Applications and utility of the surface elevation table – marker horizon method for measuring wetland elevation and shallow soil subsidence-expansion Discussion/reply to: Byrnes M,...

Article *in* Geo-Marine Letters · May 2020

DOI: 10.1007/s00367-020-00656-6

6 authors, including:

Donald Cahoon
United States Geological Survey

Denise J. Reed
University of New Orleans

John W Day
Louisiana State University

James Lynch
National Park Service

Applications and utility of the surface elevation table–marker horizon method for measuring wetland elevation and shallow soil subsidence-expansion

D.R. Cahoon, D.J. Reed, J.W. Day, J.C. Lynch, A. Swales & R.R. Lane

ONLINE FIRST

Geo-Marine Letters
An International Journal of Marine Geology

ISSN 0276-0460

Geo-Mar Lett
DOI 10.1007/s00367-020-00656-6

Springer

Geo-Marine Letters
https://doi.org/10.1007/s00367-020-00656-6

DISCUSSION/REPLY

Applications and utility of the surface elevation table–marker horizon method for measuring wetland elevation and shallow soil subsidence-expansion

Discussion/reply to: Byrnes M., Britsch L., Berlinghoff J., Johnson R., and Khalil S. 2019. Recent subsidence rates for Barataria Basin, Louisiana. *Geo-Marine Letters* 39:265–278

D.R. Cahoon[1] · D.J. Reed[2] · J.W. Day[3] · J.C. Lynch[4] · A. Swales[5] · R.R. Lane[6]

Received: 22 January 2020 / Accepted: 15 April 2020

Abstract

Byrnes et al. (Geo-Marine Letters 39:265–278, Byrnes et al. 2019) present subsidence data for Barataria Basin located south and west of New Orleans in coastal Louisiana to better inform wetland protection and restoration planning by the Louisiana Coastal Protection and Restoration Authority. They measured subsidence using geodetic GPS elevation surveys of rod benchmarks, similar to the rod benchmarks of the surface elevation table–marker horizon (SET-MH) method used to measure surface biophysical processes influencing elevation dynamics and shallow subsidence (i.e., subsidence occurring above the base of the rod) in coastal wetlands. Byrnes et al. (Geo-Marine Letters 39:265–278, Byrnes et al. 2019) argue that (1) SET-MH measures should not be included in subsidence measures because subsidence is a purely geologic process, separate from biophysical processes occurring in the active marsh zone, (2) shallow subsidence measured by the SET-MH method in deep Holocene sediments are not valid because of downdrag on the rod, and (3) high spatial variability of wetland surface processes precludes the ability to make meaningful estimates of subsidence using the SET-MH method. This reply paper presents an extensive summary of the peer-reviewed literature that refutes all three of these claims and demonstrates that it is not only reasonable but also essential to apply the SET-MH method to obtain a complete as possible assessment of surface elevation dynamics to inform coastal wetland restoration and management planning in Barataria Basin and other coastal wetlands worldwide.

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s00367-020-00656-6) contains supplementary material, which is available to authorized users.

✉ D.R. Cahoon
dcahoon@usgs.gov

1 U.S. Geological Survey, Patuxent Wildlife Research Center, Laurel, MD 20708, USA

2 University of New Orleans, Pontchartrain Institute for Environmental Sciences, New Orleans, LA 70148, USA

3 Department of Oceanography and Coastal Sciences, Louisiana State University, Baton Rouge, LA 70803, USA

4 Northeast Coastal and Barrier Network, National Park Service, 4598 MacArthur Blvd. NW, Washington, DC 20007, USA

5 National Institute of Water and Atmospheric Research, P. O. Box 11-115, Hamilton, New Zealand

6 Comite Resources, P.O. Box 66596, Baton Rouge, LA 70896, USA

Background

Byrnes et al. (2019) report on recent subsidence rates for Barataria Basin in the Mississippi Delta of coastal Louisiana. Their article is based on data provided in a technical report prepared for the Louisiana Coastal Protection and Restoration Authority (CPRA) submitted in 2018 (Byrnes et al. 2018). The goal of their subsidence research is to better inform coastal wetland protection and restoration planning by the CPRA. One of the methods they used to estimate subsidence rates was geodetic GPS elevation measurements of rod benchmarks set into deep Holocene sediments. In these publications, they raise three issues with the surface elevation table–marker horizon (SET-MH) method that uses rod benchmarks (Cahoon et al. 2002a, b; Callaway et al. 2013; Lynch et al. 2015), as noted below:

> Issue 1. Surface biophysical accretionary dynamics measured by the SET-MH method should not be included in an estimate of subsidence, as subsidence is a purely geologic process.

