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Wrack and ruin: Legacy hydrologic effects of hurricane-deposited wrack on hardwood-hammock coastal islands

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LETTER • **OPEN ACCESS**

Wrack and ruin: Legacy hydrologic effects of hurricane-deposited wrack on hardwood-hammock coastal islands

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Wrack and ruin: Legacy hydrologic effects of hurricane-deposited wrack on hardwood-hammock coastal islands

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3 June 2020John T Van Stan II^{1,2} , Scott T Allen³ , Travis Swanson^{1,2} , Melissa Skinner² and D Alex Gordon²¹ Applied Coastal Research Laboratory, Georgia Southern University, Savannah, GA, United States of America² Department of Geology & Geography, Georgia Southern University, Statesboro, GA, United States of America³ Geology and Geophysics, University of Utah, Salt Lake City, United States of AmericaE-mail: jvanstan@georgiasouthern.edu**Keywords:** hurricane, coastal change, ecohydrology, back-barrier island, marsh wrack, plant litter, *Spartina alterniflora*Supplementary material for this article is available [online](#)

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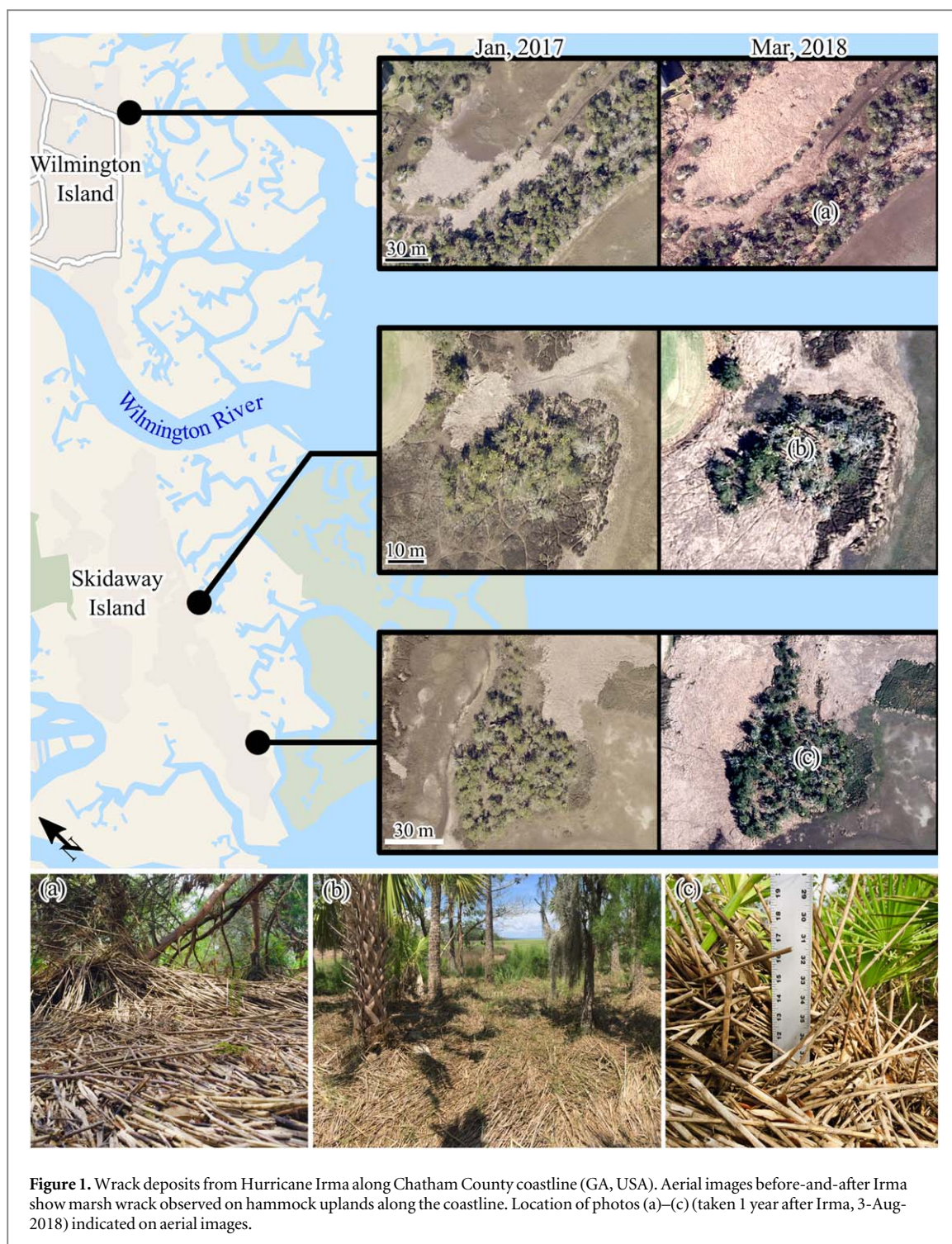
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**Abstract**

