable of insertion to greater
463 depths (up to ~30 m). In both cases the base of the benchmark rods serve as a fixed point against
464 which wetland surface elevation change is measured. Benchmark rods are usually installed in
465 replicates of three to characterise a location of homogenous vegetation and hydroperiod. The portable
466 SET arm is attached to the benchmark at each visitation and nine replicate pins are lowered to the
467 wetland surface at four fixed bearings for a total of 36 readings per SET per sampling date.
468 Measurements of the height of each pin above the portable arm are taken at each visit. At
469 commencement, replicate (3 to 4) marker horizons (feldspar, clay or similar distinguishable material)
470 were laid on the wetland soil surface within 0.25 m² square plots adjacent to each SET; and these MH
471 were subsequently buried by the accumulation of tidally borne sediments and in situ root growth. A
472 shallow core was extracted from each replicate plot on each sampling date, and the depth of the
473 marker horizon was recorded at each visit. The difference between the rates of surface accretion, as
474 measured from cores extracted from the MH, and surface elevation change, as measured using the
475 SET, is a measure of shallow subsidence or expansion occurring between the base of the marker
476 horizon and base of the SET benchmark (Cahoon, Reed et al. 1995) (Extended Data Fig. 1). The SET
477 pin measures have a reported precision of 1.3-4.3 mm under field conditions (Cahoon, Lynch et al.
478 2002).

479

480 The mangrove SET-MH network consists of 601 SET-MH monitoring stations installed using
481 common protocols in 141 locations and across five continents (North America, South America,
482 Australia, Asia, Africa). From this network, changes in surface elevation and vertical accretion were
483 determined from repeated measurements at regular intervals across total record lengths ranging from
484 1.0 to 24 years for 480 stations (mean 7.6 yr, median 5.4 yr: Data 1). This dataset, presented here for

the first time, allowed quantification of rates of surface elevation change, and, where possible, vertical accretion at each site. The network may be characterised on the basis of geographic and geomorphic context (Data S1): Group I, Atlantic-East Pacific: intermediate-field locations (sensu Saintilan et al. 2020) in Florida, Louisiana, the Caribbean (Belize, Honduras, San Andrés Island (Colombia) and the US Virgin Islands) and the Pacific coast of Honduras (Gulf of Fonseca). The network contains no stations on the Atlantic coasts of South America or Africa, and Group I is not representative of the Atlantic-East Pacific province as a whole. These locations are characterised by rising sea levels during the late Holocene, relatively higher sea-level rise than the global average, highly organic soils, low tide range and low rates of mineral sediment input. The remaining groups (Groups II-IV) are far-field Indo-West Pacific locations for which post-glacial sea-level high-stand was reached 6000-7000BP and have been stable or declining over the latter Holocene. Group II, IWP Tropical Islands, show low rates of sediment input, and low rates of accretion. Group III, Tropical, represents the high rainfall/high biomass mangrove forests of Equatorial Africa, Asia and northern Australia with relatively high rates of sediment input. Group IV brings together the Southern Hemisphere subtropical mangroves of southern Australia, New Zealand and South Africa, low biomass forests of *Avicennia marina*, situated in marine embayments and in barrier estuaries of restricted tide range.

The global mangrove SET network has limited distribution within the true tropics with most SET-MHs located along subtropical and warm temperate coastlines (median, Q1-Q3 MAT: 23, 18-25.5 °C). In terms of annual precipitation, SET-MHs are mostly concentrated in intermediate rainfall regions (< 1300 mm) relative to precipitation patterns observed across the global mangrove area (median, Q1-Q3 AP: 2100, 1400-2900 mm). Relative to potential evapotranspiration (PET) there are few SET-MH sites in high PET areas such as semi-arid and arid mangrove coastlines. Regarding tidal amplitude, the SET-MH network is distributed mostly along microtidal (< 2 m) coasts with much of the meso- (2-4 m) and macrotidal (> 4 m) coastal regions still underrepresented. A similar pattern is observed for muddy deltaic coastlines with SET-MHs distributed along mangrove coastlines with relatively lower suspended sediment concentration.

Six stations at Porong, Indonesia, were excluded from all analyses; this site is affected by sediment loading from an anthropogenic mud volcano and returns elevation rates up to 155 mm yr⁻¹, more than an order of magnitude above any natural setting in the network.

