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# Measuring and Interpreting the Surface and Shallow Subsurface Process Influences on Coastal Wetland Elevation: A Review

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## Abstract
A century ago, measuring elevation in tidal wetlands proved difficult, as survey leveling of soft marsh soils relative to a fixed datum was error prone. For 60 years, vertical accretion measures from marker horizons were used as analogs of elevation change. But without a direct measure of elevation, it was not possible to measure the total influence of surface and subsurface processes on elevation. In the 1990s, the surface elevation table (SET) method, which measures the movement of the wetland surface relative to a fixed point beneath the surface (i.e., the SET benchmark base), was combined with the marker horizon method (SET-MH), providing direct, independent, and simultaneous measures of surface accretion and elevation and quantification of surface and shallow subsurface process influences on elevation. SET-MH measures have revealed several fundamental findings about tidal wetland dynamics. First, accretion [$A$] is often a poor analog for elevation change [$E$]. From 50–66% of wetlands experience shallow subsidence ($A > E$), 7–10% shallow expansion ($A < E$), 7% shrink-swell, and for 24–36% $A$ is an analog for $E$ ($A = E$). Second, biological processes within the root zone and physical processes within and below the root zone influence elevation change in addition to surface processes. Third, vegetation plays a key role in wetland vertical dynamics. Plants trap sediment and increase resistance to erosion and compaction. Soil organic matter accumulation can lead to shallow expansion, but reduced plant growth can lead to subsidence, and plant death to soil collapse. Fourth, elevation rates are a better indicator of wetland response to sea-level rise than accretion rates because they incorporate subsurface influences on elevation occurring beneath the marker horizon. Fifth, combining elevation trends with relative sea-level rise (RSLR) trends improves estimates of RSLR at the wetland surface (i.e., $RSLR_{wet}$). Lastly, subsurface process influences are fundamental to a wetland's response to RSLR and plant community dynamics related to wetland transgression, making the SET-MH method an invaluable tool for understanding coastal wetland elevation dynamics.

**Keywords** Coastal wetlands · Surface elevation change · Vertical accretion · Surface elevation table · Marker horizon · Salt marsh · Mangrove forest

## Introduction

With the invention and widespread use of accurate tide gauges and the development of multi-decadal records of sea-level change came the realization by the early twentieth century that sea level is rising in many parts of the world (e.g., Emery and Aubrey 1991). Thus, it became necessary to understand the response of coastal wetlands to rising sea levels to determine if marsh elevations would keep pace with sea-level rise and thereby remain stable. Today, the surface elevation table—marker horizon (SET-MH) method (Cahoon et al. 1995, 2002a, b; Callaway et al. 2013; Lynch et al. 2015)—provides millimeter-resolution measures of wetland accretion and elevation dynamics for this purpose and has become the global standard for assessing wetland resilience to sea-level rise (Webb et al. 2013). But, in the early twentieth century there was no reliable method for measuring surface elevation change at the millimeter-resolution of sea-level trends measured by tide gauges, as revealed by early attempts to measure changes in wetland elevation, as described below.

Carey and Oliver (1918) were among the first to address the need for measuring coastal wetland surface elevation

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change in their handbook "Tidal Lands: A Study of Shore Problems." In a section of their report titled, "The Measurement of Vertical Rise in Level of Salt Marshes," they explained "The method by which these results were obtained was not that of placing the levelling staff on the same spot at convenient intervals of time and comparing the readings with a fixed benchmark. The expansion and contraction to which tidal soils are liable and the varying state of muddiness of the surface render such a method quite unreliable for the determination of small increments [page 202]". Their solution to not being able to make mm-resolution measures of surface elevation change directly was to "…lay a new surface closely similar in texture to the actual ground, harmless to vegetation, and of a distinctive and permanent colour [page 202]". Today, we call these layers artificial soil marker horizons or marker horizons in brief (e.g., Stoddard et al. 1989; Cahoon and Turner 1989). Marker horizons are used to measure soil vertical accretion based on the depth to which the horizon becomes buried over time; hereafter referred to as vertical accretion. Carey and Oliver (1918) used vertical accretion as an analog for surface elevation change in their assessment of the ability of salt marsh elevation to change in response to sea-level rise. The analog approach assumes that vertical accretion drives surface elevation change. However, the marker horizon method does not measure any potential shallow subsurface influence on elevation change (e.g., soil subsidence or expansion processes) occurring below the depth of the marker horizon, typically the upper few centimeters of soil. The research by Carey and Oliver (1918) marks the beginning of a century-long and ongoing effort by coastal scientists to develop new methods and technologies to measure wetland surface elevation change with millimeter resolution to evaluate surface and subsurface influences on wetland vertical development and to monitor coastal wetland response to sea-level rise.

This review is organized around two topics. The first topic is the evolution of methods for measuring wetland elevation dynamics and how our knowledge improved. Herein are described, in sequence, three methodological approaches developed during the past century. The approaches investigate coastal wetland elevation trends, and surface and shallow subsurface controls on wetland elevation, beginning with the accretion-as-surrogate-for-elevation method of Carey and Oliver (1918) and culminating in the surface elevation table—marker horizon (SET-MH) method of Cahoon et al. (1995). The second topic is an in-depth review of what the SET-MH method has revealed on two research topics over the past three decades, (1) hypothesis-based inquiries into the shallow subsurface processes influencing wetland elevation and the biological and physical forces driving them and (2) assessing coastal wetland response to sea-level rise.

## Evolution of Methods

During the past century, a variety of methodological approaches have been used to measure and understand process influences on wetland elevation change (Table 1). Each of the three approaches identified herein includes multiple methods, and this review briefly describes the range of methodologies with representative examples, terminology, what is measured, and how the data are interpreted. The initial approach used vertical accretion methods as analog for elevation change, as described above, but this method does not measure any subsurface process influences on the change in level of the wetland occurring beneath the marker horizon. The next approach measured elevation directly, i.e., the combined influence of surface and shallow subsurface processes on elevation. But the readings from most methods were interpreted as vertical accretion or erosion. The third approach combined methods from the first two approaches, comparing elevation and vertical accretion measures directly, making it possible to discern surface from subsurface process influences on wetland elevation. The simultaneous, independent measures of accretion from a marker horizon at the surface and elevation relative to a fixed point beneath the wetland surface from a vertical structure allows for the quantification of process influences on elevation occurring between the marker horizon and the base of the vertical structure (e.g., Cahoon et al. 1995).

### Approach 1: Accretion as Analog for Elevation Change

The marker horizon method for measuring vertical accretion was commonly used in the twentieth century as an analog for elevation to estimate the increase in marsh level (Reed and Cahoon 1993). A range of marker materials was used, including colored sand, brick dust, aluminum glitter, beach sand, feldspar, and sand-feldspar mixture (see references, Table 1), laid by hand on a variety of local wetland surfaces, usually in multiple replicate plots. These marker horizons could be expected to be recovered for at least a few years, in some cases longer, although the horizon is gradually consumed by repeated sampling, erosion, and/or bioturbation. Eventual disintegration of horizons is common, with new horizons having to be laid in new locations. The method overestimates the change in level of the marsh by not measuring any subsurface processes influencing elevation occurring below the marker horizon. An additional marker horizon, $^{137}$Cs, was deposited globally as fallout from atmospheric nuclear weapons testing (DeLaune et al. 1978). The first year of significant $^{137}$Cs fallout was 1954, and peak fallout accumulations occurred by 1963 when atmospheric testing was banned.

**Table 1** A review of methods representative of three approaches developed during the past century for assessing recent (<100 years) trends of coastal wetland surface elevation change.

| Approach and Methods[a] [soil depth, m][b] | Representative References |
|---|---|
| *Approach 1: Surface Accretion as Analog for Elevation* | |
| Marker Horizon Methods [surface] | |
| Colored sand | Carey and Oliver 1918 |
| Brick dust | Stearns and MacCreary 1957 |
| glitter | Harrison and Bloom 1977 |
| | Richard 1978 |
| $^{137}$Cs | DeLaune et al. 1978 |
| Feldspar | Cahoon and Turner 1989 |
| Dune sand | Stoddard et al. 1989 |
| Sedimentation Methods | |
| $^{210}$Pb [< 1 m] | Armentano and Woodwell 1975 |
| Filter pad [surface][c] | Reed 1989 |
| Anchored tile [surface][c] | Pasternack and Brush 1998 |
| *Approach 2: Elevation Measured Directly*[d] | |
| Pegs [<0.5 m] | Carey and Oliver 1918 |
| Stakes [<0.5 m] | Ranwell et al. 1964, Bird and Barson 1977 |
| Pins [< 1.5 m] | Spenceley 1977, 1982 |
| Sedi-Eros Table [?] | Schoot & de Jong 1982 |
| Contour Plotting Frame [0.8 m] | Hartnall 1984 |
| Sedimentation Erosion Level [?] | van Eerdt 1985 |
| Fixed 3-m arm, sleeved poles [?] | Nuttle et al. 1990 |
| Sedimentation-Erosion Table [6-10 m] | Boumans and Day 1993 |
| | Childers et al. 1993 |
| Sedimentation – Erosion Bar [1 m] | van Duin et al. 1997 |
| *Approach 3: Elevation and Accretion Methods Combined*[f] | |
| Sedimentation Erosion Table-Marker Horizon | Cahoon et al. 1995 |
| Sedimentation Erosion Table-Marker Horizon [serial] | Cahoon et al. 2000a |
| Surface Elevation Table-Marker Horizon[g] | Cahoon et al. 2002a |
| Rod Surface Elevation Table: | - |
| <u>Shallow</u>: <0.5 m [i.e., live root zone] | Cahoon et al. 2002b |
| | Cahoon et al. 2013 |
| <u>Deep</u>: 10-25 m | Cahoon et al. 2002b |
| | Callaway et al. 2013 |
| Rod Surface Elevation Table-Marker Horizon | Cahoon et al. 2003 |
| Long-arm Rod Surface Elevation Table-Marker Horizon | Langley et al. 2009 |
| Mini Surface Elevation Table-Marker Horizon | Cherry et al. 2009 |
| Continuous Elevation Sensor [0.15 m] | Cahoon et al. 2011a |
| Sedimentation Erosion Bar-Marker Horizon [≤1 m] | van Wijnen and Bakker 2001 |
| Modified SEB-Marker Horizon [0.8 m] | Lang'at et al. 2014 |

[a]The timescale of measurement was seasonal for all methods except $^{210}$Pb (century), $^{137}$Cs (decadal), filter pads and anchored tiles (biweekly), and Continuous Elevation Sensor (hourly).

[b]Soil depth indicates the vertical portion of the substrate incorporated in the measurement of accretion or elevation change. A question mark [?] indicates the depth was not reported.

[c]Accretion is calculated from sediment accumulation rates (g cm$^{-2}$ y$^{-1}$) and bulk density (g cm$^{-3}$) of the soil deposited.

[d]For the most part, these methods were conceived to measure surface accretion and erosion as indicated by their names, and the data were typically interpreted as such. But these methods measure elevation directly relative to the base of the vertical structure.

[e]Methods that measure elevation directly shown above this line typically interpreted data as surface accretion or erosion. Methods shown below this line interpreted data as measures of elevation.

[f]Combining these methods makes it possible to distinguish surface from shallow subsurface process influences on elevation (Cahoon et al. 1995).

[g]The Sedimentation – Erosion Table [SET] designed by Boumans and Day [1993] was modified by D. Cahoon and J. Lynch and later renamed the Surface Elevation Table [Cahoon et al. 2002a].

This 1963 peak horizon has been recoverable for decades globally from a variety of wetland soil types, although it appears that it is becoming increasingly difficult to recover due to major deterioration in clarity of the peak horizon 60 years after its deposition (Drexler et al. 2018). Given the depth of this marker horizon, up to ~ 30 cm or more in some instances, vertical accretion measured by $^{137}Cs$ incorporates compaction and expansion processes of the soil profile above the peak horizon.

Other sedimentation methods can be used to calculate vertical accretion (Table 1). Short-term (biweekly) surface sediment accumulation methods such as filter pads (Reed 1989) and anchored tiles (Pasternack and Brush 1998) used on an annual basis to investigate the influence of microhabitats, tides, and storm events on highly localized sediment deposition provide estimates of vertical accretion from sediment accumulation rates (g $cm^{-2}$ $year^{-1}$) and bulk density (g $cm^{-3}$) of the soil deposited. The radiometric soil-dating method $^{210}Pb$ measures the activity of this naturally occurring radioisotope through the soil profile (~ 1 m depth) over the span of about one century. Assuming a constant rate of sedimentation and flux of $^{210}Pb$ to the sediment, an accretion rate (cm $year^{-1}$) is calculated by regression (Armentano and Woodwell 1975; Appleby and Oldfield 1978). Unlike marker horizons, this method incorporates compaction processes occurring over the depth (~ 1 m) of the dated soil profile.

