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Intertidal zone particulate organic carbon redistribution by low-tide rainfall

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Abstract

We present field data and data from the literature to highlight the effects of low-tide rainfall on particulate organic carbon (POC) redistribution in intertidal landscapes. The POC exchanges reported from disparate but related studies were standardized to a *storm-induced exchange rate* (gPOC m^{-2} $mmRain^{-1}$) and compared. Results show that these intertidal areas have a characteristic response to rainfall with an average flux of 0.040 ± 0.038 gPOC m^{-2} $mmRain^{-1}$. Further, low-tide rainfall can entrain and redistribute 7–54% of annual sedimentary POC accumulation, or 12–75% of annual POC export, based on current outwelling assessments. Finally, we provide a conceptual model describing the variability of rainfall-driven POC exchange through the hierarchical structure of intertidal landscapes and how observations of POC flux can be expected to change across the intertidal landscape. This information should be used to guide sampling strategies for continued intertidal zone rainfall work.

Intertidal landscapes are essential components of the coastal ocean carbon pool (e.g., Saintilan et al. 2013), and thus play an important role in global carbon cycles (Chmura et al. 2003). Biogeochemical models for organic carbon (OC) cycling in intertidal landscapes typically include inputs from rivers, ocean and groundwater (Fig. 1a) (Valiela et al. 1992) and subsequent OC transformations help support both autotrophic and heterotrophic production (Fig. 1a). For example, biogeochemical processes such as respiration and mineralization transform OC into carbon dioxide; it constantly transforms between particulate and dissolved phases through the food web, and it undergoes decomposition, aggregation, and adsorption. In many cases particulate organic carbon (POC) can accumulate in intertidal zone sediment, and some may be reintroduced to the water column by biological and physical processes (Amos et al. 2004; Sakamaki and Nishimura 2007). Eventually, intertidal zone OC may reach the coastal ocean (Fig. 1a) through the process of "outwelling" (e.g., Odum and de la Cruz 1967; Nixon 1980; Dame et al. 1986), the local export of nutritious organic material.

This conceptual view of estuarine carbon cycling (Fig. 1a), however, overlooks one important facet: the effects of low-tide rainfall (e.g., Torres et al. 2004). In salt marshes tidal currents and shallow water waves typically do not generate shear stresses that exceed sediment shear resistance (Amos 1995; Callaghan et al. 2010); thus intertidal landscapes are sites of incipient long term sediment storage. Conversely, during low-tide storms raindrop impacts can break loose and eject the cohesive sediment, and overland flow facilitates its transfer in the downslope direction (Torres et al. 2004). In addition, the fresh water input by rainfall promotes deflocculation (Mwamba and Torres 2002; Tolhurst et al. 2008) and gives rise to lower critical shear stress (Pilditch et al. 2008). Consequently, after low-tide rainfall the surface sediment is susceptible to mobilization and transport by tidal currents and shallow water waves with subsequent tidal cycles (Tolhurst et al. 2006). Taken together these observations and inferences indicate that rainfall-runoff processes directly transport organic matter, and they facilitate tidal current mobilization of POC from the intertidal sedimentary surface to the water column (e.g., Chalmers et al. 1985; Roman and Daiber 1989; Mwamba and Torres 2002; Tolhurst et al. 2008) (Fig. 1b).

Several studies reported direct measurements of intertidal zone POC exchange generated by rainfall-runoff processes (Chalmers et al. 1985; Mwamba and Torres 2002; Pilditch et al. 2008; Chen 2013), or made field measurements that highlight the direct and indirect effects of rainfall events (Roman and Daiber 1989; Leonard et al. 1995*a*; Nowacki and Ogston 2012) across a range of intertidal environments, and

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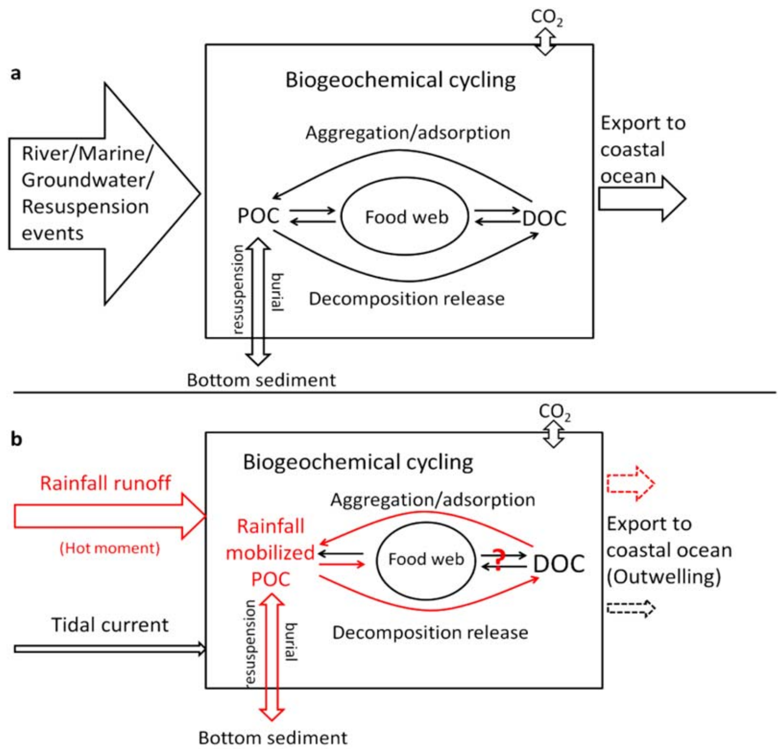

Fig. 1. (a) Biogeochemical conceptual view of OC in an intertidal environment. Boxes represent the water column, block arrows represent fluxes. Line arrows represent biogeochemical pathways. Modified from Bianchi (2007). (b) Adding rainfall effect to (a). Red arrows highlight processes that may be influenced by rainfal-runoff. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

with various approaches. However, the reported findings are site specific and event based. Consequently, these research efforts individually provide limited insight on the overall role of low-tide rainfall on POC cycling. We propose that an assessment of these studies in the context of rates of POC transport will improve our understanding of rainfall-driven OC and biogeochemical cycling. This is particularly relevant when considering the effects of climate change, and an expected intensification of the hydrologic cycle of many coastal landscapes (Hayhoe et al. 2007). Therefore, the potential for low-tide rainfall to influence intertidal zone biogeochemical processes can be expected to increase, and therefore, a more comprehensive understanding of rainfall-runoff effects on intertidal landscape material cycling is needed.

