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Soil Salinity and Water Level Interact to Generate Tipping Points in Low Salinity Tidal Wetlands Responding to Climate Change

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Abstract
Low salinity tidal wetlands (LSTW) are vulnerable to sea level rise and saltwater intrusion, thus their carbon sequestration capacity is threatened. However, the thresholds of rapid changes in carbon dynamics and biogeochemical processes in LSTW due to changes in hydroperiod and salinity regime remain unclear. In this study, we examined the effects of soil porewater salinity and water level on changes in net primary productivity (NPP) and greenhouse gas fluxes [GHG: methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2)] in LSTW using a wetland biogeochemistry model, Tidal Freshwater Wetland Denitrification and Decomposition (TFW-DNDC). TFW-DNDC was run with a series of combinations of soil salinities (0.1, 0.5, 1, 2, 4, 6, 8, 10 psu) and water levels relative to soil surface (-30, -20, -10, -5, 0, 5, 10, 20, 30 cm) for tidal forest and oligohaline marsh sites along the Savannah River and Waccamaw River, USA. Our results indicate that soil salinity and water level have antagonistic effects on CH_4 emissions and synergistic effects on CO_2 release. A soil salinity of 2-3 psu is the tipping point for the ecosystem level functional changes (e.g., NPP and CH_4 emissions) in LSTW. There are negative and nonlinear responses (NPP and CH_4 emission) to soil salinity. Furthermore, a soil water level from 10 cm below to 10 cm above the surface is a critical range in which biogeochemical processes respond strongly to hydrological changes. The presence of nonlinear tipping points in LSTW has large implications for understanding and predicting the effects of climate change on coastal wetland blue carbon storage and ecosystem dynamics.

Keywords Greenhouse gas emission · Low salinity tidal wetlands · Soil salinity · Water level · Thresholds · Tipping points

Introduction

Low salinity tidal wetlands (LSTW) are located in the transitional zone between terrestrial ecosystems and estuarine ecosystems in upper estuaries and include tidal freshwater forested wetlands (TFFW) and tidal freshwater and oligohaline marshes along a range of soil salinities from 0 to 5 practical salinity units (psu) (Krauss et al. 2009; Ensign et al. 2014; Krauss et al. 2018). Even in relatively non-saline tidal freshwater wetlands close to zero psu (true freshwater wetlands), elevated soil porewater salinity is a periodic reality, and can become as high as 10 psu during drought and persistent sea level rise (Wang et al. 2020). Soil salinity and soil water level are found to be two critical stressors affecting the structure (e.g., the plant species composition and distribution), function (e.g., carbon sequestration and greenhouse gas (GHG) emissions of tidal wetlands) (Poffenbarger et al. 2011; Ardón et al. 2016; Wang et al. 2017a; Chamberlain et al. 2019; Luo et al. 2019; Wang et al. 2022). Tidal freshwater wetlands are highly sensitive to salinization since even slight increases in salinity could affect their microbial organisms that facilitate critical biogeochemical transactions (Neubauer 2013; Sutter et al. 2014; Herbert et al. 2018). Changes in plant community structure and changes in biogeochemical processes could affect carbon and nitrogen cycling, major pulses of carbon

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fluxes, and eventually the capacity of carbon sequestration and storage in tidal wetlands.

Ecological thresholds are becoming a critical component of ecological research due to the increasing needs in understanding ecosystem responses to changing environmental stressors (Larsen and Alp 2015; Toms and Villard 2015; Hillebrand et al. 2020). Ecological thresholds are defined as the point at which an ecological process or parameter changes abruptly in response to relatively small changes in a driving force (Larsen and Alp 2015; Toms and Villard 2015). The responses of LSTW's structure and function depend on the tolerances of plant species and biogeochemical processes as affected by soil salinity and water level, and there are important thresholds (tipping points, regime shifts, breakpoints) that mediate responses. For example, an average salinity of 2 psu is a threshold for TFFW shifts from multiple species with low salinity tolerance to few species with relative high salinity tolerance (Hackney et al. 2007; Krauss et al. 2009; Cormier et al. 2013; Thomas et al. 2015); however, this threshold is more nuanced in reality as mortality rates manifest at different thresholds with TFFW submergence versus tidal flooding (Krauss et al. 2009). On the other hand, some thresholds are likely more consistent; when salinity is larger than 10 psu, the soil microbial community will change causing the inhibition of methanogenesis and promoting the dominance of sulfate reduction (Poffenbarger et al. 2011; Wang et al. 2017a). Across a large salinity (0-30 psu) gradient, a salinity of 10-15 psu was found to be the threshold of methane (CH_4) emission (Wang et al. 2017a), and water level 5-10 cm above soil surface was found to be a threshold for methane emission (Zhao et al. 2020).