3. Relative sea-level rise

For each site we estimated a 20-year rate of relative sea-level rise (RSLR) from the nearest suitable tide gauge. Gauge records came from NOAA CO-OPS, from national and local agencies, and

519 from the Permanent Service for Mean Sea Level (PSMSL) Revised Local Reference dataset. Trends
520 were fitted by ordinary least squares to monthly mean sea level over the 20 years ending 2024-2025.
521 A window of this length spans most of the 18.6-year lunar nodal cycle, which keeps nodal bias in the
522 trend small. Where the full window was not available, we used the longest continuous record within
523 it. Two Southeast Asian and Caribbean sites were added this way. San Andrés (Colombia) uses
524 PSMSL station 2116 (2005–2024; 3.91 ± 1.81 mm yr⁻¹), and the Bali sites use Benoa B (PSMSL
525 2200; 2006–2024; 5.15 ± 5.16 mm yr⁻¹). We rejected gauges whose records showed datum
526 discontinuities.

527

528 Where no suitable gauge existed, RSLR was estimated from satellite altimetry ([NOAA
529 Laboratory for Satellite Altimetry regional trends, 1993–2025). For the Honduran sites, the altimetric
530 rate was corrected for vertical land motion (VLM) using Oelsmann et al. (2024). Calauit (Palawan,
531 Philippines) uses the uncorrected altimetric rate. To check for consistency with the tide gauge
532 network, we compared VLM-corrected altimetric rates with gauge-derived rates at the 41 gauges
533 where both were available. The median difference was -0.65 mm yr⁻¹. Agreement was poor where
534 local subsidence dominates, for example Ko Taphao Noi, where the gauge rate exceeds the altimetric
535 rate by about 10 mm yr⁻¹. We therefore used altimetry only for tectonically stable island and open-
536 coast settings, and not for deltaic or rapidly subsiding coasts. Two groups of sites were left without
537 an RSLR estimate and excluded from deficit analyses: the Andaman Islands sites; and Porong
538 (Sidoarjo, Indonesia), where elevation change is dominated by mud-volcano sediment and local
539 subsidence is unconstrained. The RSLR source for each station (gauge or altimetry, with or without
540 VLM correction) is given in Data S1.

541

542 4. Climate, vegetation, soil properties and geomorphic setting

543 To assess the influence of environmental drivers on surface elevation change, we used the
544 latitude and the longitude for each SET-MH location to retrieve site-specific environmental correlates
545 from global gridded and vectorized datasets (Extended Data Table 1). Bioclimatic variables were
546 retrieved from the Worldclim (Fick and Hijmans 2017) and the ENVIREM (Title and Bemmels 2018)
547 global gridded datasets. Total suspended mater was retrieved from a time-composited image derived
548 from merged MERIS and MODIS imagery (Maritorena, d'Andon et al. 2010). Geomorphic and
549 sedimentary classes were attributed to each SET-MH site after a global mangrove distribution map
550 of coastal typologies (Worthington, Zu Ermgassen et al. 2020). Raster and vector manipulations and
551 data extraction procedures were performed in R computing environment (Team 2020) using the
552 packages ‘raster’ (Hijmans 2018) and ‘sf’ (Pebesma 2018, Pebesma and Bivand 2023). With the

exception of sea level rise and vertical land movement, which needed to be rasterized before data extraction could be performed, all other variables were extracted as provided, without altering their native resolution (e.g., aggregating or resampling). The percentage of organic matter within the upper 10cm of soil depth was measured for only some of the SET-MH monitoring sites (n= 176). Dominant mangrove species was recorded (Data 1).

5. Surface water and mangrove change analysis

We used two earth-observation derived global datasets to estimate mangrove conversion to open water across the SET-MH monitoring network. The Global Tidal Wetland Change (GTWC) dataset(Murray, Worthington et al. 2022) depicts losses and gains of tidal marshes, tidal flats and mangroves (collectively termed ‘tidal wetlands’) at 30-m resolution over a 20-yr period (1999-2019). The data were developed through a machine-learning classification of more than 1.1 million Landsat scenes acquired over the global coastal zone since 1999. GTWC data layers include tidal wetland losses, gains, and the probability of occurrence of tidal wetlands for the first (1999) and last (2019) time steps of the analysis. The Global Surface Water dataset depicts the location and temporal distribution of surface water from 1984 to 2020 at 30-m resolution (Pekel, Cottam et al. 2016). The data were generated from >4.4 million Landsat scenes by individually classifying each Landsat pixel into water and non-water using an expert system. Although the two datasets are developed using Landsat data, the datasets differ in their temporal spans (2 to 4 decades), methodological approaches to mapping change dynamics, post-processing methods and minimum mapping unit. We therefore used both datasets to estimate the extent of mangrove conversion to open water in relation to observed RSLR (Supplementary Information Data 1).

To estimate net mangrove change and the extent of conversion to open water at each SET-MH monitoring site, we developed a buffer feature around the SET installation with an area of 5 km². The area of losses and gains was computed, yielding a net change estimate of mangrove habitat associated with each SET site. For Global Surface Water, we used the water occurrence change intensity layer, which is computed as the absolute difference in the per-pixel mean water occurrence between two distinct epochs (1984-1999 and 2000-2020) (Pekel, Cottam et al. 2016). The average surface water change in each SET buffer feature was computed (Supplementary Information Data 1).

