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REPLY

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Key Points:

- Organic carbon burial rates are not altered by auto-compaction and do not include a density correction
- Increasing rates of sea-level rise are supported by regional data and analyses from the literature

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Reply to Comment by R. Parkinson on "Increasing Rates of Carbon Burial in Southwest Florida Coastal Wetlands" by J. Breithaupt et al.

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Abstract Breithaupt et al. (2020, https://doi.org/10.1029/2019JG005349) investigated why rates of organic carbon (OC) burial in coastal wetlands appear to increase over the past ∼120 years. After comparing dating methods and applying biogeochemical analyses, we concluded that neither dating method nor carbon degradation contribute to the observed trend. Rather, we concluded that OC burial has increased in the past century. Parkinson's (2021) Comment disagrees with our conclusion, contending that: (1) use of a density correction to account for soil auto-compaction is a flawed methodology that artificially shortens a core's length, (2) there is limited evidence for an acceleration in the regional sea-level rise (SLR) rate, and (3) vertical accretion rates in previous papers by Breithaupt et al. (2014, https://doi.org/10.1002/2014JG002715; 2017, https://doi.org/10.1016/j.margeo.2017.07.002) are lower than the regional mean rate of SLR and are not to be believed as these wetlands should have converted to open water by now. We reject these contentions because: (1) no density correction was applied to the cores in this study, (2) local tide gauge records and analyses in the literature support an increase in SLR rates coinciding with the timeframe of our OC burial records, and (3) Parkinson's comparison of the 100-yr mean rate of SLR neglects temporal variability and uncertainties in the long-term sea-level record, as well as biophysical feedbacks between wetland surface elevation and SLR. Here, we provide detailed responses to Parkinson's contentions and establish the importance of differentiating operational definitions of OC burial and accretion to clarify why an auto-compaction correction is not applicable for OC burial measurements.

1. Background

Breithaupt et al. (2020), addressed a blue carbon knowledge gap about apparently increasing rates of coastal wetland organic carbon (OC) burial that had been identified by Breithaupt et al. (2014), concluding that increasing OC burial rates during the past century represent a net acceleration. In Breithaupt et al. (2014), dated mangrove soil cores from southwest Florida showed that rates of sediment accumulation, OC burial, and vertical accretion had all increased in the past century. At that time an explanation for these increases could only be surmised as representing: "(a) a recent increase in delivery, (b) a recent increase in preservation, (c) the regular occurrence of ongoing degradation at each depth over the past century, or (d) some combination of the above including a recent increase combined with ongoing degradation" (Breithaupt et al., 2014). We subsequently applied a combination of radiochemical, geomorphological, and biogeochemical analyses to "determine whether previously documented increases in OC burial rates over the past century represent real acceleration or whether the increases can be attributed to post-depositional degradation of older material or to artifacts of the methods used to measure soil accumulation" (Breithaupt et al., 2020). Our findings indicated the trend of increasing OC burial rates could not be explained by the use of different dating methods, nor by the occurrence of preferential degradation of OC at different soil depths, leading to our conclusion that "increasing OC burial rates during the past century represent a net acceleration" (Breithaupt et al., 2020). Parkinson's (2021) Comment disagrees with this conclusion and raises the following contentions:

> Parkinson Contention 1: The use of a density correction to account for soil auto-compaction is a flawed methodology that artificially shortens a core's length, does not represent *in situ* conditions, and lowers the rate of accumulation.
>
> Parkinson Contention 2: There is limited evidence and no broad consensus for an acceleration in the rate of regional sea-level rise (SLR) since the beginning of the 20th Century, something we propose as one of four potential drivers of increasing OC burial rates.
>
> Parkinson Contention 3: Vertical accretion rates published in previous papers by Breithaupt et al. (2014; 2017) are not to be believed because they are lower than the regional mean rate of SLR for extended periods of time and therefore these wetlands should have been converted to open water by now.