Published online: 08 May 2020

Issue 2. It is not valid to calculate shallow subsidence rates from the SET-MH method when using unsleeved rods in deep Holocene sediments because of downdrag on the rods.

Issue 3. High spatial variability on the wetland surface precludes the ability to make meaningful estimates of subsidence based on elevation and accretion measurements from the SET-MH method.

It is our contention that it is not only reasonable but also essential to apply the SET-MH method in coastal Louisiana to obtain a complete as possible assessment of surface elevation change to inform restoration and management planning. This paper begins with a brief description of the purpose of the SET-MH method (Cahoon et al. 1995) and then addresses the three issues raised by Byrnes et al. (2019).

The SET-MH method

The SET-MH method is designed to simultaneously measure both wetland surface elevation change (E) and surface accretion-erosion (A) with mm accuracy (Fig. 1a, b). There are several common uses of these data. First, calculation of rates of elevation change and accretion can determine how well the height of the wetland surface is being maintained within the tidal frame (i.e., elevation capital; Cahoon et al.

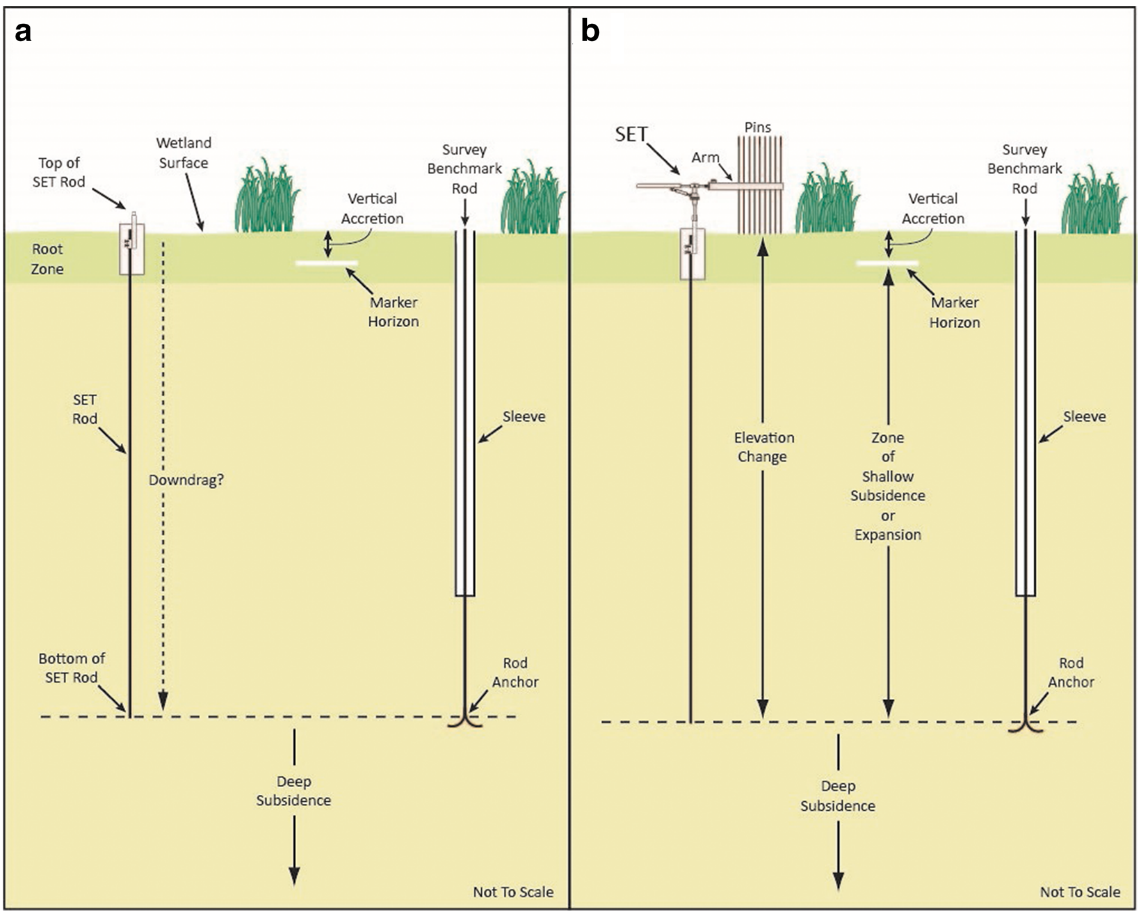

Fig. 1 Diagram (not to scale) showing the relationship among the surface elevation table (SET) attached to an unsleeved rod, marker horizon (MH), and a sleeved and anchored survey benchmark rod in a coastal marsh. A This panel shows the unsleeved SET rod and the sleeved and anchored survey rod relative to deep subsidence processes occurring beneath the rods as measured by repeat GPS surveys, and surface accretionary processes as measured by the MH method. Note the relationship between the wetland surface and top of the SET rod. Consolidation of the soil above the base of the unsleeved SET rod may cause downdrag on the rod, although occurrence and rates of downdrag are not well understood for SET rods. In contrast, the sleeved survey rod is isolated from consolidation processes, and the rod anchor prevents downdrag. B In this panel, the SET device has been attached to the SET rod and the pins deployed to the wetland surface at one of the eight fixed positions around the rod. Repeat measures of the wetland surface by the SET yield a rate of elevation change. Repeat coring of the MH yields a rate of vertical accretion. Data from the two methods are used to calculate rates of shallow subsidence or shallow expansion (vertical accretion minus elevation change; Cahoon et al. 1995) that occurs between the bottom of the SET rod and the marker horizon. Repeated GPS surveys of the top of the sleeved rod measure deep subsidence at the base of the rod, but not any of the shallow subsidence-expansion processes occurring above the base (Note, it is not practical to install a sleeved rod in coastal wetland sediments to support the SET because the heavy drilling equipment required for installation potentially would disrupt the sediment surface where the SET measurements would be taken. Thus, this diagram represents an ideal, hypothetical situation in regard to sleeved and anchored rods in coastal wetlands.)