6. Data Analysis

The rate of elevation change was calculated as a linear regression pin height against time. For each SET monitoring station, relative pin height was calculated by subtracting baseline pin height

587 from all subsequent measurements. Relative pin heights were averaged hierarchically within each
588 SET arm position and then across positions to integrate small-scale variation in surface elevation.
589 Accretion for each SET-MH at each sampling period was calculated as the average of readings from
590 the three replicate feldspar plots established in association with each SET at the time installation. The
591 trend in accretion was established as a linear trend against time. Shallow subsidence was calculated
592 as the difference between accretion and elevation change.

593

594 Simple and multiple linear regression analyses were used to test relationships among quantitative
595 variables. Generalized additive models (GAM) from mgcv package (Wood 2011): default formula =
596 $y \sim s(x, bs = "cs")$ with cubic regression spline as the smoothing basis) were used to test the
597 relationship between subsidence and accretion rate. RandomForest (RF) regression (Breiman 2001)
598 were used to examine relationships of accretion, elevation and subsidence rates with predictor
599 variables (Table S1). RF is a machine learning approach which operates by constructing thousands
600 ($n = 100,000$) of small classification trees, results of which are then tallied across the entire forest.
601 An unbiased estimate of error is obtained at each step internally by using a different bootstrap
602 resample from the original data. Approximately 33% of observations were used to test each
603 classification's performance as the out-of-bag error (OOB). Data compilation, analyses and
604 visualizations were undertaken in R (version 4.5.1 (R Core Team and Team 2022)) using *tidyr*
605 (Garnier, Ross et al. 2018), *randomForest* (Liaw and Wiener 2002) and *viridis* (Garnier, Ross et al.
606 2018) packages.

607

608 To estimate the probability of a deficit between elevation gain and RSLR, we follow ref (Horton,
609 Shennan et al. 2018) by converting the deficits to binary response variables (positive deficit = 1,
610 negative = 0, and stable (within +/- 1 mm deficit) randomly assigned to 1 or 0). We summarize the
611 probability of a deficit by modelling their relationship with 20-year rates of RSLR in a Bayesian
612 framework.

613

614 The relationships between surface water and mangrove change vs. RSLR and elevation deficit
615 were tested using multiple linear regression. Predictive variables are provided in Extended Data Table
616 1, and consist of climatic, hydrological and edaphic properties associated with each SET-MH station
617 (Data S1). Potential collinearity of predictors was assessed using variance inflation factor (VIF) from
618 the car package (Fox and Weisberg 2019). VIF was found to be below the level usually considered
619 problematic (3.22). The overall relative importance of the key predictors was assessed using Random
620 Forest (RF) regression analyses (Breiman 2001), a machine learning approach which tallies the results

621 of small classification trees ($n = 100,000$) while retaining a bootstrapped subset of all observations
622 for out-of-bag (internal) error testing. We used random forests to test, non-parametrically and without
623 assuming a functional form, whether surface-water change could be predicted from the environmental
624 setting and from the SET-derived elevation terms. Predictors comprised 31 numeric variables (tidal
625 amplitude statistics, suspended sediment concentration, fluorescence line height, relative and absolute
626 sea-level rise, vertical land motion, biomass, position within the intertidal profile, absolute latitude,
627 and 19 climate and evapotranspiration terms), and accretion for the elevation models, and 5
628 categorical variables (region, geomorphic setting, tidal class, sediment class and biogeographic
629 province). We used conservative imputation where predictors with a only few ($<10\%$) missing values
630 were median-imputed (na.roughfix in randomForest), whereas predictors with more missingness were
631 omitted from the model (e.g., soil organic carbon, mangrove biomass). Forests comprised 400 trees
632 with a minimum of three observations per leaf and $\sqrt{p}$ predictors sampled per split.

633

634 Because the satellite-derived variables are computed over a 5 km buffer, all stations sharing a
635 buffer share a value, and most environmental predictors are likewise constant within a site. Station-
636 level cross-validation therefore leaks site identity: for normalised surface-water change, random five-
637 fold cross-validation returned $R^2 = 0.70$, which fell to 0.00 when whole sites were held out. All models
638 reported here were consequently fitted to site-level means, and skill was assessed by cross-validation
639 blocked on site (GroupKFold, five folds). Predictor importance was estimated by permutation on
640 held-out folds only (five permutations per predictor) and is reported as the mean and between-fold
641 standard deviation of the resulting decrease in R^2 or AUC. Because the two coastal wetland area
642 variables are strongly zero-inflated (64% of stations recording zero) and vary within fewer than a fifth
643 of sites, they were modelled as site-level presence/absence, with the magnitude of loss modelled
644 separately among sites recording any loss. Analyses used scikit-learn 1.8.0.

