Wetlands Ecol Manage (2016) 24:263–278
DOI 10.1007/s11273-015-9466-7

ORIGINAL PAPER

Can mangroves keep pace with contemporary sea level rise? A global data review

Sigit D. Sasmito · Daniel Murdiyarso · Daniel A. Friess · Sofyan Kurnianto

Received: 31 January 2015 / Accepted: 14 October 2015 / Published online: 20 October 2015

Abstract Coastal vegetated wetlands such as mangrove forests provide multiple ecosystem services, though are potentially threatened by contemporary accelerated sea level rise (SLR), in addition to other immediate threats such as agriculture and coastal development. Several studies have revealed that mangroves are able to adapt to, and keep pace with local relative SLR through vertical surface elevation change (SEC), however data are lacking, with often only surface accretion rate (SAR) data available. We systematically review published studies of SEC and SAR from globally distributed monitoring sites using meta-analysis, and compare them with the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5) SLR scenarios. Hydro-geomorphic setting plays an important role, with basin mangroves potentially less vulnerable to SLR through land building processes. We find that SAR in both basin and fringe mangroves can cope with low SLR scenario (RCP 2.6) throughout the 100 years projection period. However, SAR can only keep pace with high SLR scenario (RCP 8.5) up to year 2070 and 2055 in basin and fringe mangrove settings respectively. These were associated with potential sediment accumulation of 41 cm and 29 cm respectively from the baseline. Mangrove degradation promoted lowering trends of SEC, while mangrove management such as rehabilitation practice stimulated positive trends of SEC. Mangrove ecosystems may be vulnerable to contemporary SLR in small island locations such as the Caribbean, East Africa and parts of the Indo-Pacific that are dominated by fringe mangroves and where SEC cannot keep pace with both low and high IPCC AR5 SLR scenarios. A global expansion of current mangrove surface elevation monitoring effort is urgently needed in order to better assess the vulnerability of mangroves, and the factors affecting their resiliency in the face of rising sea levels.

Keywords Hydro-geomorphic · Restoration · Sediment availability · Sediment deposition · Surface elevation change · Surface accretion · Wetland

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Electronic supplementary material The online version of this article (doi:10.1007/s11273-015-9466-7) contains supplementary material, which is available to authorized users.

S. D. Sasmito (✉) · D. Murdiyarso · S. Kurnianto
Center for International Forestry Research (CIFOR), Jalan CIFOR, Situ Gede, Sindang Barang, Bogor 16115, Indonesia
e-mail: s.sasmito@cgiar.org

D. Murdiyarso
Department of Geophysics and Meteorology, Bogor Agricultural University, Darmaga Campus, Bogor 16680, Indonesia

D. A. Friess
Department of Geography, National University of Singapore, 1 Arts Link, Singapore 117570, Singapore

S. Kurnianto
Department of Fisheries and Wildlife, Oregon State University, Corvallis, OR 97331, USA

Introduction

Mangrove forests are a pan-tropical coastal wetland ecosystem, providing numerous ecological services such as fish nursery functioning, coastline protection, carbon storage and erosion control (Barbier et al. 2011; Lee et al. 2014). However, multiple stressors potentially threaten this intertidal ecosystem. More than half of the world's mangrove area has been lost during the past three decades (FAO 2007), predominantly due to mangrove deforestation for urban, agricultural and aquacultural expansion (Giri and Muhlhausen 2008; Giri et al. 2008, 2015). Mangroves are also facing threats due to climate change, especially sea level rise (Gilman et al. 2007; Ellison 2014). To a lesser extent, mangroves are also threatened by a predicted increasing frequency and magnitude of extreme events such as tropical storms (Cahoon et al. 2003; Alongi 2008).

Contemporary global sea levels are expected to rise substantially in the coming century (Cazenave and Llovel 2010; Church and White 2011). In the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), global mean sea level was projected to rise by between 0.52 and 0.98 m by 2100 under several Representative Concentration Pathway (RCP) scenarios (IPCC 2013). SLR is expected to have substantial impacts on the coastal zone at local to regional scales, and coastal adaptive capacity needs greater assessment (Nicholls and Cazenave 2010). Coastal wetlands such as mangroves are threatened by SLR (Gilman et al. 2007), as increasing tidal inundation period and frequency pushes vegetation beyond species-specific thresholds of flooding tolerance (Ball 1988; Friess et al. 2012). Mangroves may adapt to rising sea levels through surface accretion rates (SAR), which is the process of sediment accumulation on the surface, and positive surface elevation change (SEC), which is the culmination of several biotic and abiotic processes (Krauss et al. 2010; Lovelock et al. 2010; McKee 2011; Krauss et al. 2014). The difference between SAR and SEC represents the proportion of sub-surface change (SSC), which can be positive due to root biomass production, or negative due to compaction, or subsidence caused by organic matter decomposition (Cahoon and Lynch 1997; McKee 2011). When compared with SLR, these processes all contribute to a wetland's elevation capital, which determines whether a wetland is experiencing accretionary surplus or deficit, and ultimately its submergence potential (Cahoon 2014).

To evaluate small changes in mangrove soil surface elevation, the field-based high precision Rod Surface Elevation Table and Marker Horizon (RSET-MH) method has been progressively developed (Boumans and Day 1993; Cahoon and Lynch 1997; Cahoon et al. 2002). The RSET requires the installation of a solid steel rod benchmark that is driven to refusal (e.g. bed rock or consolidated basement sediments), upon which a leveled arm can measure SEC in relation to this stable datum. The RSET is often coupled with a feldspar clay or sand marker horizon (MH), which is placed on the surface to measure SAR by the depth of accumulated sediment. This method has been extensively used in coastal wetlands, especially in the US, Europe and Australia (e.g., Day et al. 1999; Morris et al. 2002; Rogers et al. 2006; Lovelock et al. 2011; Spencer et al. 2012), and is a higher resolution and more cost-effective method compared to other field- and satellite-based elevation monitoring techniques (Webb et al. 2013). However, there are very few studies using RSET-MH method in tropical mangrove systems, especially those most vulnerable to SLR, such as the Caribbean, East Africa and parts of the Indo-Pacific (Alongi 2008; Webb et al. 2013). This is due to multiple reasons, including lack of funding, poor knowledge exchange between researchers, lack of associated infrastructure (including geodetic benchmarks and national vertical datums) and logistical challenges in accessing and repeatedly monitoring remote field locations (Webb et al. 2013).