## Approach 2: Elevation Measured Directly

Numerous and widely used methods for directly measuring wetland elevation change (Table 1) involve inserting a single vertical structure such as a rod, peg, stake, pin, pipe, or pole made from a variety of materials (e.g., bamboo, stainless steel, pvc, or aluminum) permanently into the soil. Initial versions of this approach (Table 1) were simple structures, such as pegs (Carey and Oliver 1918), bamboo stakes, (Ranwell et al. 1964), or pins (Spencely 1982, Bird and Barson 1977), located at a single point on the wetland surface, driven up to ~ 1 m into the sediment with 10–20 cm of the structure exposed above the sediment surface. The height of the stake or pin above the sediment surface was measured repeatedly over time with a ruler providing a direct measure of elevation change relative to the base of the stake or pin. However, readings were typically erroneously interpreted as being the sole result of surface sedimentation or erosion (i.e., pins were commonly referred to as erosion pins), even though the measurements include both surface processes of sedimentation and/or erosion and subsurface processes occurring between the sediment surface and the base of the structure that contribute to elevation loss (e.g., compaction, decomposition) or gain (e.g., root production) but do not include any processes occurring beneath the structure. However, during the past two decades, measurements from pins inserted into the sediment have been interpreted appropriately as elevation, and the limitations of the method for measuring elevation recognized, with various names ascribed to the pin method, including sediment pin (Krauss et al. 2003; Kumara et al. 2010; Hongwiset et al. 2022), stakes (Gilman et al. 2007), erosion pin (Stokes et al. 2009), pin (Huxham et al. 2010), sediment elevation pin (Hayden and Granek 2015), surface elevation change pin (Potouroglou et al., 2017), and surface elevation pin (Alemu et al. 2022).

Later versions of the structural approach are more complex and involve installing a fixed reference plane, such as a table or bar, to the vertical pipe or rod, which is driven to greater depths to bear the weight of the structure. Structures driven to shallow depths are supported by multiple pipes or rods. This approach allows for multiple elevation readings in relation to the fixed reference height across a 1–2 $m^2$ area of the wetland surface by passing pins through the table or bar to the sediment surface and measuring the height of the pin above the reference plane. The reference plane is installed only during measurements and then removed. In the 1980s, three methods were developed or adapted for use in coastal wetlands (e.g., the Sedi-Eros Table (Schoot and de Jong 1982), contour plotting frame (Hartnall 1984), and sedimentation erosion level (van Eerdt 1985, Table 1)). Like pins, measurements from these methods provide direct measures of elevation change relative to the base of the vertical structure and include both surface and subsurface process influences on elevation but were typically interpreted as accretion or erosion influencing marsh level as indicated by the method names. In the 1990s, Nuttle et al. (1990) developed a 3-m fixed arm attached to sleeved poles driven into the substrate to which was attached a dial gauge that measured the distance to the marsh surface with 0.03-mm accuracy. The readings from the fixed arm were reported as elevation. Boumans and Day (1993) developed a large device called the sedimentation erosion table (SET), with an arm supported at one end (i.e., an unbalanced arm) by an aluminum pipe driven up to 6–10 m into the substrate (Table 2), based on the smaller Sedi-Eros Table design. Both the Sedi-Eros Table and SET were designed to sample shallow open water sediment surfaces. However, the SET was used to sample marsh sediment surfaces as well (Childers et al. 1993), and then modified to facilitate its use and improve its resolution in vegetated wetland surfaces (Cahoon et al. 2002a). van Duin et al. (1997) developed the sedimentation erosion bar

(SEB) with a 1-m-long bar placed across two poles driven 1 m into the substrate. Data from the SET and SEB methods were routinely interpreted as measures of elevation (e.g., Boumans and Day 1993; Childers et al. 1993; van Wijnen and Bakker 2001).

## Approach 3: Elevation and Accretion Methods Combined

Kaye and Barghoorn (1964) described the process of auto-compaction of a marsh soil beneath its own weight, resulting in a change in level of soil particles, or what they called settlement. The implications for the relationship between vertical accretion and surface elevation change are important, as marker horizons do not measure settlement occurring beneath them (i.e., beneath the top few centimeters of the soil). For example, the brick dust marker horizon study by Stearns and MacCreary (1957), where 10–13 cm of vertical accretion over 20 years resulted in no measurable increase in elevation, suggests that vertical accretion methods are not a good surrogate for, and overestimate, surface elevation change. Kaye and Barghoorn (1964, p.69) further recognized that "…most

**Table 2** Evolution of Surface Elevation Table (SET) technology

| Device Name | Device Purpose | Habitat | Mechanism | Technological Advance | References |
|---|---|---|---|---|---|
| **Sedi-Eros Table** [with <1-m long unbalanced arm] | Measures change in level of sediment surface: reported as accretion or erosion | Polders | Remote release of 11 pins from a table attached to a pole driven into the sediment | Multiple pins remotely released to reduce sediment disturbance during measurement | Schoot and DeJong 1982 |
| **Sedimentation-Erosion Table** [with 1.1-m long unbalanced arm] | Measures surface elevation change from a pipe driven up to 6-10m into the sediment | Open water | Sliding plate mechanism remotely releases 9 pins from table attached to benchmark | Larger version of Sedi-Eros Table; floats attached to pins reduce descent velocity of the pins through water | Boumans and Day 1993 |
| | | Vegetated wetland | Sliding plate mechanism partially releases pins | Pins manually placed on sediment surface | Childers et al. 1993, Cahoon et al. 1995 |
| **Surface Elevation Table** [with 1.1-m long unbalanced arm] | Measures surface elevation change from a pipe driven up to 6-10 m into the sediment | Vegetated wetland | Sliding plate mechanism replaced with single plate, each of 9 pins secured with an individual locking mechanism | Pins manually placed on sediment surface; 3 evolutions of the locking mechanism and pin material | Cahoon et al. 2002a |
| **Rod Surface Elevation Table: Deep Rod SET** [with 0.5-m long balanced arm] | Measures surface elevation change from a benchmark driven up to or >25 m into the sediment | Vegetated wetland; open water | The rod SET is a balanced, light-weight mechanical leveling device attached to a rod inserted into a deep rod benchmark | Measures change in elevation up to or >25 m depth; pins held in place by clips and manually placed on sediment surface | Cahoon et al. 2002b, Callaway et al. 2013 |
| **Rod Surface Elevation Table: Shallow Rod** [with 0.5-m long balanced arm] | Measures surface elevation change in the root zone from a shallow rod benchmark driven <1 m into sediment | Vegetated wetland | The rod SET is a balanced, light-weight mechanical leveling device attached to a vertical rod supported by a table with legs driven to depth of root zone | Measures change in elevation within root zone; light-weight balanced SET design and four hollow table legs keep benchmark from tilting or sinking when SET is attached | Cahoon et al. 2002b, Callaway et al. 2013 |
| **Deep Rod Surface Elevation Table** [with 4-m long balanced arm] | Measure surface elevation change in adjacent plots across 4 m of wetland surface | Vegetated wetland | The rod SET with 100 pins is attached to the deep rod and supported at the opposite end by a stabilizing rod. | Simultaneous elevation measurements in adjacent field plots; pins manually placed on sediment surface | Langley et al. 2009 |
| **Deep Rod Surface Elevation Table: shallow pipe benchmark** | Measures surface elevation change over both the depth of the deep rod and the root zone | Vegetated wetland | Shallow pipe benchmark is installed under two pins of the deep Rod SET; height of both the wetland surface and shallow pipe benchmark are measured by pins simultaneously. | Simultaneous measures of the wetland surface and shallow pipe benchmark enables calculation of elevation change within the root zone and between the root zone and base of the rod. | Langley et al. 2009 |
| **Mini-Surface Elevation Table** [attached to a plant growth container] | Measure surface elevation change over soil depth in the container | Vegetated wetland | The SET attaches to the container, which acts as the benchmark. | Allows measurement of elevation change in field and laboratory manipulative experiments where traditional SET technology is impractical. | Cherry et al. 2009, Payne et al. 2019 |

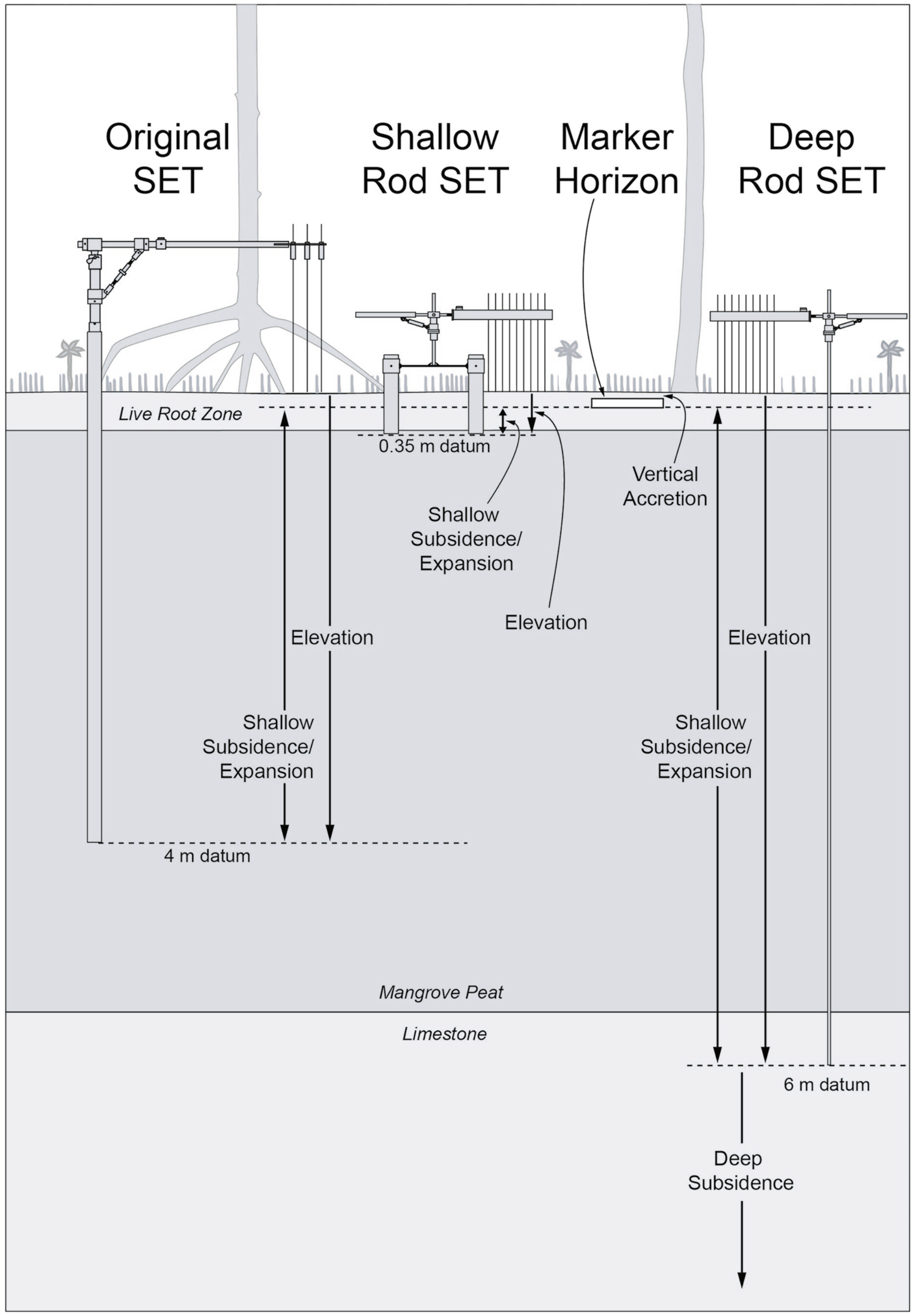


**Fig. 1** Profile diagram of a mangrove substrate showing a marker horizon for measuring vertical accretion (**A**) and three SET types for measuring elevation (**E**) relative to the base of the SET benchmarks driven to different depths of the substrate: the original SET (pipe benchmark, up to 6–9 m depth), deep Rod SET (up to 25 + m depth), and shallow rod SET (typically < 1 m depth but can be driven as deep as the pipe benchmark). Vertical land motion occurring between the marker horizon and the base of the SET benchmark indicates shallow subsidence ($A > E$) or expansion ($A < E$) of the substrate. But an outcome of $A = E$ indicates there is no shallow subsurface influence on E. Vertical land motion occurring beneath a SET benchmark is referred to as deep subsidence that is not incorporated in the SET elevation measurement. Modified from Whelan et al. (2005). Drawing at 1:24 scale

accretion studies have paid scant attention to settlement of marsh surfaces, assuming instead that accretion raised the level of marshes." For this reason, it became necessary to simultaneously measure both vertical accretion and surface elevation change to quantitatively evaluate the relationship between the two variables, which marks the beginning of the third methodological approach.

