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Processes affecting the spatial distribution of seagrass meadow sedimentary material on Yao Yai Island, Thailand

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ABSTRACT

Many islands throughout SE Asia are experiencing rapid development and land-cover conversion that potentially threaten sensitive coastal ecosystems, such as seagrasses, through increased loading of sediment and nutrients originating from disturbed catchments draining to the sea. To evaluate this threat for one such island in Southern Thailand (Yao Yai), we perform sediment source tracing via end-member mixing analysis using stable isotopes $\delta^{13}C$ and $\delta^{15}N$ in organic matter to explore sediment loading in a seagrass meadow. The analysis indicates that sedimentary material in the meadow originates mostly from ocean-associated sources (~62% from seagrass detritus, seston, and ocean sediments). Terrestrial material comprises ~19% of the organic material found in the seagrass meadow, with another 20% originating from an adjacent mangrove forest. Approximately one-fourth of the seagrass meadow material (24%) is detritus that has been (re)deposited internally. The high contribution of terrestrial-derived organic matter deposited near the river mouth demonstrates that substantial quantities of sediment are being transferred from upslope erosion sources into the seagrass meadow. However, only a small amount of this material is deposited throughout the entire bay because much of the terrestrial- and mangrove-derived sediment is transferred to the open ocean via channels that are periodically dredged to allow boat access to two small inland harbours. This positive affect of dredging has not received very much attention in existing literature. River water flowing to the channels during falling tide delivers sediment to these efficient pathways, where much of it bypasses the seagrass meadow at periods of time when sediment deposition would normally be the greatest. There is growing concern that ongoing land-cover changes and planned urbanization related to tourism and agriculture on the island may boost sediment/nutrients above a critical threshold, beyond that revealed in our baseline survey. Our tracer-based sediment source approach did not corroborate our observations of substantial erosion and land degradation in the upper catchment—but this could be a result of sediment flushing through the dredged channels. We encourage others to combine such methods with sediment budgeting approaches to triangulate results for consistency. Finally, from an ecological perspective, the high presence of seagrass detritus we found in bay sediments suggests seagrass is potentially a key source of nutrients for the meadow itself, as well as other connected ecosystems.

1. Introduction

Seagrasses are aquatic flowering plants that are widely distributed along temperate and tropical coastlines of the world (Orth et al., 2006; Gattuso et al., 2006). Globally, seagrass meadows are increasingly facing rapid degradation and destruction (Waycott

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et al., 2009; Orth et al., 2006) and several species are in danger of extinction (Short et al., 2011). The mean annual decline in seagrass area has been 7% yr^{-1} since 1990, reflecting the devastating effect of a broad spectrum of anthropogenic and natural stressors concentrated at the coasts (Short and Wyllie-Echeverria, 1996; Duarte, 2002; Salomons et al., 2005; Waycott et al., 2009; Elliott and Whitfield, 2011).

Human-induced disturbances in particular can cause long-lasting changes in the sedimentary environment, often resulting in seagrass loss (Lee et al., 2006; Erftemeijer and Lewis III, 2006; Cabaco et al., 2008; Yaakub et al., 2014b). Prolonged reduction of underwater irradiance from increased turbidity from the loading of fine sediments inhibits photosynthesis and seagrass growth, leading to large-scale seagrass die-offs (Burkholder et al., 2007; Lee et al., 2007; Yaakub et al., 2014a). Short et al. (2014) found that seagrass meadow cover was in decline for seven of ten study sites in the Western Pacific. Three of the sites of decline experienced degradation related to sedimentation; the other four, nutrient loading. One site in Palau showed low-level seagrass decline from increased sediment loading due to road construction. Two sites in Sabah, Malaysia, were affected by forest cover change in headwater catchments that produced massive sediment loading. One site on Komodo Island, Indonesia, was affected by nutrient loading from beachside tourist cabins. The commonality (and relevance to the present study) among all sites experiencing seagrass loss is the direct linkage between the coast and sources of terrestrial pollution (e.g. sediment and/or nutrients).

Here, we investigate sediment loading using carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) stable isotope signatures of seagrass meadow sediments to identify the sources of organic material accumulating in a sheltered bay on Yao Yai Island, southern Thailand. The overarching framework of the study is the catchment-coast continuum, which supports the notion that rivers link coastal systems with potential degradation sources through the transfer of water, mineral sediment, organic matter, and inorganic nutrients (Owens, 2007; Salomons et al., 2005). Thus, the extent that pollution-causing activities contribute to degradation in downstream ecosystems is in part related to hydrological connectivity, as well as the level of disturbance upslope (Bracken and Croke, 2007). While we do not examine habitat degradation per se, we are motivated by observations of impacted coral reefs, islander reports of fish decline, and reductions in dugong sightings (perhaps related to seagrass meadow deterioration). Yao Yai Island is typical of many islands in Thailand where modification of watersheds and coastlines is associated with economic development, hence we anticipate that our finding will be relevant to other sites beyond the one studied in detail here.

We are also guided by fundamental ecological questions related to the role of mangroves in outwelling nutrients to the coastal zone (Odum, 1980). In a prior investigation, Gillis et al. (2014a) used sediment traps to identify sources of particulate organic matter samples along transects extending from the mangroves to the open ocean. They determined that organic matter in the traps was divided unevenly between oceanic (34–50%), mangrove (24–38%), seagrass (16–19%), and terrestrial (6–17%) sources. Based on habitat area, however, the contribution of particulate organic matter derived from seagrass meadows was disproportionally high relative to land-based sources, demonstrating the potential of seagrass meadows to provide nutrients to surrounding ecosystems. Our rationale for revisiting the site is to examine the connectivity between inland erosion sources and the coastal zone, as well spatial distribution of organic material in the bay.

2. Study area

The bay is located at the southern end of Yao Yai Island (98°35′E, 7°55′N), which is situated in Pang Nga Bay, Thailand (Fig. 1). The bay is approximately 1.2 km wide and 3 km long, and receives runoff water, sediment, and other materials from nine small catchments draining to the coast (Fig. 1). The dry season extends from November to April; the wet season extends from May to October (Southwest monsoon). Mean annual precipitation is approximately 2200 mm (Chansang, 1984). The main stream draining to the bay is perennial and flow is affected by the tides. Streams draining into the main stream from mountain headwater catchments are ephemeral, producing flow only during the wet monsoon season or immediately following storms. The study area is subjected to semidiurnal tides with a tidal range of ~2.5 m during spring tide (Chansang, 1984). Water depth of the bay where the seagrass meadow is located has less than a 5 m range during the highest observed tide (Fig. 2). The sheltered bay likely protects the seagrass and coral reef ecosystems from strong open sea waves, thereby limiting mixing (Fig. 3A).

The livelihoods of islanders was once predominantly fishing, but now plantation agriculture is an important source of income, as is a growing tourism industry. The extent of natural forest has been in decline for a number of years—much of the forest on the inward slopes and flat areas of the island has been converted to plantations

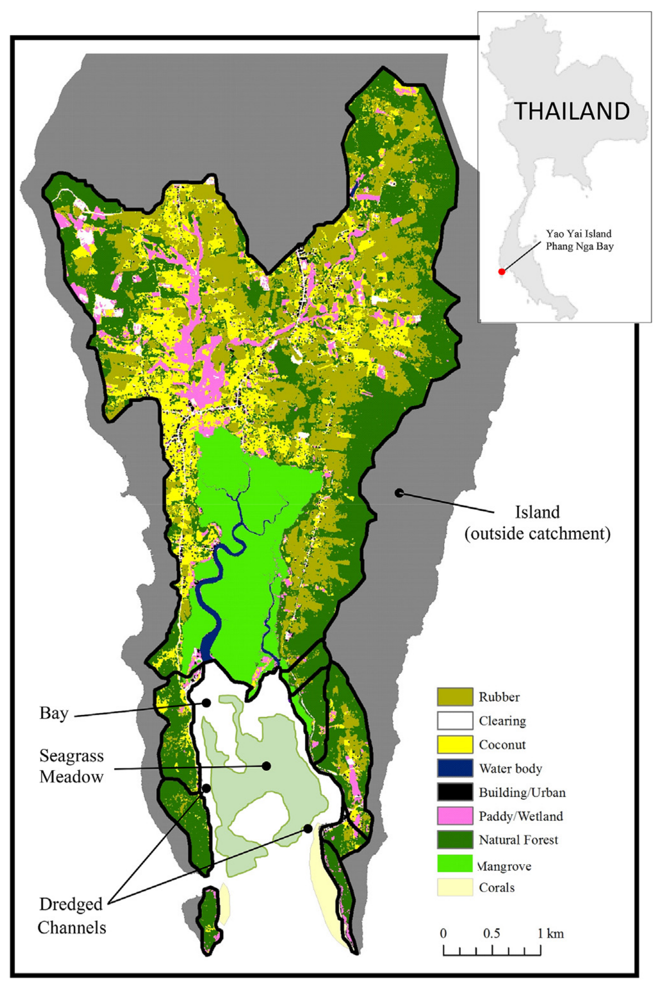

Fig. 1. Land-cover map of Yao Yai Island (2012). Rubber and coconut plantations are the dominant land covers. The 1.2 km by 3 km bay is fed by nine sub-watersheds (delineated with the black solid line). Land-cover analysis was carried out with a 2-m resolution DigitalGlobe satellite image (Date of image: July 2012), using a supervised classification technique in ArcGIS v10.1. Groundtruthing was performed during the two visits to the study site.

