2013

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Webb, Edward L.; Friess, Daniel A.; Krauss, Ken W.; Cahoon, Donald R.; Guntenspergen, Glenn R.; and Phelps, Jacob, "A global standard for monitoring coastal wetland vulnerability to accelerated sea-level rise" (2013). *USGS Staff -- Published Research*. 987.
https://digitalcommons.unl.edu/usgsstaffpub/987

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PERSPECTIVE
PUBLISHED ONLINE: 25 APRIL 2013 | DOI: 10.1038/NCLIMATE1756
nature climate change

A global standard for monitoring coastal wetland vulnerability to accelerated sea-level rise

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Sea-level rise threatens coastal salt-marshes and mangrove forests around the world, and a key determinant of coastal wetland vulnerability is whether its surface elevation can keep pace with rising sea level. Globally, a large data gap exists because wetland surface and shallow subsurface processes remain unaccounted for by traditional vulnerability assessments using tide gauges. Moreover, those processes vary substantially across wetlands, so modelling platforms require relevant local data. The low-cost, simple, high-precision rod surface-elevation table–marker horizon (RSET-MH) method fills this critical data gap, can be paired with spatial data sets and modelling and is financially and technically accessible to every country with coastal wetlands. Yet, RSET deployment has been limited to a few regions and purposes. A coordinated expansion of monitoring efforts, including development of regional networks that could support data sharing and collaboration, is crucial to adequately inform coastal climate change adaptation policy at several scales.

Coastal wetlands cover a huge area globally, with mangroves occupying as much as 150,000 km^2 in the tropics[1] and temperate tidal marshes more than 45,000 km^2 (ref. 2). Coastal wetlands provide essential direct livelihood services to millions of people, as well as critical regulating services such as maintenance of water quality, protection from storms and erosion, and carbon sequestration[3,4]. Yet sea-level rise (SLR) threatens human populations around the world and coastal wetlands sensitive to increased inundation[5,6], making SLR adaptation a top priority for civil society[6,7]. Recent (1993–2009) global mean SLR has been estimated at 3.4 ± 0.4 mm per annum[8], but it is expected to accelerate significantly over the coming century due to thermal expansion and ice melt[9,10]. Contemporary global models suggest that by the 2080s, up to twenty per cent of global coastal wetlands may disappear as a result of SLR alone[11]; such a loss of coastal wetlands would lead to massive economic and societal costs resulting from increased carbon emissions, the loss of direct and indirect ecosystem services, increased vulnerability to extreme storm events (cyclones, storm surges), and increased costs of adaptation and/or mitigation[12]. A possible 1 m rise in sea level could affect 6.1 million people living on the Nile delta, and a 1.5 m rise could flood 22,000 km^2 of the deltaic areas of Bangladesh, affecting 17 million people[6].

Although the extent of coastal wetlands has historically tracked rising and falling sea levels (for example, refs 13–15), recent transformation of the surrounding terrestrial landscape (notably by agriculture and urbanization) has often introduced embankments that constrain lateral landward wetland migration, so that rising sea levels could significantly reduce coastal habitat area[16]. Under these circumstances, a key determinant of coastal wetland vulnerability to SLR is whether the surface elevation in the intertidal zone can keep pace with rising sea level. It is crucial to quantify the vertical movement of coastal wetland surfaces, which will help identify sites under threat from SLR, thus informing conservation, mitigation and adaptation. This is particularly important given the need for targeting climate change funding to support cost-effective responses. For example, without reliable predictions of wetland vulnerability in specific regions, management commitments might be implemented in areas not requiring immediate action, possibly to the detriment of threatened sites that could be saved through swift intervention[17,18].

Although the science behind global SLR variability is well-advanced[8,9], large gaps exist in the quantification of wetland surface elevation change globally, so assessing relative vulnerabilities of coastal wetlands remains unresolved for most coastal wetlands around the world. In this Perspective we discuss the current data limitations to understanding coastal wetland SLR vulnerability, and how these gaps can be filled with precise, low-cost direct measurements of wetland surface and shallow subsurface processes using the rod surface-elevation table–marker horizon method (RSET-MH)[19]. RSET data can inform assessments of wetland vulnerability to SLR and bolster SLR wetland models to support science-based policy. Our analysis reveals gaps in organized research and geographic coverage using RSET-MH, particularly for wetlands that may be most threatened by accelerated SLR. To fill this gap, we propose the development of systematic and coordinated coastal wetland monitoring networks, calculate the baseline costs to establish networks of RSETs in vulnerable coastal wetlands and provide a roadmap for network development among governments, civil society and regional agencies. We further discuss the associated policy benefits of such networks, and their unprecedented potential to critically inform local and regional coastal conservation, mitigation and adaptation action.