To generalize the findings from a range of studies that directly or indirectly assess POC cycling by low-tide rainfall and runoff processes we use information in published reports and ancillary information to calculate a storm-induced exchange rate, hereafter referred to as “R_S” (mass POC per unit area-per unit rainfall), and an annual exchange rate, “R_A” (mass POC per unit area-per year) at various locations. This assessment will help provide a standard to highlight and compare rainfall-driven POC exchange for a range of intertidal environments, and it will help shed light on the role of intra-estuarine POC cycling on estimates of carbon storage, and the redistribution of nutrient rich particulate matter on intertidal zone ecosystem sustainability under the influence of climate change and sea level rise.

Rainfall and POC exchanges

Previous studies

We found ten studies that quantified various components of rainfall-driven POC exchange, or provided sufficient detail to allow the estimation of POC exchange (Table 1). Most of these studies are from the Atlantic coast of the U.S. with one site in the Pacific northwestern U.S. and one in the United Kingdom. Seven of these studies were conducted in salt marshes, two on mudflats and one in a complex environment of forest, cultivated fields and salt marsh (Table 1). Each study was conducted with a different experimental design, and the reported POC exchanges were determined using different approaches; the original information from these studies that was used in our analyses is listed in Table 1.

Experimental settings

Below, we briefly introduce the experimental settings of each study and the reported POC exchange calculation

Table 1. The original information provided in previous literature about rainfall-driven flux. The information includes the study sites, contributing areas, environments, rainfall types, numbers of rain events, sampling constructions, sampling protocols, flux calculation methods, and the original data in the literatures.

Ref.	Study site	Contributing area (m^2)	Environment	Rainfall type	Numbers of rain events	Sampling construction	Sampling protocol	Flux calculation	Original data
Chalmers et al. (1985)	Sapelo Island Georgia	96	Salt marsh	Natural rainfall	5	Flume	Rainfall-runoff water samples from flume every 10 or 15 min	gPOC s^{-1}=POC×ΔVolumn measured by the difference of water height	Annual rainfall-driven POC yield is 177.67 gC m^{-2} yr^{-1} with 830 mm of low-tide rainfall annually
Chen (2013)	Maddieanna Island, North Inlet, South Carolina	3.2×10^4	Salt marsh	Natural rainfall	23	Natural Channel	Rainfall-runoff water samples from creek surface every 10 or 15 min	gPOC s^{-1}=current profile by ADCP×POC of water samples×cross-section area	0.020±0.002 gPOC m^{-2} $mmRain^{-1}$
Jordan et al. (1986)	Rhode River Maryland	2.05×10^7	Salt marsh/ forest/ agriculture	Natural rainfall	Seven years long term observation	Natural Channel with a V-notched weir	Water samples from weir every week	gPOC s^{-1}= POC×ΔVolumn measured by the difference of water height	Sediment flux during weeks with more than two centimeter precipitation is 28000000 × *g*; for weeks with less than two centimeter precipitation it is 5000000 × g.
Leonard et al. (1995*a*)	Cedar Creek Florida	5×10^6	Salt marsh	Natural rainfall	1	Natural Channel	Hourly velocity profile and water samples	gSed s^{-1}=hourly current profile×SSC by water samples× cross-section area	Net transport of sediment for one rain event is 23725000 × g of sediment
Nowacki and Ogston (2012)	Willapa Bay, Washington	Not provided	Mudflat	Natural rainfall	2	Natural Channel	Continuous OBS and ADV observation for 45 d	gSed s^{-1}=current profile by ADV×SSC estimated by OBS× cross-section area	Net storm driven sediment flux is $6.56\times10^5-2.7\times10^6$ g m^{-2} d^{-1}
Roman and Daiber (1989)	Canary Creek Delaware	1.9×10^6	Salt marsh	Natural rainfall	1	Natural Channel	Water samples from creek every two hours for three consecutive tidal cycles	gPOC s^{-1}= POC×Δ Volume measured by the difference of water height	Transport of POC during storm ebb tide: 3000 kgPOC $cycle^{-1}$

TABLE 1. Continued

Ref.	Study site	Contributing area (m^2)	Environment	Rainfall type	Numbers of rain events	Sampling construction	Sampling protocol	Flux calculation	Original data
Voulgaris and Meyers (2004)	Bly Creek, North Inlet, South Carolina	Not provided	Salt marsh	Natural rainfall	1	Natural Channel	Continuous OBS and ADV observation for eight days	gSed s^{-1}=current profile by ADV× SSC estimated by ADV×cross-section area	Net sediment mass per tidal cycle is 13.63×10^3 kgSed cycle⁻
Wolaver and Spurrier (1988)	Bly Creek, North Inlet, South Carolina	9×10^3	Salt marsh	Natural rainfall	4	Natural Channel with a V-notched weir	Water samples from weir every 11.8 d for two years	gPOC s^{-1}= POC×ΔVolume measured by the difference of water height	13.9 gPOC m^{-2} yr^{-1} was mobilized by storms
Mwamba and Torres (2002)	North Inlet, South Carolina	2	Salt marsh	80 mm total rain simulation rain	1	Plot	Rainfall-runoff water samples from plot every 1-2 min	gPOC s^{-1}= POC×water discharge	Time series of water discharge, %OC and SSC of the entire rainfall simulation. Obtained from Mwamba's Master thesis
Pilditch et al. (2008)	Tavy estuary, UK	0.17	Mudflat	25 mm total rain simulation rain	1	Plot	Rainfall-runoff water samples from plot continuously	gPOC s^{-1}=POC× water discharge	106 gSed m^{-2} were mobilized during the simulation