In this study we evaluated mangrove surface elevation dynamics measured by the RSET-MH method, in the context of rising sea levels. We conducted a meta-analysis on previously published RSET-MH studies from around the world, and projected trends of mangrove SEC and SAR against recent IPCC AR5 scenarios of long-term SLR under two contrasting low and high RCP scenarios. This study updates previous understanding on global coastal wetland vulnerability to relative SLR (Cahoon et al. 2006), by providing more comprehensive data and analysis focused on mangroves specifically and comparing SEC with new SLR projections. Furthermore, we identified current study gaps in order to broaden the RSET-MH method for mangrove vulnerability monitoring. The possibility of using different methods to monitor mangrove surface elevation and implications for mangrove management practices are also discussed.

Materials and methods

Literature survey and data collation

In August 2014 we conducted a comprehensive literature survey through the ISI Web of Science (Thompson Reuters), Google Scholar, Mendeley, the United States Geological Survey Patuxent Wildlife Research Center (USGS-PWRC) website, and a RSET-MH database compiled by Webb et al. (2013), to identify peer-reviewed data articles that measured SEC and SAR in mangrove forests. We used structured topics and the following keyword string:

TOPIC: (((MANGROVE* OR COAST* OR WETLAND*) AND (SEDIMENT* OR SURFACE ELEVATION OR ACCRETION RATE*) AND (ESTUARY OR RIVERINE OR FRINGE OR TRANSITION OR OVERWASH OR DWARF OR SCRUB))).

In total, we found 1379 relevant studies for all publication dates using the above search strings. We applied general literature review screening steps including title, abstract and full text reading in order to collate an appropriate database for meta-analysis, following Ilstedt et al. (2007). During the literature selection, we focused on SEC and SAR studies in tropical mangrove ecosystems and excluded subtropical coastal wetland and salt marshes. The final database consisted of 19 peer-reviewed publications, measuring SEC and SAR in 74 study locations from throughout the world as summarized in Table 1 and mapped in Fig. 1. Each location was defined by its hydro-geomorphological setting, dominant species and study site condition and length of monitoring periods.

Meta-analysis: the effect of hydro-geomorphic setting

Meta-analysis was employed to investigate statistical differences between the two independent variables SEC and SAR. Following meta-analysis requirements, we used three basic statistical properties: sample mean, standard deviation and number of study replicates. We used 41 data points instead of all 74 points in the dataset as meta-analysis input, since some of studies did not present data on either basic statistical properties or hydro-geomorphic setting. We chose raw mean difference (D), which defines one of the effect size in meta-analysis procedures (Borenstein et al. 2009). In addition, D allows an intuitively meaningful scale of meta-analysis outcome since SEC and SAR in all studies used the same scale or unit. In this case, D denotes SSC, or the difference between SEC and SAR. Comprehensive Meta-Analysis Version 2.2.064 was used to calculate D and standard error of D (SE_D), which are defined as:

$$D = X_1 - X_2$$

$$SE_D = \sqrt{\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}}$$

where X_1 and X_2 denotes sample mean, n_1 and n_2 are sample size for SEC and SAR, and S_1 and S_2 are standard deviation for SEC and SAR respectively (Biostat, Englewood, NJ 2011). Negative D values denote that SEC is lower than SAR, meaning that the mangrove surface subsides, while positive D values indicate that belowground expansion processes are taking place. All coastal wetland variables used in this study were summarized in Table 2.

All statistical tests in the meta-analysis were considered significant at the 95 % confidence level. Once D had been calculated, we performed Cohran's Q heterogeneity test in order to determine the use of either a fixed-effects (for statistically non-significant heterogeneity) or random-effects model (for significant heterogeneity). Under random-effects model we allowed the true effect size to vary across studies (Borenstein et al. 2009). We performed meta-analysis based on different mangrove hydro-geomorphic settings (basin and fringe mangroves) following Lugo and Snedaker (1974) in order to assess their vulnerability to SLR.

Table 1 Summary of most recent published studies showing measured SEC and SAR values across different mangrove hydrogeomorphic settings and disturbances

No.	Site	Hydro-geomorphic setting	Dominant species	Study condition	Surface elevation change			Surface accretion rates			Monitoring period (year)	Meta-analysis code	Reference
					Mean (mm year^{-1})	SD	N	Mean (mm year^{-1})	SD	N			
1	Rookery Bay, Florida, USA	Fringe	*R. mangle*	Pristine	1.4	0.1		7.2	0.0		2	FR-01	Cahoon and Lynch (1997)
2	Rookery Bay, Florida, USA	Basin	*A. germinans*	Pristine	3.7	0.1		6.0	0.1		2.5	BA-01	Cahoon and Lynch (1997)
3	Rookery Bay, Florida, USA	Overwash forests	*R. mangle*	Pristine	2.5	0.1		6.3	0.1		2	OV-01	Cahoon and Lynch (1997)
4	Rookery Bay, Florida, USA	Overwash forests	*R. mangle*	Pristine	0.6	0.1		4.4	0.0		2	OV-02	Cahoon and Lynch (1997)
5	Guanaja and Roatan, Honduras	Fringe	*R. mangle*	Storm impacted	9.9			14.0			1.2	FR-02	Cahoon et al. (2003)
6	Guanaja and Roatan, Honduras	Fringe	*R. mangle*	Storm impacted	4.8			2.0			1.2	FR-03	Cahoon et al. (2003)
7	Guanaja and Roatan, Honduras	Fringe	*R. mangle*	Storm impacted	4.8			2.0			1.2	FR-04	Cahoon et al. (2003)
8	Guanaja and Roatan, Honduras	Basin	*R. mangle*	Storm impacted	−9.5			2.0			1.2	BA-02	Cahoon et al. (2003)
9	Guanaja and Roatan, Honduras	Basin	*R. mangle*	Storm impacted	−9.2			2.0			1.2	BA-03	Cahoon et al. (2003)
10	Guanaja and Roatan, Honduras	Basin	*R. mangle*	Storm impacted	4.8			2.0			1.2	BA-04	Cahoon et al. (2003)
11	Homebush Bay, Australia	Basin	*A. marina*	Urban development	2.0	0.7	2	1.3	0.2	2	3.6	BA-05	Rogers et al. (2005)
12	Homebush Bay, Australia	Basin	*A. marina*	Urban development	3.5	1.0	2	2.5	0.5	2	3.6	BA-06	Rogers et al. (2005)
13	Homebush Bay, Australia	Basin	*A. marina*	Pristine	6.2	2.4	2	4.9	0.5	2	3.6	BA-07	Rogers et al. (2005)
14	Shark River, Florida, USA	Basin	*R. mangle*	Pristine	0.9			6.6				BA-08	Whelan et al. (2005)
15	Shark River, Florida, USA	Basin	*R. mangle*	Pristine	3.6			6.6				BA-09	Whelan et al. (2005)
16	Ukerebagh Island, Tweed River, Australia	Basin	*R. stylosa*	Pristine	2.4	2.4	3	2.2	0.7	6	3.5	BA-10	Rogers et al. (2006)
17	Kooragang Island, Hunter River, Australia	Basin	*A. marina*	Pristine	2.0	0.9	3	4.7	0.1	6		BA-11	Rogers et al. (2006)
18	Minnamurra River, Australia	Basin	*A. marina*	Pristine	0.6	0.8	3	6.6	1.3	6	1.5	BA-12	Rogers et al. (2006)
19	Cararma Inlet, Jervis Bay, Australia	Basin	*A. marina*	Pristine	−0.8	1.7	3	3.0	1.0	6	2.0	BA-13	Rogers et al. (2006)
20	Currambene Creek, Jervis Bay, Australia	Basin	*A. marina*	Pristine	0.3	3.5	3	0.7	0.8	6	3.0	BA-14	Rogers et al. (2006)
21	French Island, Western Port Bay, Australia	Fringe	*A. marina*	Pristine	−2.1	2.9	3	9.5	6.6	6	3.5	FR-05	Rogers et al. (2006)