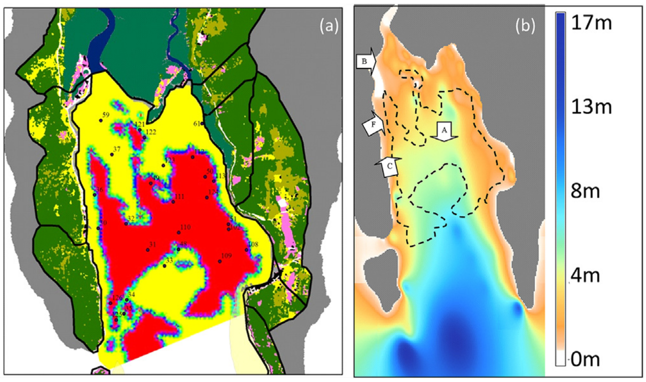

Fig. 2. (a) Extent of healthy seagrass meadow in the sheltered bay (red) on Yao Yai Island. The numbers refer to sample locations used in this analysis. (b) The water depth of the bay and location of the seagrass meadow (dotted line). These maps were determined in a separate unpublished exercise. The arrows refer to the location and direction of some of the photos shown in Fig. 3. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(based on comparisons of 2003 and 2013 DigitalGlobe imagery). Most remaining forest is located on the ocean-facing slopes where access is limited by steep terrain (Fig. 1). Dominant land covers now include coconut and rubber plantations (Fig. 3F). The geology of the island is mostly sandstone. Several quarries are located on the island where fill material was extracted for construction (Fig. 3E). Unpaved roads are frequently cut into hillslopes to provide access to the coastline and agriculture sites up-catchment (Fig. 3D). A dense road network is also present within the agricultural areas of the center of the island. As in other coast areas of Thailand (Ziegler et al., 2012), roads and agriculture lands are potentially important erosion sources that contribute sediment and organic material to river systems draining to the bay (Fig. 3D).

The largest river channel originates in the upper part of the main catchment where agriculture land and settlements are located (Fig. 1; Fig. 3B). This channel flows through the western portion of the mangroves before entering the bay (Fig. 1). The other river channel flows along the east edge of the mangroves and stretches only half the length of the forest (Chansang, 1984). Infrequent dredging is used to maintain boat navigation to small communities

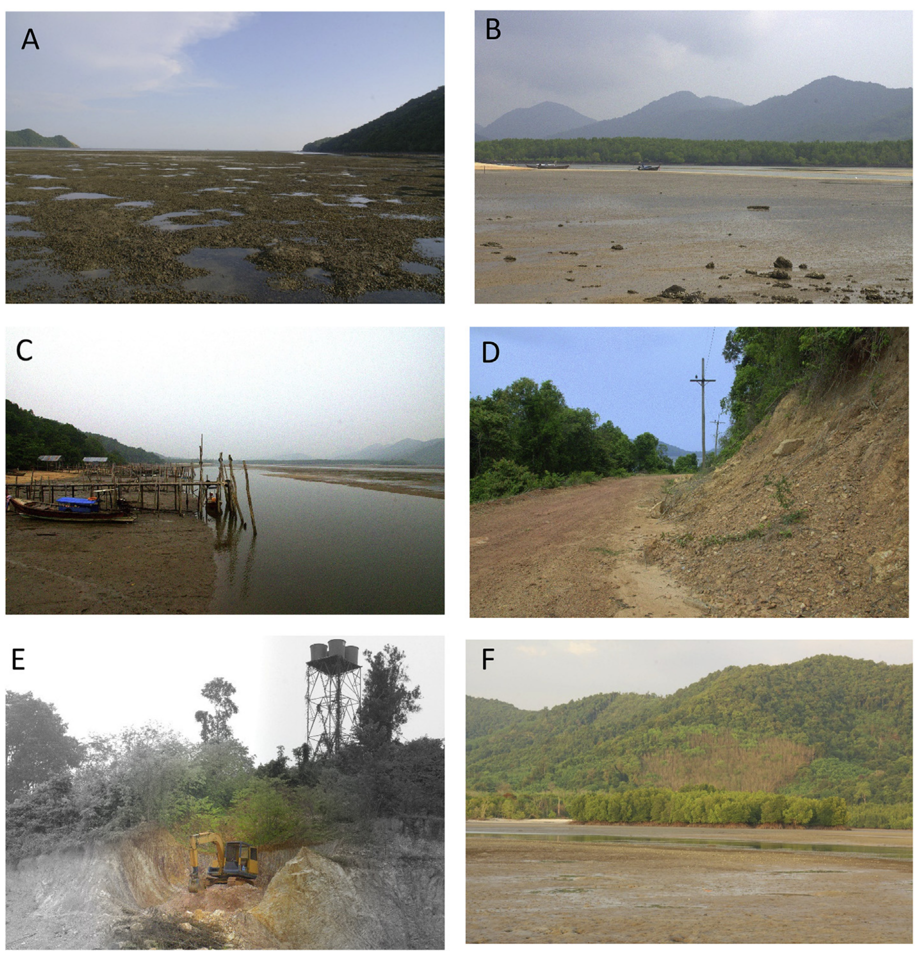

Fig. 3. (A) Seagrass meadow at low tide, showing the microtopography of the seagrass beds. The roughness of the leaves slows velocity and encourages deposition of sediment material as the tide recedes, meanwhile material is deposited in the depressions where water is left standing during low tide; (B) The north part of the bay where the west river flows into the bay and consequently seagrass does not establish; (C) The western dredged channel which is created with a boat-mountain backhoe. The channel is roughly a meter deep, and excavated material is typically deposited alongside the channel, on the landward side (not shown in the photo); (D) The recently widened road on the eastern side of the bay. Runoff water and sediment drain directly into the bay, which is located immediately below the road; (E) The excavation of fill material for building is a sign of increasing development on the island; also shown are water towers that feed hotels in a recently developed area of the island (F) Rubber plantations are located amongst degraded forest on the hillslopes that ultimately drain into the bay. Photography locations and directions of some the images of the seagrass meadow are shown in Fig. 2.

located along the western and eastern flanks of the bay (Fig. 3C). The riverine mangrove forest occupies a narrow strip ~1 km wide and stretches ~3 km inland (Fig. 1). There are at least 10 tree species found in the mangrove forest, of which *Rhizophora apiculata* is dominant (Chansang, 1984). Five species of seagrasses are found in the bay: *Halodule pinifolia*, *Cymodocea rotundata*, *Thalassia hemprichii*, *Enhalus acoroides* and *Halophila ovalis* (Chansang, 1984; Chansang and Poovachiranon, 1994). The seagrasses grow on shallow sandy and muddy substrates located in the center of the bay in water that is generally less than 5 m deep (Fig. 2). Degraded coral reef is found near the coastline on both the western and eastern flanks of the bay.

3. Methods

Stable isotopes $\delta^{13}C$ and $\delta^{15}N$ are useful for tracing the sources of material entering aquatic ecosystems due to the distinct isotopic signatures of various types of terrestrial and aquatic organisms (Wada, 2009; Davis and Fox, 2009; Gillis et al., 2014a). Fingerprinting approaches focusing on stable carbon and nitrogen isotopes of bulk sediment-bound organic matter have been used in a number of studies where conventional budgeting was not feasible (Collins et al., 2013; Mckinley et al., 2013; Walling, 2013; Laceby et al., 2014).