Nevertheless, there are few studies that examine mechanistically derived soil salinity thresholds of GHG emissions for LSTW (< 10 psu) that can consider the many environments for which LSTW exist globally. Large variation in methane emission from tidal wetlands with salinity under 10 psu does indicate that other stressors such as soil water level need to be considered interactively for salinity threshold determination (Krauss and Whitbeck 2012; Luo et al. 2019; Zhao et al. 2020). Furthermore, there are also a limited number of studies that examine the thresholds of soil salinity and soil water level on plant productivity, soil respiration (CO_2 emissions), and nitrous oxide (N_2O) emission. Field studies are difficult to use for threshold determinations from lack of experimental control, and laboratory or mesocosm studies may not reflect the actual in situ biogeochemical conditions created through simulated freshwater flow, tidal exchange, resultant plant community composition, and vertical soil mixing. Process-driven biogeochemistry models provide an alternate means and are useful tools that can estimate the effect of the combined environmental conditions on carbon and nitrogen biogeochemistry. A process-driven biogeochemistry model, Tidal Freshwater Wetland Denitrification and Decomposition (TFW-DNDC) was developed and validated and can be applied to threshold determinations among salinity and water level combinations on carbon fluxes and storage in LSTW (Wang et al. 2022, 2023b).

The objectives of this study are to: 1) explore the synergistic effect of soil salinity and water level on net primary productivity (NPP) and emissions of greenhouse gases (GHG: CH_4, N_2O, and CO_2) emissions in LSTW; 2) estimate the thresholds of soil salinity and water level interactions that effect shifts in NPP and GHG emissions balances, and 3) examine the variability in soil salinity and water level thresholds on NPP and GHG emissions, if existing, at different tidal forest and oligohaline marsh sites in LSTW. We hypothesize that thresholds of soil salinity on primary productivity and GHG emissions are dependent upon water level, such that a two-stressor based threshold must be considered when relating environmental variables to ecosystem function among LSTW. The validated TFW-DNDC was run with a series of combinations of soil salinities and water levels for tidal forest and oligohaline marsh sites along the Savannah River and Waccamaw River, USA to estimate the tipping points. Data and information from this study on tipping points of soil salinity and water level on NPP and GHG emissions can be helpful to LSTW managers for ecosystem process-driven monitoring, assessment, and prediction of carbon budget and carbon credit for decision-making of carbon loss mitigation from future climate change and sea level rise.

Methods

Study Sites

The LSTW sites in this study are located in coastal floodplains of the Waccamaw River in South Carolina and the Savannah River in Georgia, USA (Fig. 1). Four sites along each river were selected based on increasing soil porewater salinity concentrations: tidal freshwater forests (upper, 0.1 psu), moderately salt-impacted forests at the freshwater–oligohaline transition (middle, 1.2 -1.4 psu), highly salt-impacted forests (lower, 2.4 - 4.3 psu), and oligohaline marshes (marsh, 3.1-4.9 psu) (Krauss et al. 2018). The study area has a humid climate with hot summers and mild winters: mean annual rainfall ranges from 92 to 152 cm and annual temperature averages 17.4 ºC with a maximum annual mean of 18.5 ºC and a minimum mean of 16.6 ºC during 1985-2014 (Thomas et al. 2015). Tides are semi-diurnal on the Waccamaw and Savannah rivers, and tidal ranges at the river mouths are 1.1 m and 2.3 m, respectively (Cormier et al. 2013; Krauss et al. 2018). Wetting and drying (depth, duration, frequency) vary with local site conditions including surface elevation and distance to tidal creeks and the river (Noe et al. 2013; Ensign et al. 2014). Saltwater with salinity above 2 psu can reach as