methods and additional information. Later we perform analyses with these data to estimate storm and annual POC exchange rates at each site, but with a single, uniform approach to facilitate comparison between sites. In the following studies intertidal zone material was mobilized by natural rainfall or by sprinkler irrigation, and sampling was at the mouth of a flume, or from grab samples in intertidal creeks, or creek mouths (Table 1). Also, sampling duration and methods of sampling were highly variable.

Mwamba and Torres (2002) irrigated a 2 m^2 salt marsh plot at 80 mm h^{-1} for 0.75 h and sampled runoff at the down slope end. Pilditch et al. (2008) irrigated a 0.17 m^2 mud flat plot at 240 mm h^{-1} for 0.1 h. Chalmers et al. (1985) used a much more extensive 1.6 × 60 m^2 "plot" or flume built on the marsh surface and they sampled runoff at about 0.25 h intervals during five rainfall events. The following studies evaluated samples from tidal creeks. For example, Jordan et al. (1986) and Wolaver and Spurrier (1988) installed V-notched weirs in intertidal creeks for weekly to biweekly sampling to measure both tidal current-driven (background), and rainfall-driven sediment exchanges. Chen (2013) collected water samples from the mouth of a tidal creek at about 0.25 h intervals from 23 storms, and for comparison sampled the background conditions during no rain. Leonard et al. (1995*a*) measured velocity profiles hourly and collected water samples from a tidal creek during one storm event, and Roman and Daiber (1989) collected water samples near the creek mouth every two hours for a duration of three consecutive tidal cycles that included a low-tide storm. Lastly, both Voulgaris and Meyers (2004), and Nowacki and Ogston (2012) deployed acoustic Doppler velocimeters and optical backscatter sensors to measure current profiles and suspended sediment concentration (SSC). Nowacki and Ogston (2012) had a relatively long deployment of 45 d observing six low-tide storms while Voulgaris and Meyers (2004) deployed for eight days with one low-tide storm.

Reported POC fluxes

All ten studies provide instantaneous rainfall-driven POC exchange rates as mass of POC per time (gPOC s^{-1}), but they employ four different methods (Table 1). The first approach made use of the product of POC concentration, current velocity and cross-section area of flow to compute the instantaneous POC exchange. Two studies used this approach and they are Leonard et al. (1995*a*) who reported a net transport of 2.37 × 10^8 g of sediment for one storm event, and Chen (2013) who used better constraints on time and rain-affected area to report an average $R_S = 0.020 \pm 0.002$ gPOC m^{-2} $mmRain^{-1}$ based on 23 storms (Table 1).

The second approach for instantaneous POC exchange rate relied on rate of change in water level to estimate changes in water volume. In this case the corresponding water volume exchange over a time interval gives the "instantaneous" ΔV and the instantaneous POC exchange is the product of instantaneous ΔV and POC concentration. With this approach Chalmers et al. (1985) reported that 830 mm of low-tide rainfall produced an $R_A = 177.$ 7 gPOC m^{-2} yr^{-1} while Wolaver and Spurrier (1988) simply reported $R_A = 13.9$ gPOC m^{-2} yr^{-1}. Further to the north Roman and Daiber (1989) found the transport of POC during a storm on ebb tide was 3.0 × 10^6 g. Also, Jordan et al. (1986) observed that sediment flux from the week-long intervals with more than two centimeter of precipitation was up to 2.8 × 10^7 g $week^{-1}$ while for the weeks with less than two centimeter precipitation it was 5.0 × 10^6 g $week^{-1}$. In our calucations below we assume that the latter was the background sediment flux, and therefore, the net rainfall-driven sediment flux was 2.3 × 10^7 g $week^{-1}$ (Table 1).

The third method of determining exchange rate was performed by Voulgaris and Meyers (2004), and Nowacki and Ogston (2012). In these cases they did not require water sampling; instead, they estimated SSC from backscatter and the velocity profile data. Voulgaris and Meyers (2004) observed that 1.4 × 10^7 g of sediment were generated by one rainfall event, and Nowacki and Ogston (2012) determined a net rainfall-driven sediment flux of 6.6 × 10^5 to 2.7 × 10^6 g m^{-2} d^{-1} (Table 1). These data were then converted to POC fluxes using the weight percent of bulk OC content reported in the literature for their respective locations.

The fourth method of estimating instantaneous POC exchange is from Mwamba and Torres (2002) and Pilditch et al. (2008). In their plot studies they collected rainfall-runoff samples directly from a known area, therefore, the sample volume per time was the instantaneous water discharge, and the instantaneous POC exchange was taken as the product of instantaneous discharge and the measured instantaneous POC concentration (Table 1).