Cahoon et al. (1995) combined two methods, the recently developed sedimentation-erosion table (SET, Boumans and Day 1993) with the feldspar marker horizon (MH, Cahoon and Turner 1989), creating the SET-MH method to test quantitatively if vertical accretion is a good analog for elevation change. Combining the two methods makes it possible to discern the separate influence of surface and shallow subsurface processes on elevation calculated as the difference between accretion and elevation (*A* minus *E*, Figs. 1 and 2). Prior to development of the SET-MH method 30 years ago, there was no empirical evidence that shallow subsurface processes occurring in the uppermost 10–25 m of a wetland substrate influenced coastal wetland elevation. There were only measures of deep subsidence from upland surfaces adjacent to a coastal wetland (e.g., from a geodetic benchmark driven typically up to 25 + m deep in upland soil), and measures of surface accretion from within the wetland. But there were no measures of subsurface processes occurring between the wetland surface and wetland soil depths above the 10–25-m depths where deep subsidence of the adjacent upland is measured (Cahoon 2015 and Figs. 2 and 3). When surface sediment accumulation of mineral and organic matter (i.e., surface vertical accretion (*A*)) measured by the marker horizon method is equal to surface elevation change (*E*) measured independently by the SET method, then surface accretionary processes are the primary driver of *E* and an appropriate analog for *E* because subsurface processes had no measurable influence on *E*. In contrast, if *A* is statistically significantly greater or less than *E*, then shallow subsurface processes (e.g., shallow subsidence or expansion, respectively) exert significant influence on *E* in addition to the influence of *A* on *E*. In this case, *A* is not an appropriate analog for *E* as *A* does not incorporate subsurface processes occurring beneath the marker horizon and above the base of the SET benchmark, only those occurring within the surface deposits located above the marker horizon. Lastly, subsidence occurring below the base of the SET benchmark is called deep subsidence (Cahoon et al. 1995) and is not included in the SET measures of elevation (Fig. 1).

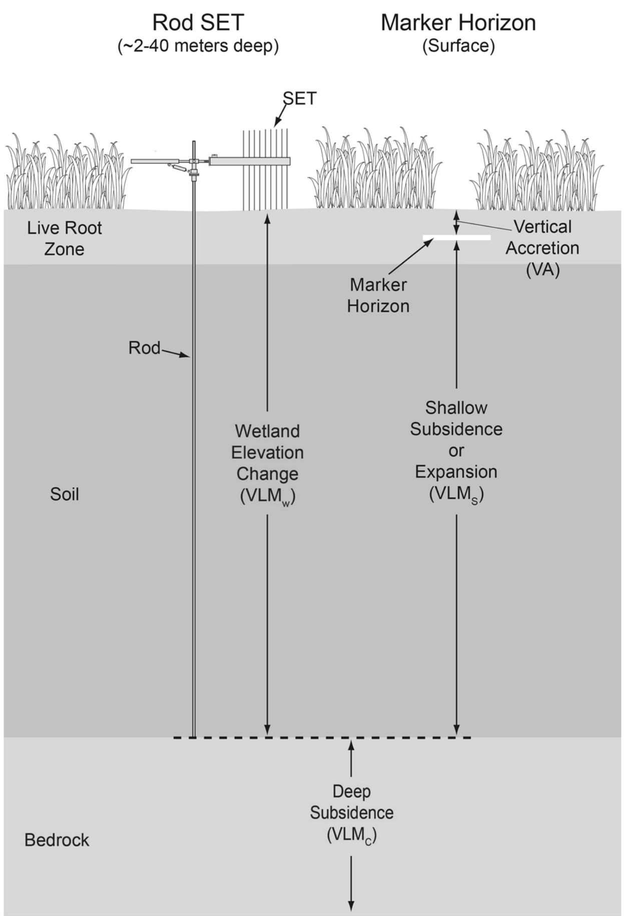


**Fig. 2** Profile diagram of a marsh substrate showing measures of surface elevation change ($VLM_w$), vertical accretion from marker horizons, and calculations of shallow subsidence or expansion ($VLM_s$). Deep process influences ($VLM_c$) occurring below the base of the SET rod mark are not captured by the SET method. Modified from Cahoon (2015)

Cahoon et al. (1995) deployed the SET-MH method in four salt marshes across the southeast USA and found that rates of elevation change were significantly lower ($P < 0.05$) than rates of accretion indicating shallow subsidence occurred at all four marshes. Shallow subsidence was apparently driven by either subsurface processes of compaction or shrink-swell from dilation water storage (e.g., Nuttle et al. 1990), or reductions in root production and/or increases in decomposition. Hence, the assumption that vertical accretion equals elevation change is too simplistic a generalization of the interactions between accretionary and substrate processes. Furthermore, the potential for coastal marsh submergence from sea-level rise should be expressed in terms of an elevation deficit rather than an accretion deficit (Cahoon et al. 1995). Several design changes were made to the sedimentation-erosion table to improve its accuracy, and the device was renamed the surface elevation table to reflect more accurately what it measures (Cahoon et al. 2002a). A detailed explanation of the advances in SET technology over the past 30 years is provided in Table 2.

With the knowledge that subsurface processes occurring within and immediately below the living root zone directly influence elevation change, it became necessary to develop SET devices and vertical structures that can be secured at a range of depths (e.g., bottom of the live root zone, 6–10 m, 10–25 m or more) to quantify subsurface process influences from each of those depths (Table 1 and 2). The unbalanced, heavy long arm of the sedimentation erosion table was unsuitable to attach to a shallow pipe benchmark (< 0.5 m), as it would not remain vertically stable and would lean over in the soft wetland sediments. Furthermore, the pipe benchmarks were limited in depth (i.e., 6–10 m) by the length of pipe that could be transported to and installed in the wetland. To this end, the rod surface elevation table (Cahoon et al. 2002b; Callaway et al. 2013) was created, which is a small, lightweight arm that attaches at its center to a rod benchmark (i.e., the arm is balanced). The rod SET attaches to a portable rod device called an insert collar (Callaway et al. 2013) that is inserted into two types of benchmarks: a deep benchmark established by driving a stainless-steel rod into the sediment and adding 1.2-m rod sections until it cannot be driven further to depths up to 25 m or more (referred to as the deep rod SET) and a multi-legged platform driven to the depth of the root zone, typically ≤ 0.5 m (referred to as the shallow rod SET). The shallow rod SET is a proven stable benchmark.

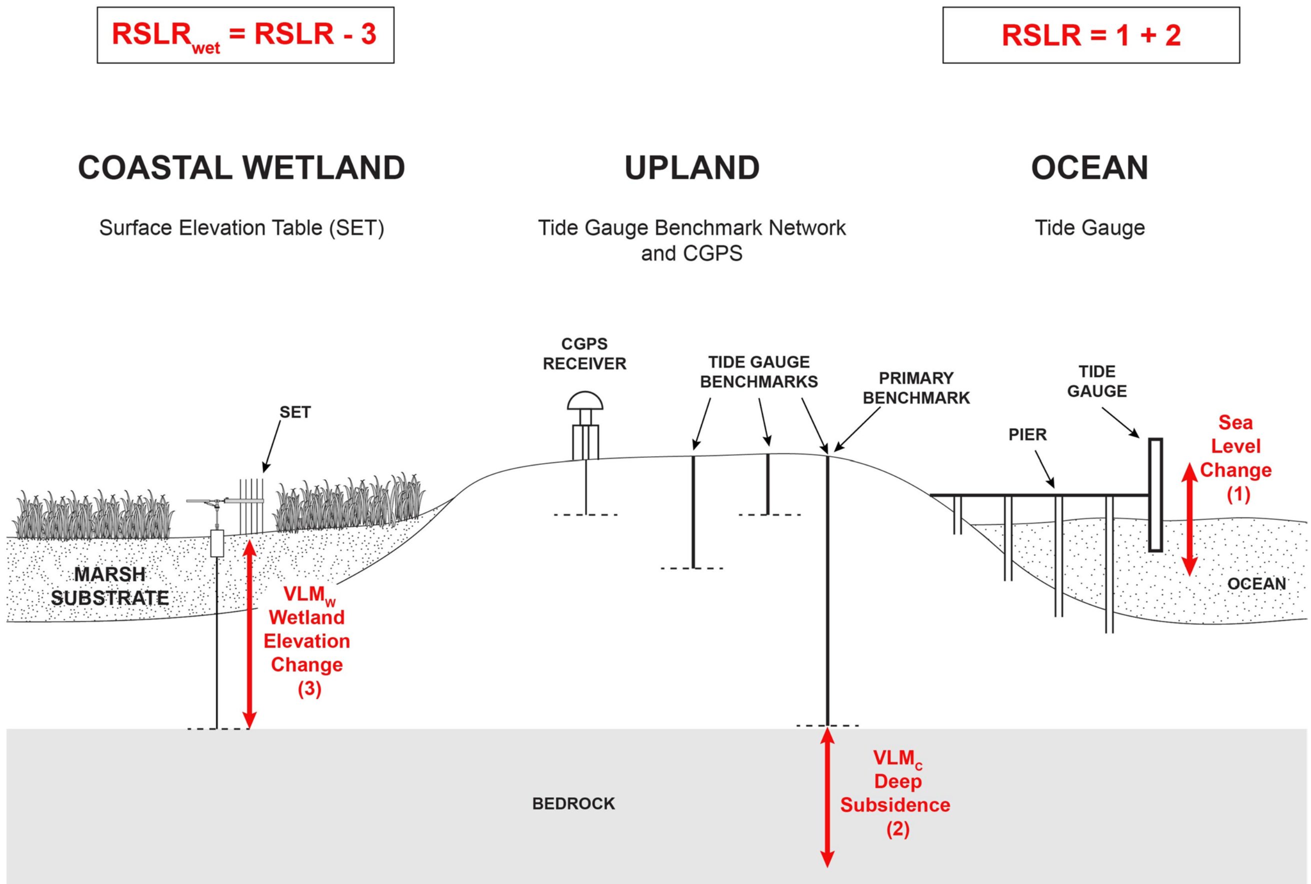


**Fig. 3** Diagram showing the relationship between measures of vertical land motion recorded by the tide gauge benchmark at a coastal upland ($VLM_c$) and the rod SET in a coastal wetland ($VLM_w$). Relative sea-level rise (RSLR) is the combination of sea level change measured by the tide gauge (1) and $VLM_c$ (2). $RSLR_{wet}$ is calculated as RSLR minus $VLM_w$ (3). If $VLM_w$ is positive, then RSLR is reduced by that amount and if it is negative then RSLR is increased by that amount. Modified from Cahoon (2015)

For example, Blum et al. (2021) reported that the height of shallow rod SETs deployed in a Chesapeake Bay salt marsh in Virginia, USA remained stable over a nearly two-decade-long study as revealed by repeated surveys to a local datum. These shallow SETs were embedded in the upland sediments underlying the < 0.5-m-thick marsh substrate as were the shallow SETs deployed in salt marsh and tidal fresh forest wetlands in Chesapeake Bay and South Carolina and Georgia described in Stagg et al. (2016) and Krauss et al. (2023). Simultaneously deploying the original pipe SET, deep rod SET, and shallow rod SET allows for evaluation of processes from a range of subsurface strata (Fig. 1; Table 2). Of these three methods, the deep rod SET is the most widely used to measure wetland elevation dynamics over the past 20 years (Webb et al. 2013), and a few studies during that time combined the deep rod SET with the shallow rod SET to investigate root zone influences on elevation (Whelan et al. 2005, 2009; Cahoon et al. 2011a, b; Stagg et al. 2016; Krauss et al. 2017, 2023; McKee and Vervaeke 2018; Blum et al. 2021; Maher and Starke 2023; Lal et al. 2023).

Additionally, less commonly used applications of the SET-MH method and other innovative technologies have been developed. For example, in an open-water setting with a high sedimentation rate, new marker horizons were laid down repeatedly in combination with the SET to measure the amount of soil compaction occurring between sequential marker horizons (Cahoon et al. 2000a). To accommodate measurements in manipulative experiments where it is impractical to install traditional SET devices, the deep rod SET has been modified to a long arm (up to 4 m in length and 100 pins), combined with a shallow pipe benchmark for root zone measurements (in place of the shallow rod SET, Langley et al. 2009), and a short-arm (i.e., mini-SET) designed to fit onto containers holding vegetation in a greenhouse or field setting (Cherry et al. 2009; Payne et al. 2019; Stagg et al. 2022). To better understand the influence on elevation of changes in local hydrology and groundwater related to soil shrink-swell, the continuous elevation sensor (Cahoon et al. 2011a) was created to provide continuous sub-hourly readings of elevation in conjunction with a water level sensor to measure short-term variations in elevation related to local hydrologic changes. The sedimentation-erosion bar (SEB, van Wijnen and Bakker 2001) and a modified version of the SEB (Lang'at et al. 2014), like the SET, have been combined with the marker horizon method in salt marsh and mangrove wetlands, respectively, to quantify subsurface process influences on elevation in the upper 1 m of the substrate. More recently, the SET has been combined with modern survey methods to expand areal coverage of surface elevation measures (Cain and Hensel 2018; Kargar et al. 2021; Lynch et al. 2023; MacKenzie et al. 2023).

The millimeter precision of SET-MH method measurements enables hypothesis testing of the process influences and related biophysical drivers on elevation change. In addition, long-term monitoring of elevation trends by SETs enables comparisons to millimeter-precision sea level rise trends from tide gauges. Hence, the SET-MH method and related technologies have become the global standard for evaluating subsurface process influences on elevation and for monitoring coastal wetland vulnerability to sea-level rise from direct measures of elevation change (Webb et al. 2013; Cahoon 2015).