Table 1 continued

No.	Site	Hydro-geomorphic setting	Dominant species	Study condition	Surface elevation change			Surface accretion rates			Monitoring period (year)	Meta-analysis code	Reference
					Mean (mm $year^{-1}$)	SD	N	Mean (mm $year^{-1}$)	SD	N			
22	Koowerup, Western Port Bay, Australia	Fringe	*A. marina*	Pristine	0.0	3.9	3	7.2	2.1	6	3.5	FR-06	Rogers et al. (2006)
23	Quail Isalnd, Western Port Bay, Australia	Fringe	*A. marina*	Pristine	−2.6	3.6	3	6.8	1.9	6	3.5	FR-07	Rogers et al. (2006)
24	Rhyll, Western Port Bay, Australia	Fringe	*A. marina*	Pristine	0.9	3.2	3	5.1	1.8	6	3.5	FR-08	Rogers et al. (2006)
25	Big Sable Creek, Florida, USA			Storm impacted	4.0			1.0				NA	Cahoon (2006)
26	Shark River, Florida, USA			Storm impacted	48.0			77.0				NA	Cahoon (2006)
27	South West Florida, USA			Storm impacted	−20.0							NA	Cahoon (2006)
28	Guanaja, Honduras			Storm impacted	−9.0			2.0				NA	Cahoon (2006)
29	Twin Cays, Belize	Basin	*R. mangle*	Pristine	−3.7	1.7	3	0.7	0.5	3	3.0	BA-15	McKee et al. (2007)
30	Twin Cays, Belize	Basin	*R. mangle*	Pristine	−5.8	2.8	3	2.2	2.1	3	3.0	BA-16	McKee et al. (2007)
31	Twin Cays, Belize	Basin	*R. mangle*	Nutrient enrichment	4.8	1.7	3	3.5	0.2	3	3.0	BA-17	McKee et al. (2007)
32	Twin Cays, Belize	Basin	*R. mangle*	Nutrient enrichment	−1.1	2.6	3	2.0	2.3	3	3.0	BA-18	McKee et al. (2007)
33	Twin Cays, Belize	Basin	*R. mangle*	Pristine	2.2	2.8	3	1.8	1.6	3	3.0	BA-19	McKee et al. (2007)
34	Twin Cays, Belize	Basin	*R. mangle*	Nutrient enrichment	4.4	3.3	3	1.7	0.5	3	3.0	BA-20	McKee et al. (2007)
35	Twin Cays, Belize	Fringe	*R. mangle*	Nutrient enrichment	4.1	3.8	3	1.6	1.2	3	3.0	FR-09	McKee et al. (2007)
36	Twin Cays, Belize	Fringe	*R. mangle*	Pristine	0.1	2.6	3	2.1	2.1	3	3.0	FR-10	McKee et al. (2007)
37	Twin Cays, Belize	Fringe	*R. mangle*	Nutrient enrichment	1.6	1.2	3	2.8	1.7	3	3.0	FR-11	McKee et al. (2007)
38	Shark River, Florida, USA	Basin	*R. mangle*	Pristine	1.4	11.7	9	6.5	3.6	9	3.3	BA-21	Whelan et al. (2009)
39	Shark River, Florida, USA	Basin	*R. mangle*	Storm impacted	6.2	14.7	9	11.5	11.7	9	3.5	BA-22	Whelan et al. (2009)
40	Hunter Estuary, NSW, Australia	Fringe	*A. marina*	Rehabilitated	2.5			3.7			6	FR-12	Howe et al. (2009)
41	Hunter Estuary, NSW, Australia	Fringe	*A. marina*	Pristine	3.3			1.9			6	FR-13	Howe et al. (2009)
42	Tauranga Harbour, New Zealand	Riverine	*A. marina*	Cleared	−14.0						1	RI-01	Stokes et al. (2010)
43	Tauranga Harbour, New Zealand	Riverine	*A. marina*	Pristine	3.0						1	RI-02	Stokes et al. (2010)
44	Yela River, Kosrae, FSM	Fringe	*R. apiculata*	Pristine	−3.0	2.0	6	11.6	3.9	9	3	FR-14	Krauss et al. (2010)
45	Yela River, Kosrae, FSM	Basin	*R. apiculata*	Pristine	−2.7	1.5	6	12.9	6.3	9	3	BA-23	Krauss et al. (2010)
46	Yela River, Kosrae, FSM	Basin	*R. apiculata*	Pristine	1.3	1.7	6	12.0	3.6	9	3	BA-24	Krauss et al. (2010)