Hurricanes can cause immediate catastrophic destruction of marsh vegetation and erosion of soils; however, they also have long-lasting ecological impacts. Those impacts include the deposition of tremendous amounts of saltmarsh litter ('wrack') onto upland ecosystems, the hydrologic effects of which have not previously been investigated. When Hurricane Irma battered the southeastern US coastline, widespread wrack deposition was reported (often exceeding 0.5 m depth), especially in vulnerable coastal hammock ecosystems: locally-elevated forests within the saltmarshes that rely on freshwater inputs from rain. We report the impacts of this deposited wrack, which has persisted for 2 years, on effective precipitation inputs to coastal hammock soils. At a coastal hammock site, wrack deposits of 22–38 cm depth were estimated to store 10.2–19.9 mm of rain, reducing net rainfall to the surface by 66% over the study period (Oct 2018–Jun 2019). Three months of calibration data collected from wrack lysimeters in the field supported this interception estimate, as only 49 mm of the total 170 mm (29%) of rain that fell on the wrack was transmitted through to the soil surface. These litter interception effects on precipitation inputs far exceed those that have been described in other ecosystems and we hypothesized that they alter the growing conditions of these precipitation-dependent trees. The marshgrass (*Spartina alterniflora*), from which the wrack that was studied originates, is a globally abundant native and often invasive plant; thus, understanding the duration and extent of those effects on ecohydrological processes may be crucial to managing and conserving these ecosystems, especially given rising sea levels and changing hurricane regimes.

Introduction

Beyond the direct costly and deadly effects of hurricanes (National Center for Environmental Information 2018), they have long-lasting impacts on coastal ecosystems (Paerl *et al* 2018, Osburn *et al* 2019). One long-lasting impact is the large transfer of wrack (saltmarsh organic litter (Reidenbaugh and Banta 1980)) onto isolated salt-intolerant, hardwood forests situated within marshes (hereafter 'coastal hammocks'). The effect of these deep (0.2 m to >2 m thick (Roman *et al* 1994, Guntenspergen *et al* 1995, Bush *et al* 1996, Platt *et al* 2015)), persistent (often lasting years (Roman *et al* 1994, Guntenspergen *et al* 1995, Bush *et al* 1996, Platt *et al* 2015)) wrack layers on precipitation inputs to the soils of upland ecosystems has not yet been investigated, but we hypothesize that they are large because even order-of-magnitude thinner organic litter layers heavily influence ecosystem water budgets (Gerrits and Savenije 2011, Coenders-Gerrits *et al* 2020). Other ecological effects of wrack deposition, like the smothering of vegetation and altered habitat use by related fauna, have been previously described (Bertness and Ellison 1987, Roman *et al* 1994, Guntenspergen *et al* 1995, Bush *et al* 1996, Pennings and Richards 1998, Stalter *et al* 2005, Stalter *et al* 2006, Platt *et al* 2015).



When Hurricane Irma passed the Georgia coastline in 2017, wrack primarily consisting of dead *Spartina alterniflora* (Loisel., saltwater cordgrass) was deposited atop coastal hammocks and other upland areas along the coast (figure 1); as of October 2019, that wrack layer continued to persist. Scant records exist quantifying the amount and extent of wrack deposition at these sites; however, aerial photographs (figure 1) and communications with management agencies show that wrack deposits throughout the Georgia coastal region ranged from 0.6 m to >1.0 m deep in uplands (beyond saltmarshes and hammocks), extending up to 50 m inland (Bennett 2019, Burgess 2019). Photographs demonstrate that wrack was deposited deep into the coastal hammock forests, resulting in complete coverage of the understory along the coastlines of Wilmington and Skidaway Islands, GA, USA (figures 1(a)–(c)). Marsh wrack is ubiquitous within this system; a recent summary of wrack in the coastal counties of Georgia suggests that there is >700,000 m² of wrack adjacent to uplands (Alexander 2011).