## SET-MH Method: Hypothesis-Based Inquiries of the Processes Influencing Wetland Elevation Change

Development and evolution of the SET-MH method (Table 2) led to research that is expanding our understanding of the processes and drivers of wetland elevation change. Only by simultaneously measuring accretion and elevation can both surface and subsurface process influences on elevation be elucidated and quantified. Statistical comparisons of accretion and elevation change trends in early literature reviews (Cahoon et al. 1998; Cahoon et al. 1999; Cahoon 2006; Cahoon et al. 2006) of salt marsh and mangrove wetland sites ($n = 60$) often with $\leq 3$ years of SET-MH data revealed significant differences ($P < 0.05$) indicating subsurface processes were the dominant influence on wetland elevation for 64% of sites (Fig. 4a, total chart). For 50% of all the sites, accretion was significantly greater than elevation ($A > E$) indicating that shallow subsidence occurred. For 7% of all sites, elevation was significantly greater than accretion ($A < E$) indicating shallow expansion of the substrate, and for 7% of all sites, the substrate underwent shrink/swell from groundwater fluctuation. Lastly, for 36% of all

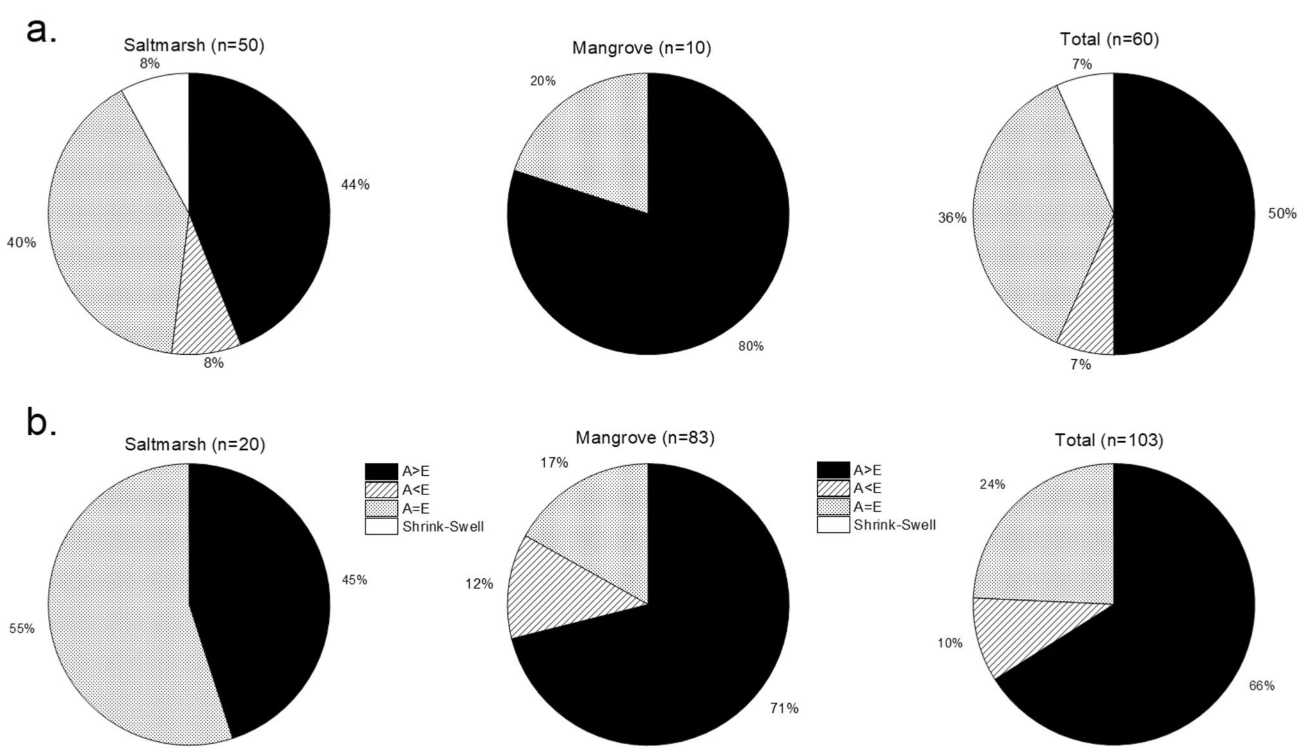


**Fig. 4** Synthesis of comparisons of accretion ($A$) and elevation ($E$) trends in published literature reviews of saltmarsh and mangrove wetlands; potential outcome categories include A > E, A < E, A = E, and A and E uncoupled (i.e., shrink-swell). **a** Percent of wetland sites in each outcome category based on statistical analyses of raw data trends (Cahoon et al. 1998 ($n = 13$); Cahoon et al. 1999 ($n = 27$); Cahoon 2006 ($n = 20$)); **b** percent of wetland sites in each outcome category based on metadata analyses of site means (Lovelock et al. 2015 ($n = 26$); McKee et al. 2021 ($n = 45$); Saintilan et al. 2023a, b ($n = 32$)

sites, accretion and elevation were not significantly different ($A = E$) indicating that surface accretion or erosion processes were the primary driver of elevation change.

Later reviews on a multi-national geographical scale spanning a greater range of salt marsh and mangrove environmental settings with longer data records (> 3 years up to 1–2 decades) revealed a similar pattern of $A$ versus $E$ trends (ranked from highest to lowest frequency of occurrence: $A > E$, $A = E$, $A < E$, shrink-swell) (Lovelock et al. 2015; McKee et al. 2021; Saintilan et al. 2022, 2023a), based on metadata analysis of wetland site means ($n = 103$, Fig. 4b, total chart). Statistical comparison of $A$ and $E$ trends revealed subsurface processes were the dominant influence on wetland elevation for 76% of sites, with $A > E$ indicating shallow subsidence for 66% of sites and with $A < E$ indicating shallow expansion for 10% of sites. For 24% of sites, $A = E$ indicating surface processes were the primary driver of elevation change. These later reviews with longer record lengths revealed the importance of accretion contributing to elevation, but that shallow subsidence increased as accretion rate increased, sometimes nonlinearly, resulting in elevation gain being lower than the accretion rate (Saintilan et al. 2022, 2023a).

The pattern of $A$ versus $E$ trends differed importantly between saltmarsh and mangrove wetlands as revealed by both early and later reviews (Fig. 4a, b). For 80–82% of mangrove wetlands, subsurface processes were the dominant influence on elevation, with $A > E$ occurring in 71–80% of sites, and surface process drivers ($A = E$) accounting for no more than 20%. For saltmarshes, subsurface processes were the dominant influence on elevation for 45–60% of sites, and surface processes ($A = E$) were the primary driver of elevation change for 40–55% of sites. Note, although the review articles cited here do not report shrink-swell in mangrove wetlands, Whelan et al. (2005) reported shrink-swell of mangrove soils in Shark River, Florida, related to river stage-driven groundwater fluctuations.

Numerous hypothesis-based inquiries of subsurface process influence on elevation revealed or implicated multiple subsurface processes and biophysical drivers influencing wetland elevation across a wide range of wetland settings (e.g., deltaic, back-barrier, fringe, riverine, karst) and environmental conditions. Mineral sediment supply, sedimentation rate, and vegetative growth (e.g., stem density and root and rhizome production) play important roles in wetland soil vertical development (Nyman et al. 2006; Baustian et al. 2012; Krauss et al. 2014; Cahoon et al. 2021; Stagg et al. 2022). For example, plants modify mineral sediment deposition and retention, organic matter contributions to soil volume, and resistance to compaction and erosion (Cahoon et al. 2021). The SET-MH method can quantify the relative contribution of these surface and subsurface processes to wetland elevation.

## Subsurface Processes Influencing Wetland Elevation

A detailed summary is presented in Table 3 and Fig. 5 of the subsurface process influences on elevation and the biophysical drivers of each process as determined by the combined, simultaneous measurements of accretion and elevation using primarily the SET-MH method but also the SEB-MH method and the device of Nuttle et al. (1990). The subsurface soil processes at work include compaction ($A > E$), collapse from a combination of ongoing compaction with partial or total reduction of vegetative growth ($A > E$), expansion ($A < E$), and shrink-swell ($A$, $E$ uncoupled). The categories of biophysical drivers include sedimentologic, hydrologic, and biologic events (Fig. 5b,c). Sedimentologic drivers affect compaction through sediment overburden from both daily (e.g., tides) and acute (e.g., storms) sedimentation events. Hydrologic drivers affect (1) soil compaction by water overburden from storm surge and winter ice loading, (2) soil collapse from reduced root production as a result of prolonged flooding or drought, and (3) shrink-swell from dilation water storage (e.g., daily tides, seasonal river stage and rainfall). Biologic drivers of plant growth, density, death, and decomposition affect both soil collapse (e.g., death or reduced plant growth from herbivory) and subsurface expansion (e.g., increased growth and accumulation of belowground biomass). Note that wetland sediments are typically highly compressible and shrink when dried, making them susceptible to compaction and shrink-swell processes (e.g., the salt marsh sediments described in Nuttle et al. 1990). Most subsurface soil process effects reported in the literature are from salt marshes, but an increasing number of reports are being published from mangroves, brackish marsh, tidal fresh marsh, tidal fresh forest, and open water (Table 3).

### Compaction (A > E)

Soil compaction, what Kaye and Barghoorn (1964) called settlement and is also known as autocompaction, is the most commonly occurring subsurface influence on elevation reported in the SET-MH literature (Table 3; Fig. 5a). Compaction negatively affects elevation and constrains elevation gain even when accretion is positive, resulting in shallow subsidence ($A > E$), which is reported in Table 3 for a range of habitats. The primary biophysical force driving compaction-related shallow subsidence is the weight of sediment overburden in conjunction with soil texture and moisture. But the weight of water overburden is also a driver of compaction.

Compaction from sediment overburden results mostly from cumulative daily sedimentation, but acute sediment addition by episodic storm surge and restoration actions

**Table 3** Shallow subsurface soil processes influencing surface elevation change (only published reports with statistically significant outcomes of A>E, A<E, and shrink-swell are referenced), the biological and physical forces influencing each process, and the timescale of effect presented by tidal wetland type as revealed by the Surface Elevation Table – Marker Horizon method with a few additional examples from the Sedimentation-Erosion Bar-Marker Horizon method (van Wijnen and Bakker 2001), the modified Sedimentation-Erosion Bar – Marker Horizon method (Lang'at et al. 2014), and the method of Nuttle et al. (1990)

| Subsurface Soil Process | Biophysical Force | Timescale | Tidal Wetland Type | References |
|---|---|---|---|---|
| Soil compaction (A > E) | Sediment overburden | Cumulative daily sedimentation | Salt marsh | Cahoon et al. 1995, 1998, 1999, 2000a, b, van Wijnen and Bakker 2001, Rybczyk and Cahoon 2002, Rogers et al. 2005a, 2006, 2013, Cahoon 2006, Erwin et al. 2006, Lane et al. 2006, Roman et al. 2007, Baustian et al. 2012, Beckett et al. 2016, Raposa et al. 2016a, b, Wang et al. 2016, Jankowski et al. 2017, McKee and Vervaeke 2018, Fennessy et al. 2019, Kamrath et al. 2019, Payne et al. 2019, Xiong et al. 2019, Howard et al. 2020, Haaf et al. 2022, Feher et al. 2022, Moon et al. 2022, Pitchford et al. 2022, Saintilan et al. 2022, Steinmuller et al. 2022, Maher and Starke 2023, Roman et al. 2023 |
| | | | Mangrove | Cahoon and Lynch 1997, Cahoon et al. 1998, 1999, Rogers et al. 2005a, Cahoon 2006, Lovelock et al. 2011, 2015, Sasmito et al. 2016, Krauss et al. 2017, Fu et al. 2018, McKee and Vervaeke 2018, Swales et al. 2019, Xiong et al. 2019, Howard et al. 2020, McKee et al. 2021, Feher et al. 2022, Lal et al. 2023 |
| | | | Fresh marsh | Baldwin et al. 2009, Cahoon et al. 2011b, Beckett et al. 2016, Raposa et al. 2016b, Haaf et al. 2022 |
| | | | Fresh forest | Cahoon et al. 2011b, Stagg et al. 2016, Krauss et al. 2023 |
| | | | Open water | Cahoon et al. 2000a, Erwin et al. 2006, Cahoon et al. 2011b |
| | | Acute sediment addition: episodic storms & restoration action | Brackish marsh | McKee and Cherry 2009 |
| | | | Salt marsh | Cahoon et al. 1995, 2019, Raposa et al. 2022, Steinmuller et al. 2022 |
| | | Acute sediment addition: storms & elevated CO2 | Fresh forest<br>Brackish marsh<br>Mudflat | Stagg et al. 2022 |
| | Water overburden | Daily tidal inundation | Salt marsh | Nuttle et al. 1990 |
| | | Winter ice loading | Salt marsh | Argow and Fitzgerald 2006 |
| | | Storm surge: episodic | Salt marsh | Cahoon et al. 1995, Cahoon 2003, 2006, Elsey-Quirk 2016 |
| Soil collapse: reduced root/rhizome production; ongoing compaction (A > E) | Herbivory | Cumulative seasonal effect | Brackish marsh | Ford and Grace 1998 |
| | Nutrient enrichment | Cumulative seasonal effect | Oligohaline marsh | Graham and Mendelssohn 2014 |
| | Vegetation death | Chronic stress: prolonged flooding | Salt marsh | Day et al. 2011 |
| | | | Brackish marsh | Cahoon et al. 2004 |
| | | | Mangrove | Krauss et al. 2018, Cormier et al. 2022 |
| | | Acute stress: storm, vegetation removal | Mangrove | Cahoon et al. 2003, Stokes et al. 2009, 2023, Lang'at et al. 2014, Osland et al. 2020 |
| | | Acute Stress: drought | Salt marsh | Baustian et al. 2012 |
| Soil expansion: plant root/rhizome production (A < E) | Soil nutrients: ambient | Cumulative seasonal effect | Salt marsh | Cahoon et al. 2000b, Ibanez et al. 2010, Fennessy et al. 2019, Blum et al. 2021 |
| | | | Mangrove | McKee 2011, Krauss et al. 2017, Lal et al. 2023 |
| | | | Fresh forest | Stagg et al. 2016, Krauss et al. 2023 |
| | Soil nutrients: ambient + prescribed fire | Cumulative seasonal effect | Brackish marsh | Cahoon et al. 2004 |
| | Soil nutrients: ambient + forest thinning | Cumulative seasonal effect | Mangrove | Chen et al. 2021 |
| | Soil nutrients: elevated N, CO2 | Cumulative seasonal effect | Brackish marsh | Langley et al. 2009, Cherry et al. 2009, Zhu et al. 2022 |