Table 1 continued

No.	Site	Hydro-geomorphic setting	Dominant species	Study condition	Surface elevation change			Surface accretion rates			Monitoring period (year)	Meta-analysis code	Reference
					Mean (mm $year^{-1}$)	SD	N	Mean (mm $year^{-1}$)	SD	N			
47	Utwe River, Kosrae, FSM	Fringe	*R. apiculata*	Urban development	1.2	0.7	6	11.9	5.1	9	3	FR-15	Krauss et al. (2010)
48	Utwe River, Kosrae, FSM	Basin	*R. apiculata*	Urban development	6.3	1.2	6	18.7	6.6	9	3	BA-25	Krauss et al. (2010)
49	Utwe River, Kosrae, FSM	Basin	*R. apiculata*	Urban development	1.3	0.5	6	12.9	12.9	9	3	BA-26	Krauss et al. (2010)
50	Enipoas River, Pohnpei, FSM	Fringe	*R. apiculata*	Pristine	−5.8	2.2	6	6.6	9.3	9	1.4	FR-16	Krauss et al. (2010)
51	Enipoas River, Pohnpei, FSM	Basin	*R. apiculata*	Pristine	−1.4	5.4	6	6.3	2.7	9	1.4	BA-27	Krauss et al. (2010)
52	Enipoas River, Pohnpei, FSM	Basin	*R. apiculata*	Pristine	−2.8	1.0	6	2.9	4.2	9	1.4	BA-28	Krauss et al. (2010)
53	Sapwalap River, Pohnpei, FSM	Fringe	*R. apiculata*	Pristine	−2.3	1.5	6	4.1	4.5	9	1.4	FR-17	Krauss et al. (2010)
54	Sapwalap River, Pohnpei, FSM	Basin	*R. apiculata*	Pristine	−0.6	2.0	6	14.1	5.1	9	1.4	BA-29	Krauss et al. (2010)
55	Sapwalap River, Pohnpei, FSM	Basin	*R. apiculata*	Pristine	0.9	1.2	6	8.2	3.6	9	1.4	BA-30	Krauss et al. (2010)
56	Pukusruk, Kosrae, FSM	Basin	*R. apiculata*	Urban development	0.9	1.0	6	20.8	7.2	9	1.4	BA-31	Krauss et al. (2010)
57	Twin Cays, Belize	Fringe	*R. mangle*	Pristine	4.1	3.9	3	1.6	1.2	3	3.5	FR-18	McKee (2011)
58	Rookery Bay, Florida, USA	Basin	*A. germinans*	Pristine	3.9	1.6	3	2.0	0.6	3	3.0	BA-32	McKee (2011)
59	Rookery Bay, Florida, USA	Basin	*A. germinans*	Pristine	1.1	2.0	5	7.6	2.1	5	3.0	BA-33	McKee (2011)
60	Rookery Bay, Florida, USA	Fringe	*R. mangle*	Pristine	0.6	4.1	5	5.7	1.7	5	3.0	FR-19	McKee (2011)
61	Rookery Bay, Florida, USA	Basin	*R. mangle*	Rehabilitated	9.9	0.9	3	6.0	0.8	3	3.0	BA-34	McKee (2011)
62	Twin Cays, Belize	Scrub	*R. mangle*	Pristine	−1.1	1.5		2.0	1.3		3.5	SC-01	McKee (2011)
63	Twin Cays, Belize	Dwarf	*R. mangle*	Pristine	−3.7	1.0		0.7	0.3		3.5	DW-01	McKee (2011)
64	Moreton Bay, Queensland, Australia	Riverine	*A. marina*	Pristine	5.9			8.5			4	RI-03	Lovelock et al. (2011)
65	Moreton Bay, Queensland, Australia	Riverine	*R. stylosa*	Pristine	1.4			9.6			4	RI-04	Lovelock et al. (2011)
66	Minnamurra River, Australia	Basin	*A. marina*	Pristine	0.6						9	BA-35	Oliver et al. (2012)
67	Moreton Bay, Queensland, Australia	Basin	*A. marina*	Pristine	4.1			3.7			4	BA-36	Lovelock et al. (2013)
68	Tweed River (Ukerebagh Island), Australia	Basin	*A. marina*	Pristine	1.4						12	BA-37	Rogers et al. (2014)

Table 1 continued

No.	Site	Hydro-geomorphic setting	Dominant species	Study condition	Surface elevation change			Surface accretion rates			Monitoring period (year)	Meta-analysis code	Reference
					Mean (mm year^{-1})	SD	N	Mean (mm year^{-1})	SD	N			
69	Gazi Bay, Kenya	Basin	*R. mucronata*	Pristine	4.2	1.4	5.0	6.4	1.4	5	2.5	BA-38	Lang'at et al. (2014)
70	Gazi Bay, Kenya	Basin	*R. mucronata*	Cleared	−32.1	8.4	5.0	5.2	4.6	5	2.5	BA-39	Lang'at et al. (2014)
71	Moreton Bay, Queensland, Australia	Riverine	*A. marina*	Pristine	2.5			3.2			4	RI-05	Lovelock et al. (2015)
72	Moreton Bay, Queensland, Australia	Riverine	*A. marina*	Pristine	2.4			4.8			4	RI-06	Lovelock et al. (2015)
73	Moreton Bay, Queensland, Australia	Riverine	*R. stylosa*	Pristine	0.1			3.0			4	RI-07	Lovelock et al. (2015)
74	Moreton Bay, Queensland, Australia	Riverine	*R. stylosa*	Pristine	2.4			6.5			4	RI-08	Lovelock et al. (2015)

SD standard deviation, *N* number of replicates within study location

All data were measured by using RSET-MH method, except a study in Africa by Lang'at et al. (2014) used combination of two meter shallow rods and marker horizon

Fig. 1 Geographical distribution of literature study sites, in North America and Caribbean (34 studies), East Africa (2 studies), Australia (23 studies), New Zealand (2 studies) and the Federated States of Micronesia (FSM) with 13 studies

Table 2 Summary of the terminology description used in this study

Variable	Description	Reference
Surface accretion rate (SAR)	Low rates of coastal wetland vertical surface accumulation brought by the contribution of surficial sedimentation (sediment deposition and surface root growth and measured by marker horizon (MH)	Cahoon and Lynch (1997)
Surface elevation change (SEC)	Low rates of coastal wetland vertical surface elevation caused by contribution of vertical accretion and sub-surface change processes such as compaction, decomposition and shrink-swell, and measured by Rod Surface Elevation Table (RSET)	Cahoon and Lynch (1997)
Sub-surface change (SSC)	Rates of sub-surface subsidence or expansion were calculated as the difference between surface accretion rates and surface elevation change measured by RSET-MH	Cahoon et al. (1995)
Hydro-geomorphic setting	The formation and physiognomy of mangroves controlled by local tidal characteristic and terrestrial surface hydroperiod. There are five mangrove hydro-geomorphically structured, which are fringe, riverine, overwash forest, basin and dwarf mangroves	Lugo and Snedaker (1974)
Sea level rise (SLR)	Long-term changes of increasing relative sea level brought about by an alteration to the volume of the world ocean	IPCC (2013)