Critical gaps in quantifying coastal wetland vulnerability

Measuring the vertical movement of the coastal wetland surface and its constituent processes is necessary to determine — either empirically or through modelling — whether a wetland can keep pace with SLR. The vertical movement of a coastal wetland surface is the sum total of deep subsidence, and surface and shallow subsurface processes[20].

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Deep subsidence includes processes such as compaction, coseismic and interseismic subsidence and postglacial isostatic adjustments. For any site, a long-term tide gauge anchored at some depth below the surface measures relative SLR, which is the sum of eustatic SLR + deep subsidence[21] at that depth (Fig. 1). Tide-gauge measurements are fundamental for analyses inferring broad coastal vulnerability to future SLR[11].

In coastal wetlands, however, surface and shallow subsurface processes (above a tide-gauge anchor depth) contribute to a net positive or negative surface elevation change (Fig. 1). These processes include sediment accretion, erosion, biotic contributions (for example, belowground primary production and bioturbation), organic matter decomposition, autocompaction and soil shrink–swell from fluctuation in the water table and pore-water storage[22]. These shallow processes must be quantified and incorporated with relative SLR rate estimates from a local tide gauge to contribute to a complete wetland vulnerability assessment.

Annual rates of both SLR and wetland surface elevation change operate on millimetre scales, so prevailing mapping techniques — satellite/airborne altimetry, Light Detection and Ranging (LiDAR), GPS technologies, surveying — lack sufficient precision to track surface elevation change on an annual basis (Table 1). For example, airborne LiDAR data with a root mean square error of 14–15 cm realizes a maximum vertical axis linear error at the 95% confidence interval of ±27.4–29.4 cm (refs 23,24) that is, ten times larger than the annual rate of SLR. These technologies provide informative three-dimensional base layers of wetland structure (for example, digital elevation models). Time-series mapping data can be used to visualize spatial heterogeneity in wetland geomorphology resulting from wetland evolution over broad timescales, and from high-magnitude events such as tsunamis, storm surges and major deposition events[25,26]. Baseline maps can be integrated with more precise point-based measures of surface elevation change made with the RSET-MH method (see next section).

Numerous modelling approaches have been used to address the relationship between SLR and coastal wetland vulnerability. They provide a method of predicting the influence of SLR by isolating it from other drivers. Coastal wetland models continue to evolve, and vary in the extent that they incorporate complex ecological and physical processes occurring at the surface and shallow subsurface levels[27]. Recent numerical models that integrate nonlinear feedbacks among inundation, plant growth, organic matter accretion and mineral sediment deposition have been developed to identify the circumstances that lead to coastal wetland resilience and thresholds that result in the submergence of coastal wetlands[27,28]. These models are addressing a major knowledge gap in understanding the limits of wetland adaptation to SLR[28] and the processes affecting coastal marsh response. Indeed, marshes are also subjected to other external drivers that may interact with inundation and lead to wetland loss apart from changes in surface elevation. For instance, wave erosion is a stochastic event influencing marsh loss[29,30], and has only recently received attention in models[31].

Crucially, however, previous studies have revealed high across-site variability in the processes that contribute to surface elevation change[32–34], making assumptions of uniformity in processes across wetlands inappropriate. This highlights the need for site-specific data that accurately represent local processes to initialize, calibrate and validate site-specific wetland models, and to evaluate the outcome of different SLR scenarios[35,36].