Samples were collected in February and October 2012 from seagrass meadows and five potential end-members: soil from terrestrial erosion sources ($n = 32$), mangrove mudflats ($n = 31$), the ocean floor ($n = 15$), seagrass detritus ($n = 12$) and seston in the ocean column ($n = 10$). Seston includes suspended particulate matter in the water column and encompasses detritus, organic matter, inorganic matter, suspended sediments, zooplankton, and phytoplankton. Sampling of sediments within and around the seagrass meadows was stratified across the bay to ensure good spatial representation of deposition patterns ($n = 27$). Terrestrial erosion sources included quarries, road/slope cuts, plantation soils, dry creeks and channel heads. Mangrove mudflat sediment samples were collected near the edges of the mangrove forest. The ocean floor samples were collected outside of the seagrass meadow. Seagrass detritus, including fresh and decaying leaves, was collected from several locations within the bay during low tide.

For all sediment samples, the top 5–10 cm of material was collected using a PVC scoop then stored in individual plastic bags. Approximately 1 kg of material was collected at each sampling point to ensure that sufficient amount of fine material (<63 μm) was obtained for geochemical analysis. Samples were dried at 105° C for at least 48 h. The material was then lightly crushed in a mortar and pestle, then passed through aluminium sieves to obtain the <63 μm fraction. This fine material was then pulverized in a mortar and pestle to obtain a homogeneous sample.

Seston samples were collected from surface waters (max depth 0.5 m) at the mouth of the bay using a 50 μm plankton net. This material was stored in pre-combusted glass vials, as was seagrass detritus. To isolate seston, water samples were filtered with pre-combusted 0.7 μm GF/F Whatman Glass Filter Fibres (450 °C, 4 h). Following collection, leaf and detritus samples were dried (60° C, at least 24 h), ball-milled with a Retsch Planetary Ball Mill PM400 using Zirconium Oxide balls, passed through a <63 μm sieve, then pulverized (as above).

Prior to isotopic analysis, all sediment samples were subject to acid fumigation to remove inorganic carbon (Harris et al., 2001; Walthert et al., 2010). The desiccator was first leached with 12 M HCl acid for four hours (Brodie et al., 2011). Samples undergoing $\delta^{15}N$ analysis were not fumigated. Approximately 30–35 mg of sediment material was placed into silver (Ag) foil boats and wetted with deionized (DI) water using a pipette to enhance acid permeation (Brodie et al., 2011; Komada et al., 2008). Less material (2–3 mg) was used for leaf, detritus, and seston samples. Samples were placed in the desiccator with 12 M HCl for six hours before overnight drying at 60° C. The silver boats were encapsulated within tin (Sn) foil boats to prevent leakage if Ag boats became brittle from the acid fumes.

All samples were analysed for $\delta^{13}C$ and $\delta^{15}N$ isotopes using a PDZ Europa 20-20 isotope ratio mass spectrometer (Sercon Ltd., Cheshire, UK) at the University of California, Davis. Replicates of an isotopic Certified Reference Material (CRM; B2151, Cert no. 162517, $\delta^{13}C = -26.27 \pm 0.15‰$, $\delta^{15}N = 4.42 \pm 0.29‰$) were included to verify reproducibility across a range of sample masses (mean $\delta^{13}C$: $-26.53 \pm 0.12‰$ and $\delta^{15}N$: $4.93 \pm 0.27‰$, with $n = 25$). The standard deviations (SD) lie within the SD range of those given by the standard, and the long-term SD of 0.2‰ for $\delta^{13}C$ and 0.3‰ for $\delta^{15}N$ (UC Davis SIF, n.d.).

Samples were interspersed with several replicates of at least two different laboratory standards that were compositionally similar to collected samples to determine accuracy of absolute values. These standards were calibrated against NIST Standard Reference Materials (IAEA-N1, IAEA-N2, IAEA-N3, USGS-40, and USGS-41). Triplicates of each leaf and seagrass detritus sample were also tested. The absolute difference between repeated determinations on the same sample was usually less than 0.2‰ for $\delta^{13}C$ and 1.0‰ for $\delta^{15}N$.

All stable isotope data results are reported as per mille (‰) deviations from a standard Vienna-Pee Dee Belemnite (PDB) for $\delta^{13}C$ and atmospheric air for $\delta^{15}N$:

$$\delta = \left(\frac{R_{sample} - R_{standard}}{R_{standard}}\right) * 1000‰$$

where values of R represent either $^{13}C/^{12}C$ or $^{15}N/^{14}N$. Stable isotope data were first analysed by plotting values on a scatter diagram to identify the boundaries of the mixing polygon, which were defined by the end member samples.

The *SIAR* (Stable Isotope Analysis in R) mixing model (Parnell et al., 2010) was used to partition all seagrass meadow samples into percent contributions from each end-member source. The model uses Markov chain Monte Carlo algorithms and includes an overall residual error term. Default values were used for concentration dependence (*concdep = 0*) in the *siarmcmcdirichletv4* command model for multiple sediment mixture data points. Trophic enrichment factors (TEF) and prior information were not utilized. The number of iterations was set at 1,000,000 with 100,000 initial iterations to be discarded. For organic matter to be a reliable source tracer, the signatures of seagrass meadow samples should plot within the boundary of the mixing polygon. Furthermore, the data should meet the following constraints: 1) contributing proportions must sum to one; 2) all source contributions must be positive values between zero and one; and 3) the partitioning of sources is the same for both δ13C and δ15 N tracers (Phillips, 2001, 2012).

Using the outputs of the SIAR mixing model on 27 samples, we performed ordinary kriging interpolation (ArcGIS v10.1) to create maps showing the spatial distribution of the contribution of each end member to sediments in the bay.

4. Results

4.1. Source contributions

All five end member sources plotted in distinct groups with respect to their $\delta^{13}C$ and $\delta^{15}N$ signatures (Fig. 4). Organic matter associated with mangroves and terrestrial erosion sources are mainly differentiated by their range of $\delta^{15}N$ isotope values (Table 1).

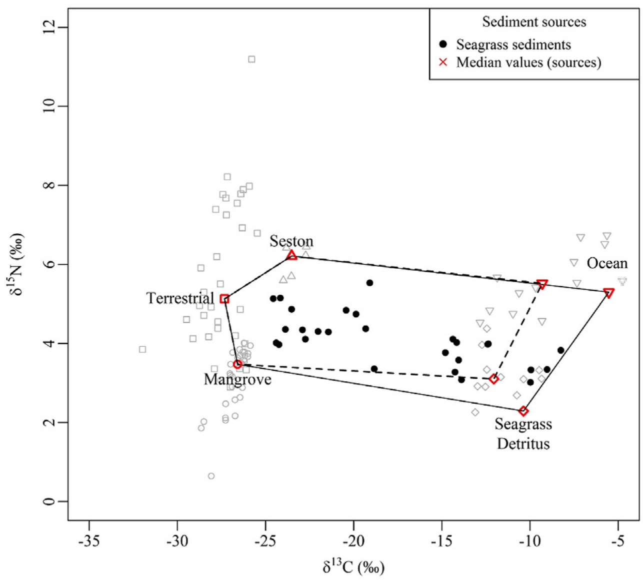

Fig. 4. The 27 sediment samples collected within seagrass beds (black dots) are plotted on the end-member mixing polygon, which is based on δ^{13}C and δ^{15} N values for terrestrial erosion sources, mangrove substrate, seagrass detritus, ocean sediment, and seston. The boundaries of the mixing polygon were originally plotted through median values for each end member. However, the boundary was shifted by choosing other points in the coral and seagrass detritus data fields such that all seagrass sediment values plotted inside the polygon.

Organic material in ocean substrate and seagrass detritus are distinctly different from the other end members because of less negative δ^{13}C values (all values were > −15‰). Seston sample values plot near to those of terrestrial erosion sources, but are separated sufficiently to justify this source as an end member (Fig. 4). When the seagrass sediment values are plotted with the end members, all but five plot inside the boundary of the mixing polygon, which is defined by the median δ^{13}C and δ^{15}N isotope values of all five end members (dotted line in Fig. 4).