645

646 Direct and indirect effects on shallow subsidence and on accretion were partitioned using
647 structural equation modelling in the lavaan package (Rosseel 2018) with maximum-likelihood
648 estimation. Soil organic carbon and inorganic suspended matter were modelled as endogenous to tidal
649 range and temperature range, and subsidence ($n = 150$ due to missingness in soil organic carbon data)
650 as a function of all four. Accretion was modelled as a function of inorganic suspended matter and
651 tidal and temperature ranges ($n = 220$). Several alternative models were tested, including models with
652 latent variables and with and without indirect effects, and best fitting models penalized for complexity
653 were selected using modification indices accounting for unexplained variation, Akaike Information
654 Criterion (AIC) and Sample-size adjusted Bayesian Information Criterion (SABIC). Model fit was

655 assessed using Comparative Fit Index (CFI), more complexity-penalized Tucker-Lewis Index (TLI),
656 SRMR and RMSEA.

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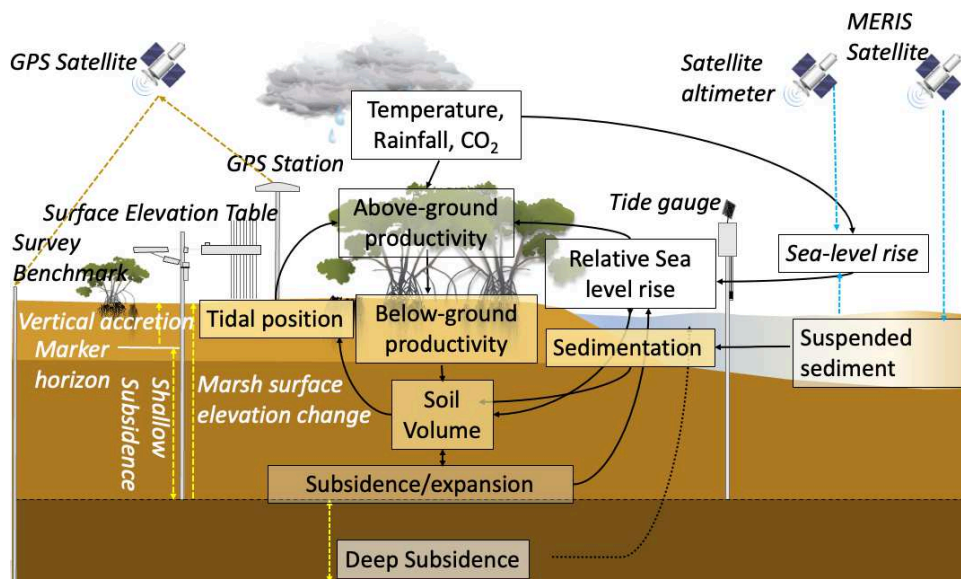
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671 **Extended data Fig 1: Conceptual diagram of processes measured by the SET-MH station.**

672 Mangrove surface elevation is a function of accretion (root mass development, organic and mineral
673 sediment inputs), and subsidence resulting from autocompaction of sediment, decomposition and
674 water volume changes. Accretion is measured by an introduced marker horizon, and elevation
675 change by the SET. Concurrent readings of water level are sourced from tide gauges.