We appreciate the critical analysis of our paper as it shows that operational definitions and timescales of OC burial in blue carbon systems remain poorly understood and potentially contentious. However, we reject the three contentions in Parkinson (2021) because:

(1) No density correction was applied to the cores in our study (Breithaupt et al., 2020).
(2) Tide gauge records in south Florida and analyses in the literature support an increase in the rates of SLR coinciding with the timeframe of our OC burial records.
(3) An incorrect comparison relying on the 100-yr mean rate of SLR overlooks: (i) temporal variability and uncertainties in the regional long-term sea-level record, and (ii) biophysical feedbacks between wetland surface elevation and SLR that include periods of leading and lagging SLR.

Here, we provide detailed responses to the three contentions proposed by Parkinson. These issues represent common misunderstandings within the blue carbon field about operational definitions related to OC burial and vertical accretion and the relevance of auto-compaction, as well as questions of how to relate those measurements to SLR. We welcome this opportunity to clarify misconceptions about these methods and provide impetus to improve the community's understanding of carbon burial dynamics in coastal wetlands.

1.1. Response to Contention 1: OC Burial Rates are Not Altered by Auto-Compaction and do Not Include a Density Correction

Parkinson argues that our finding of increased OC burial over the past century in Breithaupt et al. (2020) is an artifact of using a density normalization to mathematically correct for auto-compaction. We did not use a density correction as it is not applicable to OC burial measurements; therefore, Parkinson's argument is misplaced. Parkinson (2021) appears to misunderstand operational differences between vertical accretion and OC burial (expressed, respectively, in units of mm yr^{-1} and g m^{-2} yr^{-1}), as almost all the references cited in support of his points about OC burial are, in fact, not about OC burial. That Parkinson would misunderstand operational distinctions between OC burial and accretion implies that similar misunderstandings may be prevalent in this area of study, facilitated by a lack of clear delineation between these terms in the literature. For example, it is not uncommon to see the term "carbon accretion" used in the literature when referring to mass-based measurements of soil carbon accumulation (e.g., Charles et al., 2020; Lovelock & Reef, 2020; Neubauer et al., 2002; Schile et al., 2017; Windham-Myers et al., 2018), nor is this interchangeability of the terms unique to blue carbon literature (Bernal & Mitsch, 2012; Nahlik & Fennessy, 2016; Rieger et al., 2014; Zehetner et al., 2009). Conflation of "accretion" and "burial" is understandable because the etymology of "accretion" is itself somewhat ambiguous, with usage referring both to changes in size (implying a change in length or width) and changes in mass (Oxford English Dictionary, 2020). Parkinson's misunderstanding of our work and the interchangeable application of these terms in the literature indicates a need for standardization to avoid further confusion related to blue carbon geomorphology and biogeochemistry. Below we provide brief operational descriptions of OC burial and accretion, including an explicit focus