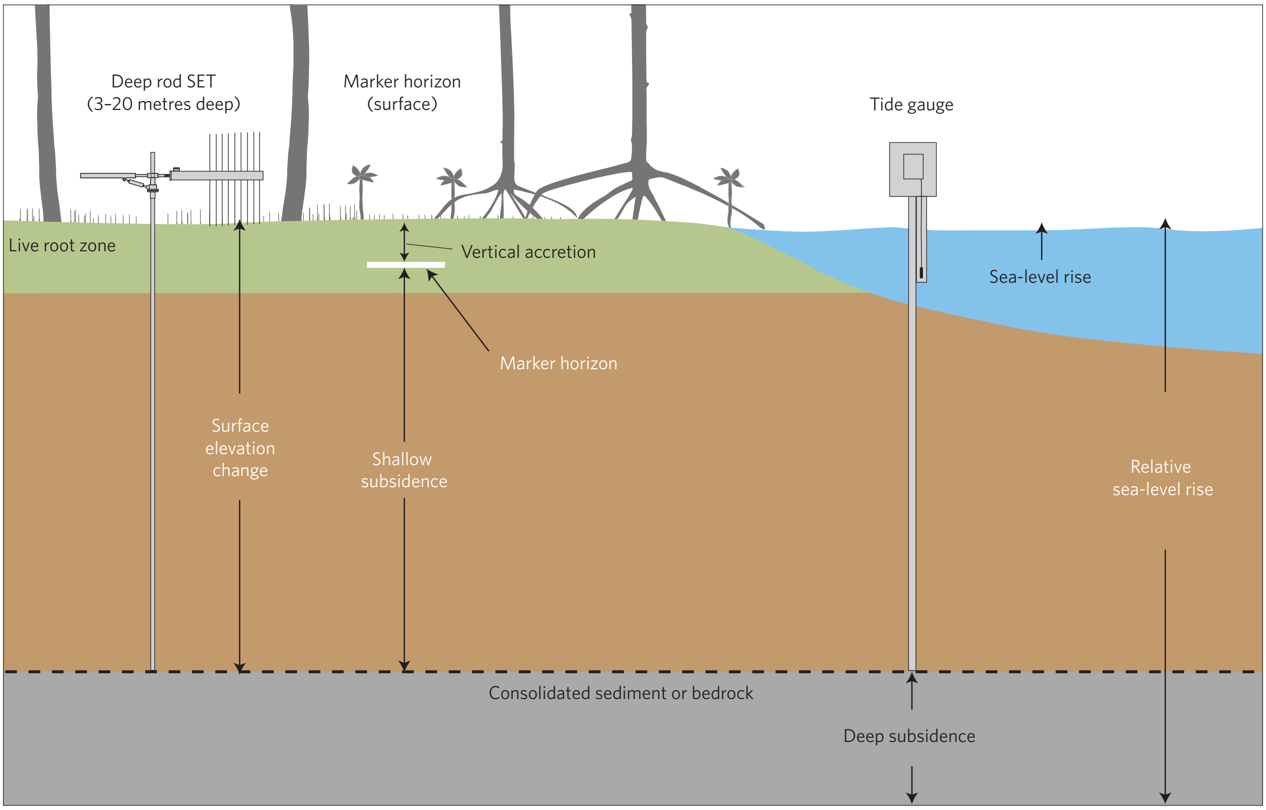

Figure 1 | RSET-MH and tide gauge set-up in a coastal mangrove. The RSET measures net surface elevation change (vertical accretion + shallow subsidence) relative to the RSET anchor point (but does not measure deep subsidence). The marker horizon (MH), in conjunction with RSET, permits separate calculations for vertical accretion and shallow subsidence. A tide gauge measures relative SLR (RSLR; sea-level change + deep subsidence below the tide gauge and RSET anchor points). For a wetland maintaining its position relative to sea-level, surface elevation change is equal to RSLR. If surface elevation change is greater or less than RSLR, then the wetland is accreting or subsiding relative to sea level, respectively. Figure courtesy of James C. Lynch, US National Park Service.

Table 1 | Accuracy and coverage of techniques for measuring wetland surface elevation.

	Field	Field	Field	Airborne	Satellite	Satellite
	RSET–MH	d/RTK-GPS	Total station	LiDAR	ASTER	SRTM data products
Vertical accuracy (RMSE) (m)	0.0010–0.0015[19]	0.02–0.12[94]	0.0005–0.005 at 100 m*	0.14–0.29[23]	9–11, 10–25[95]	3.3–9.73[95,96]
Spatial resolution (m)	Fine within instrument reach (point measurements)	Depends on survey effort; can be fine over site scale	Depends on survey effort	Variable (m scale)	15[96]	30–90[97]
Spatial coverage (m^2)	Point (but easily replicable)	Small	Small	Medium	Large	Large
Cost (magnitude of $ per site)	10^3	10^3–10^5	10^3–10^5	10^5–10^6	Free†	Free†
Other issues	Marker horizons can be affected by bioturbation and trampling	Time- and labour-intensive	Time- and labour-intensive	Poor vegetation penetration; requires high level of expertise	Few time-steps available; requires high level of expertise	

*Calculated from specification sheets of several commercial total station manufacturers. †Data products are freely available, though platform cost is considerable. d/TRK-GPS, Differential/real time kinematic global positioning system; ASTER, Advanced spaceborne thermal emission and reflection; SRTM, Shuttle radar topography mission; RMSE, Root mean square error.