With regard to the four outliers, it is possible that the acid fumigation treatment did not remove all inorganic carbon in these samples, resulting in δ^{13}C values that were too high—or less negative (Fig. 4). However, we assume that an insufficient number of samples for the seagrass detritus and ocean end members were collected to fully define the end-member mixing polygon. For example, the δ^{13}C range for the ocean material we collected is so large that additional samples with high δ^{13}C values would expand the boundary sufficiently. Further, our range of δ^{13}C values for seagrass (−13.10‰ to −9.34‰) is lower than what has been reported for several species present in the bay (McMillan et al., 1980; Hemminga and Mateo, 1996): e.g., *Cymodocea rotundata* (δ^{13}C range = −8.9‰ to −7.4‰) *Thalassia hemprichii* (−5.2 to −8.1‰) *Enhalus acoroides (*-4.9‰ to −6.7‰*)*, *Halophila ovalis (*-15.5‰ to −6.4‰*)* and *Halodule pinifolia* (mean = *-12.0‰).* Thus, it is possible we failed to capture the true midpoint of this end member. It is probably not the case we missed an end member, because the δ^{13}C values of other possible major contributors tend to be lower (e.g., < −10.5‰, Cloern et al., 2002; Wang and Yeh, 2003). To resolve this problem we incrementally expand the polygon boundary by selecting new end member points from the datasets until all seagrass sediment samples plot inside the polygon (solid line in Fig. 4).

The results of the SIAR mixing model ran on the 27 seagrass sediment samples and the modified mixing polygon show that the median contribution of each source is the following (Table 2): seagrass detritus (24%), ocean sediment (19%), mangrove sediments (20%), terrestrial erosion source material (19%), and seston (18%). The range of contributions of each source for the 27 sample locations is large (Table 2): seagrass detritus (6–58%), ocean sediment (5–51%), mangrove sediments (5–37%), terrestrial erosion source material (4–32%), and seston (4–29%).

4.2. Spatial patterns of sedimentation

The spatial distribution of the percent contribution of each source (based on ordinary kriging) shows that approximately 50–60% of the organic matter composition of seagrass sediments in close proximity to river mouths and in the vicinity of the mangroves is derived from terrestrial sources or the mangroves (Fig. 5A and B). The contributions of these two sources to seagrass meadow material decreases with distance from the river mouth and shoreline to the ocean (through the seagrass meadow). Most material associated with ocean sands accumulates in the cove and on the eastern flank of the bay (Fig. 5D).

Seston is deposited in a somewhat uniform spatial distribution throughout the bay (i.e., no isolated or distinct deposition location). It does, however, range in composition from 4 to 27%, with a slightly higher percentage occurring near land, suggesting an inland source, where productivity is high (Fig. 5E). The highest concentration of seagrass-derived organic matter occurs on the eastern flank of the bay, where the seagrass meadow is thick (Fig. 2) and a protected cove may limit mixing of ocean and terrestrial waters (Fig. 5C). The percent composition of seagrass detritus in seagrass meadow sediments ranges from 40 to 45% in this area (Fig. 5C). In contrast, very low percentages (6–10%) of seagrass detritus are found at the mouth of the main river and near the mangroves (Fig. 5C), suggesting that little organic matter is entrained from the seagrass meadows by the incoming tide and transported to the interior of the bay. In addition, very little seagrass grows in this location, limiting the amount of material originating *in situ*.

Table 2
SIAR mixing model results.

End member	Contribution (%)	Range (%)
Terrestrial	19 ± 10	(4–32)
Mangrove	20 ± 10	(5–37)
Ocean	19 ± 11	(5–51)
Seston	18 ± 10	(4–29)
Seagrass	24 ± 16	(6–58)

Contribution values are medians ± the median absolute deviations (n = 27).

Table 1
Isotopic signatures of source end members.

End member	δ^{13}C (‰)	δ^{15}N (‰)	n
Terrestrial	−27.33 ± 0.90 (−31.97 to −25.47)	5.13 ± 1.47 (2.90–11.20)	32
Mangrove	−26.59 ± 0.39 (−28.64 to −25.86)	3.47 ± 0.31 (0.65–4.01)	31
Ocean	−9.31 ± 2.08 (−12.84 to −4.78)	5.47 ± 0.40 (4.53–6.70)	14
Seston	−23.52 ± 0.38 (−23.99 to −22.69)	6.21 ± 0.22 (5.60–6.44)	6
Seagrass	−12.05 ± 0.98 (−13.10 to −9.34)	3.10 ± 0.23 (2.26–4.38)	12

Values are medians ± the median absolute deviations; ranges are listed in parentheses.

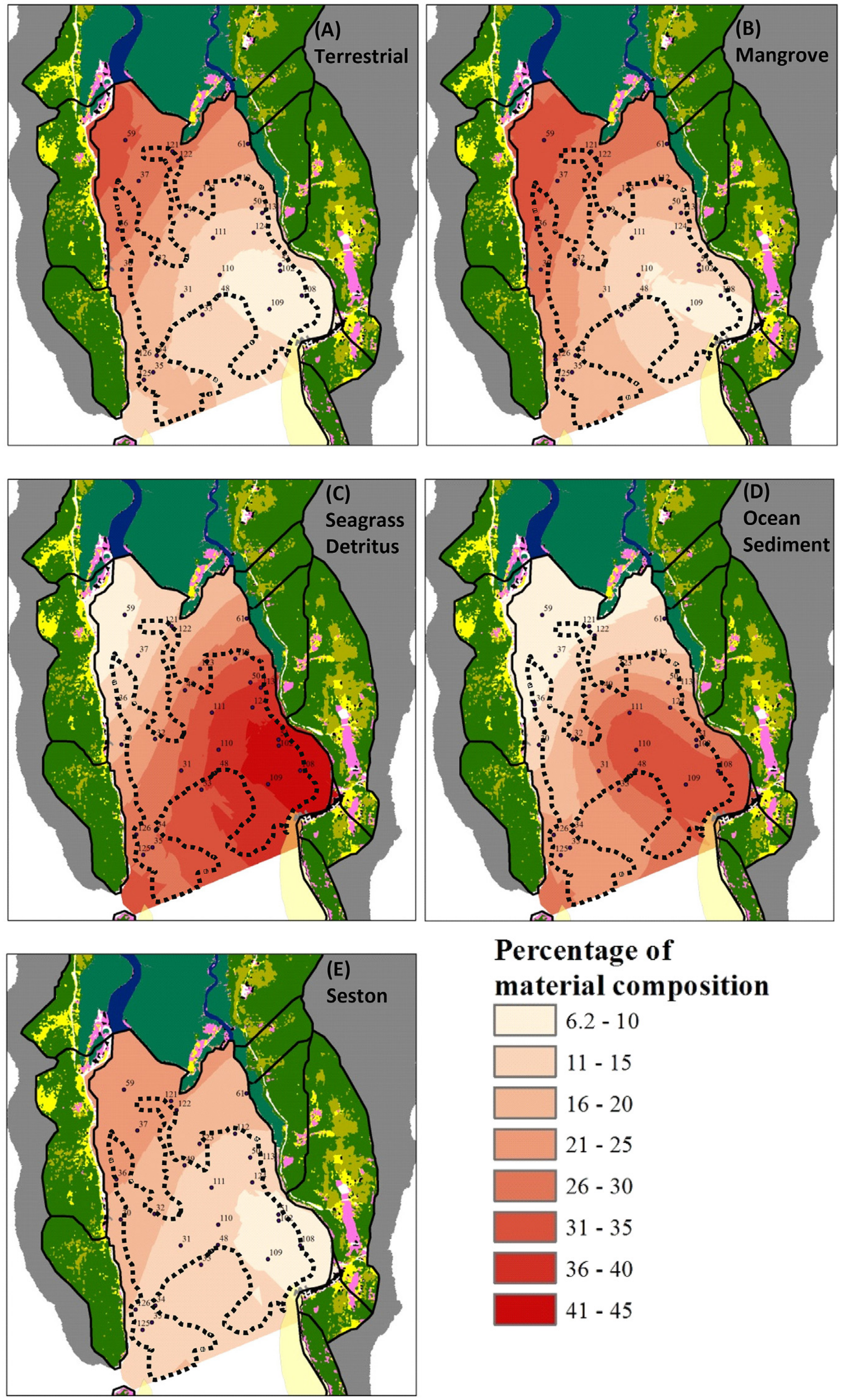

Fig. 5. Spatial interpolation (ordinary kriging) of organic matter composition for each end-member source. About 50–60% of sediments at the river mouth consist of terrestrial- and mangrove-derived sediment sources (A,B). Seagrass detritus and ocean floor sediments reflect similar distributions – low percentage composition (6–10%) at river mouth, but high percentage composition in the cover at the right side of the bay (C, D). Seagrass detritus was also high (40–45% of the total composition) on the right side of the bay and the interior where much of the seagrass meadow is located (C). Seston-derived material was low in percentage composition (6–25%) throughout the entire bay, with a slightly higher concentration near the river mouth (E).