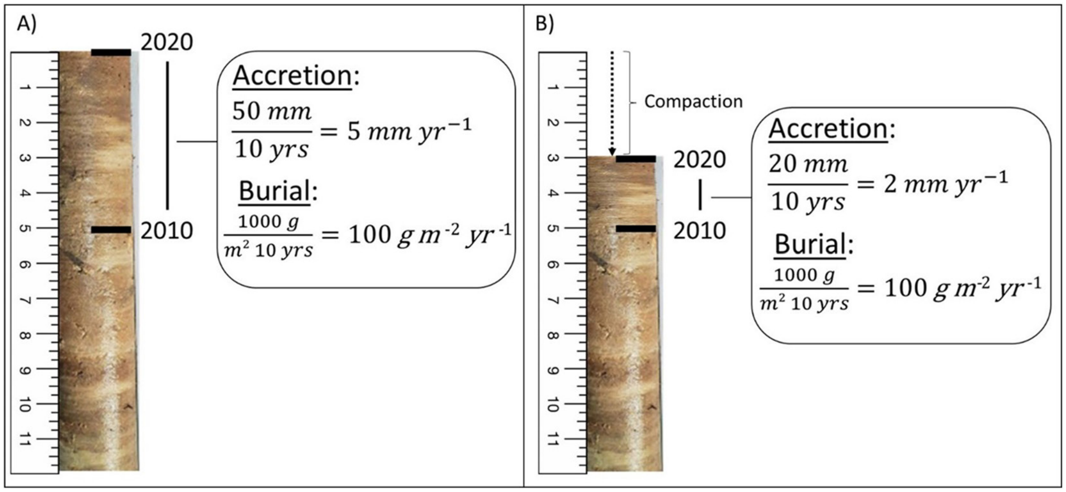

Figure 1. (a) An uncompacted, dated soil core from which both accretion and carbon burial can be measured. (b) a compacted soil core in which the thickness of the dated soil interval has been altered from its original state. Accretion measurements from the compacted core are underestimated, but Organic Carbon (OC) burial measurements are unaffected because the mass between dated horizons is unchanged.

on the units of measurement, and an explanation of why an auto-compaction correction is not applied to measurements of OC burial.

Vertical accretion is the rate of increase in soil thickness above a dated reference plane and is typically reported in units of mm yr^{-1} (for coastal wetlands) (Figure 1a). The dated reference plane can be a layer of feldspar dust applied to the soil surface at a known date or a radiometrically determined horizon such as the 1963 peak for ^{137}Cs or dates derived from the ^{210}Pb Constant Rate of Supply (CRS) dating model. All three methods were used in Breithaupt et al. (2020). In order to obtain an accurate accretion measurement, a soil interval must maintain fidelity both with regards to its thickness (measured by a ruler) as well as to the dated reference planes for the beginning and ending dates of the interval's formation (Figure 1a). Organic C burial is the rate of mass increase above a dated reference plane and is often reported in units of g m^{-2} yr^{-1}. In contrast to accretion, OC burial is measured only in relation to the dated reference plane, without regard to the thickness of the soil interval (compare Figure 1a to Figure 1b).

Compaction is the process of removing gas and sometimes liquid from void spaces within the soil, consequently altering a soil interval's fidelity to its original thickness (Figure 1b). However, compaction does not remove or mix the dated reference planes; it simply moves them closer to one another. Compaction alters the thickness, and therefore the volume, of a soil column, but not its mass. Auto-compaction is a specific kind of compaction that occurs as the accumulation of surface material gradually compresses underlying soil (Kaye & Barghoorn, 1964). Over time, the low-density material at the soil surface will be compressed. As Parkinson notes in his Comment, auto-compaction can be mathematically accounted for by standardizing all sectioned intervals of a soil core. Typically, this is done by dividing the observed density of each soil interval by the average density at the bottom of a core where a theoretical density asymptote has been reached. However, wetland soil density trends as a function of depth are often not clear or even discernible (Holmquist et al., 2018), so care is required when applying this correction. Such a correction is necessary for determining whether accretion rates (mm yr^{-1}) of material at the soil surface are different from those intervals beneath the surface. It can be applied or retracted as it is only a mathematical correction of the accretion number. Auto-compaction corrections are irrelevant for the study of OC burial rates (g m^{-2} yr^{-1}), as this metric is independent of soil interval thickness and relies solely on mass and age of the reference planes (Figure 1b). Because it does not change mass accumulation, such a correction has no bearing in assessing the mass of carbon accumulated within the soil column over time. The Breithaupt et al. (2020) examination of accelerating OC burial rates therefore involved no auto-compaction correction.

1.2. Response to Contention 2: Evidence for Regional SLR Acceleration

Parkinson incorrectly states the principal thesis of our paper is "change in relative SLR is the most likely large-scale driver of increased OC burial in the region" (Breithaupt et al., 2020; Parkinson lines 111–112). In fact, our central thesis is:

> "Based on the combination of evidence ... from different methods used to measure OC burial, lignin: OC profiles, and indices of lignin decay, we propose that increasing OC burial rates during the past century represent a net acceleration rather than a record influenced by postdepositional degradation of OC or an artifact of the method employed." (Breithaupt et al., 2020, pp. 16–17).

In the second section of the Discussion, we considered four likely drivers of this finding. These include the suggestion that change in SLR is the most likely large-scale driver, in addition to hypotheses about the influence of hurricanes, enhanced primary production, and an increase in factors related to soil OC preservation. Parkinson's critique engages with only one of our discussion points and not the central finding of our paper.

