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Success of coastal wetlands restoration is driven by sediment availability

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Shorelines and their ecosystems are endangered by sea-level rise. Nature-based coastal protection is becoming a global strategy to enhance coastal resilience through the cost-effective creation, restoration and sustainable use of coastal wetlands. However, the resilience to sea-level rise of coastal wetlands created under Nature-based Solution has been assessed largely on a regional scale. Here we assess, using a meta-analysis, the difference in accretion, elevation, and sediment deposition rates between natural and restored coastal wetlands across the world. Our results show that restored coastal wetlands can trap more sediment and that the effectiveness of these restoration projects is primarily driven by sediment availability, not by wetland elevation, tidal range, local rates of sea-level rise, and significant wave height. Our results suggest that Nature-based Solutions can mitigate coastal wetland vulnerability to sea-level rise, but are effective only in coastal locations where abundant sediment supply is available.

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Coastal wetlands provide a wide range of ecosystem services (valued up to US\$194,000 ha^{-1} yr^{-1}), including the support of commercial fisheries, carbon sequestration, natural coastal protection, and water quality improvement[1,2]. Historically, salt marshes and mangroves have been converted in urban development or agricultural fields at staggering rates; it is estimated that Europe has lost 50% of salt marshes to reclamation[3]. In Southeast Asia deforestation destroys 1.3% of mangrove forests every year[4].

In recent decades, a leading cause of widespread coastal wetland loss is the inability to build vertically at rates comparable to relative sea-level rise (SLR)[5,6], and global-scale assessments of coastal wetland dynamics indicate that SLR represents a critical threat to these ecosystems[7,8]. Wetland disappearance can accelerate due to the substantial increase in inundation and flooding triggered by accelerated SLR, storm surges, and land subsidence[9,10]. A reduction in sediment supply due to river damming can further compromise the resilience of coastal wetlands[11,12]. Recent results have suggested that the vulnerability to SLR might be lower than expected due to feedbacks between ecology and geomorphology[13] and the availability of inland areas for marsh migration[14]. Even if a smaller fraction of wetland area will be affected by SLR, there is still the need to reestablish these important ecosystems where they were historically reclaimed. In fact, a growing world population has turned coastal wetlands into agricultural fields, urban and industrial developments, and intensive aquaculture. This conversion has resulted in a loss of habitat for many fish and birds, as well as loss of important ecosystem services such as erosion mitigation, water purification, carbon storage, and natural flood defense[10,15].

In recent years, large investments have been made to protect the coast from SLR and storms, mostly by building traditional hard structures like seawalls and breakwaters. These solutions are expensive and non-sustainable in the long term[16,17]. Numerical and field studies suggest that coastal wetlands have a high potential to reduce flooding and coastal erosion[18–20]. Government agencies, nonprofit organizations, and businesses have developed an increasing interest in Nature-based Solutions, which are defined as actions to protect, sustainably manage, create, and restore natural or modified ecosystems for providing solutions to climate mitigation and adaptation challenges[21–23]. In coastal wetlands, Nature-based Solutions encompass the creation of living shorelines through vegetation planting, hydrological reconnection of reclaimed wetlands to the sea, managed retreat from the shore through removal of flood defenses, and thin-layer sediment placement that increases wetland elevation and enhances coastal resilience[10,24–27]. There is a growing body of studies showing that Nature-based Solutions are a long-term and cost-efficient strategy to help safeguard wetlands from SLR, thus protecting associated ecosystem services[26,28]. However, the effectiveness of Nature-based Solutions for SLR mitigation and adaptation has not been globally assessed, owing to the complex feedbacks of multiple environmental processes driven by elevation, vegetation, local relative SLR rate, tidal range, and sediment availability[29]. Recent modeling advances have provided the ability to conduct meta-analyses to fill research gaps at a global scale[13,30].

The vulnerability of coastal wetlands to SLR depends on whether they are able to vertically build at rates equal or greater than relative SLR[13,31,32]. Here we provide the first global synthesis and meta-analysis of the contributions of Nature-based Solutions to vertical accretion and surface elevation gain. Our aims are: (1) to quantitatively assess the effects of Nature-based Solutions on accretion, elevation change, and sediment deposition in comparison to natural wetland sites; and (2) to examine the relationship between effect size and environmental factors, including suspended-matter concentration, elevation, tidal range, local relative SLR, and wave height.

Results

In general, Nature-based Solutions significantly enhance resilience to SLR along the shorelines of the Atlantic, Pacific, and Indian Oceans. Hedges' g^* effect size of surface elevation change rate in the European Atlantic coast is significantly higher than that of the US Atlantic coast, while the US Pacific coast has the lowest Hedges' g^* value. Although the sample size in the Indo-Pacific region (China and Sri Lanka) is small, results show the enormous potential in enhancing vertical accretion rate in this region[33,34] (Fig. 1). These solutions will prevent coastal wetland loss in the future, by storing sediment near the shore.