Woody plants in coastal upland hammocks—even those associated with saline ecosystems—often depend on freshwater from rainfall (Ish-Shalom *et al* 1992, Tolliver *et al* 1997, Hsueh *et al* 2016), but these thick, absorbent wrack deposits may reduce effective precipitation to soils because they intercept and evaporate considerable quantities of rainfall. We investigated how these persistent wrack layers altered rainwater inputs to these systems, to better understand their effects on the edaphic conditions on which coastal hammock forests depend. To estimate freshwater losses to coastal hammock soils due to hurricane-related wrack deposits, we monitored sub-canopy rainfall (throughfall), estimated storage and evaporation of throughfall by the wrack, and monitored soil conditions beneath hurricane-related wrack deposits. We investigate whether disturbances to the water balance of these isolated coastal hammocks could lead to their ‘wrack and ruin’ by fundamentally altering their ecosystem structure; the exclusion of the salt-intolerant trees would have cascading effects on productivity, coastal buffering of wind and wave energy (Fritz *et al* 2008) and habitat provisioning to resident and migratory wildlife (Whitaker *et al* 2004). These results may be informative for coastal management across a wide range of geographic settings as *S. alterniflora* is globally common and abundant as a native and invasive coastal plant (Kirwan *et al* 2009, Zhu *et al* 2013).

Methods

Study site

A wrack-covered hammock (31.9188 °N, 81.0369 °W, center aerial in map: figure 1(b)) was instrumented in subtropical humid (Köppen *Cfa*) coastal Georgia, USA for hydrometeorological monitoring (throughfall, radiation, wind speed, and air temperature/relative humidity) from September 29, 2018 to July 17, 2019, and soil moisture and conductivity monitoring from the same start date to May 1, 2019. The monitoring site is sandy, flat (0 to 2 m above mean sea level, amsl), and hosts overstory vegetation consisting of *Quercus virginiana* Mill. (Southern live oak), *Juniperus virginiana* L. (Eastern red cedar), and *Sabal palmetto* (Walt.) Lodd. (cabbage palm) that hosts an abundant epiphytic plant community (*Tillandsia usneoides*, *Pleopeltis polypodioides*, and foliose lichen). Wrack deposits covered the entire forest floor, ranging from 22 to 38 cm in depth (figure 1(b))—similar to wrack depths on other hammocks within the saltmarshes between Skidaway Island (a secondary backbarrier island) and Wassaw Island (the barrier island) (figure 1). Note that local wrack depths could exceed 50 cm. Negligible understory vegetation was present.

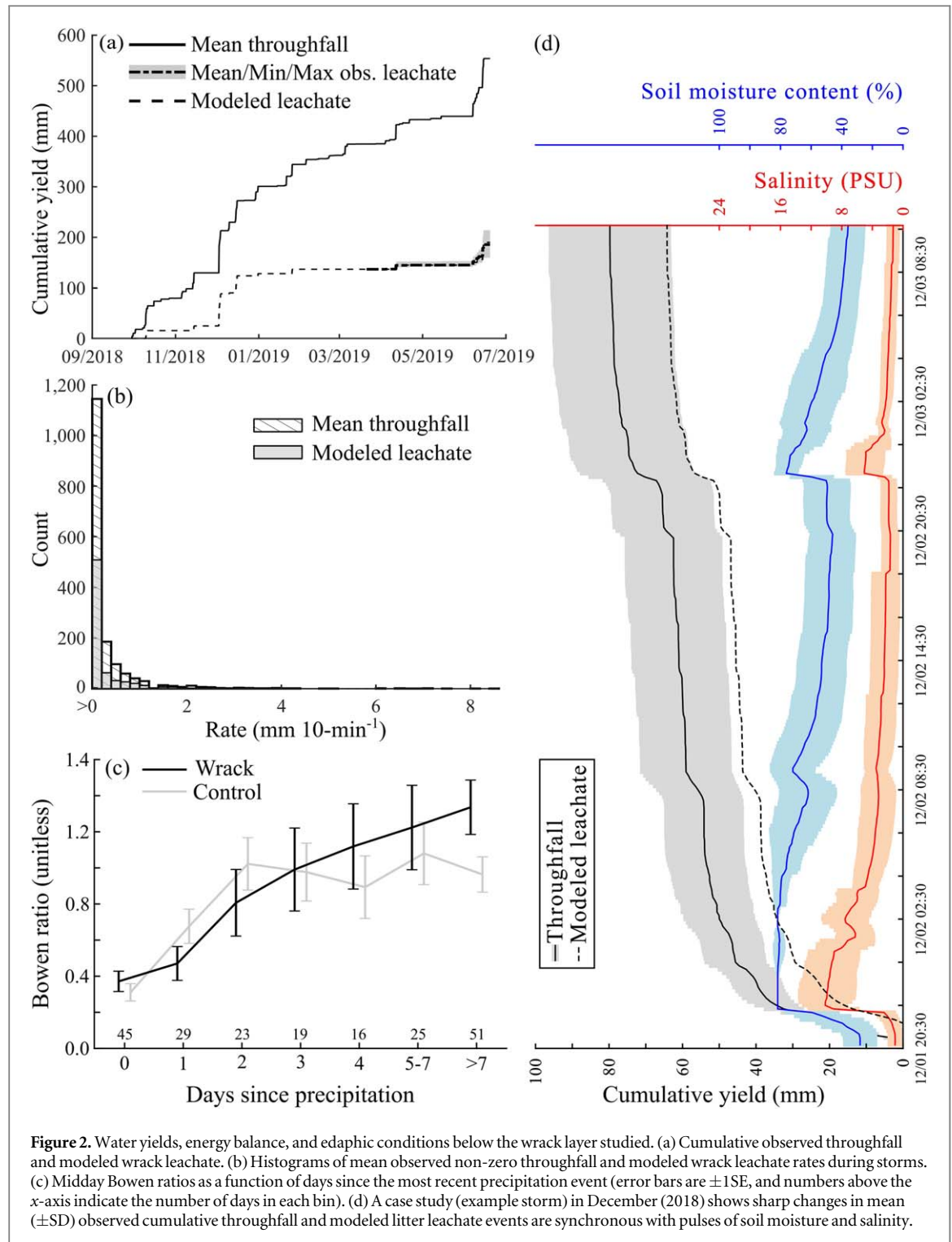
To compare hydrometeorological data and energy partitioning in the wrack-covered study site to a reference site with an undisturbed understory, a nearby hardwood hammock immediately south of the wrack-covered hammock (31.9168 °N, −81.0378 °W) was also used. The overstory vegetation of the undisturbed hammock consists of the same species and canopy condition (including epiphyte cover); however, unlike the wrack-covered hammock, the undisturbed hammock has dense, continuous understory herbaceous vegetation (figure S2). Only meteorological data from the undisturbed hammock were used in this study for estimating Bowen ratios (as described later). Both hammocks have similar geographical characteristics. The nearest NOAA tide station to our study sites is about 18 km north at Fort Pulaski (Station ID #8670870).