**Table 3** (continued)

| Subsurface Soil Process | Biophysical Force | Timescale | Tidal Wetland Type | References |
|---|---|---|---|---|
| | Soil nutrients: elevated N, P | Cumulative seasonal effect | Mangrove | McKee et al. 2007 |
| | | | Salt marsh | Cahoon et al. 2019, Wigand et al. 2014, Morris et al. 2002, Anisfeld and Hill 2012, Davis et al. 2017, Morris and Sundberg 2024 |
| Soil shrink-swell (A, E uncoupled) | Dilation water storage from groundwater fluctuations | Seasonal river stage, rainfall, ENSO | Mangrove | Whelan et al. 2005, Rogers et al. 2005a, b, Rogers and Saintilan 2008, Krauss et al. 2010 |
| | | | Salt marsh | Cahoon et al. 1995 |
| | | Cold front passage: days | Salt marsh | Cahoon et al. 2011b |
| | | Daily tides | Salt marsh | Nuttle et al. 1990 |
| | | Evapotranspiration: daily | Salt marsh | Paquette et al. 2004 |
| | | Storm surge: episodic | Mangrove | Whelan et al. 2009, Elsey-Quirk 2016, Feher et al. 2020, Morris et al. 2020 |

such as thin-layer deposition of sediment can also lead to compaction. The range of biophysical forces driving soil compaction is summarized in Table 3 and Fig. 5b. Furthermore, rates of shallow subsidence related to soil compaction are reported from a variety of salt or brackish marsh settings, including river deltas (Cahoon et al. 1995, 2000a, b; Rybczyk and Cahoon 2002; Lane et al. 2006; Baustian et al. 2012; Wang et al. 2016; Jankowski et al. 2017; McKee and Vervaeke 2018; Fennessy et al. 2019), coastal barrier marshes (Wijnen and Bakker 2001; Erwin et al. 2006; Roman et al. 2007, 2023; Moon et al. 2022; Steinmuller et al. 2022), and estuarine-riverine fringe marshes (Rogers et al. 2005a, b; Rogers et al. 2006; Rogers et al. 2013; Beckett et al. 2016; Raposa et al. 2016a, b; Kamrath et al. 2019; Payne et al. 2019; Xiong et al. 2019; Howard et al. 2020; Haaf et al., 2022; Feher et al. 2022, Steinmuller et al. 2022). Similarly, soil compaction leads to shallow subsidence in mangrove wetlands in estuarine-riverine settings (Cahoon and Lynch 1997; Lovelock et al. 2011; Krauss et al. 2017; Fu et al. 2018; Swales et al. 2019; Xiong et al. 2019; Howard et al. 2020; Feher et al. 2022; Lal et al. 2023), oceanic island settings (dwarf interior forest, McKee et al. 2007), and deltas (McKee and Vervaeke 2018).

Compaction of soft, shallow-water sediments was measured directly by the SET-MH method using repeated application of marker horizons in a crevasse splay of the Mississippi River delta (Cahoon et al. 2000a). The chronosequence of two marker horizons made it possible to measure the compaction rate of newly deposited sediments (21 mm year$^{-1}$ above the new horizon) and of recently deposited sediments above the original horizon but below the new horizon (18 mm year$^{-1}$), what is called shallow compaction. Similarly, in a separate crevasse study, Cahoon et al. (2011a) reported rates of shallow subsidence of shallow-water delta sediments of 20–50 mm year$^{-1}$, although the rates were not significant ($P > 0.05$) due to high variances in the highly dynamic setting. An investigation of elevation dynamics in both vegetated salt marsh and associated open water ponds

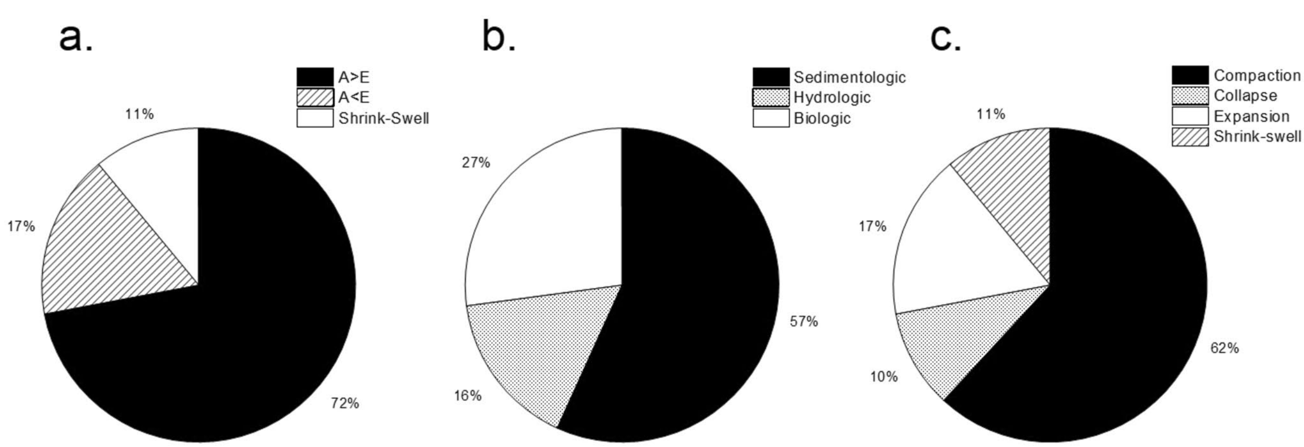


**Fig. 5** Percent of published reports from Table 3 (total $n = 122$) describing subsurface process influences and their drivers on wetland elevation, organized by: **A** subsurface soil processes ($A > E$ $n = 88$, $A < E$ $n = 21$, shrink-swell $n = 13$), **B** biophysical driver categories (sedimentologic ($n = 70$), hydrologic ($n = 19$), and biologic ($n = 33$)), and **C** biophysical drivers for each subsurface soil process (compaction, $n = 76$; collapse $n = 12$, expansion $n = 21$, shrink-swell $n = 13$)

by Erwin et al. (2006) revealed shallow subsidence of pond bottom sediments in barrier marshes on the US Atlantic coast. Similar rates of shallow subsidence occurred in mangrove forests located along a gradient in accommodation space (medium to high) in Comerong Island in southeast Australia (Lal et al. 2023).

Compaction-related shallow subsidence has been reported for tidal fresh marshes and tidal fresh forested wetlands. Rates of shallow subsidence of 13 mm year$^{-1}$ and 17 mm year$^{-1}$ were reported for two restored freshwater marshes in the Anacostia River, Washington, DC, USA (Baldwin et al. 2009). Shallow subsidence was also reported from tidal fresh marsh in the Nanticoke River in the Chesapeake Bay (Beckett et al. 2016). In the crevasse study described above, Cahoon et al. (2011a) reported shallow subsidence (15.7 mm/y) in a *Sagittaria*-dominated fresh marsh and in the black willow (*Salix nigra*) forest at the head of the splay lobe (5.7 mm year$^{-1}$). In an analysis of elevation dynamics in National Estuarine Research Reserve (NERR) sites, Raposa et al. (2016b) reported shallow subsidence in tidal fresh marsh in the Chesapeake Bay. Similarly, in a tidal fresh marsh at Crosswicks Marsh in Delaware Bay, Haaf et al. (2022) reported shallow subsidence of 7 mm year$^{-1}$. In Apalachicola NERR, shallow subsidence occurred in both sawgrass (*Cladium jamaicense*) and swamp cypress (*Taxodium distichum*) freshwater, riverine wetlands (Steinmuller et al. (2022)). Studies by Stagg et al. (2016) and Krauss et al. (2023) along a salinity gradient of tidal fresh forests and brackish marsh in rivers of South Carolina, Georgia, and in the Chesapeake Bay using both shallow and deep RSETs revealed shallow subsidence across the salinity gradient within the root zone. Furthermore, there was shallow subsidence between the root zone and base of the deep rod SET for tidal fresh forests in the middle reach of the river.

Acute sediment addition from either a storm deposit or thin-layer placement of dredged material for restoration of marsh elevations can result in shallow subsidence. In a *Spartina alterniflora* marsh with low soil shear strength in Louisiana, Hurricane Andrew deposited a 3-cm-thick layer of sediment. But a 5-cm loss of elevation occurred from the storm impact caused by either the weight of the sediment deposit or the ~ 3-m deep flood waters on the marsh surface, or both, and the elevation loss persisted for the next 2 years (Cahoon et al. 1995). The thin-layer placement of 48 cm of sediment to restore elevation in a degraded salt marsh in Jamaica Bay, New York, resulted in an initially high rate of shallow subsidence (21 mm year$^{-1}$) for the first 1.5 years (Cahoon et al. 2019). Following this period of consolidation, the rate of elevation change remained static (1.1 mm year$^{-1}$) for the next 5 years, and shallow subsidence persisted as accretion remained ~ 4 mm year$^{-1}$. Then, the rate of elevation change increased to match the accretion rate as the marsh continued to recover over the next 5 years. Across the geomorphic wetland settings of Apalachicola NERR, acute storm deposits from Hurricane Michael initially increased surface elevation rates in these subsiding marshes to the level of the accretion rates (Steinmuller et al. 2022). But the initial increase in elevation trends was temporary for the bayside wetlands, as the initial increase in elevation trends was followed by elevation losses, apparently the result of the sediment overburden or decomposition of the organic sediment deposits, or both.

In a greenhouse mesocosm experiment using a mini-SET device, Stagg et al. (2022) investigated the interactive effects of acute sediment deposition under future elevated atmospheric $CO_2$ concentrations on elevation change along a plant community gradient of mudflat to herbaceous marsh to tidal fresh forest wetlands. Notably, elevated $CO_2$ had no effect on belowground biomass production or surface elevation change, in contrast to the positive effect of elevated $CO_2$ on elevation reported in the section “Expansion” (see Table 3 for references). Acute sediment deposition also had no effect on belowground biomass production. But post-deposition elevation change rates were diminished compared to control treatments, although elevation change remained positive. The lack of change in belowground production suggests that the diminished elevation gain was related to compaction from sediment overburden ($A > E$), although there was no measure of surface accretion in the treatment or control plots to confirm this.

Lastly, in an innovative experimental approach using laser leveling and settling disks on the marsh surface, not the SET-MH method, Graham and Mendelssohn (2013) applied sediment additions of varying thickness to determine if wetland elevation, compression of the underlying soil, and consolidation of the new sediment layer are differentially affected by sediment thickness. Sediment addition initially increased surface elevation in all treatments. But after ~ 2.5 years, elevation had subsided to pre-treatment levels driven by compression of the underlying soil, whereas consolidation of the added soil had little negative effect on elevation. The numerous examples in the previous paragraphs demonstrate that acute sediment deposition by storms often does not result in a positive gain in wetland elevation.

Compaction driven by water overburden results from daily tidal inundation, seasonal winter ice loading, and episodic storm surge. Nuttle et al. (1990) measured compression of the marsh surface when it was inundated by daily tides. When the tide receded, the compressed surface rebounded. In an experiment simulating ice loading on the highly organic soils of a *Spartina patens* marsh in Maine, USA, SET readings revealed that ice thicknesses > 10 cm can depress the marsh surface by 2 mm for each 1 cm of total ice thickness (Argow and Fitzgerald 2006). Yet, the compaction was not permanent as elevation rebounded to near control levels within 2 weeks of removal of the simulated ice. In a *Juncus roemerianus* back barrier marsh with a highly organic substrate at Cedar Island, North Carolina, storm surge from Hurricane Emily in 1993 resulted in a significant loss of elevation (i.e., compaction) that persisted for > 1 year after the storm (Cahoon et al. 1995). Subsequent hurricane storm surges to strike this marsh in 1994 and 1995 caused a similar loss of elevation by compaction of the organic substrate (Cahoon 2003). However, the elevation of the compacted organic soils eventually returned to pre-surge levels 2 years after the storms. Storm surge from Hurricane Sandy compressed a salt marsh substrate that rebounded to pre-surge levels 5 months later (Elsey-Quirk 2016).