Nature-based Solutions significantly increased the accretion rate by 19.58 ± 6.66 mm yr^{-1} in salt marshes and by 2.91 ± 0.63 mm yr^{-1} in mangroves (Fig. 2c). The standardized effect size of the accretion rate was lower in salt marshes than in mangroves (mean Hedges' g^* are 1.66 and 4.09, respectively) (Fig. 2a). Rates of surface elevation change in restored sites were higher by 10.35 ± 1.56 mm yr^{-1} in salt marshes and by 2.55 ± 0.63 mm yr^{-1} in mangroves (Fig. 2c). The standardized effect size of surface elevation gain was not significantly different among salt marshes and mangroves (Fig. 2a). For rates of elevation change, salt marshes can keep pace vertically with current local relative SLR in restored sites, but not in natural reference sites. In pristine areas, some salt marsh ecosystems are slowly drowning because their mean accretion deficit (elevation change rate minus relative SLR rate) is greater than 0.5 mm yr^{-1} (Fig. 2d). Nature-based Solutions can shift elevation change from deficit to gain. In general, Nature-based Solutions in salt marshes could increase sediment trapping by on average 185.71 ± 56.35 ton ha^{-1} yr^{-1} with respect to adjacent natural wetlands (Fig. 2b).

On a global scale, rates of accretion and elevation change in Nature-based Solutions projects are significantly correlated to the concentration of total suspended matter (TSM) in the water column (Fig. 3 and Supplementary Fig. 2). These relationships link the supply of sediments to the maintenance of soil elevation in salt marshes and mangrove forests across the Atlantic, Pacific, and Indian Oceans. Other variables (elevation relative to mean sea level (MSL), significant wave height, tidal range, regional rate of SLR, and elevation difference between restored and natural sites) explain a smaller proportion of the variation in accretion and rates of elevation change in salt marshes (Figs. 3 and 4, and Supplementary Figs. 2, 3, and 5).

The effect of Nature-based Solutions significantly increases with increasing TSM; trends are generally similar in salt marshes and mangroves (Fig. 3a, b and Supplementary Fig. 2a, b). For the first time we prove with field data collected across the world that the success of restoration projects is primarily driven by sediment availability. Consistent with numerical models, the effect of Nature-based Solutions is always positive when suspended sediment concentrations are greater than 20 g m^{-3} in salt marshes[35]. Hedges' g^* of accretion and rates of elevation change in mangroves is negatively correlated with wetland elevation (Fig. 3d and Supplementary Fig. 2d). The effect size of accretion in salt marshes increases first, and then decreases with an increase in elevation (Fig. 3c), however, the effect size of elevation change rate in salt marshes does not display a significant change when elevation increases (Supplementary Fig. 2c). Hedges' g^* of accretion and rates of elevation change in salt marshes is negatively correlated with elevation difference between restored and natural sites (Supplementary Fig. 5a, c), however, the effect size for mangroves does not display a significant change when the difference in elevation between restored and natural sites increases (Supplementary Fig. 5b, d). The effect size of accretion rate for salt marshes is positively correlated with SLR and tidal range, however, Hedges' g^* is not correlated with significant wave height (Fig. 4). The effect size of rates of elevation change for salt marshes is also positively