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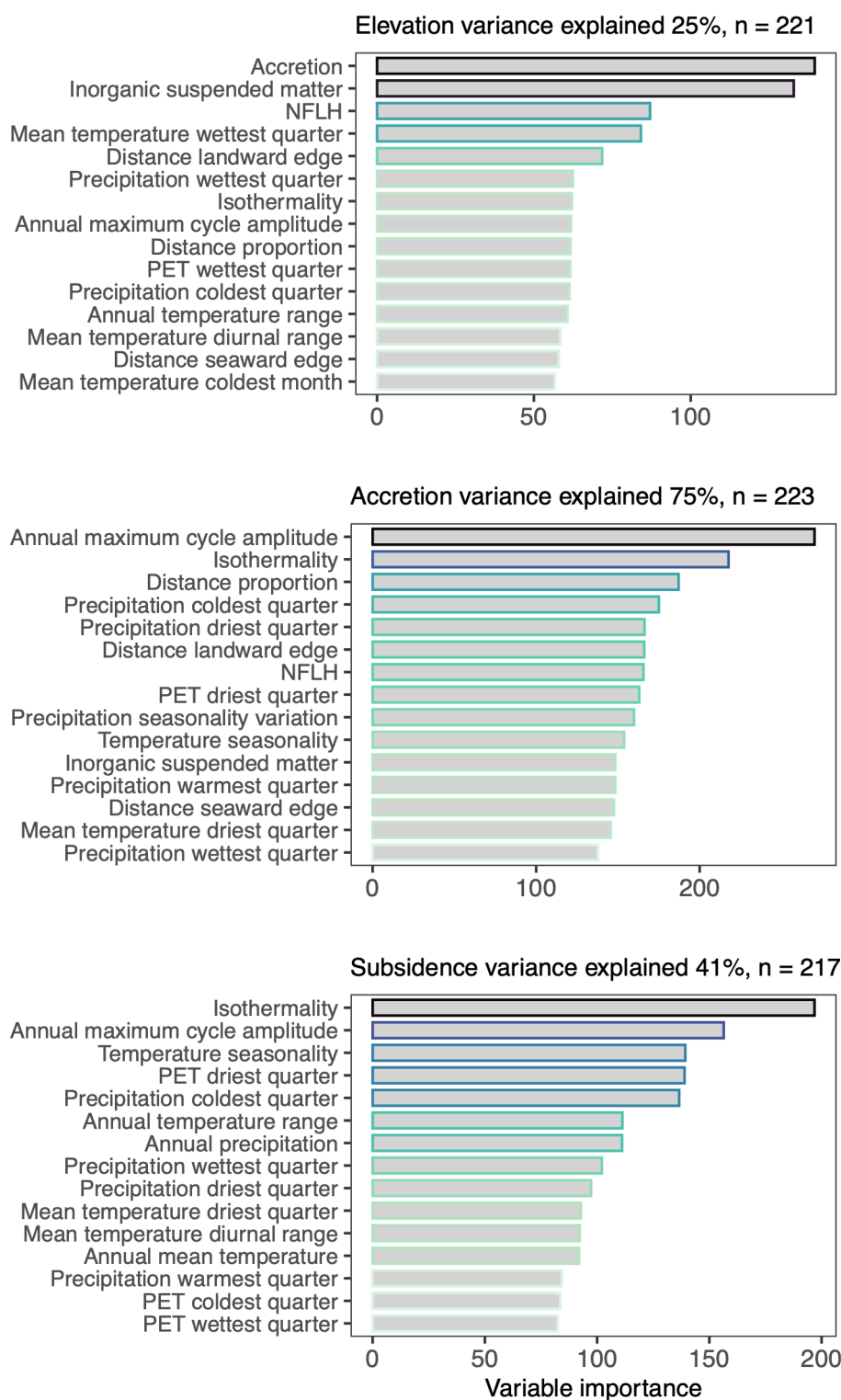
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691 **Extended Data Fig 2: The relative importance of variables contributing to models of mangrove**
 692 **vertical accretion and surface elevation gain at global scales.** The total percentage of variation
 693 explained by the Random Forest model and sample size are included in plot title. Relative importance
 694 as percent increase in mean standard error (%IncMSE). Variables used as explained in Extended Data
 695 Table 1 (from Data 1). Soil data and other predictors with more than 10% missingness (canopy cover,
 696 mangrove biomass) are excluded.

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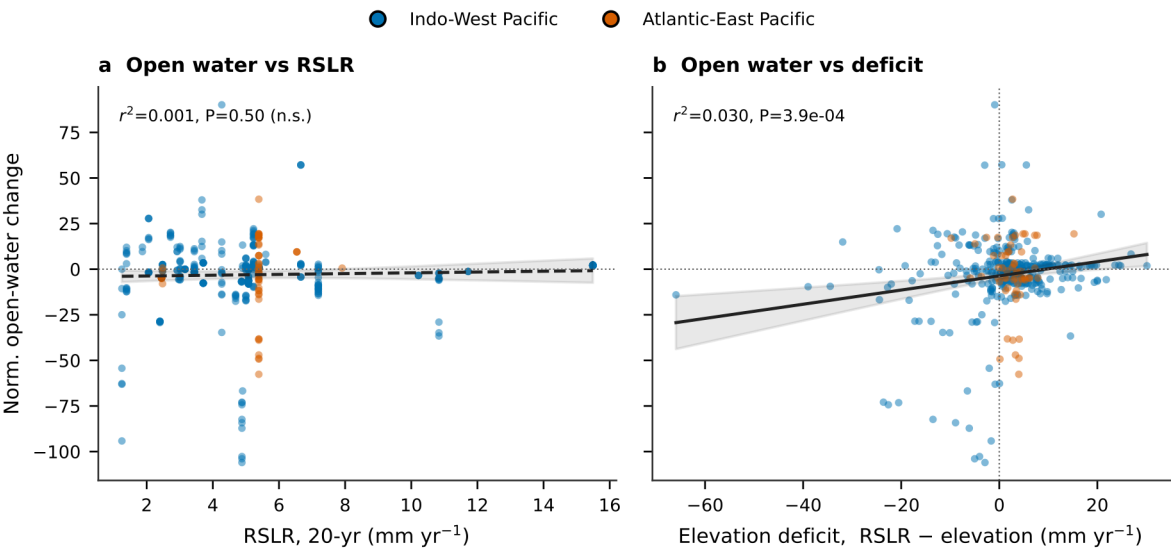
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701 **Extended Data Fig. 3 | Open-water change in relation to RSLR and elevation deficit.** a, Normalised change