Calculation of R_S *and* R_A from published data

Due to the differences in the measurement of rainfall-driven POC exchange above, and to standardize and broaden the utility of these disparate but related studies it is necessary to derive a common unit to facilitate the comparison between sites. First we estimate the storm-induced exchange rate R_S with units of gPOC m^{-2} $mmRain^{-1}$. R_s is proposed as a keystone unit because with any given intertidal landscape if the total low-tide rainfall is known, and if the contributing area to runoff sampling can be determined then the rainfall-driven POC exchange or flux can be estimated based on R_S. Further, to evaluate the rainfall-driven POC exchange in the context of overall intertidal zone POC cycling we define an annual flux R_A with units of gPOC m^{-2} yr^{-1} where R_A is simply the product of R_S and annual low-tide rainfall. Moreover, the units of R_A are equivalent to the units used in presenting POC exchange rates from outwelling studies (e.g., Nixon 1980; Dame et al. 1986), and for organic matter accumulation rates (e.g., Orsen et al. 1990; Leonard et al. 1995*a*; Vogel et al. 1996). Therefore, R_A can be evaluated in the context of two widely reported intertidal landscape metrics. In the following sections, we describe the procedures and assumptions for calculating R_S and R_A. We also summarize the information needed for these calculations in Table 2.

Here we provide an intertidal zone geomorphic context to the ten studies identified above. Typically, the intertidal landscape is comprised of a broad platform area with decimeter scale relief, and intertidal creeks that feed into a larger subtidal channel (Allen 2000) (Fig. 2a). Rainfall-entrained particulates are transported by overland flow on the platform and toward the intertidal creek. The material reaching the creek is then routed through the intertidal creek networks, and then through the subtidal channel system. In some areas the material may eventually reach the coastal ocean through ebb tide circulation. The boundaries between these landscape features are characterized as the interfaces where rainfall-driven POC exchanges were measured in the studies identified above and are illustrated in Fig. 2a. Hence, each researcher measured POC exchanges at one of three locations: (1) on the marsh platform as plot-plot transfer (A in Fig. 2a), (2) at the plot-intertidal creek (B in Fig. 2a) and (3) at the intertidal creek-subtidal channel interface (C in Fig. 2a). Once the material reaches the subtidal channel system it is susceptible to export depending on the duration of the storm, tide stage, tide conditions, and proximity of the intertidal-subtidal interface to the estuary inlet or mouth. Conversely, rainfall-entrained sediment interacting with a flood tide most likely leads to intra-estuarine sediment redistribution and sedimentation, and the extent of redistribution depends on the exact timing of the rainfall event relative to the area inundated by the rising tide.

Mwamba and Torres (2002) and Pilditch et al. (2008) measured exchanges on the platform at a plot-plot interface (Table 2). Samples taken in these studies represent particles mobilized by rain drops and transported by overland flow across a very short distance (plot length). To calculate the R_S of Mwamba and Torres (2002) we obtained the time series of discharge, SSC and loss on ignition values from Mwamba (2001) and calculated an R_S of 0.31 gPOC m^{-2} mmRain^{-1}. A two year high resolution rainfall record from a site within two kilometer of Mwamba and Torres gives an annual average of 1515 mm. However, when compared with tidal records Chen (2013) reported that 682 mm or 45% of this annual total rain occurred at low tide. In the following calculations for all ten study sites (Table 1) we assume the occurrence of low-tide rainfall was comparable and taken as 45% of the annual total; we refer to value of 45% of the annual total as the low-tide rainfall or "effective precipitation", P. This assumption has no effect on R_s but it does affect R_A because R_A is the product of R_S and P. A detailed evaluation of the 45% assumption is provided in the discussion section. With this approach the R_A for the Mwamba and Torres study is 211.4 gPOC m^{-2} yr^{-1}. Likewise, Pilditch et al. (2008) reported that the mass of rainfall-entrained sediment was 106 gSed m^{-2} and the bulk OC content and therefore the R_S for this study in the Tavy estuary, UK was 0.37 gPOC m^{-2} mmRain^{-1}. Also, the annual rainfall is ~ 900 mm (http://www.metoffice.gov.uk), P = 410 mm and $R_A = 152$ gPOC m^{-2} yr^{-1} (Table 2).

The samples from Chalmers et al. (1985) taken at the downslope end of the flume provides information on the plot-intertidal creek interface (B in Fig. 2a; Table 2). They observed five low-tide rainfall events over the study period and reported an R_A of 177.67 gPOC m^{-2} yr^{-1} with $P = 830$ mm. This gives an R_S of 0.21 gPOC m^{-2} mmRain^{-1} (Table 2). These samples taken at the end of the very long flume include rain drop impact and extensive winnowing or density separation as the material traverses the marsh in a likely water depth up to 2 cm (*see* Mwamba and Torres 2002).

The remaining studies were conducted at the intertidal creek-subtidal channel interface (C in Fig. 2a). The POC exchanges here include the processes acting on the two above interfaces in addition to further winnowing over the length of the flume, and the higher salinity effects as the freshwater and sediment mix with more saline water as both water and sediment move toward the creek mouth. Field observations indicate that low-tide water depths at this interface are typically less than about 1 m. In this case Chen (2013) collected samples during 23 low-tide rainfall events over three summers and analyzed the SSC and %OC as well as velocity profiles of intertidal creeks. They concluded that the average R_S was 0.020 ± 0.002 gPOC m^{-2} mmRain^{-1} and the R_A was 13.64 ± 1.36 gPOC m^{-2} yr^{-1} (Table 2).

Roman and Daiber (1989) reported 3.0×10^6 g of POC exchanged by a rainfall event over a 1.9×10^6 m^2 area. We estimated their rainfall amount by the mass balance of the tidal prism and assumed that half of their reported imbalance was caused by a single storm with unmeasured rainfall. Dividing this water volume from the inferred watershed area (GoogleEarth) gives a low-tide rainfall total of 30 mm. With this R_S was found to be 0.053 gPOC m^{-2} mmRain^{-1}. The annual average rainfall at this study site is 1170 mm (www.nationalatlas.gov) and the effective P gives an R_A of 28.20 gPOC m^{-2} yr^{-1}.