2019). This determination cannot be made from subsidence data alone, although subsidence clearly has an influence on surface lowering. Second, comparison of accretion and elevation change rates (A minus E) can determine the separate influence of surface and subsurface process controls on wetland elevation (accretion/erosion processes, and shallow subsidence and shallow expansion processes, respectively, Fig. 1b). In combination with measures of deep subsidence and eustatic sea-level rise (i.e., relative sea-level rise), such comparisons can be used to inform wetland restoration and management practices (e.g., Ibañez et al. 1997; Vandenbruwaene et al. 2011; Erwin et al. 2006; Cahoon et al. 2011a, 2019). Third, measures of elevation change and shallow subsidence from the SET-MH method can be used to calculate local estimates of relative sea-level rise (RSLR) and submergence potential at a wetland (Cahoon 2015). Both SET-measured elevation change trends and local estimates of RSLR have been used to assess coastal wetland vulnerability to sea-level rise in a variety of coastal settings (e.g., Day et al. 1999, 2011a, b; Hensel et al. 1999; Morris et al. 2002; Rybczyk and Cahoon 2002; Lane et al. 2006; McKee et al. 2007; Ibanez et al. 2010; Krauss et al. 2010; Lovelock et al. 2011; Webb et al. 2013; Cahoon 2015). In contrast to measurements of subsidence relative to a datum (e.g., Dokka 2006), measurements of shallow subsidence using the SET-MH method are relative to the wetland surface allowing the data to be used to track elevation change without precise geodetic survey. A more detailed explanation of the methodology is provided in Supplementary Material A.

Issue 1: Active marsh zone and total subsidence

As Byrnes et al. (2019) state, subsidence has an impact on the active marsh zone, i.e., the part of the substrate influenced by vegetation growth/decay and sedimentation/erosion. But how representative is subsidence (sensu Byrnes et al. 2019) of the total elevation change of the wetland surface? Byrnes et al. (2019) considered subsidence rates calculated from repeated surveys of unsleeved benchmark rods to represent subsidence of the entire sediment column, not just that portion beneath the base of the rod. Yet, because, by their definition, subsidence is a geological process not related to variations in biological and physical processes occurring within the active marsh zone, it cannot be used to assess the full extent of processes influencing surface elevation change.