5. Discussion

5.1. Conceptual model of deposition

The observed pattern in source contribution to seagrass meadow sediment (Fig. 5) reflects a complex interaction of several phenomena including: (a) location of source material relative to sampling points; (b) mobilization and deposition of organic matter as related to tidal fluctuations; (c) natural and artificially maintained drainage patterns in the bay during the tidal cycle; (d) rainfall runoff processes that deliver water, sediment, and particulate matter from upstream; and (e) catchment-wide erosion processes. These patterns, when considered with our observations of flow patterns over a two year period, led to the development of a conceptual model of sediment deposition processes (Fig. 6).

Water enters the bay as the tide rises—initially in low lying areas and the dredged channels (at least 1 m deep) on the east and west sides of the bay (red dotted lines; Fig. 6). The channel on the west (left-hand side) connects the river and open ocean, mixing terrestrial- and ocean-derived material (Fig. 6A). The eastern channel is truncated at the cove, but facilitates the import of seston and fine sand-sized material from the ocean floor partially into the bay. The rising tide then carries suspended material inland, and probably redistributes some of seagrass detritus that is stored temporarily in the meadow (Fig. 6B). During high tide, oceanic material is transported up the river and into the mangroves to its maximum extent.

Material from all sources is transported ocean-ward with the falling tide, including terrestrial material delivered to the rivers from upland sources during runoff events (Fig. 6C). As water depth and velocity of the out-flowing tide decreases, the hydraulic gradient of the stream "steepens" and it is likely that during this time much of the stream-associated sediments are moved across the bay to the ocean. Suspended material is also deposited throughout the bay, first in areas with high roughness, such as seagrass meadows, then in areas where water ponding occurs and microtopography restricts drainage. As low tide approaches, out-flowing water drains from the rivers, dredged channels, the mangroves, and depressions in the seagrass meadow (Figs. 6D, 3A).

Runoff at any time during the tidal cycle brings material, including mineral sediment, organic matter, and riverine seston into the bay from the river. During high tide, runoff water mixes with ocean water inside the river and small streams in the mangroves. When runoff coincides with low tide, sediments, organic material, and seston are transported into the upper part of the bay, but it may not flow to the ocean until the hydrological connection is re-established once the tide rises. If runoff occurs as the tide is rising or falling, the sediments will mix with ocean water sediments, then follow the progression of transport and deposition described above.

The inflow of river water during different times of the tidal cycle partially explains the spatial pattern in the terrestrial- and mangrove-derived organic material we observe in the bay. The distribution is also affected by dredging, which is performed as

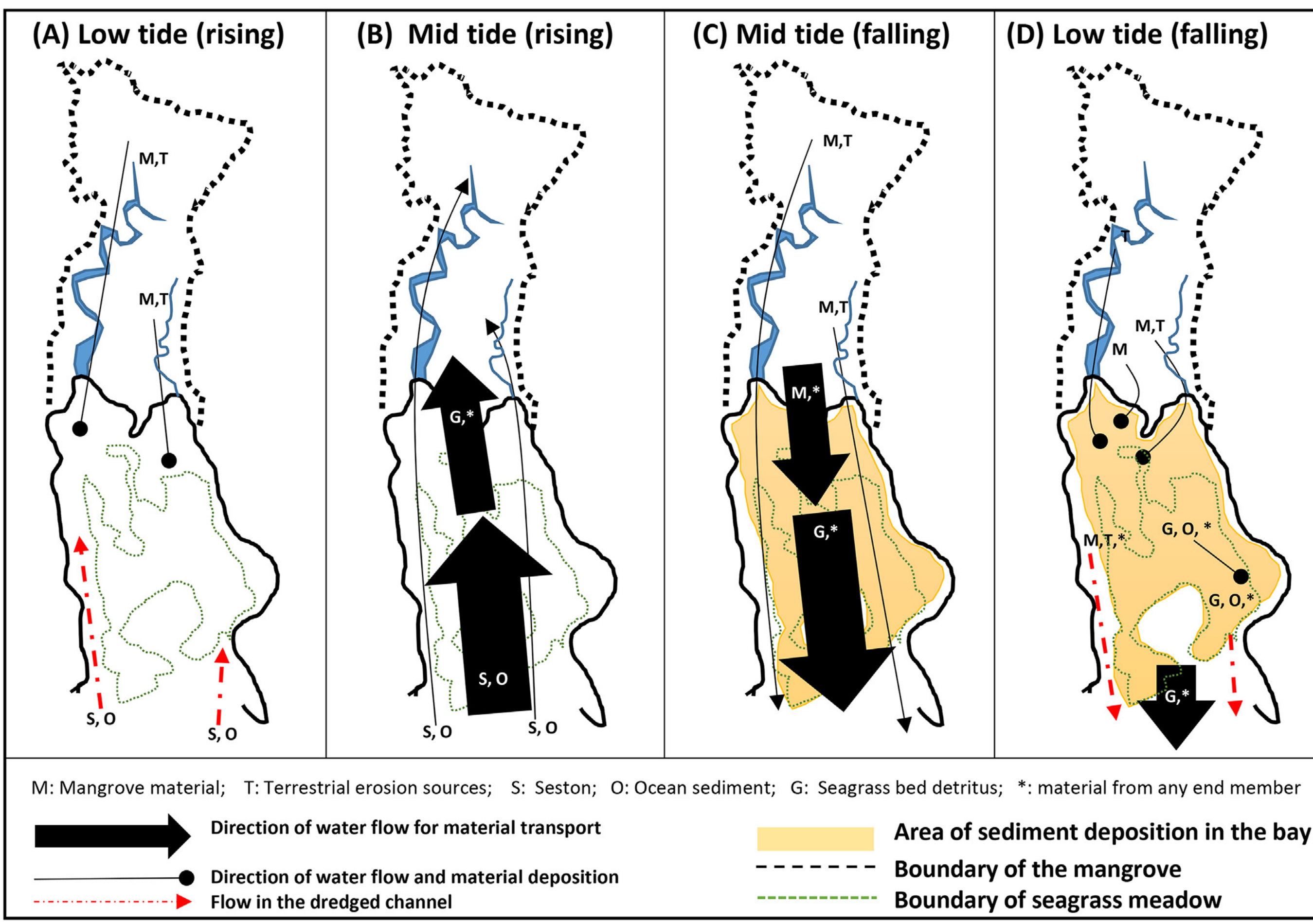

Fig. 6. Conceptual model of material (sediment and organic matter) flows into, from, and within the bay with respect to four phases of the tidal cycle: (A) low tide (rising); (B) mid-tide (rising); (C) mid-tide (falling) (D) and low tide (falling). (A) At low tide, as the water depth begins to rise some terrestrial-derived (T) and mangrove (M) material is still draining from the two main rivers and the mangrove, as seston (S) and material from the ocean floor (O) move into the bay through lower dredged channels (fine hashed lines) on the left and right sides of the bay. (B) At high tide, ocean water brings seston and ocean floor material into the bay and picks up seagrass-detritus (G) from the meadows in the interior of the bay; all types of material considered here are moved into the mangrove and up the rivers. (C) As the tide recedes, material from all sources (*) moves ocean-ward, particularly that from terrestrial sources (via the rivers), the mangrove, and the seagrass beds; (D) near low tide, material draining from inland sources is deposited in the bay, as is seagrass and other material in the cove on the river; most drainage to the ocean occurs within the dredged channels on the left and right sides of the bay. The position and length of the dredged channels are represented by the red dotted lines. North is to the top of the diagram. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

needed to maintain navigable channels on both the western and eastern sides of the bay. These artificially-maintained channels facilitate water flow both inward (rising tide, Fig. 6A and B) and outward (falling tide, Fig. 6C and D), thereby acting as a conduit for moving ocean-associated material inland and terrestrial-derived material out to the ocean. The western channel in particular transports terrestrial- and mangrove-derived organic material to the ocean, allowing some to bypass the seagrass meadows in the interior of the bay—inferred from the patterns shown in Fig. 5A and B and observations. In the absence of the channel, we would expect more of the mangrove and terrestrial material to be deposited in the interior of the bay because of greater mixing during the tidal cycle. The influence of the dredged channel on the east (right-hand side in the figure) appears to have less of an effect on the distribution of particulate matter in the bay, as it does not extend inland past the cove and the seagrass meadow.