702 in open-water occurrence against 20-year RSLR ($r^2 = 0.001$, $P = 0.50$). b, The same against the 20-year

703 elevation deficit ($r^2 = 0.030$, $P = 0.0004$). Points coloured by province; shaded bands are 95% confidence
704 intervals on the linear fit. $n = 410$ stations.

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882 **Extended Data Table 1.**
883 Identifiers and Variables used in the analysis (Data S1).

Variables IDs	Description	Time period	Native resolution	Source
site.SET.identifier	Unique SET station ID used for linking all other data			Provided by SET custodians
site.label	Site name for SET or replicate SETs			Provided by SET custodians
Country	Country within which SET is situated			
Latitude	Decimal degrees			Measured and provided by SET custodians (Methods)
Longitude	Decimal degrees			Measured and provided by SET custodians (Methods)
Biogeographic	Mangroves of Atlantic-East Pacific of Indo-West Pacific			
Region	Geographic cluster of SETs (Divided into 4 regions)			
First reading	Initial SET reading			Provided by SET custodians (Methods)
Last reading	Final SET reading			Provided by SET custodians (Methods)
Reading Duration	Time record for the SET readings (yr)	Provided for each SET		Calculated
Elevation.rate	Rate of elevation gain from the SET record (mm yr ⁻¹)	Rate of elevation gain from the SET record (mm yr ⁻¹)		Measured and provided by SET custodians (Methods)

Elevation rate R2	r^2 of the trend in elevation through time			Measured and provided by SET custodians (Methods)
Dominant species	Dominant mangrove species at the SET-MH installation	Dominant mangrove species at the SET-MH installation		Provided by SET custodians
RSLR 50	RSLR for the most recent 50-year linear trend (mm yr^{-1})	1973-2023		National Oceanic and Atmospheric Administration (NOAA) (https://tidesandcurrents.noaa.gov/sltrends/sltrends.html), or local tide gauges Australian Baseline Sea Level Monitoring Project (ABSLMP) (http://www.bom.gov.au/oceanography/projects/abslmp/abslmp.shtml)
RSLR 20	RSLR for the most recent 20-year linear trend (mm yr^{-1})	2003-2023		NOAA (https://tidesandcurrents.noaa.gov/sltrends/sltrends.html), or local tide gauges (ABSLMP) (http://www.bom.gov.au/oceanography/projects/abslmp/abslmp.shtml)
RSLR contemp	RSLR for each site for the period of SET measurement. Linear trend (mm yr^{-1})	Period of individual SET measurement		NOAA (https://tidesandcurrents.noaa.gov/sltrends/sltrends.html) (ABSLMP) (http://www.bom.gov.au/oceanography/projects/abslmp/abslmp.shtml)
Gauge	The name of the tide gauge			NOAA (https://tidesandcurrents.noaa.gov/sltrends/sltrends.html) (ABSLMP) (http://www.bom.gov.au/oceanography/projects/abslmp/abslmp.shtml)
Elevation deficit RSLR20	Elevation Deficit, defined as RSLR 20 minus elevation rate (mm yr^{-1})	2003-2023		Calculated

Elevation deficit contemporaneous	Elevation Deficit, defined as RSLR contemporaneous minus elevation rate (mm yr ⁻¹)	Period of individual SET measurement		Calculated
slr_noaa_mmyr	Local sea-level trend obtained from National Oceanic and Atmospheric Administration (NOAA) (mm yr ⁻¹)	1992-2024	Rasterized to 0.5 degrees (~5x5 km at the equator)	NOAA, 2024 (https://www.star.nesdis.noaa.gov/socd/lisa/SeaLevelRise/LSA_SLR_maps.php)
Elevation deficit slr_noaa	Elevation Deficit, defined as slr_noaa minus elevation rate (mm yr ⁻¹)	1992-2024		Calculated
Dist seaward edge	Distance from the mangrove location to the seaward edge (m)	Distance from the mangrove location to the seaward edge (m)		Google Earth
Dist landward edge	Distance from the mangrove location to the landward edge (m)	Distance from the mangrove location to the landward edge (m)		Google Earth
Dist proportion	Distance proportion calculated by Dist seaward edge/(Dist seaward edge+Dist landward edge)			Calculated