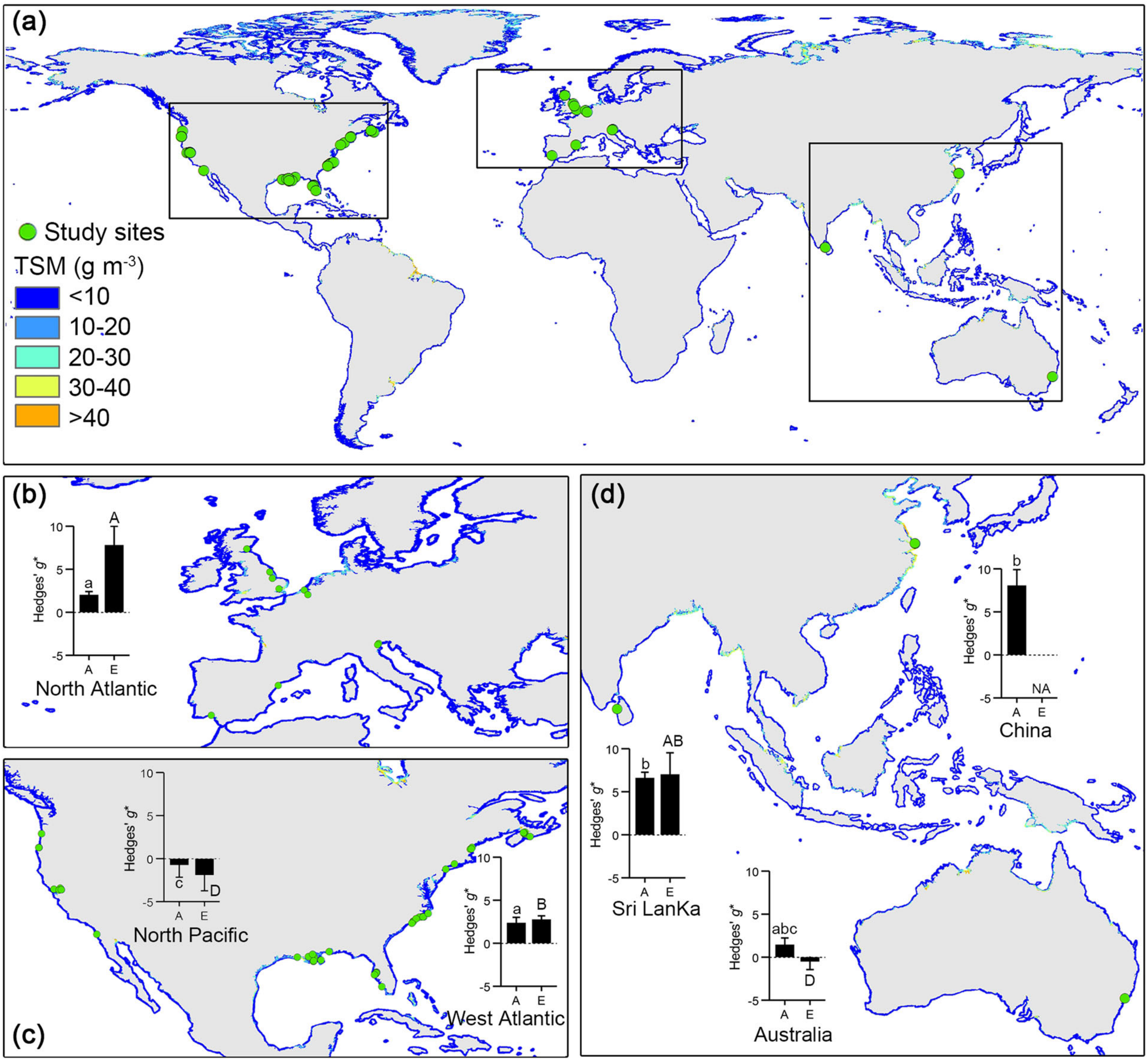

Fig. 1 Global distribution of study sites and difference in effect size of rates of accretion and elevation change between restored and natural wetlands. **a** Global distribution of Nature-based Solutions studies included in this synthesis. The average monthly total suspended matter (TSM) along the coastline was derived from MERIS satellite imagery (data freely available from http://hermes.acri.fr/). **b–d** Average effect size of accretion and elevation change rates between restored and natural wetlands in the North Atlantic (**b**), Indo-Pacific (**d**), and North Pacific and West Atlantic (**c**) regions. The A and E bars indicate the *Hedges g** effect size of the difference in accretion and elevation change rates between restored and natural wetlands, respectively. Error bars represent standard error. Identical lowercase letters and uppercase letters above the bars indicate means of accretion and elevation change rates that do not differ significantly among different study zones, respectively (LSD, ANOVA, $p > 0.05$).

correlated with SLR, but it is not correlated to tidal range and significant wave height (Supplementary Fig. 3). For mangrove ecosystems, the effect size of accretion rate in areas with large waves is significantly higher than in areas with small waves (Supplementary Fig. 4), which is consistent with sediment resuspension during storms or wave set up facilitating the flux of inorganic sediments into low-lying mangroves[36,37]. The effect size of both accretion and elevation change is not correlated to the percentage of sediment trapped by dams in nearby large rivers (Supplementary Fig. 6).

In general, effect size of accretion is more correlated to the variables we considered than to the effect size of surface elevation change (Fig. 3 vs Supplementary Fig. 2, Fig. 4 vs Supplementary Fig. 3, and Supplementary Fig. 5a, b vs Supplementary Fig. 5c, d). The surface elevation table – marker horizon (SET–MH) method has been used to successfully measure sediment vertical accretion, changes in relative elevation, and shallow soil processes (subsidence and expansion due to root production) worldwide[13,32,38]. This method allows to separate the contribution to surface elevation change due to surface accretion processes from that due to subsurface processes such as shallow subsidence, water table fluctuations, and root accumulation[39,40]. Therefore, changes in surface elevation depend not only on vertical accretion, but also on shallow subsidence, sediment compaction, and root zone expansion[41]. Local shallow subsidence complicates the relationship between changes in surface elevation and the physical factors investigated here. In salt marshes, elevation change is much lower than accretion, because of the large fraction of organic matter that can be compacted or that decays in time (Fig. 2c)[42]. In mangroves, less organic material is accumulated in the soil and mangrove roots better resist the decay, as a result, elevation change is closer to accretion[41,43].