Environmental monitoring

Rainfall reaching the wrack below the overstory canopy (i.e., throughfall) was monitored by 20 tipping bucket gauges (Texas Electronics TR-525I, Dallas, TX, USA) distributed throughout a 0.2 ha area. This throughfall monitoring network is the subject of another study, but here it is used to define the input to the wrack layer. Tipping bucket gauges were interfaced with a datalogger (Campbell Scientific CR3000, Logan, UT, USA) that recorded observations at 10 min intervals. Care was taken to ensure that the tipping buckets were level and that their funnels, bucket mechanisms, and drainage holes were clear of debris.

Meteorological sensors (all by HOBO, Onset Computer, Bourne, AM, USA) were installed to measure radiation (model S-LIB-M003) and wind speed (model S-WSB-M003) at 1 m height above the wrack (below the overstory canopy), as well as air temperature and relative humidity (model S-THB-M002) at two elevations: immediately above (~10 cm) and 1 m above the wrack surface. Temperature-and-humidity sensors were placed in radiation shields (HOBO model RS3-B). All meteorological sensors were interfaced with a HOBO datalogger (model H21-002) and logged at 10 min intervals. Observation times were manually matched to within 10 s between the two dataloggers. All meteorological sensors were routinely checked and cleaned. The wrack cover extended for at least ~50 m in all directions from the meteorological station. A similar setup was used as a control over natural vegetation at the previously described reference site (unaffected by wrack).

Also interfaced with the CR3000 datalogger were 15 Decagon 5TE probes (5.2 cm probe length) continuously measuring soil moisture (volumetric water content, %) and electrical conductivity (EC, dS m^{-1}) in the mineral topsoil below the wrack materials (15 to 20 cm deep) at 10 min intervals. To install the 5TE probes, thin trenches were dug to depth, just wide enough to access an undisturbed wall of soil, then each probe was



pushed vertically into the undisturbed soil wall without a pilot hole. Installation trenches were carefully filled with the local site-excavated soils. For a case study storm, EC was converted to Practical Salinity Units (PSU) (Fofonoff and Millard Jr 1983); changes during the example storm are hypothesized to be principally derived from sea salts sourced from marine aerosols, throughfall (which has been shown to have low PSU values in previous work at Skidaway Island (Gay *et al* 2015, Van Stan *et al* 2015), the wrack itself, and salts left from occasional tidal inundation (and, of course, from the hurricane storm surge that delivered the wrack). We did not monitor soil moisture and EC vertically through the soils and, therefore, have no direct observations of groundwater and capillary fringe fluctuations during storms. However, the ~ 15 – 20 -cm depth of the sensors corresponds with ~ 1.8 m above mean tide which, for this region, results in an estimated inundation rate of 1–2 times every couple of months by (high spring) tides (see example inundation events in February and March 2019: figure S1 is available online at stacks.iop.org/ERC/2/061001/mmedia in the supplemental materials).