Leonard et al. (1995*b*) reported that 2.37×10^7 g of sediment was mobilized by a rain event over a 5×10^6 m^2 salt marsh area in Cedar Creek, Florida, and the %OC in rainfall-runoff material was 13.9%. The rain event they sampled totaled 45 mm (http://www.ncdc.noaa.gov/cdo-web/quickdata) giving an R_S of 0.015 gPOC m^{-2} mmRain^{-1}. The closest site with annual rainfall data is ~ 20 km away in Weeki Wachee, Florida and it gives a value of 1280 mm (NOAA COOP ID: 089439), and the corresponding P gives an $R_A = 8.55$ gPOC m^{-2} yr^{-1} (Table 2).

Wolaver and Spurrier (1988) reported that 13.9 gPOC m^{-2} yr^{-1} was mobilized by storms. Since their study site was at North Inlet salt marsh, close to Chen (2013), we assumed their effective precipitation rate applied giving an $R_S = 0.020$

Table 2. Information needed for calculation of R_A and R_s. Original information provided in the previous studies is in black, assumptions made by the author are in red, calculations based on outside data are in green.

Interface	Ref.	Rainfall	Water flux (m^3 s^{-1})	SSC (g m^{-3})	wt. OC	Annual low-tide rainfall (mm yr^{-1})	Sediment flux per cycle or event	POC flux per cycle or event	Rainfall-runoff POC removal rate (gPOC m^{-2} $mmRain^{-1}$)	Annual rainfall-runoff POC yield (gPOC m^{-2} yr^{-1})
Plot-plot	Pilditch et al. (2008)	25 mm rainfall simulation	N/A	N/A	8.75	410	106 gSed m^{-2} $event^{-1}$	9.28 gPOC m^{-2} $event^{-1}$	0.371	152.11
	Mwamba and Torres (2002)	80 mm rainfall simulation	Mwamba (2001)	Mwamba (2001)	Mwamba (2001)	682	Mwamba (2001)	N/A	0.31	211.4
Plot-intertidal creek	Chalmers et al. (1985)	N/A	N/A	N/A	N/A	830	N/A	N/A	0.21	177.67
Intertidal creek-subtidal channel	Chen (2013)	2.79-49.02 mm	N/A	0.20-2.17	4.38	682	N/A	0.64-50.54 kgPOC/event	0.020± 0.002	13.64± 1.36
	Wolaver and Spurrier (1988)	N/A	N/A	N/A	N/A	682	N/A	N/A	0.02	13.64
	Voulgaris and Meyers (2004)	35 mm	N/A	N/A	5.04	682	13630000 $\times g$ $cycle^{-1}$	687 kgPOC $cycle^{-1}$	0.105	71.61
	Roman and Daiber (1989)	30 mm	N/A	N/A	N/A	532	N/A	3000 kgPOC $cycle^{-1}$	0.053	28.2
	Leonard et al. (1995*b*)	45 mm	N/A	N/A	13.93	582	23725000 $\times g$ $event^{-1}$	3305 kgPOC $cycle^{-1}$	0.015	8.55
	Jordan et al. (1986)	24.3 mm $week^{-1}$	N/A	N/A	4.14	532	23000000 $\times g$ $week^{-1}$	952 kgPOC $week^{-1}$	0.002	1.06
	Nowacki and Ogston (2012)	8.9 mm d^{-1}	N/A	N/A	7.8	910	6.56×10^5 -2.7×10^6 g m^{-2} d^{-1}	16.4-67.5 kgPOC m^{-2} d^{-1}	0.019-0.087	17.04-79.50
	Average								0.040± 0.038	