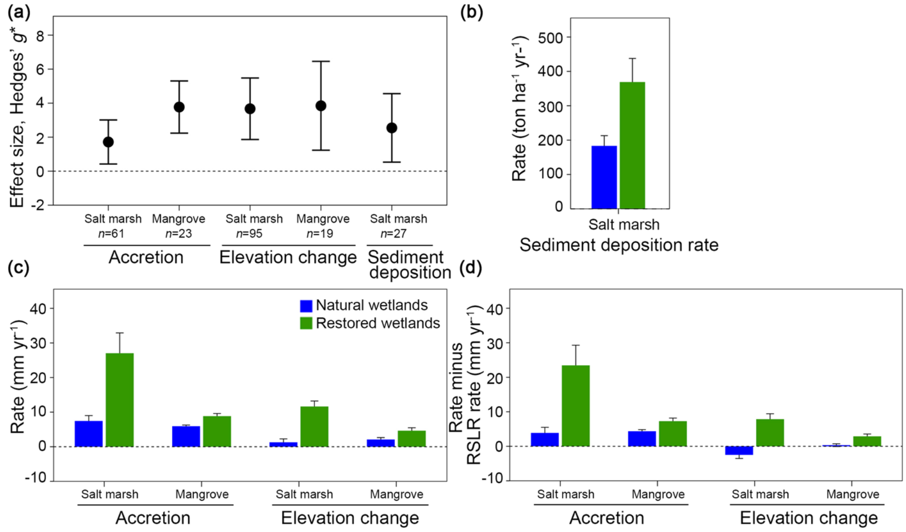

Fig. 2 Meta-analysis of vertical accretion, elevation change and sediment deposition rates between Nature-based Solution sites and reference sites. **a** Hedges' g^* effect size of Nature-based Solutions compared to natural coastal wetlands for accretion, elevation change, and sediment deposition rates. Shown are effect sizes in mean and 95% confidence interval. Effect sizes are considered significant if their 95% confidence interval does not overlap zero. Sample sizes are indicated with *n*. **b** Mean sediment deposition rates (± SE) in salt marshes; **c** accretion and elevation change rates (± SE) for Nature-based Solution sites and natural reference sites; and **d** accretion and rates of elevation change minus local relative SLR rate (± SE) for Nature-based Solution sites and natural reference sites. Two-tailed Student *t*-tests indicate that accretion, elevation change, and sediment deposition rates are significantly different between Nature-based Solution sites and natural reference sites ($p < 0.05$).

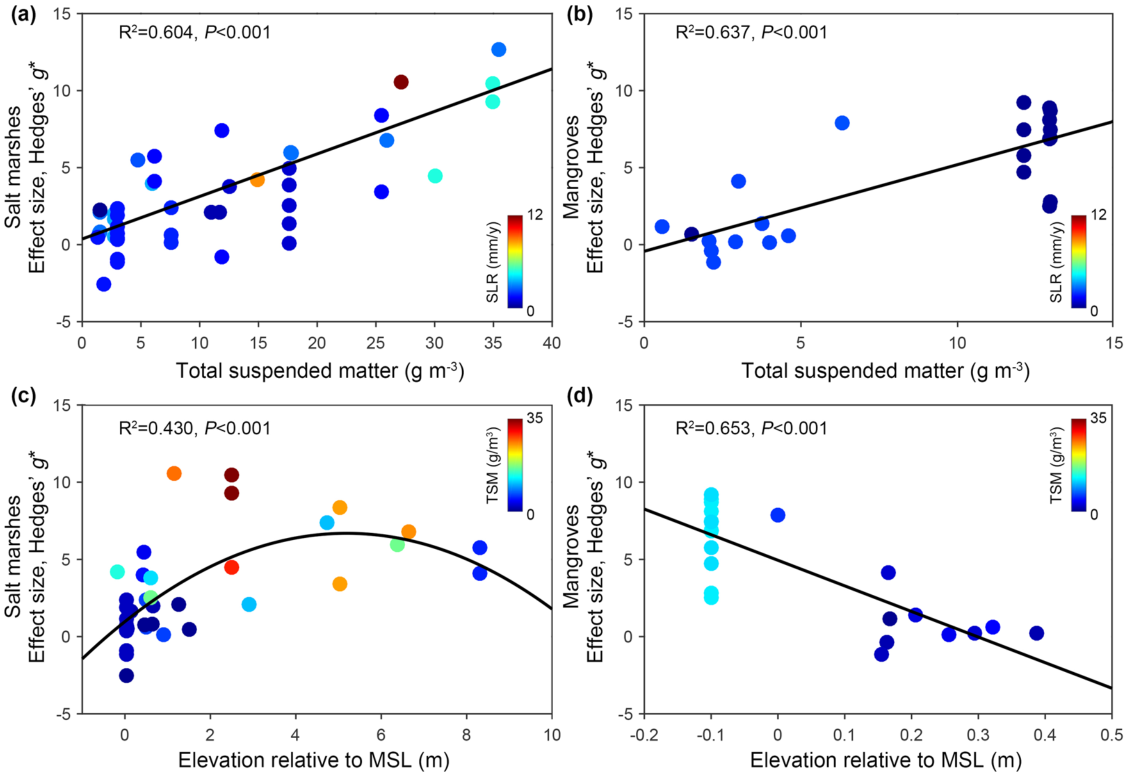

Fig. 3 Relationship between effect size of accretion rate and sediment availability or local elevation. a, b Relationship between effect size Hedges' g^* of accretion rate and the total-suspended-matter concentration in salt marshes (**a**) and mangroves (**b**). **c, d** Relationship between effect size Hedges' g^* of accretion rate and elevation above mean sea level in salt marshes (**c**) and mangroves (**d**). Regressions of effect size vs TSM and elevation (*F* test). Note: this analysis does not include restoration projects with thin-layer placement of sediment or dredged material, which strongly affect natural accretion.