Statistical analysis: the effect of management practices and stressors

We further evaluated how SEC and SAR varied across study site conditions under different management controls and anthropogenic stressors, using all 74 points in the dataset. Shapiro–Wilk tests suggested that the data were not normally distributed, so a non-parametric Kruskal–Wallis H test was used to assess the significance of SEC and SAR across six study conditions, namely cleared, pristine mangroves, urban development impacted, nutrient enrichment, storm disturbed and rehabilitated mangroves. Data points were assigned to each category based on descriptions of each stressor and management practice in the original papers. Due to a lack of information on each site and each stressor, it is assumed that the stressor listed in each paper is acting in isolation and does not interact cumulatively, synergistically or antagonistically, which may potentially occur in the complex intertidal environment where coastal wetlands are found (Darling et al. 2010; Friess et al. 2015). Both Shapiro–Wilk and Kruskal–Wallis H tests were performed using IBM SPSS Statistics 19.0 (IBM Corp, Armonk, NY 2010).

Surface elevation projection under SLR scenarios

In order to evaluate the potential long term future stability of coastal mangrove ecosystems we compared projected SEC and SAR against SLR under RCP scenarios of the IPCC AR5. In the IPCC AR5, four scenarios of SLR including RCP 2.6 (low SLR), RCP 4.6 and RCP 6.0 (medium SLR), and RCP 8.5 (high SLR) were simulated from various global dynamic process-based factors such as thermal expansion, glacier melt, ice sheet melt and land water storage changes until the year 2100 (IPCC 2013). Assuming that SEC and SAR changes are constant over time (which may not be a valid assumption in locations experiencing rapid development and fluvial modification), both variables were projected and compared against the changing SLR based on the IPCC RCP 2.6 and RCP 8.5 for low and high scenarios respectively. The long-term vulnerability of each mangrove hydro-geomorphic setting was also evaluated using projected SEC instead of SAR as suggested by Cahoon and Lynch (1997). All SEC and SAR projections used the same data points that were used in meta-analysis. Upper and lower limit of projections were calculated from study variance aggregation for SEC and SAR.

Results

Meta-analysis results of hydro-geomorphic setting effects

The *Forrest plot* of the meta-analysis indicates that the overall value of D effect size (denoted by filled circles) was (-4.777 ± 0.728) (Fig. 2). Further analysis depicted that mean D value in fringe mangrove was slightly lower (-5.857 ± 1.285) than basin mangrove (-4.286 ± 0.852) (Supplementary Table S1). The analyzed data were significantly heterogeneous with $Q = 504.847$, $I^2 = 92.077$ ($df = 40$; $p < 0.001$), thus there was pronounced variance between individual studies that has to be considered. This suggests that making a random-effects model in the meta-analysis calculation more suitable than a fixed-effects model (Borenstein et al. 2009).

SEC and SAR characteristics across selected study conditions

SEC and SAR characteristics varied depending on management regime, e.g. cleared or rehabilitated mangroves (Table 3). We found a significant different trends of SEC as response from across different mangrove management and stressor types ($p = 0.028$), however, there were no significant variations of SAR data ($p = 0.141$). We observed positive mean SEC rates in major mangrove conditions, however a negative mean SEC rate of -23.05 mm year^{-1} occurred in cleared mangrove studies. Alternatively, mangrove management efforts such as ecosystem rehabilitation contributed to gains in elevation by up to 6.19 mm year^{-1} through belowground expansion (SSC), and surface accretion (SAR) by 1.38 and 4.82 mm year^{-1} respectively. We identified substantial SAR of as much as 11.55 mm year^{-1} in storm-disturbed systems, and 10.50 mm year^{-1} of SAR in upstream urban development-impacted mangrove study sites.

Comparison of projected SEC and SAR with IPCC AR5 SLR scenarios

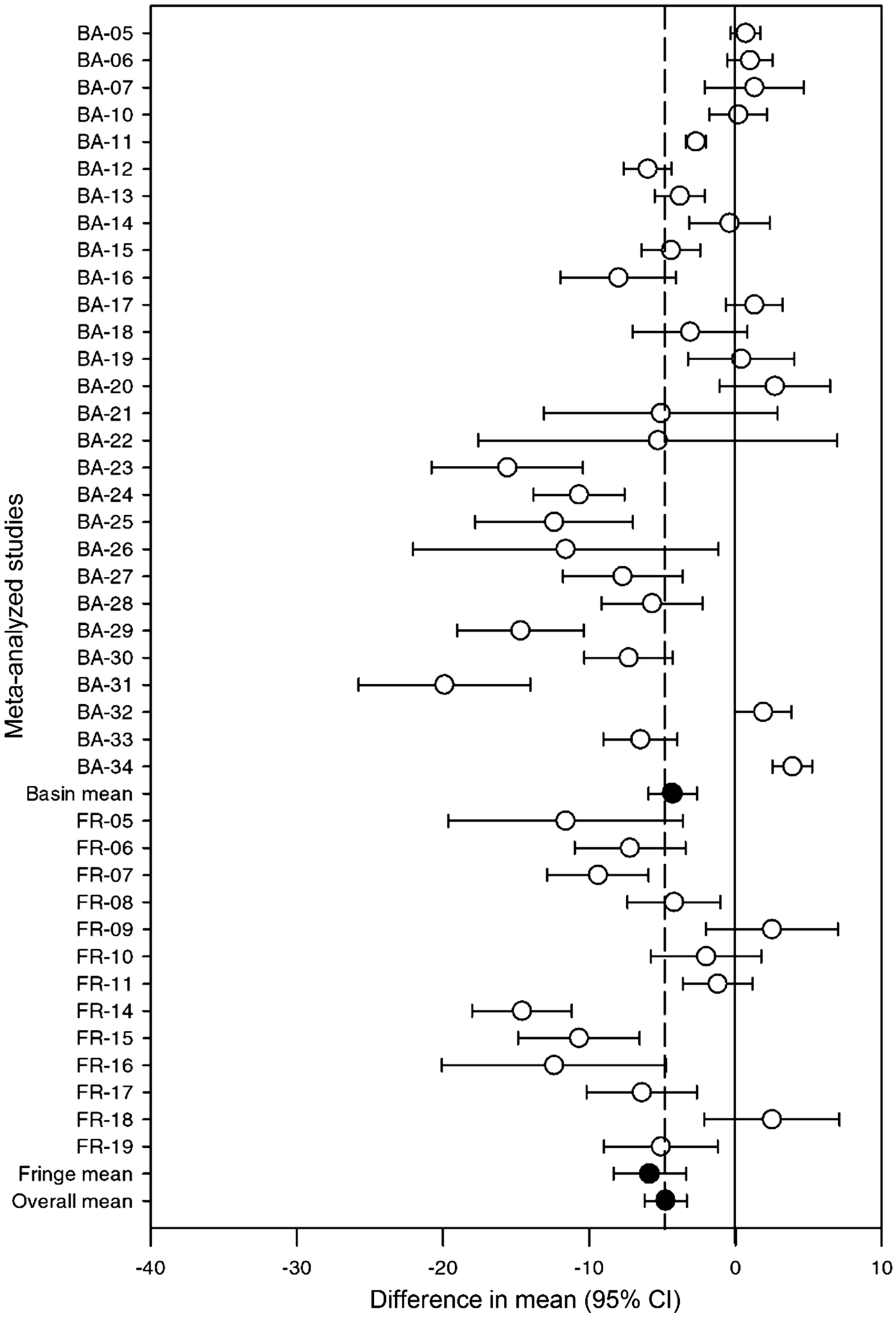
Figure 3 shows the projection of SEC and SAR from fringe and basin mangroves, with their respective variance over the 100 year period and compared with the IPCC AR5 low and high SLR scenarios (RCP 2.6 and RCP 8.5 respectively). In basin mangroves, represented by Fig. 3a, b, mean positive SEC is lower than both RCP 2.6 and 8.5 SLR scenarios, however SAR was greater than the low AR5 scenario throughout the period, and up to year 2070 in high scenario when vertical sediment was accumulated as much as 41 cm from the baseline (see panel b). SAR could only keep pace with the RCP 8.5 SLR scenario until the year 2055, at the level of 29 cm (Fig. 3d). Fringe mangrove sites sank as low as -2.39 cm below the baseline towards the end of the projection.