> [1] … because subsidence is a geological process unrelated to variations in short-term erosion and deposition processes or marsh growth and decay as a function of biological and physical processes within the active marsh zone, differencing vertical accretion and surface elevation change measurements does not primarily reflect shallow subsidence. (Byrnes et al. 2018, page 29)

By separating surficial processes of erosion, deposition, and marsh growth and decay from subsidence, the Byrnes et al.'s (2019) estimate of total subsidence (derived from data interpretations in their 2018 report cited in quotation no. 1) does not represent the total amount and perhaps the direction of change in surface elevation, which is essential information for wetland restoration and management planning. Their measure of subsidence is equivalent to "deep subsidence" described by Cahoon et al. (1995), which does not reflect biophysical surface processes and more correctly addresses the geologic nature of this term. Frederick et al. (2019) noted that processes operating below the Pleistocene-Holocene stratal contact represent "deep-seated" contributions to subsidence in Louisiana and that these include pre-Holocene compaction, glacio-isostatic forebulge collapse, Holocene sedimentary isostatic adjustment, and growth fault movement. They also note that monuments grounded 15–36 m below the surface within the area of thick Holocene alluvial-deltaic strata cannot distinguish between subsidence mechanisms operating at different depths. The main focus of the SET-MH method is to include consideration of processes contributing to surface elevation change that occur above the foundation of the SET rod. Higgins (2016) recognizes that surface elevation change in deltas is a complex phenomenon with many contributing processes and that this therefore requires an approach which crosses traditional disciplinary boundaries. Further, Higgins notes that "Few existing instruments can measure total elevation change, and none can resolve every process across all pertinent spatial and temporal scales."

Processes in coastal wetlands driving shallow subsidence or expansion, measured over the past 25 years with the SET-MH method, include as follows: root zone expansion from increased root volume (Cahoon et al. 2004; McKee et al. 2007; Langley et al. 2009; Cherry et al. 2009; and McKee 2011); root zone collapse from reduced root production, increased decomposition of plant roots, and loss of root volume (Ford and Grace 1998; Cahoon et al. 2003, 2004; Lane et al. 2006; McKee et al. 2007; Day et al. 2011a, b); shrink-swell related to changes in ground water level (Paquette et al. 2004; Whelan et al. 2005; Rogers and Saintilan 2008; Cahoon et al. 2011b); and compaction (Cahoon et al. 1995, 2000a, b; Lovelock et al. 2011). These are in addition to subsidence measured by GPS measurements taken on a benchmark (but not the wetland surface).

The impact of these near-surface, biophysical factors on elevation can be inferred from empirical measurements with the SET-MH method that monitors relative wetland surface elevation over time. These processes occur above the base of a SET and survey rod (Fig. 1b) and are not included in the total subsidence estimate derived from a GPS survey of a sleeved rod as described in Byrnes et al. (2019). Thus, a complete estimate of the total elevation change experienced by the vegetated wetland surface requires that the SET elevation trend be added to the GPS-derived deep subsidence measured from either a sleeved or unsleeved rod (Fig. 1b). This would yield an elevation response surface of the vegetated wetland that would better inform restoration planning than GPS-derived rod subsidence data alone.

Issue 2: Unsleeved rods in deep Holocene sediments

Ideally, one would attach the SET to a sleeved rod in the wetland and estimate shallow subsidence for the part of the substrate above the anchor or sleeve depth (Fig. 1b). However, installing sleeved rods in interior coastal wetlands is potentially highly disruptive to the wetland environments that are the subject of the measurements (Supplemental Information A). Byrnes et al. (2019, page 272) claim that a SET and MH difference calculation is not valid if the rod is unsleeved because of soil consolidation processes creating downdrag on the rod. Byrnes et al. (2019) do not cite any studies describing the amount of downdrag on unsleeved SET rods, either reported or that can be expected, and they present no new data to support their claim.