Simple, affordable, high-precision data

The RSET-MH method fulfils the critical need for precise and easily replicable measurements of local surface elevation change. It was developed to quantify the surface and shallow subsurface processes that contribute to wetland surface elevation change[37,38]. An RSET involves very simple technology; it consists of a benchmark rod driven through the soil profile to resistance (typically 10–25 m depth), and a portable horizontal arm that is attached at a fixed point to measure the distance to the substrate surface, using vertical pins (Fig. 1). Installation, maintenance and data collection require minor training, and a level of expertise already present in most of the governmental departments and non-governmental agencies with which we have interacted (Fig. 2). Total surface-height measurements have confidence intervals of ±1.3 mm (ref. 19), a figure well within the annual rate of eustatic SLR — the RSET is the only tool that can capture surface elevation change with this level of precision. RSET data are usually complemented with shallow accretionary monitoring using artificial soil marker horizons typically made of feldspar or sand, which simultaneously quantify rates of vertical surface accretion (that is, sediment deposition; Fig. 1). The complete RSET-MH set-up (hereafter referred to as 'RSET') therefore provides net surface elevation change above the benchmark depth; moreover, as it has been repeatedly shown that vertical accretion is not a valid substitute for surface elevation change[20,32,39], the complete set-up is necessary to identify the contribution of surface and shallow subsurface processes to surface elevation change at a specific site[39,40]. Repeated measurements allow chronicling of net surface elevation change, which can be integrated with region-specific relative SLR (tide-gauge data) to determine whether the surface elevation has kept pace with SLR over that time period[40–43]. Because the benchmark rod is immovable and permanently affixed into the wetland, data collection can be abandoned for significant periods of time (months to years), and resumed at any point in the future without compromising data quality. Installed RSETs have few, if any, maintenance requirements, meaning they have a potential lifespan of decades or longer. Typical survey intervals in this timescale range from 3–12 months so that the necessary temporal resolution can be captured.

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Figure 2 | RSET set-up and measurements. a, Driving an RSET rod through a mangrove soil profile. **b**, Measuring salt-marsh surface elevation with an RSET.

More than 55 studies dating back to 1993 report estimates of surface elevation change using RSET or SET (the precursor to the RSET method) stations (Table S1). The RSET method has been useful not only for documenting trends in surface elevation change in specific wetlands[40], but also for comparing rates of elevation change among hydrogeomorphic zones within a site (for example, a delta[41]), differentiating between sites dominated by surface processes[40] versus subsurface processes[14], documenting high variability in sediment deposition from singular storm events[44], capturing rapid peat collapse from small-scale (for example, lightning strikes) and large-scale (for example, hurricanes) disturbances[45,46], measuring the effects of elevated atmospheric CO_2 concentrations on surface elevation change[47], and disentangling complex interactions among herbivory, biomass production and surface elevation change[48]. RSET data have also contributed to more applied research assessing the impacts of management practices on site-specific vulnerability to SLR, such as prescribed burning[49], sedimentation from point-source coastal management interventions[50], water diversion[51], fence construction to enhance sediment deposition[52] and thin-layer deposition of dredged sediment[53]. Most recently, surface elevation change data collected by RSETs have been incorporated into estimates of carbon sequestration[54], and studies have begun to incorporate RSET data with spatial data (such as LiDAR and GIS) into spatial modelling platforms[35,36,55] to evaluate specific wetland vulnerability to SLR.

Surmountable limitations to RSET data

It is important to recognize the limitations of the RSET method, and the opportunities for complementarity with other technologies. First, there is a significant lag time between deployment and collection of sufficient data to make direct comparisons with local relative SLR. Trends in SLR are typically based on a minimum 30 to