5.2. Processes governing deposition

The location of high concentrations seagrass detritus aligns with the locality of the seagrass meadow in the bay (Figs. 2, 5). The greatest accumulation is in the eastern cove above the dredged channel where water pools as the tide descends. Deposition takes place in the middle of the bay because the area is elevated relative to surrounding (micro) channels. Further, the roughness of the seagrass retards flow, encouraging settling of particulate matter (Figs. 3A, 5C).

Ocean floor particulate matter also tends to accumulate in the eastern cove in the bay. We also expect a high presence of this material at the southern boundary of the seagrass meadow in the proximity to coral beds, but limited data for kriging prevents a realistic interpolation—hence this area is truncated abruptly in the map (Fig. 5). Approximately 20% of the material deposited in the seagrass meadow is ocean sediments (Table 2). Some of this bed material may be a lingering effect of the 2004 tsunami that impacted the bay. The extent of the impact is unknown other than a reported estimated 10% loss in seagrass habitat across the island (www.seagrasswatch.org/Thailand.html).

The somewhat uniform distribution of seston in seagrass meadow sediments is probably due to ocean-derived seston being transported in suspension throughout the bay during high tide and, importantly, riverine seston delivered to the bay during runoff events and with the falling tide. In the prior study, we found that seston comprised 70–90% of the suspended material during high tide (Gillis et al., 2014a). Again, the highest proportion of seston in the bay substrate was near the mouth of the river, supporting the notion that the river is an important source of seston (e.g., Cole et al., 2010). In the Lianzhou Bay in southern China, Kaiser et al. (2014) used isotopic $\delta^{13}C$ and $\delta^{15}N$ to determine that suspended and sedimentary organic matter was mainly derived from freshwater and marine phytoplankton. If this is true for Yao Yai Island, the ocean-associated contribution to the seagrass meadow material reduces by an unknown proportion.

The organic matter distribution patterns we observed in the sheltered bay suggest a catchment-coast linkage that centers on the river system. However, most deposition of terrestrial-derived sediment occurs near the river mouth, where flowing water may play a role in limiting seagrass establishment by continually disrupting the bed or causing fluctuations in salinity (Fig. 5A). In addition, this is the area where river bed load sediments (i.e., course sands that roll, slide or skip on the surface) enter the bay and are potentially deposited as flow velocity decreases. Some of the suspended load from terrestrial sources may also be deposited here as velocity decreases. The observation that seagrass cover is reduced in the vicinity to river mouths and the coastline is expected, as shown previously in Indonesia (Van Katwijk et al., 2011).

5.3. Management considerations

Much of the bay supports an extensive seagrass meadow, with few signs of degradation. Nevertheless, the linkage between upland erosion source areas and the bay, as inferred from depositional patterns (Fig. 5), reinforces the need to consider how sediment/nutrient loading in the future may increase in response to urbanization on this somewhat remote island where tourism has only recently begun to develop. Most other large and commercially-accessible islands in Thailand are now popular tourist destinations; and substantial resort development has been occurring on some parts of the island over the last decade, with more development expected in the near future.

The economic benefits of tourism (Tompkins, 2003) are often offset by negative environmental impacts stemming from construction and land conversion that accelerate erosion and create efficient pathways for eroded soil, nutrients, and chemical contaminants to enter the stream network that drains to the coast (Bégin et al., 2014; Brooks et al., 2015; Ramos-Scharron et al., 2015). For example, tourism could drive the expansion of the road network accessing the coast. Poorly maintained roads are an important and often overlooked contributor to sediment delivery to river systems in multi-use catchments worldwide, including those draining to the ocean (Sidle and Ziegler, 2012; Ramos-Scharron, 2012; Van Meerveld et al., 2014; Brooks et al., 2015). Road networks act as conduits to flow, thereby extending the hydrological network in a catchment, affecting stormflow response, as well as the delivery of sediment and contaminants to the stream (Cuo et al., 2008; Thomaz and Peretto, 2016). Further, roads built to access coastal areas directly connect hillslope erosion sources with coastal ecosystems, potentially increasing sedimentation (Ziegler et al., 2012).

While forest removal for agriculture is typically a concern because of the potential for erosion (and other environmental reasons), most of the forests draining to the bay on the interior of the island have already been converted to plantation agriculture (Fig. 1). On-site erosion is visible, particularly on steep slopes, but some of this eroded material may be stored temporarily in mid-catchment locations rather than transported to the stream system where it exits to the bay. Nevertheless, sound agriculture practices should be enforced to minimize onsite surface erosion because of the potential for this material to be remobilized during large storms or following additional disturbances that increases the catchment to coast linkage that may accompany urbanization (additional road building, artificial channelization of the stream network). Throughout the region there is increasing concern that surface runoff from active agriculture sites may carry excessive nutrients from fertilizers or harmful chemicals from pesticides (Sidle et al., 2006; Ziegler et al., 2009; Zhang et al., 2015). Seagrass meadows, in particular, are sensitive to land-derived nitrogen loads (Valiela and Cole, 2002; Burkholder et al., 2007; Van Katwijk et al., 2011).

Mangroves worldwide are considered efficient filters that reduce the export of sediment and nutrients to the ocean (Valiela and Cole, 2002; Gillis et al., 2014b; Wolters et al., 2016). Changes in the extent or biomass of mangroves might also reduce this buffering effect (Horstman et al., 2015), which in turn could affect the seagrass meadow negatively if increases in turbidity decrease light availability for photosynthesis. Our study design did not allow for quantifying the buffering influence by the mangroves on Yao Yai Island. We were, however, able to see evidence that, once in the stream system, much of the sediment generated in upland areas (fields, construction sites, urban areas, roads) bypasses the mangrove and enters the bay. The deposition patterns of organic matter suggest that a substantial portion of the material carried in the river is transported to the ocean rather than being deposited throughout the bay. Despite our inability to quantify a buffering effect, protecting the mangroves in the future as the island develops would be prudent. Degradation could have a cascading effect on the seagrass meadows because of the inherent connection between the two adjacent ecosystems (Gillis et al., 2014b).

In a prior work, Gillis et al. (2014a) showed that much of the organic material in seagrass meadows in Pang Nga Bay is internally derived from the meadows themselves. On Yao Yai Island, seagrass detritus in sediment traps on transects stretching from 50 to 300 m seaward comprise 16–19% of the total material collected. Again our median bay-wide value is only slightly higher (24%), but the range is 6–58% (Table 2). Many of the lower values are found near the river mouth where outflowing water limits deposition of ocean-derived organic material. Most of our other estimated end member contributions are in line with the prior assessment (Gillis et al., 2014a).

Collectively, the measurements from both studies support the hypothesis that seagrass meadows play an important role in supplying nutrients for internal use as well as use by adjacent ecosystems—when particulate matter is exported and then broken down into biologically exchangeable forms (Hemminga et al., 1999; Gillis et al., 2014a; Lai et al., 2013). Thus, the sensitivity of seagrass to changes in material fluxes (as described above) that may result from urbanization, agriculture expansion/intensification, or degradation of mangroves is of concern for management of all coastal ecosystems on the island. Continued monitoring of seagrass meadow health should be implemented to gauge the impacts of increasing anthropogenic activity, but also to understand the complex response of the seagrass meadow to natural and anthropogenic stressors (Slob and Gerrits, 2007). At the very least, a frequent census of seagrass extent could provide indication of emerging negative effects of sedimentation and nutrient loading. The connectivity between areas of anthropogenic disturbance and the seagrass meadows should be a fundamental part of any environmental impact assessment or planning policy (Alvarez-Romero et al., 2011).