Swales et al. (2016) report estimated bearing capacity (i.e., skin friction resistance) of SET rods driven into unconsolidated mangrove sediments in the Firth of Thames, New Zealand (NZ), relative to the force exerted by the benchmark mass and the potential point settlement. The estimated bearing capacity of the SET benchmark was 100× smaller than the estimated load bearing capacity of the soil. This resulted in a potential point settlement of the rods of ~ 0.03 mm. The Firth of Thames mangrove sites are located in a sedimentary basin up to 3 km deep. Unconsolidated Quaternary sediments extend to 0.7–1.0 km depth, suggesting subsidence in this basin (Supplementary Material B). Swales et al. (2016) concluded that the linear subsidence trends of the SET rods measured by GPS of 7.7 to 9.4 mm/year were largely due to subsidence of the sedimentary basin due to sediment compaction. Similar subsidence rates were independently estimated from ^{210}Pb sediment accumulation rates (9.3 and 9.9 mm/year) that represented the creation of sediment accommodation volume primarily due to subsidence by sediment compaction, as the mangrove forest/tidal-flat platform had vertically accreted to an elevation close to the upper limit of the tidal frame by the early 1970s.

SET rod settlement rates have not been reported for other locations, so it is not known how typical this settlement rate of NZ basement sediments is, and if it is representative of the Barataria Basin. More studies are needed from other locations. But a rod settlement of < 1 mm magnitude would not preclude differencing elevation and accretion rates to calculate shallow subsidence because it is smaller than the measurement error of the SET (~ 1.0 to 1.5 mm, Cahoon et al. 2002b), and therefore has no detectable influence on the elevation trend. Further, where unsleeved rods are driven into highly consolidated sediments or ideally to bedrock (e.g., carbonate platform), downward movement of the rod would not occur, as Byrnes et al. (2019, page 272) note.

Theoretically, if point settlement of an unsleeved SET rod occurs, it would change the wetland surface/rod height relationship, thereby affecting the elevation change measurements and accretion minus elevation calculations (A − E). The downward movement of the rod would be measured as an increase in elevation (i.e., the height of the arm relative to the surface would be lower and the height of the pins above the arm higher (Fig. 1b). Thus, elevation change would be overestimated by the amount of downward rod movement, and the A − E calculation of shallow subsidence would be underestimated. Therefore, differencing SET and MH data is valid for unsleeved rods in unconsolidated sediments, with the caveat that the A − E calculation of shallow subsidence is a minimum value if the rod moves downward.

As explained in Issue 1, subsidence estimated by repeated GPS surveys of the SET rod (i.e., geological subsidence relative to a datum), not the wetland surface, may not accurately assess total elevation change (and perhaps direction) experienced by the vegetated wetland surface. Adding the SET elevation trend (that integrates all surface and subsurface processes occurring above the base of the rod) to subsidence measured by surveys of the rod would give the best estimate of total elevation change (i.e., total subsidence) of the wetland surface (e.g., Swales et al. 2019). This conclusion is with the caveat that if downdrag on the rod occurs, and is less than the rate of deep subsidence, elevation gain would be overestimated and elevation loss underestimated.

Issue 3: Spatial variability

Byrnes et al. (2019) state that SET and MH data cannot be compared because of high spatial variability in tidal wetland systems and that using the SET-MH method to inform coastal planning ignores spatial variability.

> [2] Further, small-scale variations in vegetation growth and decay, as well as bioturbation, impact vertical accretion and surface elevation change. Differencing these parameters to derive shallow subsidence assumes no spatial variation in marsh density, vegetation type, and growth and decay processes at a given site. (Byrnes et al. 2019, page 274)

Quotation [2] implies that use of the SET-MH method is invalid in any wetland, not only wetlands overlying deep

Holocene sediments but also wetlands where the SET rod is driven to bedrock, because high spatial variability in the accretion and elevation trends would preclude establishing significant differences between them. Hence, they argue that point estimates of shallow subsidence are invalid in the context of marsh surface variability. This claim is incorrect, and Byrnes et al. (2019) present no data to support it. The question of extrapolating from point estimates to site-scale patterns is an issue of experimental design and adequate sample replication. Spatial variations of surface and near-surface processes influencing elevation and accretion are well recognized by users of the SET-MH method and are taken into account in site sampling design (i.e., plot locations and number of replicate plots), SET-MH plot design, and SET instrument design (Lynch et al. 2015) (see Supplementary Material C for a detailed explanation of sampling design and replication options used in SET-MH sampling, and SET instrument and plot designs used to reduce sampling error). There are peer-reviewed datasets and analyses published in 55 publications between 1995 and 2012 for > 85 wetlands from a wide range of settings around the world comparing SET-MH elevation and accretion trends with a high degree of statistical significance (Webb et al. 2013; Cahoon 2015).