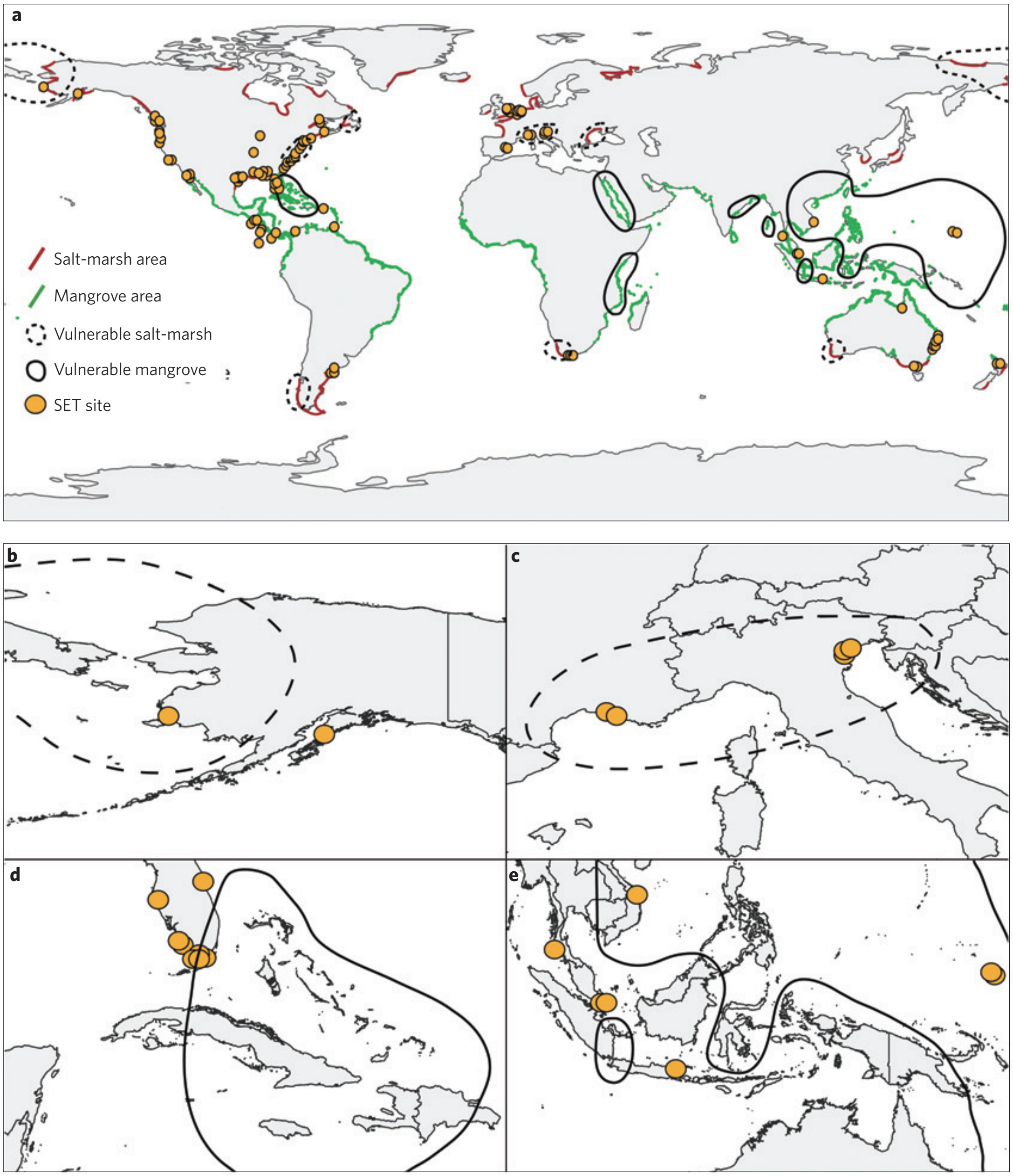

Figure 3 | Disparity in coastal wetland vulnerability and surface-elevation monitoring. a, Published global coastal wetland coverage, with wetlands hypothesized to be vulnerable to increases in relative sea-level encircled and sites of known RSET/SET locations plotted (orange circles). **b**–**e**, Examples of the current spatial overlap between vulnerable coastal wetland regions and RSET stations to monitor wetland surface elevation change in the Alaskan (**b**), north Mediterranean(**c**), Caribbean (**d**) and Asia–Pacific (**e**) regions.

70 year tide-gauge record[56,57], and RSET data sets of this duration would support direct, unqualified comparisons between long-term wetland surface elevation change and local relative SLR. This time lag heightens the need for prompt deployment. It has been our experience that qualified comparisons of RSET records of 5–10 years duration can be made with local relative SLR trends, as long as appropriate caveats about record length, variability in the documented trend and the nature of the vulnerability assessment are provided. Short-term (the minimum record length that can be used is three years) RSET data can also be analysed to discern the influences of shallow subsurface processes on elevation change. These short-term measurements of process rates (for example, sediment accretion, root expansion, belowground primary production and decomposition, autocompaction and soil shrink–swell) can be used to calibrate, parameterize and validate locally relevant models[36] to make longer-term predictions of coastal wetland response to changes in the rate of SLR. Thus, although RSET data provide direct, short-term indications of marsh resilience, modelling allows prediction at the appropriate timescales for management action[35,42,43,58].

Second, to calculate the local difference between wetland elevation change and sea-level change so that absolute site vulnerability can be compared across sites over a broad geographic area (for example, a continent), RSETs need to be levelled (referenced) into a common regional vertical datum[59]. Some industrialized countries have the infrastructure to support this referencing, including national geodetic benchmarks, tide gauges, satellite-based GPS elevation tracking systems (for example, the Continuously Operating Reference Station of the US National Oceanic and Atmospheric Administration) and a national vertical datum (such as the North American Vertical Datum of 1988). However owing to significant logistical challenges (for example, few surveying benchmarks are located in remote coastal areas), most existing RSET stations are not yet levelled, even in industrialized countries. Unlevelled RSET studies are therefore limited to assessing the relative local difference between wetland elevation change and sea-level change. Nevertheless, relative comparisons are useful for assessing differential vulnerability of specific wetlands to SLR[14,40]. Importantly, recent improvements to GPS are facilitating the development of geospatial frameworks; as vertical standards become available for specific regions in the future, previously collected local data can be calibrated, thereby making all time series linked to the same vertical datum comparable.