Discussion

Factors affecting mangrove stability in the face of SLR

Mangrove vulnerability to different SLR scenarios depends substantially on SEC dynamics, SAR driven by sediment inputs in minerogenic settings (SAR) and belowground processes (SSC). When these variables are monitored independently, as with the RSET-MH technique, a series of relationships where SEC = SAR,

Fig. 2 Summary of meta-analysis showing difference in means (*D*) with their statistical properties and *Forrest plot*. *Small solid circles* denote *D* values of basin mangroves, *large solid circles* denote *D* values of fringe mangrove, *hollow diamonds* denote mean *D* values of hydro-geomorphic settings, *solid diamond* denotes overall mean *D*



SEC < SAR, and SEC > SAR as described by Cahoon (2006) can be derived (Table 1). These different situations are strongly influenced by mangrove plant interactions with hydro-geomorphic and climatic processes to maintain soil surface elevation (Krauss et al. 2014). Meanwhile, biophysical aspects including biotic processes of root production and benthic mat formation also control SEC and SAR (McKee 2011). Furthermore, seasonal sea level characteristics and turbidity also contribute to controlling mangrove SEC and accretion (Lovelock et al. 2015).

Based on the presented meta-analysis, SSC varied between -19.90 and 3.96 mm year^{-1} (Fig. 2). The broad range of SSCs reported are a result of the wide

Table 3 The comparison of SEC and SAR trends across all identified mangrove condition studies

Management and stressor types	SEC (mm year^{-1})	SAR (mm year^{-1})
Cleared	−23.05 ± 9.05 (2)	5.20 (1)
Pristine mangroves	0.70 ± 0.40 (48)	5.49 ± 0.49 (45)
Urban development	2.52 ± 0.84 (6)	11.35 ± 3.29 (6)
Nutrient enrichment	2.76 ± 1.12 (5)	2.32 ± 0.36 (5)
Storm impacted	3.16 ± 5.28 (11)	11.55 ± 7.41 (10)
Rehabilitated	6.19 ± 3.74 (2)	4.82 ± 1.16 (2)

All data are reported as mean ± SE (N)

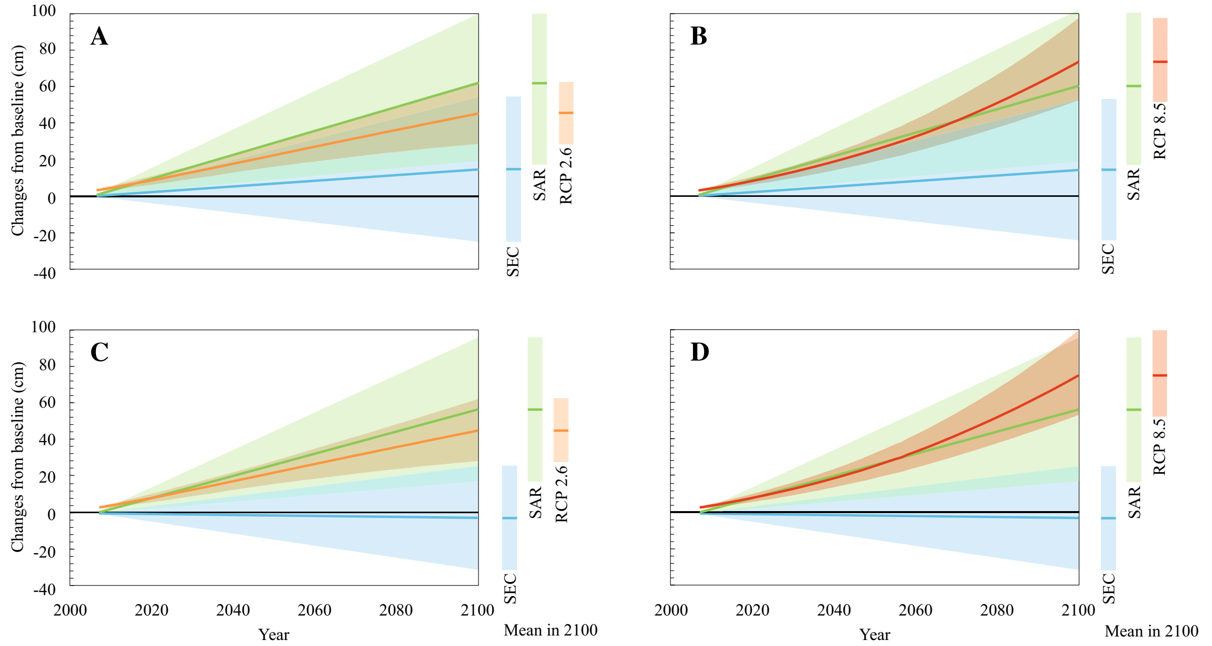


Fig. 3 The projection of SEC (*blue*) and SAR (*green*) in basin mangroves (**a**, **b**) and fringe mangroves (**c**, **d**) over 100 years. The trends are compared against the IPCC AR5 low SLR scenario (RCP 2.6, *pink*; **a**, **c**) and high SLR scenario (RCP 8.5, *red*; **b**, **d**) over the same period