6. Conclusions

Our carbon and nitrogen tracer-based results demonstrate that much of the organic material in the seagrass meadow at Yao Yai Island (Thailand) is ocean-derived, with a large portion being derived from seagrass detritus, which is recycled internally. Thus, seagrass meadows themselves may play an important role in supplying nutrients for both internal and external use by adjacent ecosystems. Counter to expectation, a relatively small contribution of the organic material in the meadow is derived from the adjacent mangroves, probably because of efficient export of mangrove-derived particulate matter to the open ocean during the tidal cycle. Only a fraction of the sediment and organic matter originating at upland terrestrial erosion sources (for example agriculture, roads, urban areas) is deposited within the seagrass meadow. In some cases, sediment from observed erosion and land degradation sites is stored temporarily at mid-catchment locations, reducing the volume transported to the bay where deposition may occur. Importantly, however, much of the loading to the bay is reduced by export to the ocean through well-maintained channels that are dredged to facilitate boat access to inland harbors. Dredging may therefore help to reduce sediment deposition in the bay, providing an unintentional conservation effect. Additional sediment budgeting/tracking studies are needed to quantify these processes. Nevertheless, the observed sediment deposition patterns verify a link between upslope areas of human activity/disturbance and the seagrass meadow in the bay. Thus, on-going and planned development could represent a threat to sensitive seagrass ecosystems if sediment/nutrient loading increases in response to upward development trajectories of the island. Planners should recognize the connection between upland pollution sources and the bay and be cognizant that additional urbanization and agriculture expansion could produce negative impacts on sensitive estuarine ecosystems, including seagrass meadows—we predict a similar situation for other islands undergoing extensive land-cover/land-use changes related to agriculture development, urbanization, and tourism.

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References

Alvarez-Romero, J.G., Pressey, R.L., Ban, N.C., Vance-Borland, K., Willer, C., Klein, C.J., Gaines, S.D., 2011. Integrated land-sea conservation planning: the missing links. Annual Review of Ecology. Evol. Syst. 42, 381–409.

Bégin, C., Brooks, G., Larson, R.A., Dragićević, S., Ramos Scharrón, C.E., Côté, I.M., 2014. Increased sediment loads over coral reefs in Saint Lucia in relation to land use change in contributing watersheds. Ocean Coast. Manag. 95, 35–45.

Bracken, L.J., Croke, J., 2007. The concept of hydrological connectivity and its contribution to understanding runoff-dominated geomorphic systems. Hydrol. Process. 21, 1749–1763.

Brooks, G.R., Larson, R.A., Devine, B., Schwing, P.T., 2015. Annual to millennial record of sediment delivery to US Virgin Island coastal environments. Holocene 25 (6), 1015–1026.

Brodie, C.R., Leng, M.J., Casford, J.S.L., Kendrick, C.P., Lloyd, J.M., Zong, Y., Bird, M.I., 2011. Evidence for bias in C and N concentrations and δ13C composition of terrestrial and aquatic organic materials due to pre-analysis acid preparation methods. Chem. Geol. 282, 67–83.

Burkholder, J.M., Tomasko, D.A., Touchette, B.W., 2007. Seagrasses and eutrophication. J. Exp. Mar. Biol. Ecol. 350, 46–72.

Cabaco, S., Santos, R., Duarte, C.M., 2008. The impact of sediment burial and erosion on seagrasses: a review. Estuar. Coast. Shelf. Sci. 79, 354–366.

Chansang, H., 1984. Structure of a mangrove forest at Ko Yao Yai, Southern Thailand. Proceedings of Asian Symposium on Mangrove Environment: Research and Management 86–105.

Chansang, H., Poovachiranon, S., 1994. The distribution and species composition of seagrass beds along the Andaman sea coast of Thailand. Phuket Mar. Biol. Cent. Res. Bull. 59, 53–64.

Cloern, J.E., Canuel, E.A., Harris, D., 2002. Stable carbon and nitrogen isotope composition of aquatic and terrestrial plants of the San Francisco Bay estuarine system. Limnol. Oceanogr. 47 (3), 713–729.

Cole, J.J., Carpenter, S.R., Kitchell, J., Pace, M.L., Solomon, C.T., Weidel, B., 2010. Strong evidence for terrestrial support of zooplankton in small lakes based on stable isotopes of carbon, nitrogen and hydrogen. PNAS 108, 1957–1980.

Collins, A.L., Williams, L.J., Zhang, Y.S., Marius, M., Dungait, J.A.J., Smallman, D.J., Dixon, E.R., Stringfellow, A., Sear, D.A., Jones, J.I., Naden, P.S., 2013. Catchment source contributions to the sediment-bound organic matter degrading salmon spawning gravels in a lowland river, southern England. Sci. Total Environ. 456–457, 181–195.

Cuo, L., Giambelluca, T.W., Ziegler, A.D., Nullet, M.N., 2008. The roles of roads and agricultural land use in altering hydrological processes in Nam Mae Rim watershed, northern Thailand. Hydrol. Process. 22, 4339–4354.

Davis, C.M., Fox, J.F., 2009. Sediment fingerprinting: review of the method and future improvements for allocating nonpoint source pollution. J. Environ. Eng. 135 (7), 490–504.

Duarte, C.M., 2002. The future of seagrass meadows. Environ. Conserv. 29 (2), 192–206.

Elliott, M., Whitfield, A.K., 2011. Challenging paradigms in estuarine ecology and management. Estuar. Coast. Shelf. Sci. 94, 306–314.

Erftemeijer, P.L.A., Lewis III, R.R.R., 2006. Environmental impacts of dredging on seagrasses: a review. Mar. Pollut. Bull. 52 (12), 1553–1572.

Gattuso, J.P., Gentili, B., Duarte, C.M., Kleypas, J.A., Middelburg, J.J., Antoine, D., 2006. Light availability in the coastal ocean: impact on the distribution of benthic photosynthetic organisms and their contribution to primary production. Biogeosciences 3, 489–513.

Gillis, L.G., Ziegler, A.D., van Oevelen, D., Cathalot, C., Herman, P.M.J., Bouma, T.J., 2014a. Tiny is mighty: seagrass beds have a large role in the export of organic material in the tropical coastal zone. PLoS ONE 9 (11), e111847. http://dx.doi.org/10.1371/journal.pone.0111847.

Gillis, L.G., Bouma, T.J., Jones, C.G., van Katwijk, M.M., Nagelkerken, I., Jeuken, C.J.L., Herman, P.M.J., Ziegler, A.D., 2014b. Potential for landscape-scale positive interactions among tropical marine ecosystems: a review. Mar. Ecol. Prog. Ser.