Discussion

Nature-based Solutions can mitigate coastal wetland vulnerability to SLR by leveraging on ecogeomorphic feedbacks between flooding, vegetation, organic matter accretion, and sediment deposition. Restored wetlands may be lower in the tidal frame than natural ones, because of erosion or soil compaction after land reclamation in pre-restoration sites[44,45]. Therefore, they experience higher hydroperiods, and more time for sediment

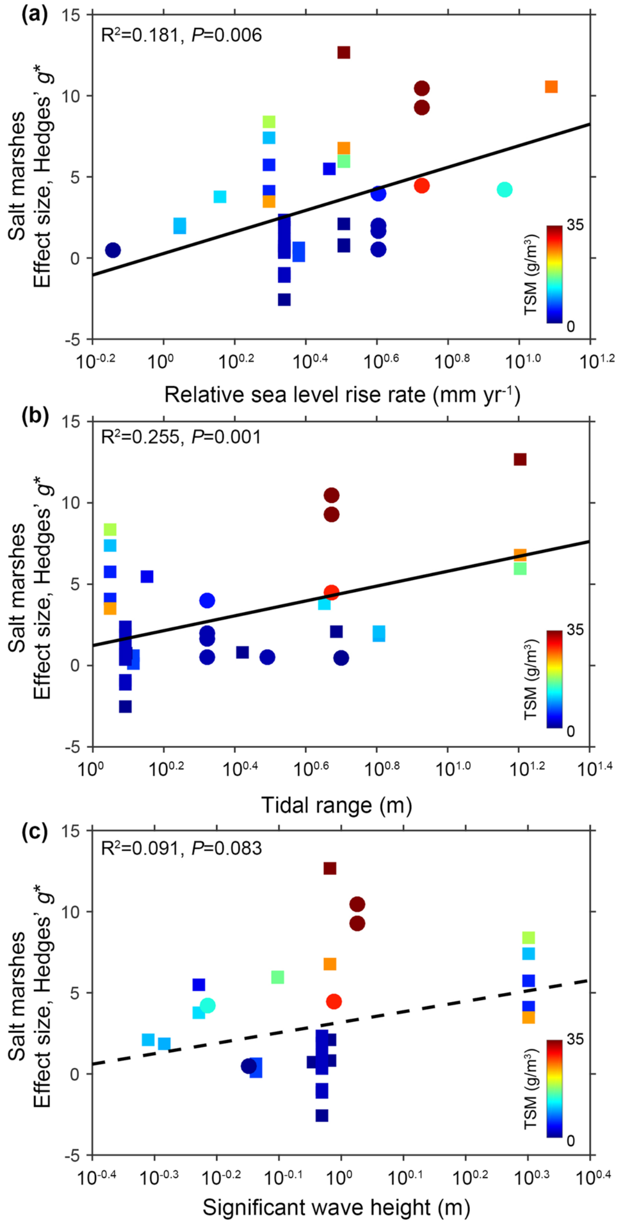

Fig. 4 Relationship between effect size of accretion rate and other environmental factors in salt marshes. a Relationship between Hedges' g^* effect size of accretion rate and sea-level rise (SLR) in salt marshes. **b** Relationship between Hedges' g^* effect size of accretion rate and tidal range in salt marshes. **c** Relationship between Hedges' g^* effect size of accretion rate and significant wave height in salt marshes. Linear regressions of effect size vs SLR rate, tidal range, and significant wave height (log-transformed) (*F* test). Significant ($p < 0.05$) and non-significant ($p \geq 0.05$) relationships are shown with solid and dashed lines, respectively. Note: this analysis does not include the restoration projects with thin-layer placement of sediment or dredged material, which artificially affect deposition rates.

deposition than natural ones (Supplementary Fig. 5). A lower elevation also increases tidal prism, and therefore the volume of water and sediments transported to the wetland. Over the course of time, if there is enough sediment supply, the elevation difference between restored and natural marsh will vanish, together with the accretion differential[45–47]. The difference in accretion rates was not significant in areas with low total-suspended-matter concentration[45]. Note that the correlation between effect size and TSM is much stronger than the correlation with elevation difference (Fig. 3a, b vs Supplementary Fig. 5), therefore sediment availability is more important for restoration success than longer hydroperiods and larger tidal prisms. This is because larger volumes of water flooding the wetlands also require high-suspended-sediment concentrations to trigger accretion. Therefore, the success of the Nature-based Solution is intrinsically linked to the location of the project and the local geomorphology, for example, to the elevation within the tidal frame and, more importantly, to sediment availability.

Restored wetlands can also have higher vegetation density, because of artificial planting or a position in the tidal frame more favorable to vegetation development. Higher vegetation biomass favors sediment trapping and accretion[41,45,48]. Salt marsh grass or mangrove planting, one of the traditional wetland restoration approaches, can reduce tidal current speeds, prevent erosion, trap more sediment, and promote belowground root production to facilitate accretion and sediment retention[49–51]. Hydrological restoration like managed realignment (MR) or controlled reduced tide (CRT) can increase tidal inundation compared to pre-restoration conditions by breaching artificial barriers and reestablishing tidal exchange between the restoration site and the adjacent estuary or sea, hence promoting more frequent and longer episodes of mineral sediment deposition, enhancing vegetation growth, and accelerating rates of mineral and organic matter accumulation[10,52]. Our results show that Hedges' g^* effect size of accretion and rate of elevation change is not significantly different between planting and hydrological restoration (Fig. 5). According to published data, however, the median cost for restoration of 1 hectare of salt marsh with planting is 10–20 times higher than the cost for hydrological restoration[26]. Therefore, hydrological restoration, in which low-lying inland areas are converted to coastal wetlands, is an economical and effective restoration strategy to facilitate accretion and vertical increase in elevation, when sufficient additional accommodation space is available[10,14]. In addition, thin-layer sediment placement (also known as thin-layer deposition, sediment augmentation, or sediment replenishment) and diversion of sediment-laden riverine discharge to wetlands can also increase sediment supply, promoting elevation gain and wetland expansion[53,54].