In the aftermath of Hurricane Katrina, McKee and Cherry (2009) reported the storm's impact on accretion, root zone elevation change, sub root zone elevation change, and total elevation change for two subsiding brackish marshes in Louisiana. The storm deposited 3 to 8 cm of sediment, yet soil elevation declined immediately following the storm due to ongoing subsidence in the newly deposited sediments, the root zone (i.e., root zone collapse) and sub root zone for one of the marshes. Two years after the storm, however, net elevation gain was positive for both marshes, despite ongoing root zone collapse, following recovery of the vegetation.

### Collapse (A > E)

Shallow subsidence related to simultaneous compaction and reduction in root and rhizome production occurs through the cumulative seasonal effect of herbivory and soil nutrient enrichment (Table 3). For example, grazing in a brackish marsh in Louisiana by large mammals (e.g., nutria and wild boar) reduced above-ground biomass and below-ground production, elevation, and root zone expansion (Ford and Grace 1998). Hence, herbivory can have a negative impact on marsh soil building processes, primarily by reducing both belowground production and expansion of the root zone. In a 13-year soil nutrient enrichment field study in an oligohaline marsh in Louisiana, the highest level of enrichment resulted in increased surface accretion driven by increased organic matter accumulation at the surface compared to the control treatments (Graham and Mendelssohn 2014). But despite the increase in accretion, elevation was not enhanced compared to control plots (where $A = E$) due to reduced root standing crop, resulting in significant shallow subsidence ($A > E$). The authors conclude that the shallow subsidence was driven by a loss of soil volume from reduced root biomass.

Total reduction in plant production (i.e., vegetation death) combined with compaction leads to sudden soil elevation loss (i.e., peat collapse, sensu Chambers et al. 2019) from chronic stress related to prolonged flooding and acute stress from episodic storm surge, vegetation removal, and severe drought (Table 3). Chronic stress from prolonged flooding leading to plant death and soil collapse has been reported from a brackish marsh in Texas (Cahoon et al. 2004), a salt marsh in Louisiana (Day et al. 2011), and a hydrologically restricted mangrove forest on Marco Island in Florida (Cormier et al. 2022). Krauss et al. (2018) investigated the mechanisms driving soil collapse in the Marco Island mangrove forest that is undergoing prolonged, gradual tree mortality by evaluating soil structural changes using traditional coring methods. The chronic stress did not lead to immediate mortality, but as trees became more stressed, live root turnover contributed less to soil volume replacement leading to compaction, as expressed by increasing soil bulk densities down core, and resulting in 6–8 cm of peat collapse under the active root zone. Krauss et al. (2018) surmise that the ongoing loss of surface elevation eventually can lead to rapid mortality many years after stress initiation in the absence of any efforts to restore natural hydrology.

The acute stress of mass mortality of mangrove trees caused by Hurricane Mitch on the Bay Islands of Honduras resulted in an elevation loss of 11 mm year$^{-1}$ because of peat collapse due to decomposition of dead root material and sediment compaction (Cahoon et al. 2003). The removal of mangrove forest in Tauranga Harbor, New Zealand (Stokes et al. 2009), resulted in a similar rate of peat collapse (14 mm year$^{-1}$). A decade later, this collapse continued at some sites, but other sites gained elevation, indicating a nonlinear surface elevation response across the estuary (Stokes et al. 2023). The impact of mangrove tree thinning was investigated in a mangrove forest in Kenya (Lang'at et al. 2014). Tree thinning induced rapid subsidence or peat collapse (32 mm year$^{-1}$) compared to 4 mm year$^{-1}$ elevation gain in control forests. The soil collapse was attributed to decomposition of dying roots and sediment compaction. Mangrove mortality in the Everglades of Florida in 1935 caused by the powerful Labor Day Hurricane led to peat collapse resulting in an elevation loss of 75 cm and the conversion of mangrove to intertidal mudflat (Osland et al. 2020).

Vegetation death from acute drought effects in a Louisiana salt marsh led to soil elevation collapse of −9.4 mm year$^{-1}$ compared to a nearby healthy marsh where elevation change was positive at 3.5 mm year$^{-1}$ (Baustian et al. 2012). Planting of vegetation in the dieback area resulted in a positive elevation trajectory (13.3 mm year$^{-1}$) through increased belowground root and rhizome production and accumulation. Yet, accretion was more than double the rate of elevation change in the dieback, restored, and healthy reference marshes resulting in significant shallow subsidence in all marsh settings.

**Expansion (A < E)**

Soil expansion through plant root and rhizome production driven by ambient and eutrophic nutrient levels, prescribed fire, and silviculture practices of forest thinning occurs through cumulative seasonal effects in tidal marsh, mangrove, and tidal freshwater forest (Table 3). Most wetlands exhibiting shallow expansion of the soil have low mineral sediment inputs. The influence of root-rhizome production on shallow expansion is inferred in some wetlands but correlated with measured increases in root-rhizome production in other wetlands.

In three back-barrier salt marshes on the North Norfolk coast of England, elevation gain was significantly greater than accretion in these minerogenic settings, suggesting shallow expansion of the substrate through organic matter accumulation (Cahoon et al. 2000b). In a deltaic salt marsh with no hydrologic connection to the Ebro River in Spain, elevation gain was greater than accretion suggesting that shallow expansion occurred from organic accumulation (Ibanez et al. 2010). In a separate study in the Ebro delta, Fennessy et al. (2019) reported significant rates of shallow expansion in marshes located near the mouth of the river and in natural and human impoundments where the marshes were isolated from the river. Root zone expansion accounted for 37% of the increase in marsh elevation over two decades in a salt marsh on the coast of Virginia, USA (Blum et al. 2021).

In seven biogenic mangrove systems in carbonate settings in Belize and southwest Florida, USA, where mineral sediment input is very limited and soil development occurs primarily through accumulation of organic matter from plant roots and stem and leaf litter fall, elevation change was positively correlated with fine and coarse root accumulation while accretion of mineral matter accounted for < 3% of total vertical change (McKee 2011). Three of the seven mangrove forests exhibited significant shallow expansion (mean = 3.3 mm year$^{-1}$). The highest gain in elevation occurred at the restored site in Florida. In a study of nine created mangrove wetlands and their associated reference wetlands in Tampa Bay, Florida, USA, analysis of shallow SET (0.5 m depth) and deep rod SET (8.7 m depth) measurements revealed that the majority of surface elevation change was constrained within the top 50 cm of soil (i.e., the root zone, Krauss et al. 2017). Vertical accretion did not significantly influence elevation change in the created mangroves but did in the reference mangroves. As the created sites aged, surface elevation gains were driven by the greater capacity of subsurface expansion than vertical accretion. In mangrove forests on Comerong Island in southeast Australia, Lal et al. (2023) report elevation gain from expansion of the substrate occurring between the base of shallow rod SETs (0.35 m depth) and the base of deep rod SET (6–18 m depth). They hypothesized that root growth occurring beneath the 0.35 m depth drove the substrate expansion.

In the study reported above by Stagg et al. (2016), one of the eight tidal fresh forest sites exhibited positive subsurface influence on elevation by root zone expansion. The remaining seven sites exhibited significant shallow subsidence. Thus, subsurface processes in the root zone are the primary driver of elevation change in these tidal fresh forests.

A prescribed fire experiment was conducted in an irregularly flooded microtidal brackish marsh on the Texas coast immediately after two successive storm surges continually flooded the marsh surface for 2 months at the peak of the growing season, killing the *Spartina patens* vegetation (Cahoon et al. 2004). The SET-MH data revealed that during the subsequent spring, elevation collapsed at 36.9 mm year$^{-1}$ in the control marsh and 67.9 mm year$^{-1}$ in the burned marsh. However, recovery of elevation during the subsequent growing season was driven by significant increases in root volume and resulted in elevation exceeding accretion ($A < E$) in both the control (0.4 < 4.0 mm year$^{-1}$) and burned (1.1 < 7.3 mm year$^{-1}$) marshes (Cahoon et al. 2004). Tree-thinning in a *Sonneratia apetala* plantation in Shenzen Bay, China, allowed expanded colonization of the understory by the mangrove *Acanthus ilicifolius*, which formed small elevation mounds that significantly increased surface elevation gains from 25.1 to 45.6 mm year$^{-1}$ and significantly reduced shallow subsidence (Chen et al. 2021). Although technically not an explicit example of shallow expansion where $A < E$, this finding indicates the importance of subsurface process controls on elevation by reducing compaction-related shallow subsidence, presumably by increases in soil organic matter accumulation.

Elevated atmospheric $CO_2$ concentration has been shown to significantly increase soil elevation in a mix of brackish marsh species (the $C_3$ species *Schoenoplectus americanus* and the $C_4$ species *Spartina patens* and *Distichlis spicata*) by stimulation of subsurface productivity, in particular fine root productivity and shoot-base expansion, in both field (Langley et al. 2009) and greenhouse (Cherry et al. 2009) experimental manipulations. Elevation gain was positively correlated with subsurface volume change of the $C_3$ species but not the $C_4$ species (Cherry et al. 2009). Elevated nitrogen concentrations (N) had no effect on elevation or interactive effect with $CO_2$ (Langley et al. 2009). However, the stimulatory effect of elevated $CO_2$ on plant production, and subsequently on elevation gain, is constrained by increases in relative sea-level rise (RSLR). Analysis of a 33-year data record of elevated atmospheric $CO_2$ effects from the marsh described in Langley et al. (2009), revealed that the stimulatory effect declined after two decades when RSLR reached a threshold that hindered root productivity (Zhu et al. 2022). Thus, benefits of $CO_2$ stimulation of elevation gain will diminish in the long term as RSLR accelerates.

In remote oceanic islands of Belize, mangrove soil vertical development occurs entirely through accumulation of mangrove peat due to the absence of mineral sediment input (Cameron and Palmer 1995). To evaluate the biological influences on peat formation and elevation, and hence mangrove sustainability, McKee et al. (2007) added nitrogen (N) and phosphorus (P) to the soils along a gradient from mangrove fringe, to transition, to dwarf interior forests. In control plots, the fringe forest exhibited shallow expansion, and the transition and interior forests exhibited shallow subsidence. The fertilizer treatments caused significant changes in the rate and direction of elevation change. Addition of N resulted in a switch to shallow subsidence in the fringe forest and greater shallow subsidence in the other two forests. The addition of P resulted in greater shallow subsidence in the fringe forest but a switch to shallow expansion in the other two forests.

In the highly impacted urban estuary of Jamaica Bay in New York City, with nutrient-enriched waters (N and P) and historically high rates of island marsh deterioration and loss, subsurface process influences on elevation varied significantly (Cahoon et al. 2019). Two marshes on JoCo Island perched high in the tidal range had high rates of vegetation integrity and shallow expansion. Analysis of soil structure by Wigand et al. (2014) suggests these marshes had enhanced belowground productivity compared to lower elevation marshes in the Bay. Black Bank marsh with moderate elevation capital, lower belowground biomass, lower abundance of roots and rhizomes, and less soil percent organic matter and shear strength was deteriorating but maintaining elevation by production of larger diameter rhizomes and presumed dilation water storage (i.e., soil volume change resulting from a change in soil moisture content) (Wigand et al. 2014). Marshes on Big Egg Island with low elevation capital and soils with low shear strength were experiencing shallow subsidence and rapidly deteriorating.

Other investigations of N and P fertilization effects on soil elevation dynamics have revealed different process influences on elevation other than shallow expansion. Morris et al. (2002) measured significantly higher rates of elevation gain in fertilized plots than control plots in a South Carolina, USA, salt marsh. The elevation gain was attributed initially to increased sediment trapping caused by increased aboveground productivity, based on a 3-month record of marker horizon data. Sediment macro-organic matter was historically lower in fertilized plots than control plots and the increased elevation trajectory persisted after fertilizer application ceased. More than 20 years later (Morris and Sundberg 2024), decadal SET and vegetation biomass records reveal elevation change in fertilized plots is related to increased belowground biomass and turnover with fertilized plots gaining 4.7 mm year$^{-1}$ compared to 1 mm year$^{-1}$ in control plots. In a Long Island, USA, salt marsh, Anisfeld et al. (2012) reported that fertilization had no significant effect on belowground production despite increased gross carbon loss from the sediment, but elevation gain significantly increased from accretion processes. In a North Carolina, USA, salt marsh, Davis et al. (2017) showed that fertilization resulted in increased aboveground biomass and surface elevation change, but only during the period of fertilizer application, not afterwards. However, they measured only elevation using SETs without accompanying marker horizons, so it was not possible to separate surface accretion influences from subsurface compaction or expansion processes.