Accretion rate	Rate of accretion above the feldspar horizon (mm yr ⁻¹)			Measured and provided by SET custodians (Methods)
Subsidence rate	Calculated as by accretion minus elevation rate. (mm yr ⁻¹)			Measured and provided by SET custodians (Methods)
Soil Organic Carbon	Organic carbon in the upper 10cm by weight (%)			Measured and provided by SET custodians (Methods)
Soil Dry Bulk Density	Bulk density of the upper 10 cm (dry, g cm ⁻³)			Measured and provided by SET custodians (Methods)
SET elevation	Elevation of the SET in relation to local datum (m)			Measured and provided by SET custodians (Methods)
annual_mean_temp_C	Annual mean temperature (°C)	1970-2000	~1x1 km at the equator	37 (Title and Bemmels 2018) (Fick and Hijmans 2017)(https://www.worldclim.org/data/worldclim21.html)
mean_temp_warmest_quarter_C	Mean temperature of the warmest quarter (°C)	1970-2000	~1x1 km at the equator	(Fick and Hijmans 2017)(https://www.worldclim.org/data/worldclim21.html)
mean_temp_coldest_quarter_C	Mean temperature of the coldest quarter (°C)	1970-2000	~1x1 km at the equator	(Fick and Hijmans 2017)(https://www.worldclim.org/data/worldclim21.html)
annual_precipitation_mm	Annual precipitation (mm)	1970-2000	~1x1 km at the equator	(Fick and Hijmans 2017)(https://www.worldclim.org/data/worldclim21.html)
precip_wettest_month_mm	Precipitation of the wettest month (mm)	1970-2000	~1x1 km at the equator	(Fick and Hijmans 2017)(https://www.worldclim.org/data/worldclim21.html)
precip_driest_month_mm	Precipitation of the driest month (mm)	1970-2000	~1x1 km at the equator	(Fick and Hijmans 2017)(https://www.worldclim.org/data/worldclim21.html)
precip_seasonality_CV	Precipitation seasonality (coefficient of variation)	1970-2000	~1x1 km at the equator	(Fick and Hijmans 2017)(https://www.worldclim.org/data/worldclim21.html)

precip_wettest_quarter_mm	Precipitation of the wettest quarter (mm)	1970-2000	~1x1 km at the equator	(Fick and Hijmans 2017)(https://www.worldclim.org/data/worldclim21.html)
precip_driest_quarter_mm	Precipitation of the driest quarter (mm)	1970-2000	~1x1 km at the equator	(Fick and Hijmans 2017)(https://www.worldclim.org/data/worldclim21.html)
precip_warmest_quarter_mm	Precipitation of warmest quarter (mm)	1970-2000	~1x1 km at the equator	(Fick and Hijmans 2017)(https://www.worldclim.org/data/worldclim21.html)
precip_coldest_quarter_mm	Precipitation of coldest quarter (mm)	1970-2000	~1x1 km at the equator	(Fick and Hijmans 2017)(https://www.worldclim.org/data/worldclim21.html)
mean_temp_diurnal_range_C	Mean diurnal range (mean of monthly (max temp - min temp))	1970-2000	~1x1 km at the equator	(Fick and Hijmans 2017)(https://www.worldclim.org/data/worldclim21.html)
isothermality	Isothermality (mean_temp_diurnal_range_C / temp_annual_range_C) (×100)	1970-2000	~1x1 km at the equator	(Fick and Hijmans 2017)(https://www.worldclim.org/data/worldclim21.html)
temp_seasonality	Temperature seasonality (standard deviation ×100)	1970-2000	~1x1 km at the equator	(Fick and Hijmans 2017)(https://www.worldclim.org/data/worldclim21.html)
max_temp_warmest_mo_C	Max temperature of warmest month (°C)	1970-2000	~1x1 km at the equator	(Fick and Hijmans 2017)(https://www.worldclim.org/data/worldclim21.html)
min_temp_coldest_mo_C	Min temperature of coldest month (°C)	1970-2000	~1x1 km at the equator	(Fick and Hijmans 2017)(https://www.worldclim.org/data/worldclim21.html)
temp_annual_range_C	Temperature annual range (max_temp_warmest_mo_C - min_temp_coldest_mo_C)	1970-2000	~1x1 km at the equator	(Fick and Hijmans 2017)(https://www.worldclim.org/data/worldclim21.html)
mean_temp_wettest_quarter_C	Mean temperature of wettest quarter (°C)	1970-2000	~1x1 km at the equator	(Fick and Hijmans 2017)(https://www.worldclim.org/data/worldclim21.html)