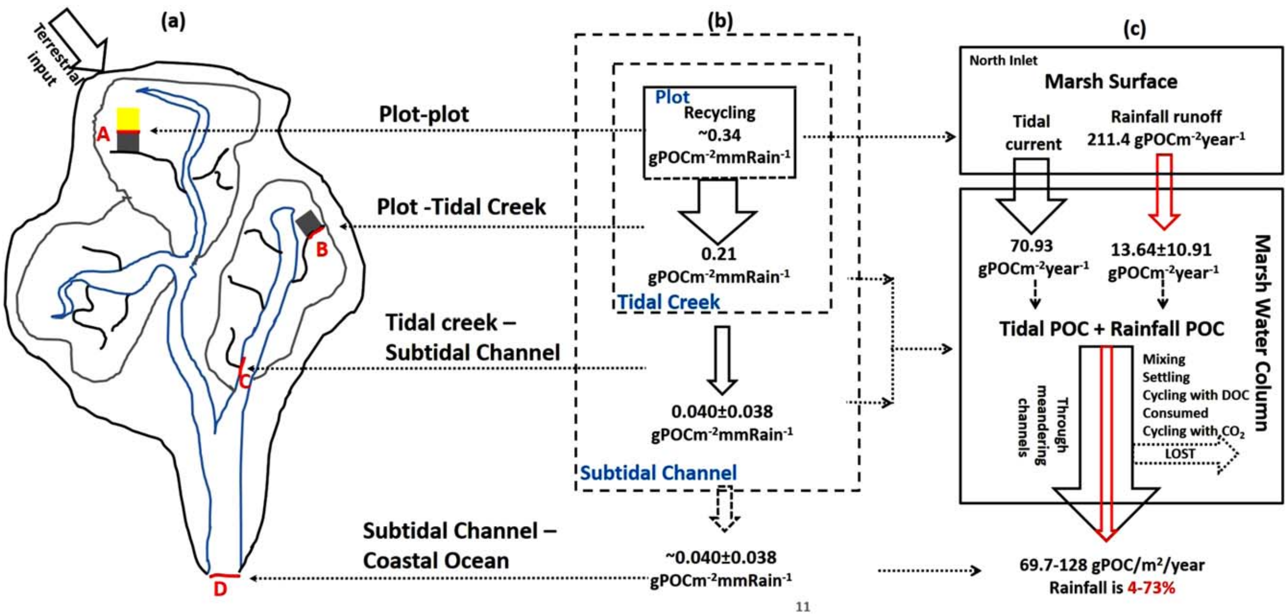

Fig. 2. (a) The landscape compartments and POC exchange interfaces in a hypothetical intertidal environment. Boxes represent plots on the sediment surface; black lines represent intertidal creeks; blue lines outline larger subtidal channels; gray outlines delineate the subtidal channel watershed boundary; black outlines delineate the boundary of the entire intertidal environment. The block arrow on the top-left corner indicates that some environments may have terrestrial input. Four interfaces are shown using red lines. They are A: plot-plot; B: plot-intertidal creek; C: intertidal creek-subtidal channel; D: subtidal channel-coastal ocean. (b) A conceptual model describes the rainfall-driven storm-induced exchange rate of four geomorphic units of the intertidal landscape: plot, intertidal creek, subtidal channel, and entire landscape. Dashed line indicates possible material flux by rainfall-runoff. (c) Box model of POC cycling in sediment surface, water column and the export into coastal ocean using North Inlet salt marsh as an example, modified from Fig. 1. Arrows indicate annual flux of POC in North Inlet salt marsh. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

gPOC m^{-2} $mmRain^{-1}$. Voulgaris and Meyers (2004) did not provide values of the rainfall-driven sediment yield, total rainfall or the contributing area. Instead, we estimated these values from their figures (Figs 5, 7 in their paper), and estimated contributing area from a local topographic map using ArcGIS. The data indicate that the storm total was 35 mm and the net rainfall-driven sediment flux was 1.4×10^7 g. The average bulk OC content was reported as 5.04%, hence R_S was 0.104 gPOC m^{-2} $mmRain^{-1}$. Given the proximity of this site to the Chen (2013) site we apply the same P and find that $R_A = 71.5$ gPOC m^{-2} yr^{-1}. Jordan et al. (1986) reported weekly net rainfall-driven sediment flux of 2.3×10^7 g. The weekly rainfall of 24.3 mm was estimated from their figures (Figs. 2, 3 in their paper). Also, we used the weight percent OC of 4.14% as reported in Correll (1981). Thus we estimated the $R_S = 0.002$ gPOC m^{-2} $mmRain^{-1}$ and the effective precipitation, P, gives an $R_A = 1.06$ gPOC m^{-2} yr^{-1} (Table 2).

For the mudflat environment Nowacki and Ogston (2012) reported a net rainfall sediment yield of $6.56 \times 10^5 - 2.7 \times 10^6$ g m^{-2} d^{-1} and approximately 8.9 mm rainfall per day. We used GoogleEarth to outline their study site and estimated a contributing area of 2.7×10^5 m^2. In addition, the %OC in modern Willapa Bay sediment was taken as 7.8% (Gingras et al. 1999). Thus, R_S was 0.02-0.09 gPOC m^{-2} $mmRain^{-1}$. The study site receives approximately two meters rainfall annually (Nowacki and Ogston 2012) therefore we assume $P = 910$ mm giving an R_A of 17.04–79.50 gPOC m^{-2} yr^{-1}. Finally, the background tidal current-driven POC exchange, or the outwelling estimates used to compare with the abovementioned rainfall-driven POC exchanges were listed in Table 3 where outwelling is typically estimated as the product of concentration and discharge at an appropriate site, and scaled up for a full year (e.g., Dame et al. 1986).

In sum, we used limited assumptions and publicly available ancillary information to standardize the observation from these disparate sites. This was necessary because these studies used various sampling methods, and they are from a range of coastal environments. The standardized fluxes are reported as R_S and R_A in Table 2.

Results

Here we evaluate the standardized fluxes in a geomorphic context. Rainfall-driven POC exchanges at the plot-plot interface are the highest with values of 0.310–0.371 gPOC m^{-2} $mmRain^{-1}$ (Table 2). At the plot-intertidal creek interface the R_S decreases by about 30% to 0.210 gPOC m^{-2}

mmRain^{-1}. At the intertidal creek-subtidal channel interface R_S values are consistently in the range of 0.015–0.105 gPOC m^{-2} mmRain^{-1} with an average of 0.040 ± 0.038 gPOC m^{-2} mmRain^{-1}, or about 90% lower than the plot values (excluding the minimum value in Jordan et al. 1986) (Table 2). Collectively, these analyses show that low-tide rainfall-runoff processes have two effects. First, they arrest the incipient storage of POC in an otherwise low energy, depositional environment. Second, they provide the energy to make the surface sediment a non-point source of POC to the intertidal and subtidal water columns. However, as water and sediment advance through the system toward the subtidal channel the sediment and POC fluxes decline rapidly. The net effect of declining flux with distance is that the fluxes at the subtidal channel are remarkably consistent, within a factor of 7, meaning that the highest value is at most seven times more than the lowest value. This is a relatively small range of variability given that the study sites are up to thousands of kilometers apart, as well as the differences in environmental conditions (salt marsh or mudflat), calculation methods and experimental approaches.