A third limitation is spatial in nature. RSETs provide point data, so when placed in different zones of a wetland (for example, open mudflat, shoreline or interior) they provide a broad indication of site vulnerability to SLR[60], as well as within-site heterogeneity[40]. Such information would be crucial for making fundamental management decisions locally, such as whether a site requires intervention. To draw inference from point measures for the entire site, and for upscaling from site to coastlines through modelling that uses data from an array of local sites, RSET data must be integrated into spatial datasets derived from existing mapping technologies, such as LiDAR, d/RTK-GPS and surveying. Recent successes in integrating RSET data with spatial data in models of South East Queensland and New South Wales, Australia[35,55] demonstrate how the high-precision — yet spatially limited — RSET data can be combined with lower-precision data with greater spatial coverage to make substantial advances in understanding wetland vulnerability along a coastline.

Expanding RSET coastal wetland monitoring

Although RSET stations have already been deployed in many locations around the world, the present distribution is largely the result of *ad hoc* research, has generally not been designed for integration into hierarchical assessments (with some exceptions, see below) and/or has not been designed to produce data to populate models (for example, sample sizes may be very low). We found that practically all RSET research has been case-study-oriented (Supplementary Table S1).

Coordinated regional networks exist on the northern coast of the Gulf of Mexico in the United States, and along the southeast Australian coastline, and provide a window to the immense benefits that coordinated RSET networks offer. The Coastwide Reference Monitoring System (CRMS) for the State of Louisiana, USA, established approximately 340 stations across its coastal zone, each including an elevation benchmark, tide gauge, RSET station and associated vegetation plots[61,62]. Five years of RSET data collection will allow scoring of a site's vulnerability to SLR in a 'Submergence Vulnerability Index', with vulnerable sites defined as those where the rate of elevation change is too low to offset relative SLR[63]. The southeast Australian SET network includes >100 stations, with recent research focusing on mangrove surface elevation change in relation to groundwater[64] and mangrove encroachment into salt-marshes[65]. These two examples of structured monitoring networks highlight the significant value gained by upscaling replicated, coordinated sites across a coastline. Moreover, the policy relevance of these networks will substantially increase over time. For example, the CRMS has an explicit long-term objective to monitor and evaluate the effectiveness of more than 75 restoration projects at the project, region and coast-wide levels[62], which has been mandated under the US Coastal Wetlands Planning, Protection and Restoration Act of 1990[66]. The CRMS RSET network will therefore provide quantitative evidence at several scales for assessing the degree of success of policy-mandated restoration activities.

We suggest that RSET monitoring should be expanded globally, focusing on high-priority vulnerable coastal wetlands. Site selection for expanded wetland monitoring could depend on a range of local and regional factors, however one important criterion should be whether there is an *a priori* indication of potential vulnerability to future SLR. Accurate estimates of net surface elevation change derived from RSET data could confirm whether potentially vulnerable sites are indeed vulnerable[55], and could quantify the surface and subsurface processes underlying that vulnerability to guide appropriate management interventions. We plotted the locations of known RSET sites, based on a literature review, unpublished collaborations and personal communications. We then overlaid a map of the coastal regions hypothesized to have the world's most SLR-vulnerable wetlands, defined (for mangroves[67]) as those that were not macrotidal (that is, had <4 m tidal range) and were far from a large sediment source such as a delta (this definition excludes sites vulnerable for anthropogenic reasons, such as the Mississippi and Nile deltas, although anthropogenically induced subsidence is a significant threat[68,69]). For temperate salt-marshes[70] we applied the same criteria, but excluded any regions that are experiencing tectonic uplift resulting from postglacial isostatic adjustments[71] or coseismic / interseismic uplift[72,73].

The present RSET coverage is biased towards wetlands under relatively low threat from SLR (Fig. 3). With the exception of several salt-marshes on the US Atlantic coast and South Africa, few vulnerable salt-marshes and virtually no vulnerable tropical mangroves are monitored at present with RSETs. Thus, major effort is needed to expand RSET monitoring of coastal wetlands globally, to include those at greatest risk from SLR.

Importantly, all high-priority SLR-vulnerable mangroves, with the exception of Southeast Florida, are located in developing countries, indicating a possible need for bilateral or multilateral international support for RSET monitoring; thus, it is important to evaluate the costs of this proposed expansion. Using the results from our global analysis of potentially vulnerable wetlands (Fig. 3), we calculated the baseline cost (equipment and consumables — excluding human resources or travel) of establishing a standardized, systematic RSET monitoring network in countries with potentially vulnerable coastal salt-marshes and mangroves (Supplementary Information).