Data during a case study storm that did not occur during any of the infrequent tidal inundation events (described later: figure 2(d)) shows changes in soilwater EC occurs synchronously with intense throughfall rates and observed/modeled wrack leachate rates—temporal patterns which are not similar to inferred fluctuations in the groundwater and capillary fringe.

Wrack rainwater storage capacity analyses

Wrack rainwater storage capacity was estimated in three ways: (1) submersion of samples in the lab; (2) drying and weighing of samples allowed to saturate *in situ*; and (3) derived through fitting the bucket model using *in situ* measurements of outflows from below the wrack. For submersion tests, 30 block profiles of wrack (154.84 cm² each) were randomly sampled from the site (on Oct-01-2018), dried for 72 h at 40 °C in a drying oven (Isotemp 500, Fisher Scientific, Lenexa, KS, USA), and then measured for dry weight [g]. The dried wrack samples were then submerged and periodically weighed (at 24, 26, 48, 52, and 56 h since submersion) until saturation and the saturation weight [g] recorded. Saturation weight was the mean weight of 3 consecutive weight measurements that varied <5% (which occurred at 48 h, 52 h, and 56 h). To test whether submersion approximates storm effects, five wrack profiles were sampled between 0900–0930 EST on Dec-03-2018, immediately after saturation *in situ* by a large storm (84 mm, ending around 0800 EST on Dec-03-2018) and weighed, then dried for 72 h at 40 °C and weighed again. Wrack profiles sampled on Dec-03-2018 were sampled as they were *in situ*, without an opportunity for the samples to drain. Water storage capacity for these two methods was then determined by subtracting the saturated and dried weights.

Lastly, directly-monitored wrack drainage from leachate trays was used to estimate total wrack interception losses and as another means of estimating water storage capacity. Wrack leachate trays consisted of Rubbermaid (Hoboken, NJ, USA) HDPE bins (2,358 cm²) containing 30 cm of wrack, elevated ~0.6 m from the surface, and oriented at a moderate slope to allow water drainage into a tipping bucket through tubing inserted at the base of the leachate tray (photograph provided in supplemental materials: figure S3). Wrack leachate trays were validated by confirming that the throughfall that drained from them when empty were similar to volumes measured by the other throughfall gauges (table S1 in supplemental materials). A simple bucket model was developed to interpret the leachate time series. The full details of this model are described in the supplemental materials. In abstract, wrack storage is the primary state variable, with maximum storage capacity determined through fitting the model to the time series of drainage from the leachate-tray. Input fluxes are driven by the observed throughfall data. Output evaporation fluxes are determined by potential evaporation modified by a fitted scalar and the current wrack storage (i.e., evaporation fluxes never exceed current storage). Lastly, inputs that exceed storages become the leachate output. Potential evaporation was estimated from the previously described meteorological data. This empirical, data-driven modelling exercise is designed to coarsely simulate this site's wrack water content dynamics to a) extract an independent estimate of wrack storage capacity and b) to estimate total wrack interception losses for times prior to when the leachate tray monitoring began. While these forms of models are useful in interception research, these parameter sets should not be used elsewhere for predictions without site-specific testing (*sensu* Allen *et al* 2020).

Energy partitioning

To examine possible differences in energy partitioning over wrack versus natural hammock understory vegetation, we quantified Bowen ratios (β) over the surfaces. These β values are defined as the magnitude of energy partitioned into sensible heat divided by the magnitude of energy partitioned into latent heat; thus, all else equal (i.e., equal net radiation loads and resulting available energies), lower β implies greater evapotranspiration. The temperature and humidity measurements were used to calculate Bowen ratios ($\beta = \gamma\Delta T/\Delta e$, where γ is the psychrometric constant, ΔT is the difference between the temperatures measured at the top and bottom sensors, and Δe is the difference between vapor pressures measured at the top and bottom sensors).