mean_temp_driest_quarter_C	Mean temperature of driest quarter (°C)	1970-2000	~1x1 km at the equator	(Fick and Hijmans 2017)(https://www.worldclim.org/data/worldclim21.html)
current_30arcsec_annualPET	annual potential evapotranspiration: a measure of the ability of the atmosphere to remove water through evapotranspiration processes, given unlimited moisture (mm / month)	1970-2000	~1x1 km at the equator	(Title and Bemmels 2018)(https://envirem.github.io/)
current_30arcsec_PETColdestQuarter	mean monthly PET of coldest quarter (mm / month)	1970-2000	~1x1 km at the equator	(https://envirem.github.io/)
current_30arcsec_PETDriestQuarter	mean monthly PET of driest quarter (mm / month)	1970-2000	~1x1 km at the equator	(https://envirem.github.io/)
current_30arcsec_PETWarmestQuarter	mean monthly PET of warmest quarter (mm / month)	1970-2000	~1x1 km at the equator	(https://envirem.github.io/)
current_30arcsec_PETWettestQuarter	mean monthly PET of wettest quarter (mm / month)	1970-2000	~1x1 km at the equator	(https://envirem.github.io/)
Taw.ID	The ID of the global mangrove extent macroscale units			(Worthington, Zu Ermgassen et al. 2020)(https://data.unep-wcmc.org/datasets/48)
Taw.Class	Mangroves are classified as deltaic, estuarine, lagoonal or open coast based on			(Murray, Worthington et al. 2022)(https://data.unep-wcmc.org/datasets/48)

	their proximity to coastal features			
Sediment	Mangrove sedimentary settings: terrigenous or carbonate			(Worthington, Zu Ermgassen et al. 2020)(https://data.unep-wcmc.org/datasets/48)
taw.geomorphic_topology	Combination of the geomorphic and typology of mangrove units.			(Murray, Worthington et al. 2022)(https://data.unep-wcmc.org/datasets/48)
Known lowest limit of mangrove	Threshold below which open water conversion is assumed, relative to local height datum			Derived from the literature (Methods)
Lower limit relative to MHW (Pioh)	Threshold below which open water conversion is assumed, relative to Mean High Water			Derived from the literature (Methods)
Elevation capital measured (m)	The measured elevation of the SET above the known lowest limit of mangrove			Calculated
Annual.average.cycle.amplitude	Annual average cycle amplitude	2010	~6x6 km at the equator	https://doi.org/10.5879/c49r-x993 (Obst 2017)(https://snd.se/en/catalogue/dataset/ecds0243-1)
Annual.average.duration.of.tidal.cycles	Annual average duration of tidal cycles	2010	~6x6 km at the equator	https://doi.org/10.5879/c49r-x993 (Obst 2017)(https://snd.se/en/catalogue/dataset/ecds0243-1)
Annual.maximum.cycle.amplitude	Annual maximum cycle amplitude	2010	~6x6 km at the equator	https://doi.org/10.5879/c49r-x993 (Obst 2017)(https://snd.se/en/catalogue/dataset/ecds0243-1)

Annual.number.of.cycles	Annual number of tidal cycles	2010	~6x6 km at the equator	https://doi.org/10.5879/c49r-x993 (Obst 2017)(https://snd.se/en/catalogue/dataset/ecds0243-1)
Annual.standard.deviation.of.cycle.amplitude	Annual standard deviation of tidal cycle amplitude	2010	~6x6 km at the equator	https://doi.org/10.5879/c49r-x993 (Obst 2017)(https://snd.se/en/catalogue/dataset/ecds0243-1)
VLM_Oelsmann2024_NatGeosci	Vertical land movement (mm yr ⁻¹)	1995-2020	Rasterized to 0.5 degrees (~5x5 km at the equator)	(Oelsmann, Marcos et al. 2024)(https://zenodo.org/records/8308347)
SLR-VLM	An independent estimate of SLR based on VLM			(Oelsmann, Marcos et al. 2024)(https://zenodo.org/records/8308347)
New_ISM	Inorganic suspended matter (g m ⁻³)	1997-2024	~4x4 km at the equator	(Maritorena, d'Andon et al. 2010)(https://www.globcolour.info)
nflh	Normalized fluorescence line height (mW cm ⁻² μm ⁻¹ sr ⁻¹), calculated as the difference between the observed nLw(678) and a linearly interpolated nLw(678) from two surrounding bands.	2002-2022	250x250 m at the equator	NASA Goddard Space Flight Center, Ocean Ecology Laboratory, Ocean Biology Processing Group. Moderate-resolution Imaging Spectroradiometer (MODIS) Aqua Ocean Color Data, NASA OB.DAAC, Greenbelt, MD, USA. (https://oceancolor.gsfc.nasa.gov/)

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [DataS1Oct19cleanv6.zip](#)