The first analysis considered a 'minimal effort' design, whereby two priority sites were established per country (with some countries having several vulnerable regions), with each site consisting of four transects with 8 RSET stations each (that is, 32 RSET stations per priority site). In this scenario, 34 countries had potentially vulnerable wetlands (Indonesia, Russia and the USA had several distinct vulnerable regions), and a minimal effort monitoring network would have a baseline cost of US$36,000 per pair of priority sites, totalling about US$1.3 million globally (US$432,000 for salt-marshes and US$900,000 for mangroves; Supplementary Information and Table 2). A second analysis, performed only for mangroves, calculated the cost to establish long-term RSET sites in every vulnerable mangrove patch with an area of at least 10 km^2. In this case, global costs would be substantially higher (US$8.3 million), but more than half of the countries with potentially vulnerable mangroves could establish monitoring transects in all their patches ≥10 km^2 for less than US$500,000 (Table 2). Although developing countries would probably require external aid to accomplish this set-up, and for long-term network management, the costs are modest in the context of current and anticipated climate change spending on coastal adaptation[74]. Particularly given increased recognition that the protection of coastal ecosystems is important to national security[75], RSET monitoring may prove a relatively small, but priority investment in many countries.

Developing and managing monitoring networks

Effective coastal wetland monitoring networks require strategic, replicated installations and formalized coordination among geographically and scientifically allied sites. Figure 3 suggests a starting point for planning new regional RSET networks based on the most

SLR-vulnerable wetlands. In that scenario, regional mangrove RSET networks could be developed in the Caribbean, East Africa, the Middle East, the Indian Ocean, Southeast Asia and the Pacific, not precluding networks in less-vulnerable regions or based on other criteria such as ecology or management[61]. Each regional network would consist of 5–10 countries, each having as few as 10 RSET sites (the minimal design for five countries) to as many as 100 RSET sites (monitoring all mangrove patches >10 km^2).

Most regional networks would span several countries; therefore collaborative arrangements would be necessary to coordinate RSET expansion including integration of existing sites into structured regional networks. Regional partnerships among government agencies, academic institutions, research agencies and/or conservation organizations offer a potentially efficient, resilient mechanism for establishing RSET sites and ensuring long-term sustainable data collection. For example, at present the NOAA/ESRL/GMD Carbon Cycle Greenhouse Gas Air Sampling Network has >100 active sites, where weekly air samples for greenhouse gas analysis are collected by government agencies, academic institutions or private industry[76]. Similarly, success with a coastal wetland monitoring network would depend on significant engagement and commitment among scientists, practitioners and national climate change focal points.

Managing and sharing data would require consistent data quality standards, and would need to provide transparency, long-term data availability and security against loss. An online data-sharing portal is an obvious choice, and the Coastal Protection and Restoration Authority of Louisiana portal for surface elevation data from the CRMS is a prime example[63]. Network data could be managed by the network itself (for example, GEMSTAT[77]), coordinated by a partner (for example, UNEP-WCMC[78]) or by a private third-party (for example, iQUEST[79]).

A broad network — in terms of both geography and stakeholders — would also provide a forum for information exchange, opportunities for collaboration (network meetings, data analysis and co-publishing results), specialized technical support (for example, modelling) and outreach to policymakers. These opportunities could be gained from regional coordination, or from global coordination if regional networks are integrated into a global network. Numerous global, data-driven consortia serve as possible models, such as the United Nations Global Environment Monitoring System Water Programme[80], the Global Earthquake Model[81], the International Forestry Resources and Institutions[82] and the Center for Tropical Forest Science[83]. Although these networks vary in scale and design, they incorporate collaborations among public, private, practitioner and academic stakeholders, and offer international training opportunities and support to build local capacity and to ensure data comparability.

Policy benefits

The RSET literature so far has largely overlooked the substantive conservation or management policy implications of even single-site RSET research (with two exceptions[55,84]), and the broad policy implications of RSET networking have yet to be considered. Existing research networks have demonstrated that powerful, multi-level policy-relevant conclusions can be obtained through the adoption of standard protocols, data-sharing networks and collaborative training, analysis and interpretation[85,86]. Data that are systematically collected and made available through a collaborative network could provide significant benefits for wetland conservation, coastal planning, and climate change mitigation and adaptation policy.

RSET data can support sub-national or national wetland conservation and mitigation prioritization based on quantitative data and model-based predictions. Data from an expanded RSET network would allow governments, coastal managers, the Ramsar Convention on Wetlands Secretariat[87], the United Nations Framework Convention on Climate Change, aid agencies and non-governmental organizations to rank wetlands according to SLR vulnerability, and plan adaptation interventions and social aid accordingly. Moreover, RSET-based vulnerability analyses and wetland models supplemented with RSET data could provide realistic timelines for adaptation and possible mitigation of imperilled wetlands. This would allow policymakers to craft policies and interventions based on quantitative analyses, increasing efficiency and effectiveness of management decisions. Such broad relevance is rarely possible through a piecemeal monitoring approach, which characterizes much of the current efforts.

Table 2 | Baseline set-up costs for RSET-MH mangrove surface elevation monitoring.