We then compared the storm-induced POC exchange rates to the tidal current-driven or background POC exchanges, and the sedimentary organic matter accumulation rates to provide a broader context to these results, and to evaluate the significance of rainfall-runoff processes in overall OM cycling in the intertidal environments. The corresponding values are listed in Table 3. The comparison of the R_A to tidal current-driven exchanges, and the OM accumulation rates for studies in South Carolina shows that R_A is 4-73% of the annual tidal current-driven POC flux, and 7% of organic matter accumulation (Table 3). For a Delaware River salt marsh Roman (1981) provided tidal current-driven POC, Orsen et al. (1990) estimated the organic matter accumulation rate, and Roman and Daiber (1989) measured storm-induced POC exchange. These data together show that R_A amounts to 48% of tidal current-driven POC exchange and 54% of OM accumulation. In Cedar Creek Florida the Leonard et al. (1995*a,b*) provide results indicating that low-tide rain storms cycle POC equivalent to 26% of the annual tidal current-driven flux, and 9% of the annual OM accumulation (Table 3).

In sum, we reviewed previous studies for low-tide rainfall effects on intertidal zone material cycling, reanalyzed their data, and estimated their fluxes based on available data and data not necessarily reported in these studies, but inferred from other sources. Together the data and analyses allowed us to compute R_S for various intertidal landscapes. We also compared the R_A values with estimates of tidal current-driven or background POC flux, and organic matter accumulation rates. Overall, there was a characteristic response to rainfall-runoff processes with an average R_S of 0.040 ± 0.038 gPOC m^{-2} mmRain^{-1} at the intertidal creek-subtidal channel interface. This storm-induced POC exchange rate was 12-75% of annual tidal current-driven POC exchange, and it was 7–54% of annual organic matter accumulation. Hence, low-tide rainfall and redistribution processes have the potential to deliver large amounts of nutritious particulate matter to the water column and they substantially enhance POC cycling and net POC export, or outwelling.

Discussion

Low-tide rainfall events are a type of intra-estuarine material cycling process and they are capable of transporting significant amounts of marsh plant-derived organic matter from the surface sediment to the water column (Torres et al. 2004). The rainfall-entrained material goes through the hierarchical structure of the intertidal environment (Fig. 2a) and various processes occur during the mobilization and transportation at different parts of the landscape. For example, rainfall effects start at the surface (A in Fig. 2a,b) where rain drop impacts eject cohesive sediment, and overland flow entrains and transports it to the banks or heads of intertidal creeks (B in Fig. 2a). During this process some sediment winnowing and redeposition likely occurs but there is net R_S in the "downstream" direction (Table 2).

After the runoff material reaches the intertidal creek it travels with the extant flows along the creek and possibly to the intertidal creek-subtidal channel interface (C in Fig. 2a). The outstanding feature from this study is that regardless of all the differences between the ten study sites and with our limited assumptions we found a relatively uniform value of R_S, ranging from 0.015 to 0.105 gPOC m^{-2} mmRain^{-1}. This observation indicates that the intertidal zone surface sediment can be expected to have a characteristic response to rainfall-driven mobilization and transport of POC. We hypothesize that the characteristic response to rainfall-runoff is possibly due to the winnowing of variable density material and the preferential transport of the lighter particulate constituents (e.g., Mwamba 2001; Torres et al. 2004). Therefore, we propose that 0.040 ± 0.038 gPOC m^{-2} mmRain^{-1} represents a typically unaccounted for rainfall-driven POC flux.

Research focused on quantifying POC flux from the estuary to the coastal ocean did not account for pulses of rainfall-driven POC because the corresponding observations were made during relatively calm conditions (*see* references in Table 3). Therefore, we compared our results to reported outwelling fluxes and found that R_A amounts to 12–75% of annual tidal current POC yield as measured at the intertidal creek-subtidal channel interface (Table 3). This proportion indicates that reported outwelling measurements may in fact represent minimum values of OC export. Conversely, outwelling continues to be controversial because many salt marshes were found to be importing organic matter from coastal ocean (e.g., Woodwell et al. 1979 1977; Dankers et al. 1984; Stevenson et al. 1988), while some are exporting organic matter (e.g., Nixon 1980; Chrzanowski et al. 1983

Table 3. Summary of tidal current-driven POC flux and the proportion of rainfall-runoff in tidal current-driven POC flux.

	Tidal current-driven POC flux			Organic accumulation			Rainfall runoff driven POC flux			Proportion	
Interface	**Sources**	**Study site**	**Annual tidal current POC yield (gPOC m^{-2} yr^{-1})**	**Sources**	**Study site**	**Organic accumulation rate (gPOC m^{-2} yr^{-1})**	**Source**	**Study site**	**Annual rainfall runoff POC yield (gOC m^{-2} yr^{-1})**	**Of tide**	**Of OM accu**
Tidal creek to subtidal channel	Chen (2013)	Maddieanna Island, North Inlet, South Carolina	70.93	Vogel et al. (1996)	North Inlet, South Carolina	196	Chen (2013)	Maddieanna Island, North Inlet, South Carolina	13.64± 10.91	4-21%	7%
	Ward (1981)	Kiawah Island, South Carolina	101	Vogel et al. (1996)	North Inlet, South Carolina	196	Chen (2013)	Maddieanna Island, North Inlet, South Carolina	13.64± 10.91	3-14%	7%
	Settlemeyer and Gardner (1975)	Dill Creek, South Carolina	20	Vogel et al. (1996)	North Inlet, South Carolina	196	Chen (2013)	Maddieanna Island, North Inlet, South Carolina	13.64± 10.91	14-73%	7%
	Roman (1981)	Canary Creek Delaware	56	Orsen et al. (1990)	Delaware River	50	Roman and Daiber (1989)	Canary Creek Delaware	27.13	48%	54%
	Leonard et al. (1995*b*)	Cedar Creek Florida	69.7	Leonard et al. (2002)	Cedar Creek Florida	197	Leonard et al. (1995*b*)	Cedar Creek Florida	18.36	26%	9%

1982; Dame et al. 1986; Eyre and France 1997; Bouchard and Lefeuvre 2000; Bianchi et al. 2009), and others show no significant import or export (e.g., Dame et al. 1991; Hemminga et al. 1993). However, if these studies had included the effects of low-tide rainfall on OC redistribution and export the researchers might have characterized outwelling differently.