variation of SEC from all published data (from −5.8 to 9.93 mm year^{-1}) and SAR (from 0.65 to 18.70 mm year^{-1}). This is to be expected, as the global dataset used in this meta-analysis covers a range of climatic, sedimentological and hydro-geomorphic settings. In addition, different sites are affected by anthropogenic forcings to varying degrees. Extreme negative SSC (subsidence) was shown at Kosrae, Federated States of Micronesia (Krauss et al. 2010), which experienced forest disturbance due to urban development causing severe subsidence. In contrast, the highest SSC was demonstrated at Rookery Bay, Florida (McKee 2011) after mangrove restoration, and at Twin Cays, Belize (McKee et al. 2007) due to application of fertilizer which enhanced root biomass production. Some sites, such as Shark River, Florida (Whelan et al. 2009) demonstrated variable SSC due to the influence of Hurricane Wilma in 2005, where substantial sediment deposition and woody debris contribution were observed. To evaluate the vulnerability of coastal wetlands in the context of contemporary global SLR, it is important, therefore, to estimate SSC in addition to observable sediment accumulation (Cahoon and Lynch 1997; Whelan et al.

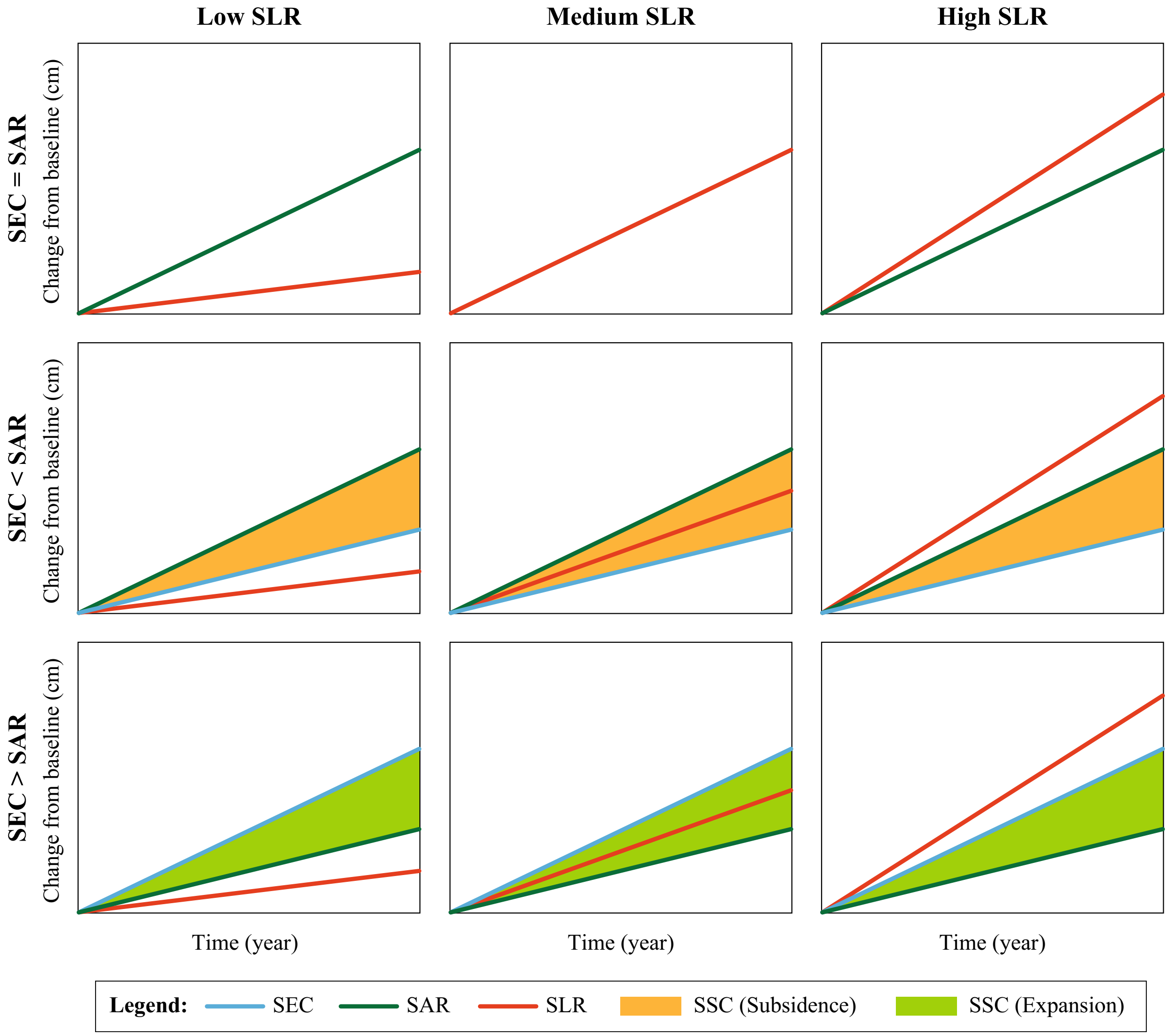


Fig. 4 Possible sub surface expansion and subsidence indicating coastal vulnerability under three different hypothetical SLR scenarios. *Top panels* represent situation with no sub surface change; *middle panels* represent situations when the surface subsides (*orange area*); *bottom panels* represent situation when the surface expands (*green area*)

2005). Net SEC may be driven over the long term by extreme events such as storms (Whelan et al. 2009), while natural and anthropogenic disturbances and concomitant belowground root mortality in organogenic systems can result in peat oxidation and rapid subsidence (Table 3) (Cahoon et al. 2003; Krauss et al. 2010; Lang'at et al. 2014).