	Minimum patch area (km^2)					Set-up costs, US$ thousands	
Country	All	≥1	≥5	≥10	≥20	All patches ≥10 km^2	Minimal design
East Africa and Middle East						2,340	288
Djibouti	7	4	–	–	–	90	36
Egypt	18	18	14	13	11	234	36
Eritrea	80	59	10	5	1	90	36
Kenya	30	30	30	27	17	486	36
Mozambique	29	29	29	28	27	504	36
Saudi Arabia	251	59	15	3	–	90	36
Sudan	18	17	15	13	10	234	36
Tanzania	68	66	43	34	20	612	36
Asia and the Pacific						3,906	396
Cambodia	52	40	22	15	7	270	36
China	166	50	21	10	3	180	36
Fiji	59	43	25	15	10	270	36
India (East)	42	36	33	32	27	576	36
Micronesia	365	1	–	–	–	90	36
Nicobar	33	25	22	18	9	324	36
Philippines	541	411	77	25	5	450	36
Sulawesi	57	57	54	46	35	828	36
Sumatra-Java	58	48	38	34	27	612	36
Vanuatu	38	5	1	–	–	90	36
Vietnam	14	14	14	12	12	216	36
Caribbean						2,052	216
Bahamas	201	106	44	33	22	594	36
Cuba (East)	773	190	74	50	28	900	36
Dominican Republic	17	16	16	16	14	288	36
Haiti	6	5	5	4	2	90	36
Jamaica	82	3	–	–	–	90	36
Southeast Florida (USA)	2,304	50	11	5	5	90	36
Totals				438	292	8,298	900

Number of vulnerable[67] mangrove patches above a minimum area, and costs associated with setting up RSET-MH coastal wetland surface elevation monitoring sites according to two scenarios. Scenario 1: monitoring all mangrove patches ≥10 km^2, with each patch receiving four transects consisting of four RSET-MH pairs; set-up costs for countries containing fewer than five mangrove patches ≥10 km^2 were calculated for five patches regardless of size, and with each patch receiving four transects. Scenario 2: A 'minimal design' of two priority mangrove patches, with each patch containing four transects of four RSET-MH pairs. Calculations do not include initial costs for equipment (US$3,500–5,000), human resources or travel to sites (see Supplementary Information).

Notably, improved data would allow policymakers to prioritize wetland sites for intervention and consider the costs and potential benefits of action[88,89]. Moreover, wetlands (especially mangroves) that exhibit a stable or positive relative surface elevation change status could be further prioritized for long-term conservation, restoration and reforestation programmes as stable carbon sinks[4,90,91]. RSET data that are linked with carbon accumulation data[54] would be instrumental in quantifying the incentive to rehabilitate degraded sites, including restoration of hydrological processes that would lead to positive surface elevation change and therefore carbon accumulation, which could potentially be monetized through emissions reduction programmes (for example, Reducing Emissions from Deforestation and Forest Degradation; REDD+)[92]. Finally, improved site-specific and regional datasets would provide policymakers with an indication of whether existing adaptation and engineering solutions that are available and affordable to them would be adequate for addressing SLR threats to wetland resources, and could guide future resource allocation and investment in new technologies for coastal protection.

Conclusion

Vulnerability analysis is the first step in creating an adaptation plan for coastal climate change[93]. Assessing the potential impacts of climate change on wetlands, their goods and services and accompanying coastal communities relies on credible and transparent predictions not only at the site level but also at the regional and global levels. Expansion of the RSET-MH network is an important component of assessing coastal wetland vulnerability to SLR; data derived from networks will address a large information gap in measuring wetland surface elevation change for either direct comparison with local SLR, or to parameterize site-specific or regional models. If RSET-MH networks are formalized and take design and management principles from existing data-sharing and collaborative networking models, they will contribute to increased confidence in identifying coastal wetland vulnerability, to more informed science-based policy, and to improved accuracy and efficiency of coastal conservation, mitigation and adaptation responses.

Received 12 January 2012; accepted 18 October 2012;

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Acknowledgements

E.L.W. and D.A.F. were supported by the Singapore-Delft Water Alliance, grants R303-001-001-272 and R303-001-024-414. E.L.W. was supported by Ministry of Education, Government of Singapore grant R-154-000-400-133. D.A.F. was supported by Ministry of Education, Government of Singapore grant R-109-000-141-133. K.W.K., D.R.C., and G.R.G. were supported by the USGS Climate and Land Use Change R&D Program. The Nelson Mandela Metropolitan University and the South African Environmental Observation Network provided South African RSET data points. C. Lovelock provided the location of the RSET site in Indonesia. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the US Government.

Author contributions

E.L.W., D.A.F. and K.W.K. conceptualized the paper; D.R.C., D.A.F. and G.R.G. compiled global RSET locations; D.A.F. and E.L.W. conducted the GIS and expenditure analyses, and E.L.W., D.A.F., K.W.K., D.R.C., G.R.G. and J.P. wrote the paper.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence should be addressed to E.L.W. and D.A.F.

Competing financial interests

The authors declare no competing financial interests.