Rainfall effects are also a notable facet of carbon accumulation and storage. For example, the intertidal environment is an important OC sink where about half of annual marine carbon burial may take place (Kirwan and Mudd 2012). However, most organic matter accumulation rate estimates ignore the rainfall-driven POC redistribution effects within the intertidal zone (e.g., sediment winnowing in overland flow), and their effects on spatial variability of OM content and composition at the surface, and in sediment cores. For instance, rainfall-driven POC erosion and deposition can give rise to anomalous estimates of sediment accumulation or marsh accretion rates in the subtle salt marsh topographic highs and lows. Also, the questions of how modern surface variability in OC content translates to vertical cores remains largely unexplored.

We propose that rainfall-runoff effects be integrated into biogeochemical models of carbon cycling in intertidal environments as shown in Fig. 2b,c. Figure 2b emphasizes R_S through the hierarchical structure of intertidal landscapes going from the surface (plot), to the intertidal creek, to the subtidal channel, and finally to the coastal ocean. Each landscape compartment has arrows showing that the rainfall-driven R_S declines from a high at the intertidal platform (plot scale) to a low at the subtidal channel (intertidal-subtidal interface) (Fig. 2b).

Figure 2c represents a translation of the rainfall-runoff effects on POC to a conceptual box model that divides the entire intertidal landscape into two parts; in this case we focus on salt marshes. The upper box represents the salt marsh surface, and the lower box represents the marsh water column. The marsh surface corresponds to the landscape "plot" in Fig. 2b; the interface between the marsh surface and the marsh water column is the interface between plot and intertidal creek (Fig. 2a,b). The box for the water column includes intertidal creeks and subtidal channels (Fig. 2a,b). The down arrows represent the R_A at each interface. The black arrows represent the background tidal current POC exchange (outwelling estimates) while the red arrows show the proportions of rainfall-driven cycling. The exchange of rainfall-driven POC decreases by about 90% during transport (Fig. 2b). Data show that for South Carolina marshes each year $\sim$ 200 gPOC m^{-2} is mobilized from the marsh surface to the water column (Table 2). This value decreases to $\sim$ 14 gPOC m^{-2} due to the POC lost via processes such as settling and aggregation-adsorption processes, and continues to decrease further along the salt marsh geomorphic hierarchy (Table 2). We do not have data on rainfall-driven POC exchange at the subtidal channel-coastal ocean interface. However, taking North Inlet estuary as an example, the system is characterized by ebb flow dominance (Kjerfve 1986) through the persistent ebb tide delta, ebb dominant bars, and documented outwelling (e.g., Dame et al. 1986). Therefore, given this ebb dominant system we contend that an unknown but potentially important fraction of storm-induced POC export occurs. The likelihood and amount of export can be enhanced by the proximity of the intertidal creek-subtidal channel interface to the estuarine inlet. The closer the rainfall-entrained POC is to the inlet, the greater the likelihood of export. Therefore, rainfall effects on OC cycling in intertidal environments are noteworthy.

Now we critically evaluate the assumed effective low-tide rainfall proportion of 45%, *P*. First, this assumption was not used to evaluate R_S and therefore it only affects R_A. Second, the 45% estimate is based on a continuous two-year, five minutes rainfall record at North Inlet. The times for "low tide" rainfall correspond to rain falling at or below mean water level and as reported above this comes to 45% of rain events. Moreover, any variation in the inferred proportion of effective rainfall, *P*, will have a corresponding linear effect on the proportion of annual rainfall-driven POC exchange, R_A and any corrections to the *p* value used here will likely give rise to nominal adjustments in $R_{A.}$ Further, lacking any additional data or literature on the subject of the frequency-intensity of low-tidal rainfall we contend that an estimate in the range half of the total rainfall may, at this time, be reasonable.

Clearly more research is needed to link tidal harmonics with rainfall conditions to more fully characterize the probability of low-tide rainfall and corresponding rainfall energetics, especially in regime of climate change. Also, it is noteworthy that previous work has shown how raindrops can generate erosive forces on bottom sediments through a shallow water column (Green and Houk 1980; Shevenell and Anderson 1984). Hence the transport effects of rainfall may not necessarily be limited to times when the marsh surface is subaerial. Taken together our estimates of material exchange shed light on the potential significance of low-tide rainfall in intertidal zone material cycling, and they are presented in terms of published tidal current-driven or background POC exchange rates, and organic matter accumulation rates. Results from this work show that outwelling estimates reported in the literature are minimum values at best, and when considering rainfall effects we contend that sites that do not demonstrate outwelling should be reevaluated within the context of this study.

Overall, this effort reveals that the low-tide rainfall-induced POC flux was surprisingly consistent between distant and disparate intertidal systems. Analyzing our own data and data in the literature that directly or indirectly report rainfall-driven POC exchange allowed us to quantify a *storm-induced exchange rate*. A significant outcome of this work is the demonstration that rainfall-driven OC exchange rates from a range of study sites were within the same order of magnitude, with an average of 0.040 ± 0.038 gPOC m^{-2} $mmRain^{-1}$. This value combined with the low-tide or effective precipitation can be applied to some intertidal environments to predict the POC exchange generated by rainfall-runoff processes; an exchange that typically is not accounted for in biogeochemical models of estuarine carbon cycling. Moreover, low-tide rainfall is not accounted for in estimates of outwelling and as a result they likely represent minimum values. Finally, our conceptual model describes the variability of rainfall-driven POC exchange through the hierarchical structure of intertidal landscapes and how observations of POC flux can be expected to change across the intertidal landscape. This information should be used to guide sampling strategies for continued intertidal zone rainfall work.

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