503, 289–303.
Harris, D., Horwath, W.R., Kessel, C., 2001. Acid fumigation of soils to remove carbonates prior to total organic carbon or carbon-13 isotopic analysis. Soil Sci. Soc. Am. 65, 1853–1856.
Hemminga, M.A., Marba, N., Stapel, J., 1999. Leaf nutrient resorption, leaf lifespan and the retention of nutrients in seagrass systems. Aquat. Bot. 65, 141–158.
Hemminga, M.A., Mateo, M.A., 1996. Stable carbon isotopes in seagrasses: variability in ratios and use in ecological studies. Mar. Ecol. Prog. Ser. 140, 285–298.
Horstman, E.M., Dohmen-Janssen, C.M., Bouma, T.J., Hulscher, S.J.M.H., 2015. Tidal-scale flow routing and sedimentation in mangrove forests: combining field data and numerical modelling. Geomorphology 228, 244–262.
Kaiser, D., Unger, D., Qiu, G., 2014. Particulate organic matter dynamics in coastal systems of the northern Beibu Gulf. Cont. Shelf. Res. 82, 99–118.
Komada, T., Anderson, M.R., Dorfmeier, C.L., 2008. Carbonate removal from coastal sediments for the determination of organic carbon and its isotopic signatures, $\delta^{13}C$ and $\Delta^{14}C$: comparison of fumigation and direct acidification by hydrochloric acid. Limnol. Oceanogr. Methods 6, 254–262.
Laceby, J.P., Olley, J., Pietsch, T.J., Sheldon, F., Bunn, S.E., 2014. Identifying subsoil sediment sources with carbon and nitrogen stable isotope ratios. Hydrol. Process. http://dx.doi.org/10.1002/hyp.1031.
Lai, S., Gillis, L.G., Mueller, C., Bouma, T.J., Guest, J.R., Last, K.S., Ziegler, A.D., Todd, P.A., 2013. First experimental evidence of corals feeding on seagrass matter. Coral Reefs 32, 1061–1064.
Lee, K.S., Park, S.R., Kim, Y.K., 2007. Effects of irradiance, temperature, and nutrients on growth dynamics of seagrasses: a review. J. Exp. Mar. Biol. Ecol. 350, 144–175.
Lee, S.Y., Dunn, R.J.K., Young, R.A., Connolly, R.M., Dale, P.E.R., Dehayr, R., Lemckert, C.J., Mckinnon, S., Powell, B., Teasdale, P.R., Welsh, D.T., 2006. Impact of urbanization on coastal wetland structure and function. Austral Ecol. 31, 149–163.
Mckinley, R., Radcliffe, D., Mukundan, R.A., 2013. Streamlined approach for sediment source fingerprinting in a Southern Piedmont watershed, US. J. Soils Sediments 13, 1754–1769.
McMillan, C., Parker, P.L., Fry, B., 1980. $^{13}C/^{12}C$ ratios in seagrasses. Aquat. Bot. 9, 237–249.
Odum, E.P., 1980. The status of three ecosvstem-level hypotheses regarding salt marsh estuaries: tidal subsidy, outwelling and detritus-based food chains. In: Kennedv, V. (Ed.), Estuarine Perspectives. Academic Press, New York, pp. 485–495.
Orth, R.J., Carruthers, T.J.B., Dennison, W.C., Duarte, C.M., Fourqurean, J.W., Heck Jr., K.L., Hughes, A.R., Kendrick, G.A., Kenworthy, W.J., Olyarnik, S., Short, F.T., Waycott, M., Williams, S.L., 2006. A global crisis for seagrass ecosystems. BioScience 56 (12), 987–996.
Owens, P.N., 2007. Introduction: background and summary of this issue on sediment linkages. J. Soils Sediments 7 (5), 273–276.
Parnell, A.C., Inger, R., Bearhop, S., Jackson, A.L., 2010. Source partitioning using stable isotopes: coping with too much variation. PLoS ONE 5 (3), e9672.
Phillips, D.L., 2001. Mixing models in analyses of diet using multiple stable isotopes: a critique. Oecologia 127, 166–170.
Phillips, D.L., 2012. Converting isotope values to diet composition: the use of mixing models. J. Mammal. 93 (2), 342–352.
Ramos-Scharrón, C.E., 2012. Effectiveness of drainage improvements in reducing sediment production rates from an unpaved road. J. Soil Water Conserv. 67, 87–100.
Ramos-Scharrón, C.E., Torres-Pulliza, D., Hernández-Delgado, E.A., 2015. Watershed- and island wide-scale land cover changes in Puerto Rico (1930s-2004) and their potential effects on coral reef ecosystems. Sci. Total Environ. 506–507, 241–251.
Salomons, W., Kremer, H.H., Turner, K., 2005. The catchment to coast continuum. In: Crossland, C.J., Kremer, H.H., Lindeboom, H.J., Marshall Crossland, J.I., Le Tissier, M.D.A. (Eds.), Coastal Fluxes in the Anthropocene. Springer Verlag, Germany, pp. 145–200.
Short, F.T., Wyllie-Echeverria, S., 1996. Natural and human-induced disturbance of seagrasses. Environ. Conserv. 23 (1), 17–27.
Short, F.T., Polidoro, B., Livingstone, S.R., Carpenter, K.E., et al., 2011. Extinction risk assessment of the world's seagrass species. Biol. Conserv. 144, 1961–1971.
Short, F.T., Coles, R., Fortes, M.D., Victor, S., Salik, M., Isnain, I., Andrew, J., Seno, A., 2014. Monitoring in the Western Pacific region shows evidence of seagrass decline in line with global trends. Mar. Pollut. Bull. 83 (2), 408–416.
Sidle, R.C., Ziegler, A.D., 2012. The dilemma of mountain roads. Nat. Geosci. 5, 437–438.
Sidle, R.C., Ziegler, A.D., Vogler, J.B., 2006. Contemporary changes in open water surface area of Lake Inle, Myanmar. Sustain. Sci. http://dx.doi.org/10.1007/s11625-006-0020-7.
Slob, A., Gerrits, L., 2007. The dynamics of sedimentary systems and the whimsicality of policy processes. J. Soils Sediments 7 (5), 277–284.
Stable Isotope Analysis in R (n.d.). Retrieved from: www.tcd.ie/Zoology/research/research/theoretical/siar.php (Accessed June 2013).
Thomaz, E.L., Peretto, G.T., 2016. Hydrogeomorphic connectivity on roads crossing in rural headwaters and its effect on stream dynamics. Sci. Total Environ. 550, 547–555.
Tompkins, E.L., 2003. Development pressures and management considerations in small Caribbean islands' coastal zones. Work. Pap. - Cent. Soc. Econ. Res. Glob. Environ. (1), 1–32.
UC Davis Stable Isotope Facility (UCDavis SIF). n.d.. Carbon (13C) and Nitrogen (15N) Analysis of Solids by EA-IRMS. Department of Plant Sciences. Retrieved from: http://stableisotopefacility.ucdavis.edu/13cand15n.html. (Assessed June 2013).
Valiela, I., Cole, M.L., 2002. Comparative evidence that salt marshes and mangroves may protect seagrass meadows from land-derived nitrogen loads. Ecosystems 5, 92–102.
Van Katwijk, M.M., van der Welle, M.E.W., Lucassen, E.C.H.E.T., Vonk, J.A., Christianen, M.J.A., Kiswara, W., Inayat al Hakim, I., Arifin, A., Bouma, T.J., Roelofs, J.G.M., Lamers, L.P.M., 2011. Early warning indicators for river nutrient and sediment loads in tropical seagrass beds: a benchmark from a near-pristine archipelago in Indonesia. Mar. Pollut. Bull. 62, 1512–1520.
Van Meerveld, H.J., Baird, E.J., Floyd, W.C., 2014. Controls on sediment production from an unpaved resource road in a pacific maritime watershed. Water Resour. Res. 50, 4803–4820.
Wada, E. (2009). Stable δ15N and δ13C isotope ratios in aquatic ecosystems. Proceedings of the Japan Academy, Series B, Physical and Biological Sciences 85, 98–107.
Walling, D.E., 2013. The evolution of sediment source fingerprinting investigations in fluvial systems. J. Soils Sediments 13, 158–1675.
Walthert, L., Graf, U., Kammer, A., Luster, J., Pezzotta, D., Zimmermann, S., Hagedorn, F., 2010. Determination of organic and inorganic carbon, $\delta^{13}C$, and nitrogen in soils containing carbonates after acid fumigation with HCl. J. Plant Nutr. Soil Sci. 173, 208–216.
Wang, W.-L., Yeh, H.-W., 2003. $d^{13}C$ values of marine macroalgae from Taiwan. Bot. Bull. Acad. Sin. 44, 107–112.
Waycott, M., Duarte, C.M., Carruthers, T.J.B., Orth, R.J., Dennison, W.C., Olyarnik, S., Calladine, A., Fourqurean, J.W., Heck Jr., K.L., Hughes, A.R., Kendrick, G.A., Kenworthy, W.J., Short, F.T., Williams, S.L., 2009. Accelerating loss of seagrass ecosystems across the globe threatens coastal ecosystems. PNAS 106 (30), 12377–12381.
Wolters, J.-W., Gillis, L.G., Bouma, T.J., van Katwijk, M.M., Ziegler, A.D., 2016. Land use effects on mangrove nutrient status in phang Nga bay, Thailand. Land Degrad. Dev. 27, 68–76.
Yaakub, S.M., Chen, E., Bouma, T.J., Erftemeijer, P.L.A., Todd, P.A., 2014a. Chronic light reduction reduces overall resilience to additional shading stress in the seagrass Halophila ovalis. Mar. Pollut. Bull. 83, 467–474.
Yaakub, S.M., McKenzie, L.J., Erftemeijer, P.L.A., Bouma, T.J., Todd, P.A., 2014b. Courage under fire: seagrass persistence adjacent to a highly urbanised city-state. Mar. Pollut. Bull. 83, 417–424.
Zhang, W.S., Swaney, D.P., Li, X.Y., Hong, B., Howarth, R.W., Ding, S.H., 2015. Anthropogenic point-source and non-point-source nitrogen inputs into Huai River basin and their impacts on riverine ammonia-nitrogen flux. Biogeosciences 12, 4275–4289.
Ziegler, A.D., Bruun, T.B., Guardiola-Claramonte, M., Giambelluca, T.W., Lawrence, D., Nguyen, thanh lam, 2009. Environmental consequences of the demise in swidden agriculture in SE Asia: Hydrology and geomorphology. Hum. Ecol. 37, 361–373.
Ziegler, A.D., Sidle, R.C., Song, M.S., Ang, J.Z., Duangnamon, D., 2012. Slope Failures and Erosion on the Ao Jak Beach Road: toward Reducing Tsunami Vulnerability on Remote Coastlines, 361. Geological Society, London, pp. 107–111. Special Publications.