Temperature-and-humidity sensors were compared in a controlled setting to validate that calibration differences did not introduce systematic biases in the inferred gradients. Bowen ratios were calculated using mid-day values (11:00-16:00), to avoid conditions where β is indeterminate or not meaningful (Perez *et al* 1999), then binned to give multi-day averages which have been shown to be accurate and more stable (Webb 1960). These calculations were done using 10-day mean gradients and gradients binned with respect to days since any daily throughfall >1 mm.

Statistical analyses

Bowen ratios of the wrack-covered and undisturbed hammock understories were compared using conventional paired *t*-tests, evaluated using several groupings of data: across all mid-day ten-day bowen ratios ($n = 22$), and independent tests for each of days with rain and days one, two, three, four, five-to-seven, and more than seven days after rain (see figure 2(c)). After visually inspecting the results from these comparisons, we report *t*-tests for

times when the wrack-covered and undisturbed hammocks deviated most: one-to-two days after rain events and more than four days after rain events. Distributions of throughfall and wrack leachate rates were compared using a two-sample Kolmogorov-Smirnov test. Descriptive statistics were computed to describe central tendency (mean) and variability (standard deviation or standard error, as indicated in text and figure captions). Analyses were performed using MATLAB (MathWorks, Natick, MA, USA).

Results and discussion

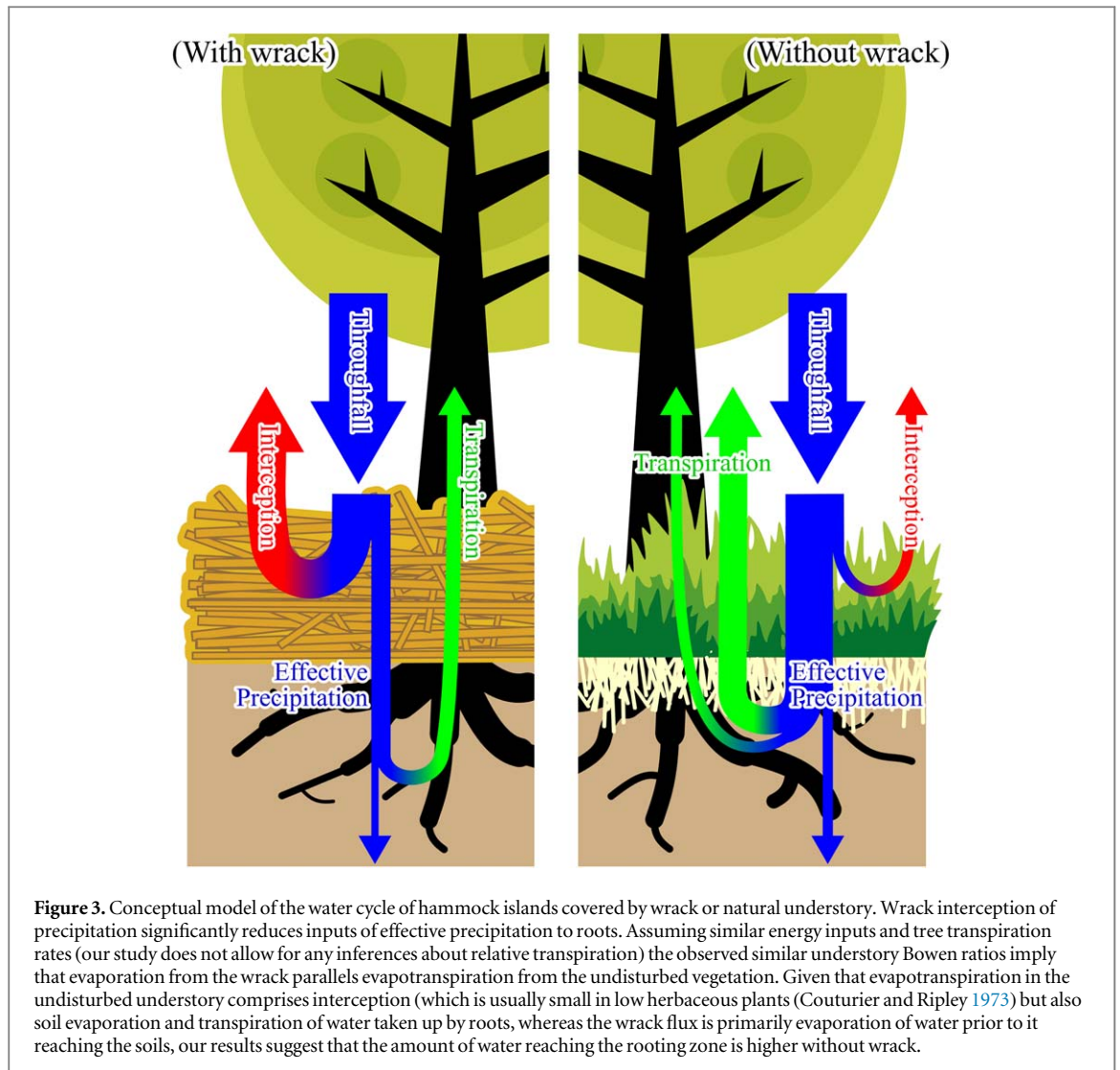
Using the calibrated bucket model, we estimate that the wrack deposited by Hurricane Irma intercepted 65.7% of the total throughfall at the study site; i.e., 191.8 mm of effective precipitation reached soils beneath the wrack out of the total 558.9 mm of throughfall (figure 2(a)). Using the leachate monitoring systems (figure S3), we directly observed 49 mm of effective precipitation below the wrack during 170 mm of throughfall over 3 months (figure 2(a)). Thus, it is likely that the majority of precipitation has been intercepted and evaporated before reaching these hammock soils in the >1.5 years since Hurricane Irma (September 2017). The amount of rainfall interception in this study has, to the authors' knowledge, not been previously observed under any other environmental conditions (see previous review of litter rainfall interception (Gerrits and Savenije 2011)). During observed storms, nonzero wrack leachate rates are less frequent than for throughfall and are substantially smaller than throughfall inputs (figure 2(b)), comprising a significantly different distribution of intensities ($p < 0.05$).