In addition, CPRA uses marsh elevation change, based on data from individual rod SET installations at Coastwide Reference Monitoring System (CRMS) sites (https://lacoast.gov/crms/), to assess variations in marsh surface elevation change among coastal basins and deltaic regions in Louisiana (e.g., McGinnis et al. 2019), and includes data from the Barataria Basin (the subject of the Byrnes et al. (2019) study). This assessment for the Calcasieu-Sabine basin has enabled CPRA to identify which areas are better at keeping up with sea-level rise and to discern areas where improvements in hydrologic management and potentially restoration will be needed.

Further, while Byrnes et al. (2019) consider spatial variability a fundamental constraint of applying point measurements for shallow processes, they do consider that point measurements of individual rods can be used to produce continuous surfaces of subsidence (their Figure 7). Reflecting spatially discontinuous subsurface processes from point or localized measurements is a challenge. The importance of local features such as faults (Dokka 2006; Chan and Zoback 2007) and changes in facies distribution (Meckel et al. 2007) on subsidence patterns is well documented. That such spatial variability is not considered important by Byrnes et al. (2019) clearly requires more detailed justification, especially when they consider spatial variability in surface processes a reason to disregard potentially important datasets. Measuring and understanding subsurface processes contributing to surface lowering across the coastal basins of the Mississippi deltaic plain is a challenge. In the absence of more synoptic techniques, and with an ongoing and active restoration program (CPRA 2017), point measurements of all types should be used, with associated caveats regarding measurement techniques and in the context of a solid conceptual understanding of the contributing processes. Dismissing some decadal scale measurements (e.g., Day et al. 2011a, b) with such little justification limits rather than expands understanding of basin dynamics.

Conclusions

The SET-MH method is a valid tool used on a global scale (Webb et al. 2013) to provide millimeter accuracy data that integrates key surface and subsurface processes influencing wetland elevation change (Lynch et al. 2015). These data are used to inform wetland management and restoration practices and provide highly accurate estimates of relative sea-level rise and potential submergence of coastal wetlands. When combined with measures of deep subsidence, they provide a measure of the total elevation change experienced by the vegetated wetland surface. Thus, the conclusions of Byrnes et al. (2019) stating that the SET-MH method is invalid are not supported by data.

Acknowledgments We thank M. Osland and two anonymous reviewers for their peer reviews of the manuscript. Use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the US Government.

References

Byrnes MR, Britsch LD, Berlinghoff JL, Johnson R (2018) Determining recent subsidence rates for Barataria Basin, Louisiana: implications for engineering and design of coastal restoration projects. Final report to Louisiana Coastal Protection and Restoration Authority, prepared by Applied Coastal Research and Engineering, Metairie, LA, 37 pages, plus appendices

Byrnes MR, Britsch LD, Berlinghoff JL, Johnson R, Khalil S (2019) Recent subsidence rates for Barataria Basin, Louisiana. Geo-Mar Lett 39:265–278

Cahoon DR (2015) Estimating relative sea-level rise and submergence potential at a coastal wetland. Est Cst 38:1077–1084

Cahoon DR, Reed DJ, Day JW (1995) Estimating shallow subsidence in microtidal salt marshes of the southeastern United States: Kaye and Barghoorn revisited. Mar Geol 128:1–9

Cahoon DR, French J, Spencer T, Reed DJ, Moller I (2000a) Vertical accretion versus elevational adjustment in UK saltmarshes: an evaluation of alternative methodologies. In: Coastal and estuarine environments: sedimentology, geomorphology and geoarchaeology, vol 175. Geological Society, Special Publication, London, pp 223–238

Cahoon DR, Marin PE, Black BK, Lynch JC (2000b) A method for measuring vertical accretion, elevation, and compaction of soft, shallow water sediments. J Sediment Res 70:1250–1253

Cahoon DR, Lynch JC, Hensel PF, Boumans RM, Perez BC, Segura B, Day JW (2002a) High precision measurements of wetland sediment elevation: I. Recent improvements to the sedimentation-erosion table. J Sediment Res 72:730–733