In mangroves, an increase in elevation decreases the difference in sediment trapping capacity between restored and natural sites (Fig. 3d). This is expected because mangroves higher in the intertidal frame and subject to lower flooding depth have likely a lower hydroperiod. With a lower hydroperiod, suspended sediment has less time to deposit, reducing sediment accretion and elevation change[55]. In salt marshes, however, the effect of restoration is more complex, with the difference in sediment accretion first increasing and then decreasing as a function of elevation (Fig. 3c). We attribute this behavior to ecogeomorphic feedbacks between elevation and salt marsh vegetation. Biomass of salt marsh plants first increases with elevation and then decreases, with optimal conditions for vegetation growth occurring at intermediate elevations[50,56]. Biomass controls sediment accretion by trapping sediment on stems and leaves, increasing belowground production of organic matter, and slowing tidal currents, thus promoting deposition[57]. This feedback between elevation and vegetation controls the relationship between accretion and elevation (Fig. 3c). Restored mangroves along shorelines with high wave energy trap more sediments than natural ones (Supplementary Fig. 4). This result is in agreement with field measurements showing that waves are instrumental in resuspending bottom material and advecting it in the mangrove forest[58]. In salt marshes, this effect is subdue because the thick canopy promotes wave dissipation reducing transport to the marsh interior[59,60]. In salt marshes, tidal range and relative SLR

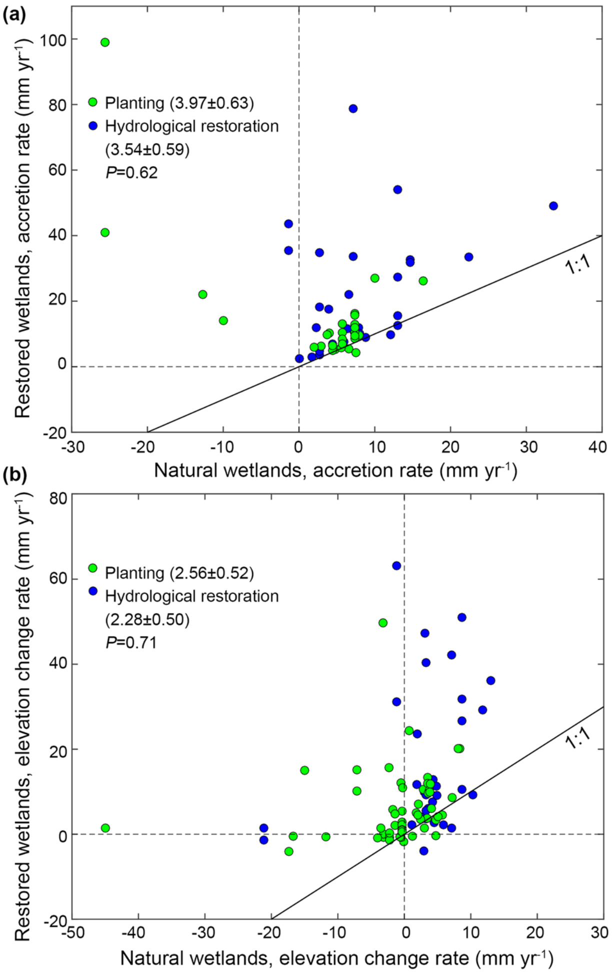

Fig. 5 Comparison of accretion and rate of elevation change between restored wetlands and natural wetlands. a Comparison of accretion rate between restored wetlands and natural wetlands. **b** Comparison of elevation change rate between restored wetlands and natural wetlands. The black line represents an equilibrium condition where restoration sites are building vertically at the same rate of reference sites. Numbers in brackets denote the mean (±SE) effect size Hedges' g^* of accretion rate or rate of elevation change. Two-tailed Student *t*-tests indicate that effect sizes are non-significantly different between planting and hydrological restoration.

rate explained a smaller proportion of the variation in the effect size of vertical accretion, however, these factors are positively correlated with the effect size (Fig. 4a, b). The trends are consistent with previous theory and results, showing that coastal ecosystems are likely to survive at sites with high tidal range and rates of SLR[35,43,50,61]. Moderate rates of SLR not only increase the frequency and duration of tidal inundation, but may also stimulate vegetation growth, accelerating the rate of accretion[50,61]. In fact, rates of mineral sediment deposition increase with the frequency and duration of tidal inundation, while stimulated vegetation growth also promote inorganic sediment trapping and in situ organic accretion[57,61]. Vegetation growth range expands with tidal range, so that vegetation surfaces in macrotidal and mesotidal marshes can more easily accommodate SLR than in microtidal marshes[43,61].