Lab and field estimates show that wrack material can store 10.2 to 13.5 mm of rainwater for 22 to 38 cm thick deposits. The higher estimate, 13.5 mm, was from the submersion of oven-dried wrack samples which has produced greater estimates than field tests and precipitation simulations in past research (Friesen *et al* 2015, Klammerus-Iwan *et al* 2020). A nonlinear least squares optimization of the bucket model (per observations from the leachate trays) resulted in an S_{\max} of 19.9 mm (figure S3 in supplemental materials). Although litter leachate trays are commonly deployed in forest ecohydrological research (e.g., Campbell *et al* 2007, Johnson *et al* 2018), we note that flow pathways through natural litter deposits may be more efficient, explaining why the modelling exercise yielded higher storage estimates. These water storage capacity estimates exceed all forest litter storage values that have been estimated to date (ranging from 0.2–8.0 mm (Gerrits and Savenije 2011)). Indeed, wrack depth also exceeded litter depths typically reported in forests (e.g., 1–22 cm (Kaspari and Yanoviak 2008)), but these large storages may also be due to the wrack structure, composed primarily of hollow tubes (*S. alterniflora* stems) where water may accumulate.

Bowen-ratio results suggest water stored in the wrack evaporates efficiently, showing that the fraction of energy partitioned into latent heat exchange in wrack is similar to that in the thick herbaceous understories in hammocks that were not disturbed by wrack deposition. Bowen ratios (β) over wrack were, overall, not significantly lower than those of the control ($p = 0.45$), undisturbed understory, site (median midday $\beta = 0.62$ v. 0.80, respectively), indicating that energy inputs to the wrack efficiently converted to latent heat exchange. These results contrast with our expectation that the litter would increase the partitioning of energy into sensible heat (i.e., higher β), mimicking a mulching effect that reduces evaporation (Burt *et al* 2005). For both sites, β was dependent on how recently rain had wetted the wrack or understory vegetation (figure 2(c)). While the only significant difference between sites in figure 2(c) was that of the >7-days category ($p = 0.04$), these data suggest that increases in the fraction of energy partitioned towards evaporation after rain may be greater with wrack than in the undisturbed site. However, this fraction decreases as the wrack dries (whereas the control continues evapotranspiring more steadily); for example, β was 35% higher in the control for 1–2 days after rain ($p = 0.06$) and was 12%–28% lower in the control for >4 days after rainfall ($p = 0.05$).

The post-rain decreases in evaporation also occur in our bucket model representation because evaporation cannot exceed the amount of water in storage, and thus evaporation is small during rainless periods or times defined by frequent, smaller events (i.e., less than a few mm per day). Indeed, figures 2(a)–(b) show that small storm events do not appear to trigger any production of outflow from the wrack implying that those inputs become stored and evaporate. While the maximum model-optimized evaporation rates are fairly high (i.e., implying that they can approximate potential evaporation rates), we suspect that our energy balance calculations may under-predict energy availability and under-represent the role of advected energy in this highly open understory. Thus, the large water storage capacity and efficient evaporation of rain by wrack necessitates high throughfall rates to induce drainage (figures 2(a)–(b)) and increase soil moisture content below (figure 2(d)). That said, this modelling exercise is empirical and thus these parameter sets and model structure should not be applied elsewhere without a calibration dataset. More detailed datasets (e.g., from eddy covariance) could support a more mechanistic model where surface conductance is directly down-regulated as a function of wrack water content (e.g., in parallel with commonly used earth-system models; Bonan *et al* 2014).