He argues that our finding "requires an acceleration in the rate of SLR" over decades or centuries (Parkinson lines 33; 119), of which he claims there is "limited" (Parkinson line 33) or "no evidence" (Parkinson line 118). The papers that we cite, although not specific to Florida, identify sea level as a primary control on soil carbon burial over multiple timescales across a broad geographic/global scale (Gonneea et al., 2019; Rogers et al., 2019; Watanabe et al., 2019). Contrary to Parkinson's argument, it is not important that these studies are not "regional" papers. We cite them to draw attention to the cutting-edge findings these papers represent, and to demonstrate the precedent they provide in support of the connection between SLR and carbon burial.

As it relates to SLR specifically, our argument is that the slow and steady, if mildly accelerating, rates over most of the Holocene have contributed to the substantial stocks of soil carbon found in blue carbon systems globally. Sweet, Horton, et al. (2017) and Sweet, Kopp, et al. (2017) provide valuable recent reviews of historical and future changes in sea-level rise rates. One of the key findings of the sea-level rise chapter of the 2017 Climate Science Special Report (Sweet, Kopp, et al., 2017) is that: "Global mean sea level (GMSL) has risen by about 7–8 inches (about 16–21 cm) since 1900, with about 3 of those inches (about 7 cm) occurring since 1993 (*very high confidence*). Human-caused climate change has made a substantial contribution to GMSL rise since 1900 (*high confidence*), contributing to a rate of rise that is greater than during any preceding century in at least 2,800 years (*medium confidence*)". The relationship between soil carbon accumulation and SLR is incontrovertible; without SLR, global blue carbon soil stocks would be negligible. Rates of SLR coinciding with the beginning of our soil core record are higher than rates observed over the Holocene—a trend consistent with studies of rates of Atlantic SLR from the Holocene to present (Kemp et al., 2011; Miller et al., 2013). Parkinson's Comment supports this point. The rates of SLR reported in Table 1 of Parkinson's Comment are for long-term trends with timeframes ranging from 500 to 8,000 years and range from flat or decelerating to 0.3 or up to 2.0 mm yr^{-1}. These rates are lower than the regional mean tide-gauge rate of regional SLR of 2.3 mm yr^{-1} for the past century cited by Parkinson. Additionally, SLR rates in south Florida in the past 20 years have been substantially higher. As noted in Breithaupt et al. (2017), the mean rate at the Key West tide gauge was 6.3 ± 0.5 mm yr^{-1} from 2003 to 2012, substantially greater than the cumulative Key West trend (1910–2019) of 2.5 ± 0.2 mm yr^{-1} (NOAA National Ocean Service 2020). Additionally, Wdowinski et al. (2016) observed mean rates at Virginia Key that increased from 3 ± 2 mm yr^{-1} prior to 2006 to 9 ± 4 mm yr^{-1} after 2006. Our hypothesis that increasing rates of SLR are a likely driver of increasing OC burial in south Florida is supported by these data and analyses from the literature.

1.3. Response to Contention 3: Comparing Rates Between Cores and SLR

Parkinson (2021) questioned the exclusion of Surface Elevation Table (SET) data from our analysis. We did not apply an analysis of SET data in Breithaupt et al. (2020) because the depths over which original or deep rod SETs operate (Cahoon et al., 2002; Whelan et al., 2005) are substantially deeper than the relatively shallow 20–40 cm cores we used. One of the critically important insights that the coupled SET-Marker Horizon (SET-MH) technique has provided about vertical development of coastal wetland soils is that surface accretion is not the sole contributor to vertical change. Rather, expansion and contraction occur due to numerous processes of addition and subtraction of material and void spaces throughout the soil profile (Cahoon, 2015; Cahoon et al., 2020), both within and below the dated intervals where rates of accretion and OC burial are measured. This idea that different parts of mangrove soil zones are expanding and contracting differently was first observed with SET-MH data (Whelan et al., 2005) obtained from some of the sites in Breithaupt et al. (2020). The best way to couple an SET with a ^{210}Pb-dated core would be with a shallow SET installed to the same depth at which excess ^{210}Pb was identified.