The success of Nature-based Solutions is not related to the percentage of sediment trapped by dams in the nearest large river (Supplementary Fig. 6). We ascribe this result to the complex and local nature of sediment supply to salt marshes. In coastal and estuarine systems, sediment supply not only depends on upstream or seaward sediment inputs, but also on sediment redistribution through riverine and tidal channels[62,63]. Many salt marshes are fed by sediments originating from tidal flats and the nearshore area[64,65]. River sediment load is rarely discharged directly on salt marshes; rather, the sediment is first delivered to coastal bays and the inner shelf and then reworked by marine processes, which can mediate and modulate the sediment flux to the marsh[62,63]. Moreover, small rivers located close to the marsh might have a stronger effect on restoration projects than the sediment discharged by distant large rivers, because sediment supply decreases with distance from the river mouth[12,53]. Several large rivers are also dammed, decreasing the flux of sediment to the coast[11,66]. For example, the sediment load of the Yellow River in China, one the world's largest, has decreased by approximately 90% from 1950s to 2010s[67]. The Mississippi River sediment load has also been reduced by 50% after the construction of dams[68]. Therefore, restored sites should be located where suspended-matter concentration is high, like in estuaries, near river mouths, or along muddy shorelines. Sediment transport pathways and budgets should be integrated into the early phases of Nature-based Solutions planning.

In conclusion, Nature-based Solutions can be an effective strategy to trap sediment along the shore and mitigate coastal wetland vulnerability to SLR[69]. Plantation and hydrologic restoration (MR or CRT), the two most common Nature-based Solutions in salt marshes and mangroves ecosystems, can enhance vegetation growth, prevent erosion, and accelerate rates of mineral and organic matter accumulation. Furthermore, results from our synthesis indicate that the effectiveness of Nature-based Solutions for SLR mitigation and adaption is strongly linked to the local availability of suspended matter in coastal waters. A reliable sediment supply is needed for wetland accretion, and is more important than the local rate of SLR for restoration success. This is why the effect size along the North-European and Indo-Pacific coasts is higher than along the US coast (Fig. 1). The North-European and Indo-Pacific coasts have more sediment availability, while the US coast is sediment starved[14] (Fig. 1). When sediment availability is scarce, restoration projects might fail, preventing the attainment of the surface elevation needed for normal wetland ecological functions[70–72]. Unfortunately, the sediment flux to the coast has been reduced in recent decades by 1.4 ± 0.3 billion metric tons per year, because of retention within dams and reservoirs[11]. As a result, the ability of Nature-based Solutions to trap sediment is diminishing[68,73]. Dam regulation, and targeted management of upstream watersheds are therefore vital for the coastal sediment budget and the survival of coastal wetlands.

Methods

Literature search. To build a comprehensive database of the impacts of Nature-based Solutions on the resilience of coastal wetlands to SLR we reviewed primary literature, reports, and other datasets. We carried out a systematic review in the ISI Web of Science database (www.isiwebofknowledge.com) on 22 April 2019 with no restriction on publication year and subject areas, using the following search terms: TS = (salt marsh* OR saltmarsh* OR tidal marsh* OR mangrove* OR mangal*) AND TS = (restor* OR rehab* OR recov* OR creat* OR reestab* OR reveget* OR afforest*) AND TS = (elevation* OR sediment* OR accretion* OR erosion* OR deposit*), and TS = (living shoreline* OR nature-based OR thin-layer placement OR dredge material OR managed realignment OR managed retreat*) AND TS = (elevation* OR sediment* OR accretion* OR erosion* OR deposit*). This resulted in 3516 publications. We also included 45 other published and unpublished papers or reports from references that were relevant.

We examined the title and abstract of each publication to assess their potential for meeting the selection criteria for inclusion in the review. In all, 268 studies were identified that potentially met the selection criterion. We only selected studies that: (1) examined the effects of Nature-based Solutions on accretion, elevation change, and sediment deposition in restoration projects or field experiments; (2) used surface elevation tables (SETs) and feldspar-marker horizons (MH) to measure soil surface elevation and vertical accretion rates, following the method of Cahoon et al.[38], and used sediment traps to measure the deposition of sediments, as indicated by Reed[74]; and (3) reported sample sizes and some measure of variance (e.g., standard deviations/errors) for each measured variable in both Nature-based Solutions and natural reference systems. Reference natural wetlands used herein were typically adjacent to the nearby wetlands where Nature-based Solutions were applied. Restored and natural sites are similar in species composition and share the same tidal range, rate of SLR, sediment supply, and wave height. We calculated the difference in elevation between restored and natural sites, because the elevation of the two sites may be different[44,45]. The literature selection procedure is shown in Supplementary Fig. 1 as a PRISMA flow diagram. This methodology resulted in 225 experiments/observations reported in 52 published and unpublished studies, which formed the basis of the meta-analysis. An overview map of the worldwide locations of Nature-based Solutions projects is provided in Fig. 1.

Data extraction and data source. For each retained publication, we extracted data at sites where Nature-based Solutions were applied and reference sites from the main text, tables, and figures of the articles. Data from plots and figures were extracted graphically using WebPlotDigitizer (available online). When accretion and/or elevation change rates were reported for multiple dates, we calculated the averaged rates across the entire measurement period to minimize the effect of restoration duration on rates of accretion and elevation change. When accretion/elevation change and sediment deposition were reported in mm or cm and $g\,m^{-2}$, respectively, we divided the results by the measurement duration (in years) to obtain $mm\,yr^{-1}$ and $ton\,ha^{-1}\,yr^{-1}$.