For storms where throughfall rates are intense enough to produce outflow from wrack, we hypothesize that salts will be mobilized from the rinsing of the wrack into soils. We observed pulses of high soil electrical



conductivities (as a salinity proxy) intermittently throughout this study (figures S1(a)–(e)); while their mechanistic relationship with the wrack remains hypothesized, we believe these pulses of apparently precipitation-initiated mesohaline conditions to be noteworthy. For example, soil moisture changes during a case study storm event were synchronous with large changes in salinity that peaked in the mesohaline solution range, 8–12 PSU (figure 2(d)). These salinity values are several times larger than what has been measured in throughfall (<2 PSU) for a wide range of storms and lab-derived vegetation leachates from forests on Skidaway Island and the nearby St. Catherine’s Island (Gay *et al* 2015, Van Stan *et al* 2015). Although infrequent tidal inundation occurred at the site during high spring tides (described in the methods), tidal inundation during this storm was unlikely as high tide elevations were >0.5 m below the approximate elevation of the sensors (figure S1(b), top panel, supplemental materials). Thus, the concomitant rise in EC and soil moisture suggests that these salinity spikes indicate the downward flushing of previously deposited or legacy salts, but not salts from events such as tidal flooding or storm surge. Coastal winds can deposit sea salt aerosols onto the wrack, which is already salty due to its origins in the saltmarsh (Reidenbaugh and Banta 1980). Given the repeated wetting and evaporation of the wrack, and the less frequent percolation of water through the wrack (especially with small events; figure 2), evapoconcentrated salts may accumulate in wrack to be later flushed during large storms that overcome the storage capacity and yield mesohaline effective precipitation (from <2 PSU to >8 PSU). Therefore, the reduction and possible salination of effective precipitation to coastal hammock soils—in addition to the physical smothering of the understory layer (figure 1 photos)—could alter plant community structure (from glycophytic to halophytic), or remove vegetation entirely (as wrack has been found to do in Marshes: Bertness and Ellison 1987, Valiela and Rietsma 1995, Alber *et al* 2008). Further research on how the wrack-induced changes to the water balance affect salinity is warranted.

Conclusions and implications for coastal ecosystems

Direct damages sustained from Hurricane Irma were extensive (\$37.5–\$62.5 billion USD (Cangialosi *et al* 2018), making it the fifth-costliest hurricane in US history. For coastal ecosystems buried by Irma's seemingly innocuous *Spartina alterniflora* (wrack) deposits, however, the ecohydrological consequences can continue long after the storm has passed. Wrack at a coastal hardwood hammock site intercepted more rainwater than has been previously described of natural litter types (65.7%)—compared to data across multiple forest types, 6%–34% (Gerrits and Savenije 2011). Low Bowen ratios (~0.62) indicate that energy inputs to the wrack efficiently evaporate from the especially large water storage between storms. While the energy partitioning above wrack was similar to that estimated for undisturbed hammock understory vegetation, the important difference is that the wrack removes much of precipitation inputs before they can potentially reach tree rooting zones (figure 3(a)). In contrast, understory and overstory plants in the undisturbed (control) site can compete for effective precipitation in topsoils (figure 3(b)). Indeed, high throughfall rates are often required to initiate drainage through the wrack. Moreover, some storm event data suggest that this drainage may be enriched in salinity compared to precipitation (figures 2(d); S1), which could alter edaphic conditions beyond those attributed to the reduced water inputs and the physical smothering of understory vegetation. Given that these hammock trees rely on fresh water from rainfall, the processes examined here may alter growing conditions and potentially alter the multitudinous hydrological, biogeochemical and/or ecological ecosystem services provided by coastal hammocks, such as storm buffering or wildlife habitat provisioning (Whitaker *et al* 2004, Fritz *et al* 2008). These hammocks represent a critical element in landscape connectivity between coastal mainland and barrier islands for a wide range of fauna (Smith and Vrieze 1979, Cramer and Portier 2001, Larkin *et al* 2004, Hether and Hoffman 2012). Therefore, the lingering effects of episodic disturbances to coastal hammock habitats, like hurricane-deposited wrack events, may have additive effects on more recognized chronic disturbances, like sea level rise.

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