Setting aside the differences that we have already defined to explain why OC burial and accretion rates represent different measurements, Parkinson's argument that our previously published rates of accretion are flawed because they lag the rate of SLR for rather long periods of time neglects three fundamentally important points. The first is that accretion does not represent surface elevation change. There is a rich and complex body of literature about this point (Cahoon, 2006; Cahoon et al., 2006; Lovelock et al., 2015). A core location's surface elevation within the tidal frame will determine the frequency and extent of its inundation. In a landscape like southwestern Florida, where landscape-scale hydrology has been extensively modified, this also means that inundation levels at various locations throughout the estuary will be additionally affected by freshwater flow volumes (Dessu et al., 2018). The second point overlooked by Parkinson's argument (represented by his Figure 3) is that wetland vegetation and soil surfaces interact with water inundation levels to cause biological productivity and organic matter stabilization feedback cycles and physical feedback cycles related to accommodation space and allochthonous sediment deposition (Morris et al., 2002). Third, Parkinson's argument oversimplifies sea-level change. A cursory glance at the regional tide gauge record, which coincides with the time periods of our dated core intervals, shows periods of non-changing as well as increasing and decreasing sea level. Rather than applying a comparison of a long-term mean rate of SLR, a nuanced comparison requires careful consideration of how to bin the time periods to acquire means and uncertainties for comparing SLR with rates of accretion and surface elevation change. As our previous analyses have noted (Breithaupt et al. 2014, 2017), whereas there may be periods when accretion is greater than or less than the contemporaneous rate of SLR, over the long-term the average rates of SLR and accretion in the region have been remarkably similar.

2. Conclusion

Our 2020 paper provided analysis of the question: "Why do rates of OC burial in coastal wetlands appear to increase over the past ~120 years?" After comparing dating methods and applying biogeochemical analyses, we concluded that neither dating method nor carbon degradation contribute to the observed trend. Rather, we find that OC burial does indeed appear to be increasing. We appreciate Parkinson's concerns for providing the present opportunity to clearly differentiate between two different processes. However, as we have shown, we did not utilize the auto-compaction correction that Parkinson suspected. Other issues that were brought up in Parkinson's comment are tangential, rather than cogent, to our original publication. That is not to say they are not important points. The understanding of blue carbon accumulation and preservation is intrinsically tied to understanding local sea level. With many different methods to measure SLR over different timescales, comparisons can be surprisingly difficult despite the general simplicity of measuring distance and time. It is important to note that although "… OC burial rates have increased over the past century [this] does not alter the fact that SLR is accelerating and will exceed rates experienced by coastal wetlands in the places where they exist today. Increasing OC burial rates will occur only as long as wetland vegetation and soil development can keep pace with accelerating SLR" (Breithaupt et al., 2020). Our findings identify important directions for future research to: (1) explain the mechanisms and provide a tighter linkage between the timing of changes in sea level and annual rates of OC burial, (2) evaluate the tipping points when SLR will exceed the OC burial and accretion potential of these wetlands, resulting in conversion to open water, and (3) consider the implications of changing wetland OC burial rates for regional and global C budgets. Our paper establishes the necessary framework for investigating these processes, and Parkinson's Comment highlights important caveats when approaching these topics.

Data Availability Statement

Soil core data are available via the Coastal Carbon Research Coordination Network (https://doi.org/10.25573/serc.9894266.v1). Marker horizon data are available via the USGS. Northern Region sites: Lynch, J.C., Cahoon, D.R., and Feher, L.C., 2019, Increasing rates of carbon burial in southwest Florida coastal wetlands: U.S. Geological Survey data release (https://doi.org/10.5066/P9ZH3R4G). Southern Region sites: Feher, L.C., Osland, M.J., and Anderson, G.H., 2017, Everglades National Park sediment elevation and marker horizon data release: U.S. Geological Survey data release (https://doi.org/10.5066/F7348HNP).

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