By using three SLR scenarios, i.e. low, medium and high rates, the possible situation of SEC = SAR, SEC < SAR, and SEC > SAR may be hypothetically reviewed in Fig. 4. When SEC is only affected by SAR (SEC = SAR), the surface elevation may cope with both low and medium SLR scenarios, but it becomes vulnerable under high SLR scenario (see top panels). When SEC < SAR, surface elevation subsides but survive in low SLR scenarios and suffers under medium and high SLR scenarios (see middle panels). When SEC > SAR, sub surface elevation expands and suffers under the high SLR scenario only. Different hypothetical scenarios may describe several possibilities of mangrove surface dynamic in coping with rising global mean sea level at a linear rate. However, in reality rates of SEC may neither be constant nor linear due to the unpredictability and long-term variability of aboveground sediment inputs and belowground processes, and external processes and stressors imposed upon a site's substrate surface. Therefore, from the scenarios, it can clearly be seen that using SEC to compare with contemporary SLR is more relevant and comparable rather than using SAR.

Implications for management and restoration under scenarios of SLR

The 74 point dataset analyzed in this study showed the influence of disturbance and management on SEC in mangrove systems, particularly at local scales (Table 3). Negative SEC values occurred in cleared mangrove habitat due to rapid belowground subsidence and increased organic matter decomposition (Stokes et al. 2010; Lang'at et al. 2014). Unaltered mangroves had relatively stable surface elevations, with a mean of 0.70 mm year^{-1} and followed SEC variations across local hydro-geomorphic setting and tidal range (Rogers et al. 2006; Krauss et al. 2010), due to different vegetation growth rates and sedimentation characteristics (Krauss et al. 2007; Adame et al. 2010). Mangrove management (e.g. restoration or rehabilitation) supported positive surface elevation dynamics through belowground root expansion, as demonstrated by Howe et al. (2009) in the Hunter Estuary, Australia and McKee (2011) in Rookery Bay, Florida, USA. Therefore, positive implications of mangrove conservation practices in contributing to ecosystem resiliency to SLR can be observed.

Ensuring mangrove resiliency to contemporary SLR (Fig. 3) requires us to understand the impact of local scale hydro-geomorphic setting and management (and related changes such as vegetation structure) on SEC, SAR and SSC, in addition to landscape-scale indicators of resiliency such as suspended sediment concentrations. Therefore, restoring basin and fringe mangroves requires different approaches concerning tidal characteristics, surface elevation, source of sediments and species to be promoted or introduced. Mangrove pioneer species such as *Avicennia* spp. and *Sonneratia* spp. in Southeast Asia may establish better in the low elevation fringing zone, rather than in higher elevation basins towards the back of the mangrove, where other, more species-rich community assemblages develop (Watson 1928; Primavera and Esteban 2008; Friess et al. 2012). This has implications for factors contributing to SAR, such as sediment deposition. Different mangrove species aerial root structures can promote different rates of sediment deposition and accretion (Krauss et al. 2003). In this example, soil accretion was higher in *Rhizophora apicalata* prop roots compared to *Sonneratia alba* pneumatophores due to greater above-ground biomass, that reduces current velocities through drag forces. Above- and below-ground biomass can also be artificially manipulated to increase sediment deposition, such as planting mangrove seedlings at high densities and undergoing artificial nutrient enrichment (McKee et al. 2007; Kumara et al. 2010).

A need for enhanced global monitoring effort

Though mangroves cover an estimated 137,760 km^2 of mangroves (Giri et al. 2011), our analysis only included 74 locations that measured SEC and SAR, across only nine countries. Thus, mangroves are poorly monitored (in the published literature) for their vulnerability to SLR in many parts of the tropics. Alongi (2008) concluded that mangroves in 25 countries or sub-national regions were most at risk from SLR. However, few of these locations are currently being monitored for SEC/SAR dynamics, with a bias towards monitoring wetlands in other locations at higher latitudes that are under lower threat from SLR (Webb et al. 2013). A higher spatial resolution view of SEC processes is particularly required in order to gain a broader understanding of mangrove stability across the range of different geomorphic, sedimentary, biological, ecological and disturbance settings that are found across the tropics (Krauss et al. 2014).

A substantial expansion of SEC monitoring using the RSET-MH method has taken place in the last 3–4 years, especially in Southeast Asia, with unpublished sites now established in Indonesia (Sumatra, Java, Bali, West Papua), the Philippines (Luzon, Palawan), Singapore, southwest Thailand and Vietnam. In the coming years this emerging dataset will contribute to providing region-specific information on SEC and SAR, reducing our reliance on information from other (predominantly sub-tropical) locations such as the US, Caribbean and Australia, where geomorphology, sediment supply, organic matter production, tidal range, species composition and aboveground biomass can vary greatly (e.g., Alongi 2008; Hutchinson et al. 2014; Jardine and Siikamaki 2014; Balke and Friess 2015). However, large regions of the world remain unmonitored, especially in Africa, South America and the Middle East.

This study has also noted the need for standardized sampling designs between sites, and standardized reporting of important information such as mean/median, standard deviation and sample numbers, as well as effect sizes and other information of use in meta-analyses. Communication between researchers in terms of sampling design and open access reporting will allow stronger meta-analyses to be conducted on future data.

Conclusions

Globally, some mangroves are particularly threatened due to their microtidal tidal range and distance from sediment sources (Alongi 2008), resulting in limited elevation capital (Cahoon 2014). This study shows that currently reported SEC rates are unlikely to keep pace with the highest IPCC SLR scenarios to the end of this century. On local scales, hydro-geomorphological setting may influence mangrove resiliency to SLR, with land building processes in basin mangroves being greater compared to fringe mangrove processes, with fringing mangroves furthermore experiencing greater rates of SSC. Small-scale disturbances and management practices can also affect the resiliency of a mangrove system to future SLR. Continued and expanded monitoring of SEC, especially in vulnerable microtidal areas and areas currently unmonitored in the developing tropics may help us better understand the vulnerability of mangroves to SLR, and identify sites at risk from increased submergence in the future.

Acknowledgments This study is supported by the United States Agency for International Development (contract No. MTO 069018) to the Sustainable Wetlands Adaptation and Mitigation Program (SWAMP)—a collaborative activity between the Center for International Forestry Research (CIFOR) and the United States Forest Service (USFS)—International Program. DAF acknowledges the Department of Geography, National University of Singapore (R-109-000-141-133).

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