### Shrink-Swell (A, E decoupled)

Soil shrink-swell is driven by dilation water storage from groundwater fluctuations (see Nuttle et al. 1990) through daily tides, daily evapotranspiration, cold front passages over several days that influence groundwater levels, seasonal river stage and rainfall amounts, and episodic storm surge (Table 3). Investigating the potential for diurnal variation in elevation related to tidal flooding, Nuttle et al. (1990) reported shrink-swell of salt marsh sediments of 2.7 to 24 mm over a tidal cycle. Paquette et al. (2004) reported that daily evapotranspiration drove changes in water storage that significantly affected elevation change over periods as short as 5 days. Using the continuous elevation sensor in a Louisiana marsh during a drought and cold front passage, Cahoon et al. (2011a) reported that elevation was controlled by subsurface hydrologic fluxes occurring below the root zone but above the base of the SET pipe (4 m). Over longer monthly or seasonal timescales, the range in variation in dilation water storage (up to tens of cm) can mask the influence of both surface accretionary and other subsurface processes (on the scale of mm year$^{-1}$), essentially decoupling *A* from *E*. Changes in dilation water storage related to seasonal patterns in river levels and rainfall have been shown to influence elevation in both mangrove (Whelan et al. 2005; Rogers et al. 2005a, b; Rogers and Saintilan 2008; Krauss et al. 2010) and salt marsh (Cahoon et al. 1995) wetlands. In mangrove forest, Whelan et al. (2009) and Feher et al. (2020) report the expansion and contraction of soils by storm surge–driven fluctuations in groundwater level. Similarly, Elsey-Quirk (2016) reported a temporary shallow expansion in a salt marsh flooded by Hurricane Sandy storm surge that subsided to pre-surge levels within 6 months. Notably, the effect of groundwater recharge on soil elevation is often transitory (i.e., seasonal or episodic) and does not typically affect long-term trajectory, but the timescale of sampling must be considered when collecting and interpreting elevation data trends (Cahoon and Hensel 2006).

## SET-MH Method: Monitoring Wetland Elevation and Response to RSLR

In addition to hypothesis-based inquiries of subsurface influences on elevation, SET elevation data are used globally to generate elevation trends for comparison to local sea-level rise rates from tide gauges (Webb et al. 2013). Many SET-MH data sets now encompass multiple decades and are proving important in understanding long-term trends and elevation dynamics in response to RSLR including the role of accommodation space (Lal et al. 2023), landward transgression upslope (e.g., Tornquist et al. 2021), storms (e.g., Cahoon 2006), and restoration-management efforts (e.g., Cahoon et al. 2019; Lu et al. 2018), among other factors.

On a multi-national scale, analysis of SET-MH data collected from multiple studies has been used to assess vulnerability to sea-level rise of mangrove forests in the Indo-Pacific region (Lovelock et al. 2015) and globally (Cahoon and Hensel 2006; Sasmito et al. 2016; McKee et al. 2021; Saintilan et al. 2023a), and of tidal marshes from multiple regions of the globe (Saintilan et al. 2022). Sediment availability is important for mangrove forests to maintain surface elevation gain to match or exceed sea-level rise. But the vast majority of the 27 mangrove sites in the Indo-Pacific region are undergoing significant shallow subsidence, and 69% of the elevation records had rates of elevation gain less than the long-term sea-level rise rate (Lovelock et al. 2015). Similarly, meta-analysis by Cahoon and Hensel (2006) and McKee et al. (2021) demonstrated the importance of calculating an elevation deficit rather than an accretion deficit to ascertain response of mangrove sites to local sea-level rise because of high rates of shallow subsidence. In tidal marshes (Saintilan et al. 2022) and mangrove forests (Saintilan et al. 2023a), contemporary rates of vertical accretion increase with sea-level rise, but shallow subsidence increases nonlinearly with accretion. Hence, marsh and mangrove elevation gain is constrained in relation to sea-level rise, and elevation deficits emerge consistent with Holocene observations of tidal marsh vulnerability.

On a national scale in Australia, scientists from six different universities combined their individual, regional SET networks to establish a national network in both salt marsh and mangrove wetlands (Saintilan et al. 2023b). Analyses of this national-scale dataset reveal that mangroves have higher rates of accretion and elevation gain than tidal marshes, attributable to their lower position within the tidal frame. Furthermore, shallow subsidence increased with the rate of accretion, with 87% of the variation in shallow subsidence explained by accretion rate in tidal marshes. On a regional scale, surface elevation, accretion, and mangrove tree growth were analyzed in mangrove and salt marsh wetlands in Moreton Bay, Queensland, Australia, over a 15-year period that spanned variations in an *El Nino/La Nina* (ENSO) cycle (Bennion et al. 2024). In high rainfall/high sea level years in mangrove wetlands, accretion and tree growth were positively influenced, but elevation was not, inferring high rates of shallow subsidence occurred. In contrast, high rainfall/high sea level positively influenced both accretion and elevation in saltmarshes.

In the USA, Federal government agencies responsible for managing and protecting coastal wetland resources use the SET-MH method to monitor wetland elevation trends and assess wetland vulnerability to sea-level rise. The National Oceanic and Atmospheric Administration (NOAA) has added SET-MH measurements to the suite of monitoring variables at their National Estuarine Research Reserve (NERR) (e.g., Raposa et al. 2016b; Pitchford et al. 2022) and Sentinel Site Cooperative network sites. The US Fish and Wildlife Service (FWS) deployed the SET-MH method on their coastal National Wildlife Refuges (NWR) to evaluate wetland vulnerability to RSLR (Moon et al. 2022). Furthermore, they created the Coastal Wetland Elevation Monitoring Program in 2012 to monitor elevation and accretion in marsh and forested wetland habitats at NWRs in the Southeast US from North Carolina to Florida (Moorman et al. 2023). The US National Park Service, Inventory, and Monitoring program uses the SET-MH technique at five regional networks on the US east coast and Caribbean territories: Northeast Temperate, Northeast Coastal and Barrier, National Capitol Region, Southeast Coast, and South Florida and Caribbean (Lynch et al. 2015).

Numerous states and organizations on the Atlantic, Gulf of Mexico, and Pacific coasts of the USA have made SET-MH measurements a regular part of their coastal monitoring programs. In the wetlands of the Mississippi River delta, Louisiana created the Coast-wide Reference Monitoring System (CRMS), which is a network of > 300 permanent monitoring sites across the wetlands of the coastal zone (Steyer et al. 2003). Each site contains a SET-MH station (the most intensive network of SET-MH stations in the world), along with tide gauge, vegetation plots, and numerous other environmental variables being measured. Recently, there was an effort to identify gaps in the distribution of SET stations for the US Gulf of Mexico coast to develop a more coordinated sampling effort on a multi-state scale (Osland et al. 2017). To better understand landscape variability in rates of mangrove and marsh elevation change, Feher et al. (2022) conducted a synthesis of SET-MH data from the Greater Everglades region of south Florida, USA. Both elevation and accretion rates varied widely among the 51 sites. Elevation change, but not accretion, was related to subsurface change. But there was no significant relationship between elevation change and wetland elevation (NAVD 88) or rate of sea-level rise. Surface elevation dynamics are confounded by a mix of biophysical processes including hurricanes, plant productivity, hydrologic exchange, and proximity to sediment and nutrient inputs. Similarly, rates of elevation and accretion varied widely among 21 sites in the SET-MH network established in coastal marshes of South Carolina in 1998 (Doar and Luciano 2023). In a network of nine marshes on Long Island, New York, USA, Maher and Starke (2023) measured the contributions of surface, root zone, and deeper processes on elevation change using deep and shallow rod SETs and marker horizons. All marshes had significant positive elevation trends, but eight of the nine marshes exhibited significant shallow subsidence ($A > E$), and the remaining marsh exhibited significant shallow expansion ($A < E$). Root zone contributions to elevation were not significant at the eight marshes, and deeper processes in four of the nine marshes contributed to elevation loss. Maher and Starke (2023) concluded the eight marshes did not keep pace with local sea-level rise because of a suboptimal contribution to surface elevation from the root zone. In California, USA, Thorne et al. (2023) used a statewide network of 54 rod SET-MH stations to track accretion and elevation change across 16 marshes and assess wetland responses to RSLR along climate and geomorphic gradients. Accretion and elevation trends were positive across years, and the key predictor of rates was marsh elevation relative to a tidal datum (i.e., higher rates at lower tidal datums). Cluster analysis revealed three groupings of wetland sites: Northern California, Central California—San Francisco Bay area, and Southern California. Elevation, accretion, and shallow subsidence were not significantly different among the three clusters. Marshes in the Central and Southern clusters were keeping pace or outpacing sea-level rise, while marshes in the Northern cluster were not.

To understand landscape-scale, horizontal vegetation shifts it is necessary to understand the rate of wetland elevation change relative to sea-level rise because a wetland must build vertically in order to migrate upslope in response to sea-level rise. Notably, landward wetland migration can occur so long as elevation change is positive, even if the wetland is not keeping pace with sea-level rise, if the wetland elevation is located high in the tidal range (i.e., has high elevation capital sensu Cahoon et al. 2019, or low accommodation space sensu Lal et al. 2023). As elevation capital becomes depleted, or accommodation space increases, due to the ongoing elevation deficit, the wetland vegetation becomes increasingly stressed while it is migrating upslope. Indeed, Stagg et al. (2024) report elevation gains for seven out of 10 submerging wetlands in the Mississippi River Deltaic Plain (MRDP) undergoing significant land loss, and an acceleration in elevation gain preceded the conversion of vegetated marsh to open water for the wetlands undergoing the highest rates of land loss. They conclude that accelerated elevation gain is an indicator of erosion in the MRDP. So, timescale is an important consideration in assessing wetland vulnerability to sea-level rise on both a vertical and horizontal landscape scale (e.g., retreat of the seaward edge of the wetland through interior marsh erosion and pond formation, and transgression upslope of the landward wetland edge; see Fig. 1 in Tornquist et al. 2021, Lal et al. 2023).

Variations in patterns of landscape-scale vegetation shifts during sea-level rise, such as mangrove encroaching landward into adjacent salt marsh, can be related to differing rates of elevation change in the mangrove and salt marsh. Elevation loss in the salt marsh from high rates of shallow subsidence coupled with elevation gains in the mangrove determines the rate of conversion of salt marsh to mangrove in the south and east coasts of Australia (Rogers et al. 2006). For example, in Westernport Bay in south Australia, there was a significant relationship between the rate of mangrove encroachment and salt marsh elevation change (Rogers et al. 2005a). In Kooragang Island on the east coast of Australia, rates of elevation change in the mangrove exceeded the long-term water level trend, but the elevation trend in the salt marsh did not, thus mangrove encroached into the salt marsh (Rogers et al. 2013). Similarly, in south Florida, USA, high rates of shallow subsidence led to significant loss of elevation in the adjacent salt marsh, while there was no loss of elevation in the mangrove forest (Howard et al. 2020), resulting in mangrove encroachment. Morris et al. (2023) revealed through the Coastal Wetland Equilibrium Model (CWEM) that mangroves growing at the northern limit of their range can migrate into salt marsh habitats because they build soil elevation four times faster than salt marsh at the same site through greater production of live and labile belowground biomass. This also means that if mangrove trees die from storm effects or severe freezing temperatures, they can rapidly lose elevation through decomposing necromass (e.g., Cahoon et al. 2003). In an exception to the CWEM model outcome, a field study of shrub mangrove encroachment into salt marsh in a Louisiana wetland experiencing an elevation deficit (i.e., sea-level rising faster than wetland elevation) revealed that salt marsh and mangrove assemblages accreted sediment and built vertically at equivalent rates (McKee and Vervaeke 2018). In all these examples, the salt marsh appears vulnerable to either submergence or conversion to mangrove forest.

Yeates et al. (2020) analyzed SET-MH data from wetlands impacted by Hurricane Sandy to determine if a major storm can alter surface elevation trajectories of a wetland. They analyzed data from a broadly disseminated collection of existing SET-MH stations to evaluate the short-term impacts of Hurricane Sandy on wetland elevation dynamics across a region spanning the track of the storm from the mid-Atlantic coast of the USA to the coast of maritime Canada. Storm impacts varied by location of the wetland relative to the storm track. Wetlands located to the right of the storm track experienced greater storm surge and higher wind speeds and were more likely to experience negative deviations in elevation. Wetlands located to the left of the storm track generally experienced gains in elevation due to sediment deposition. Storm impacts also varied by wetland setting, indicating that individual storm characteristics and local wetland setting influenced the storm's impact on elevation, and that elevation response can vary widely across a region impacted by the same storm. In another study, vertical accretion rates from salt marshes in four US national parks impacted by Hurricane Sandy did not differ before or after the storm (Morris et al. 2020). However, there was an episodic gain in elevation at three of the parks following the storm, suggesting a subsurface influence on elevation.

Response to relative sea-level rise was investigated at two Connecticut salt marshes on eastern Long Island Sound (Barn Island and Mamacoke) using either the surface elevation table (SET) method or elevation pin method, without accompanying accretion measurements from marker horizons (Carey et al. 2017). Multi-decadal elevation trends were compared to sea-level rise trends. Barn Island marsh currently is not keeping pace with sea-level rise, but Mamacoke marsh is keeping pace. Long-term vegetation data from both sites reveal that the vegetation community at Barn Island is shifting towards plant species typically found at lower elevations, while at Mamacoke marsh, there is little change in plant composition.