In addition, we also recorded the following variables for each study: author(s), year, study location, latitude, longitude, habitat (salt marshes or mangroves), project duration (in years) and restoration method, tidal range, regional relative SLR rate, elevation relative to MSL, and the difference in elevation between restored and natural reference sites. Not all information required for the database was directly available in every publication, therefore, additional information was derived where possible. Latitude and longitude data were obtained by locating the study site on Google Earth. Tidal range and regional relative SLR data were obtained from the nearest Center for Operational Oceanographic Products and Services (CO-OPS) tide station (https://tidesandcurrents.noaa.gov/) and National Oceanic and Atmospheric Administration (NOAA) tide gauge (https://tidesandcurrents.noaa.gov/sltrends/sltrends.html), respectively. Elevation relative to MSL data was obtained from other relevant references. If unavailable in the publication, the elevation of study area in the USA was calculated using the USGS National Elevation Dataset (NED; http://nationalmap.gov/elevation.html), which is a set of ~3 m resolution, best-quality elevation data widely used in geomorphic studies[75], and converted to elevation relative to local MSL.

The significant wave height was derived from the NOAA WAVEWATCH III (data freely available from https://polar.ncep.noaa.gov/waves/hindcasts/nopp-phase2.php), which contains monthly values of significant wave height in the Earth's oceans between March 2005 and April 2019. The significant wave height was extracted with MATLAB, using the significant wave height value of the pixel containing, or closest to, the Nature-based Solution sites. We calculated the monthly averages during the measurement period to represent the local significant wave height. If no data were available during the measurement period, we used the monthly averages from March 2005 to April 2019. Sediment supply is critical for surface elevation gains. Therefore, we also explored the relationship between restoration success (e.g., effect size) and TSM. The TSM in coastal waters was derived from remotely sensed GlobColour MERIS and OLCIA imagery (data freely available from http://hermes.acri.fr/), which contains monthly values of TSM in the Earth's oceans and lakes between 2002 and 2019 (data between April 2012 and March 2016 is missed). MERIS data have already been used to calculate local sediment availability in global estimates of wetland response to SLR[14,43]. TSM was extracted with MATLAB using the TSM value of the pixel containing, or closest to, the Nature-based Solution sites. We calculated the monthly averages during the measurement period to represent the local sediment availability. Monthly coverage of MERIS, however, is incomplete. If no data were available during the measurement period, we used the monthly averages from April 2002 to April 2019.

To investigate whether a reduction in sediment supply caused by dams in nearby fluvial watersheds affects the success of Nature-based Solutions, we relate accretion rates and changes in marsh elevation to a global dataset of anthropogenic sediment retention in large rivers[76]. To each salt marsh site, we assign the percentage of sediment trapped by dams in the nearest large river, and if large rivers are not present, we assign a value of zero.

Meta-analysis. To standardize and compare data, we quantified the effect size by calculating the Hedges' g^*, which is a metric commonly used in meta-analysis and can quantify the unbiased, standardized mean difference in sediment deposition between restored and natural sites[77]. Positive g^* values indicate that Nature-based Solutions increase coastal wetland resistance to SLR, by increasing the rates of accretion and elevation change, or sediment deposition, while negative values indicate Nature-based Solutions fail to increase the resistance.

$$g^* = \frac{X_{\mathrm{NbS}} - X_{\mathrm{ref}}}{S} \times J, \qquad (1)$$

where X and S denote the mean and standard deviation of the measured variable, respectively. The subscript NbS refers to Nature-based Solution wetlands (restored or newly created wetlands) and ref to reference wetlands, respectively. J is a correction factor for small sample bias, and S is the pooled standard deviation.

$$J = 1 - \frac{3}{4df - 1}, \qquad (2)$$

$$S = \sqrt{\frac{(N_{\mathrm{NbS}} - 1)S_{\mathrm{NbS}}^2 + (N_{\mathrm{ref}} - 1)S_{\mathrm{ref}}^2}{N_{\mathrm{NbS}} + N_{\mathrm{ref}} - 2}}, \qquad (3)$$

where N is the sample size, df is the degrees of freedom used to estimate S, for two independent groups is $N_{\mathrm{NbS}} + N_{\mathrm{ref}}{}^{-2}$.

Using random-effects models[77], we estimated mean effect sizes g^* and 95% bootstrapped confidence intervals (95% CI) on accretion, elevation change, and sediment deposition rates for salt marshes and mangroves. Treatment effects were considered significant if the 95% CI did not overlap zero. All analyses were conducted using R 3.6.1 (R Core Team 2019) and its metafor package.

Data availability

Data supporting the analyses and results of this study are available in the Zenodo repository, https://doi.org/10.5281/zenodo.4452745.

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Author contributions

Z.Z.L., S.F., and B.S.C. designed the study; Z.Z.L. collected and analyzed the data; Z.Z.L. and S.F. created the figures; Z.Z.L., S.F., and B.S.C. discussed the results; all authors wrote and reviewed the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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