Cahoon DR, Lynch JC, Perez BC, Segura B, Holland RD, Stelly C, Stephenson G, Hensel PF (2002b) High-precision measurements of wetland sediment elevation: II. The rod surface elevation table. J Sediment Res 72:734–739

Cahoon DR, Hensel P, Rybczyk J, McKee KL, Proffitt CE, Perez BC (2003) Mass tree mortality leads to mangrove peat collapse at Bay Islands, Honduras after Hurricane Mitch. J Ecol 91:1093–1105

Cahoon DR, Ford MA, Hensel P (2004) Ecogeomorphology of Spartina patens-dominated tidal marshes: soil organic matter accumulation, marsh elevation dynamics, and disturbance. In: The Ecogeomorphology of tidal marshes, vol 59. American Geophysical Union, Coastal Estuarine Studies, Washington, DC, pp 247–266

Cahoon DR, White DA, Lynch JC (2011a) Sediment infilling and wetland formation dynamics in an active crevasse splay of the Mississippi River delta. Geomorphology 131:57–68

Cahoon DR, Perez BC, Segura BD, Lynch JC (2011b) Elevation trends and shrink-swell response of wetland soils to flooding and drying. Est Cstl Shelf Sci 91:463–474

Cahoon DR, Lynch JC, Roman CT, Schmit JP, Skidds DE (2019) Evaluating the relationship among wetland vertical development, elevation capital, sea-level rise, and tidal marsh sustainability. Est Cst 42:1–15

Callaway JC, Cahoon DR, Lynch JC (2013) The surface elevation table – marker horizon method for measuring wetland accretion and elevation dynamics. In: Methods in biogeochemistry of wetlands, Madison, WI, Soil Science Society of America, SSSA Book Series 10, 901–918

Chan AW, Zoback MD (2007) The role of hydrocarbon production on land subsidence and fault reactivation in the Louisiana coastal zone. J Cstl Res 23:771–786

Cherry JA, McKee KL, Grace JB (2009) Elevated CO_2 enhances biological contributions to elevation change in coastal wetlands by offsetting stressors associated with sea-level rise. J Ecol 97:67–77

CPRA (Coastal Protection and Restoration Authority) (2017) Louisiana's comprehensive master plan for a sustainable coast. CPRA, Baton Rouge 169p

Day JW, Rybczyk J, Scarton F, Rismondo A, Are D, Cecconi G (1999) Soil accretionary dynamics, sea-level rise and the survival of wetlands in Venice lagoon: a field and modelling approach. Est Cstl Shelf Sci 49:607–628

Day J, Kemp P, Reed D, Cahoon D, Boumans R, Suhayda J, Gambrell R (2011a) Vegetation death and rapid loss of surface elevation in two contrasting Mississippi delta salt marshes: the role of sedimentation, autocompaction and sea-level rise. Ecol Eng 37:229–240. https://doi.org/10.1016/j.ecoleng.2010.11.021

Day JW, Ibanez C, Scarton F, Pont D, Hensel P, Day JF, Lane R (2011b) Sustainability of Mediterranean deltaic and lagoon wetland with sea-level rise: the importance of river input. Estuar Coasts 34:483–493

Dokka RK (2006) Modern-day tectonic subsidence in coastal Louisiana. Geology 34:281–284

Erwin RM, Cahoon DR, Prosser DJ, Sanders GM, Hensel P (2006) Surface elevation dynamics in vegetated Spartina marshes versus unvegetated tidal ponds along the mid-Atlantic coast, USA, with implications to wetlands. Estuar Coasts 29:96–108

Ford MA, Grace JB (1998) Effect of vertebrate herbivores on soil processes, plant biomass, litter accumulation and soil elevation changes in a coastal marsh. J Ecol 86:974–982

Frederick BC, Blum M, Fillon R, Roberts H (2019) Resolving the contributing factors to Mississippi Delta subsidence: past and present. Basin Res 31:171–190

Hensel PF, Day JW, Pont D (1999) Wetland vertical accretion and soil elevation change in the Rhone River delta, France: the importance of riverine flooding. J Cstl Res 15:668–681

Higgins SA (2016) Advances in delta-subsidence research using satellite methods. Hydrogeol J 24:587–600