## Wetland Relative Sea-Level Rise

Tide gauges measure sea-level rise with respect to a cluster of associated benchmarks (typically at least 10 per tide gauge (Bevis et al. 2002, page 90; tidesandcurrents.noaa.gov). The most stable benchmark, typically a sleeved, stainless-steel rod driven to resistance (i.e., up to 25 + m) below the upland surface near to the gauge (tidesandcurrents.noaa.gov; Cahoon 2015), is designated the primary tide gauge benchmark (PTGBM, Fig. 3). Thus, vertical land motion (VLM) measured from repeated surveys of the PTGBM is inseparable from the measure of sea-level rise by the gauge, resulting in a measure of what is known as relative sea-level rise (RSLR = sea level change + land subsidence). If the benchmarks are sleeved and/or anchored to isolate them from downdrag forces, then vertical land motion is measured at the base of the PTGBM and is often referred to as deep subsidence, such that RSLR = sea level change + deep subsidence. In coastal Louisiana, for example, NOAA PTGBM is typically driven to refusal (i.e., up to 25 m or more) and sleeved (tidesandcurrents.noaa.gov). In this case, RSLR does not incorporate VLM occurring above the base of the PTGBM, which is precisely the portion of the substrate where VLM is measured by the deep rod SET (Cahoon et al. 2020; and Figs. 2 and 3). Thus, when combined, shallow subsidence from the rod SET-MH method and deep subsidence from the PTGBM would yield total subsidence (Jankowski et al. 2017; Keogh and Tornquist 2019).

If a benchmark rod is not sleeved or anchored, the potential exists for negative skin friction (i.e., downdrag) on the rod to cause it to move downward. Notably, rod SET benchmarks are not sleeved because the wetland surfaces where they are installed will not support the heavy equipment needed to install sleeves and anchors. Byrnes et al. (2019) argue that unsleeved SET rods in coastal Louisiana likely undergo downdrag although they provide no direct empirical measures of SET rod movement to support this contention. They claim subsidence should be measured relative to the top of the SET rod and referred to as total subsidence. However, Byrnes et al. (2019) recognize that the comparative influence of downdrag on sleeved versus unsleeved rod benchmarks has not been directly investigated in Louisiana coastal environments with unconsolidated sediments.

In the only investigation of potential downdrag on rod SET benchmarks in a coastal wetland, Swales et al. (2016) calculated skin friction resistance of rod SET benchmarks in a mangrove forest in New Zealand overlying deep (> 1 km thick), mostly unconsolidated sediments and report that the bearing capacity of the SET benchmarks was 100 times smaller than the bearing capacity of the soil, resulting in a potential point settlement of only 0.03 mm. Thus, a rod SET settlement of < 1 mm would not preclude calculating shallow subsidence (*A*–*E*) because the amount is smaller than the measurement error of the SET (~ 1.5 mm, Cahoon et al. 2002a) and would have no detectable influence on the wetland elevation trend (Cahoon et al. 2020). It also means the SET-MH method measures shallow subsidence above the base of the PTGBM (Cahoon 2015; Swales et al. 2016; Cahoon et al. 2020). Although the work by Swales et al. (2016) could be repeated in other coastal wetland systems, and compared to sleeved rods as well, this finding suggests the SET method and tide gauge independently measure vertical land motion over separate depths of the substrate (Figs. 2 and 3), meaning both methods combined would define total subsidence.

Furthermore, it indicates that estimates of RSLR for an individual wetland surface (i.e., $RSLR_{wet}$) can be refined by combining the measures of wetland elevation change from the SET ($VLM_w$ in Figs. 2 and 3) with RSLR from the tide gauge and its associated benchmarks on an adjacent upland surface ($VLM_c$ in Fig. 3; Cahoon 2015; Jankowski et al. 2017; Keogh and Tornquist 2019; Cahoon et al. 2020). If $VLM_w$ is positive, then the local rate of $RSLR_{wet}$ is reduced by that amount, and for a negative $VLM_w$ trend, the rate of $RSLR_{wet}$ is increased by that amount. Cahoon (2015) reported that for 89 wetlands with a $VLM_w$ trend > 3 years duration, the trend was significantly different from 0 for 80% of the wetlands, indicating that the local tide gauge RSLR trend did not accurately reflect $RSLR_{wet}$ for those wetland surfaces.

Jankowski et al. (2017) and Keogh and Tornquist (2019) used the rates of shallow subsidence or expansion from 274 of the SET-MH stations in the Louisiana CRMS network to calculate total subsidence in the Mississippi River deltaic plain and Chenier Plain. Jankowski et al. (2017) reported that at least 60% of the total subsidence rate occurs within the uppermost 5–10 m of the substrate, the portion of the substrate measured by the rod SET but not typically captured by tide gauge RSLR measures. Furthermore, Keogh and Tornquist (2019) state that the PTGBMs in coastal Louisiana ($n = 35$) are anchored an average of 21.5 m below the land surface. In addition, the global navigation satellite system (GNSS) stations in Louisiana ($n = 10$) that measure deep subsidence are anchored an average of ~ 14 m below the land surface. Therefore, tide gauges and GNSS stations in the Louisiana coastal zone systematically underestimate total subsidence and RSLR at the wetland surface. Given that most subsidence in coastal Louisiana wetlands occurs above the depth at which deep subsidence is measured (Jankowski et al. 2017; Keogh and Tornquist 2019), $VLM_w$ rates from SETs provide a conservative estimate of wetland elevation change and the ability of these wetlands to keep pace with RSLR (Cahoon 2015). Furthermore, direct measures of $VLM_c$ by GPS monitoring of the top of SET rods to a local datum and tide gauge provide a full estimate of total subsidence (shallow + deep), as reported by Swales et al. (2016) for a mangrove forest in New Zealand.

## SET-MH Method: Emerging Research Directions

### Modern Survey and SET-MH Methods Combined

Both the SET and sedimentation-erosion bar (SEB) methods sample a relatively small area of the marsh surface at each station (< 2 m$^2$ area) with 36–72 readings for the SET, 51 readings for the SEB (van Wijnen and Bakker 2001), and seven readings for the modified SEB (Lang'at et al. 2014). Although multiple SET or SEB stations (i.e., a minimum of at least 3 for statistical reasons) are deployed per treatment or site (Lynch et al. 2015), the total areal coverage for a wetland remains relatively small. For this reason, a new emerging approach to measure elevation in wetlands is to apply modern survey techniques to expand SET elevation measurements from a 1 to 2 m$^2$ area across a much larger surface area of the wetland up to the scale of a hectare. The methods described below have potential for improving measures of wetland elevation change, but long-term data sets from a variety of wetland types are needed to fully assess their potential. Cain and Hensel (2018) tested a novel digital barcode leveling technique with millimeter scale precision in hectare-sized areas of salt, brackish, and fresh marshes with existing SET-MH stations. The precision of the two techniques was similar, although leveling error was higher than the SET-MH method in the soft sediments of the fresh marsh. Overall, leveling provided high precision, repeat sampling of marsh elevation over the marsh comparable to the SET-MH method at about the same cost. Lynch et al. (2023) measured elevation change in a 1-ha area of a structurally homogenous back-barrier salt marsh with low topographic relief using three different methods: the SET, digital level (DL), and total station (TS). Despite differences in sample size and spatial distribution of measurements among the three methods, elevation change trends did not differ among the methods, indicating they all provide comparable measures of long-term trends in elevation for that marsh setting.

Kargar et al. (2021) tested a low-cost, portable terrestrial laser scanning (TLS) system in three mangrove forests in the Federated States of Micronesia each dominated by a different tree species, which measured ~ 30,000 points over approximately a 10 m$^2$ area on the forest floor. The TLS is attached to the SET pipe or rod during operation. The standard error of the TLS was smaller than the SET in all measured plots due to the vastly greater density of data points and reduction of human error associated with the SET method, despite challenges of ground detection in the heterogenous structure of the forest floor (e.g., areal roots, logs, footprints). One drawback of TLS is that the forest floor must be exposed at low tide to make the measurements. MacKenzie et al. (2023) compared accretion and surface elevation change in mangrove forests on the high island of Pohnpei in the Federated States of Micronesia using lead-210, SET-MH, and compact biomass lidar (CBL). Accretion rates measured from lead-210 cores were not significantly different from elevation rates measured from the SET. Lead-210 cores only measure the upper 1 m of the substrate and do not incorporate deeper subsurface processes captured by the SET. The statistical similarity in rates suggests therefore either the surface accretionary processes influence elevation more than subsurface processes, or subsurface processes were not large enough to affect elevation or the SETs were not deep enough to capture all subsurface influences. CBL elevation rates also did not differ significantly from most SET elevation rates. Although CBL generates 30,000 data points versus 36 for the SET, and thus has increased precision and lower standard error, the SET method is three to 10 times less expensive and accurately tracks changes in forest floor elevation.

### Measuring Carbon Sequestration

A novel application of the SET-MH method is its use in calculating current rates of carbon (C) sequestration in mangrove and salt marsh wetlands over the recent past (Howe et al. 2009; Rogers et al. 2014, 2019; Lovelock et al. 2014; Chen et al. 2021; Castillo et al. 2022; Cormier et al. 2022; Bansal et al. 2023). Estimates of C stocks and sequestration rates are typically calculated by dating accumulated sediment C from soil cores over long periods of time (e.g., Chmura et al. 2003; Drake et al. 2015; Bansal et al. 2023). These longer-term, historic rates of C sequestration reveal the potential of these wetlands to store carbon, but as environmental conditions change (e.g., vegetation, hydrology), current rates of C sequestration can change. In this application, a known volume of soil from above the marker horizon depth or the top 5 to 6 cm of the substrate is sampled and analyzed for C content and bulk density. C sequestration is then calculated as the rate of surface elevation change (Lovelock et al. 2014; Castillo et al. 2022; Cormier et al. 2022; Bansal et al. 2023) or vertical accretion (Howe et al. 2009; Rogers et al. 2014, 2019) multiplied by the C density of the sediment. Measurements from this methodological approach are typically within the range of traditional methods and are well-suited to investigating wetland C sequestration responses to recent disturbance events (e.g., storms and hydrological alterations) and restoration actions.

## What the SET-MH Method Has Revealed

Table 3 and Figs. 4 and 5 present the subsurface process influences on elevation, with literature citations for each, which were not recognized and/or quantified before the invention of the SET-MH method provided empirical evidence of their existence and magnitude. Simultaneous, millimeter-resolution measurements of elevation and vertical accretion by the SET-MH method make it possible to discern surface from subsurface process influences on wetland elevation via hypothesis testing. Subsurface soil processes such as compaction, collapse, expansion, and shrink-swell exert significant influence on wetland elevation, necessitating simultaneous measurement of subsurface change. Biophysical forces (sediment, hydrologic, and biotic) driving these shallow subsurface processes include sediment and water overburden, dilation water storage, decomposition, increased root and rhizome production by nutrient enrichment, reduction in root and rhizome production by herbivory or plant death, and response to changes in watershed inputs to coasts and estuaries (e.g., changes in sediment delivery, freshwater, or nutrients). The SET-MH method demonstrates accretion is not an appropriate analog for elevation in most wetland settings, and subsurface influences on elevation play a fundamental role in a wetland's response to RSLR and community dynamics related to wetland transgression, succession, and restoration and management success. In sum, the SET-MH method with its evolution and breadth of applications over the past 30 years (Table 1 and 2) has become an invaluable tool for understanding the processes influencing coastal wetland elevation dynamics.

Furthermore, development of multi-decadal trends from long-term monitoring of SET-MH stations makes it possible to evaluate coastal wetland responses to RSLR, storms, other episodic events, and restoration-management actions. SET elevation trends more adequately track wetland response to drivers such as RSLR than accretion trends because they incorporate subsurface influences not recorded in accretion measures. Thus, wetland response and vulnerability to RSLR is more accurately described by elevation deficits than accretion deficits. The SET-MH method also makes it possible to relate RSLR to the wetland surface ($RSLR_{wet}$) by combining elevation change from the SET with RSLR from the tide gauge (Fig. 3; Cahoon 2015).

Multi-national comparisons of elevation and sea-level trends reveal that elevation change in tidal marshes, and mangrove forests can lag sea-level rise because of limited sediment availability and the occurrence of shallow subsidence. Although vertical accretion typically increases with the rate of sea-level rise, shallow subsidence often increases nonlinearly with accretion thereby constraining wetland elevation gain and resulting in an elevation deficit (Saintilan et al. 2023a, b). Also, the rate of landscape-scale vegetation shifts, such as mangrove encroachment into salt marsh, is influenced by differing elevation dynamics between the vegetation zones.

Limitations of the SET-MH method are being addressed by emerging research trends. Application of the SET-MH method with modern survey methods is expanding areal coverage of elevation trends across a broader portion of a wetland surface as SET measurements are limited spatially (Cain and Hensel 2018; Kargar et al. 2021; Lynch et al. 2023; MacKenzie et al. 2023). Furthermore, the range of wetland types (e.g., salt marsh and mangrove) and geomorphic settings (e.g., delta, back-barrier, riverine, open coast) where the method is applied is expanding. Initially, the method was applied most intensely in salt marsh and mangrove forests in deltaic and back-barrier settings, although recently, it has been used across brackish, oligohaline, and fresh marshes, and tidal fresh forest wetlands, and riverine and open coast geomorphic settings (Table 3). Another limitation of the SET-MH method is its use in intertidal seagrass systems, where scour around the SET benchmark can occur (Davis et al. 2024). However, small diameter pins, 1.2 m in length, have been successfully used (Potouroglou et al. 2017) to measure elevation change in seagrass beds. Thus, our understanding of coastal wetland elevation dynamics continues to expand as the SET-MH method is applied across an ever-broader range of settings and as new research methods and applications are developed.

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