Ibañez C, Antoni C, Day JW, Curcó A (1997) Morphologic development, relative sea level rise and sustainable management of water and sediment in the Ebro Delta, Spain. J Cstl Conserv 3:191–202

Ibanez C, Sharpe PJ, Day JW, Day JN, Prat N (2010) Vertical accretion and relative sea-level rise in the Ebro Delta wetlands (Catalonia, Spain). Wetlands 30:979–988

Krauss KW, Cahoon DR, Allen JA, Ewel KC, Lynch JC, Cormier N (2010) Surface elevation change and susceptibility of different mangrove zones to sea-level rise on Pacific high islands of Micronesia. Ecosystems 13:129–143

Lane RR, Day JW, Day JN (2006) Wetland surface elevation, vertical accretion, and subsidence at three Louisiana estuaries receiving diverted Mississippi River water. Wetlands 26:1130–1142

Langley JA, McKee KL, Cahoon DR, Cherry JA, Megonigal JP (2009) Elevated CO_2 stimulates marsh elevation gain, counterbalancing sea-level rise. Proc Natl Acad Sci 106:6182–6186

Lovelock CE, Bennion V, Grinham A, Cahoon DR (2011) The role of surface and subsurface processes in keeping pace with sea-level rise in intertidal wetlands of Moreton Bay, Queensland, Australia. Ecosystems 14:745–757

Lynch JC, Hensel PF, Cahoon DR (2015) The surface elevation table and marker horizon technique: a protocol for monitoring wetland elevation dynamics. Natural Resource Report NPS/NCBN/NRR—2015/1078. National Park Service, Fort Collins

McGinnis TE, Wood WB, Luent M, Mouledous M, Miller M, Sharp LA (2019) 2019 basin summary report for the Calcasieu-Sabine Basin. Coastal Protection and Restoration Authority of Louisiana, Lafayette, Louisiana. 59 pp plus Appendix

McKee KL (2011) Biophysical controls on accretion and elevation change in Caribbean mangrove ecosystems. Est Cstl Shelf Sci 91: 475–483

McKee KL, Cahoon DR, Feller IC (2007) Caribbean mangroves adjust to rising sea level through biotic controls on change in soil elevation. Glbl Ecol Biogeog 16:545–556

Meckel TA, Ten Brink US, Williams SJ (2007) Sediment compaction rates and subsidence in deltaic plains: numerical constraints and stratigraphic influences. Basin Res 19:19–31

Morris JT, Sundareshwar PV, Nietch CT, Kjerfve B, Cahoon DR (2002) Responses of coastal wetlands to rising sea level. Ecology 83:2869–2877

Paquette CH, Sundberg KL, Boumans RMJ, Chmura GL (2004) Changes in salt marsh surface elevation due to variability in evapotranspiration and tidal flooding. Estuaries 27:82–89

Rogers K, Saintilan N (2008) Relationships between surface elevation and groundwater in mangrove forests of southeast Australia. J Cstl Res 24:63–69

Rybczyk JM, Cahoon DR (2002) Estimating the potential for submergence for two wetlands in the Mississippi River delta. Estuaries 25: 985–998

Swales A, Denys P, Pickett VI, Lovelock CE (2016) Evaluating deep subsidence in a rapidly-accreting mangrove forest using GPS monitoring of surface-elevation benchmarks and sedimentary records. Mar Geol 380:205–218

Swales A, Reeve G, Cahoon DR, Lovelock CE (2019) Landscape evolution of a fluvial sediment-rich *Avicennia marina* mangrove forest:

insights from seasonal and inter-annual surface-elevation dynamics. Ecosystems 22:1232–1255

Vandenbruwaene W, Maris T, Cox TJS, Cahoon DR, Meire P, Temmerman S (2011) Sedimentation and response to sea-level rise of a restored marsh with reduced tidal exchange: comparison with a natural tidal marsh. Geomorphology 130:115–126

Webb EL, Friess DA, Krauss KW, Cahoon DR, Guntenspergen GR, Phelps J (2013) A global standard for monitoring coastal wetland vulnerability to accelerated sea-level rise. Nat Clim Chang 3:458–465

Whelan KRT, Smith TJ, Cahoon DR, Lynch JC, Anderson GH (2005) Groundwater control of mangrove surface elevation: shrink-swell of mangrove soils varies with depth. Estuaries 28:833–843

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.