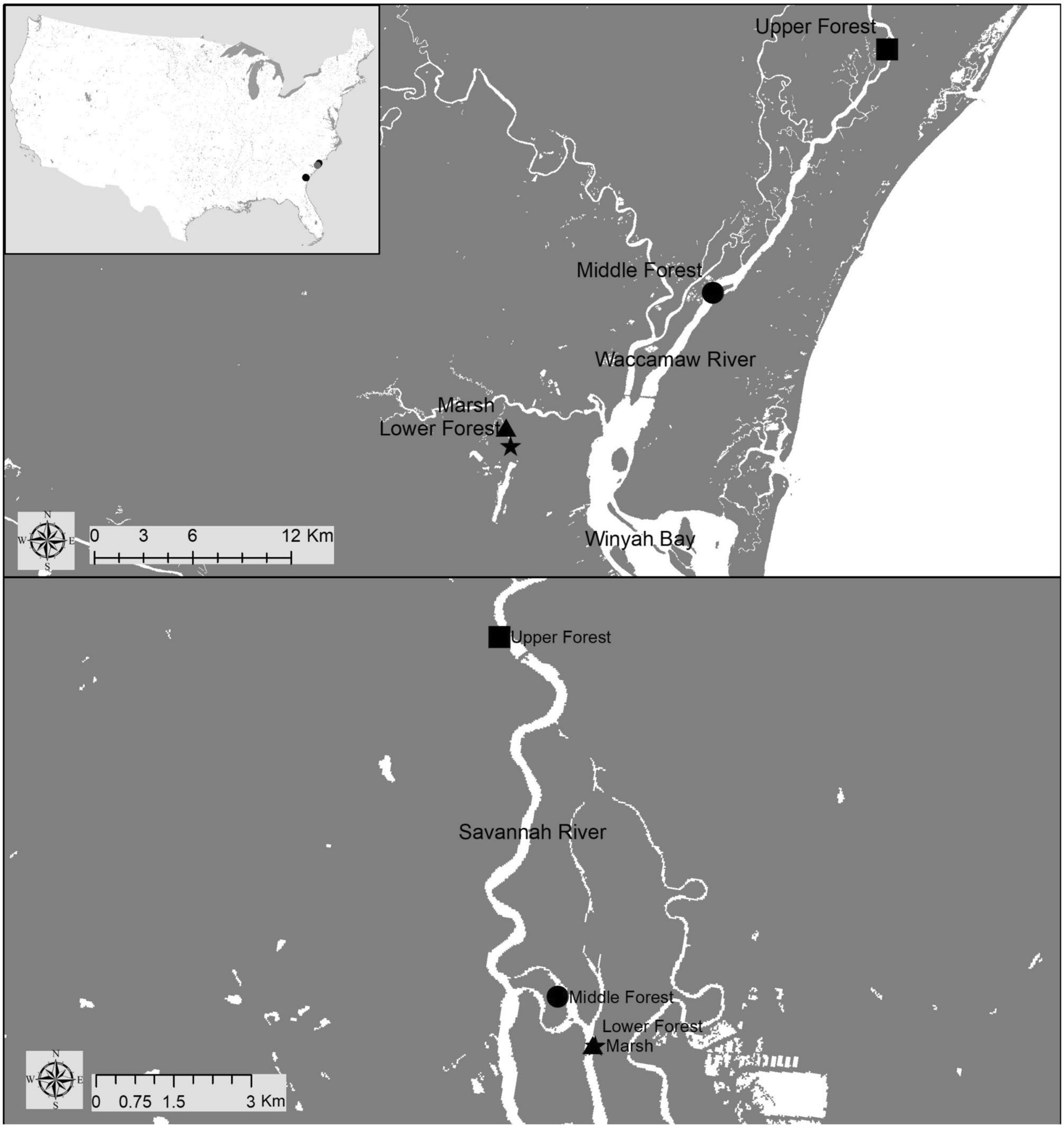


Fig. 1 Location of the low salinity tidal wetland (tidal freshwater swamp forest and oligohaline marsh) sites along the Waccamaw River, South Carolina and Savannah River, Georgia, USA

much as 32 km upstream under low flow conditions and 5 km upstream during normal river flow conditions along the Waccamaw River and approximately 45 km upstream during low flow conditions and approximately 13 km upstream during normal conditions along the Savannah River (Doyle et al. 2007, Duberstein and Kitchens 2007). The dominant tree species at the freshwater forest (upper) sites include *Taxodium distichum* (baldcypress), *Nyssa aquatica* (water tupelo), *Nyssa biflora* (swamp tupelo), *Acer rubrum* (red maple), and *Fraxinus spp*. (ash), while *T. distichum* and *N. biflora* are dominant at the moderately salt-impacted forest (middle) sites, and *T. distichum* is dominant at the highly salt-impacted forest (lower) sites. Baldcypress is a relatively tolerant species to low salinity and is distributed broadly in tidal swamps along the southeastern USA (Day et al. 2007; Thomas et al. 2015). At the oligohaline marsh sites, dominant species include *Zizaniopsis mileacea* (giant cutgrass), *Spartina cynosuroides* (big cordgrass), *Bolboschoenus robustus* (sturdy bulrush), and *Typha latifolia* (cattail) (Ensign et al. 2014). Marsh species are also actively encroaching into the highly salt-impacted forest sites. Soils at these LSTW sites were assigned to the Typic Hydraquent family in the Soil Survey Geographic Database (SSURGO). Soil texture types were silty clay loam or silt clay for these sites, soil saturated hydraulic conductivity ranged between 0.02 and 0.07 cm hr^{-1} (Wang et al. 2020), and mean soil organic matter ranged 21.2% – 51.7% (Ensign et al. 2014).

Modeling Approach and Experiments

The Tidal Freshwater Wetlands DeNitrification-DeComposition model (TFW-DNDC) (Wang et al. 2022, 2023b) is a process-driven biogeochemistry model for LSTW (< 10 psu) and was developed based on the mangrove carbon assessment tool (MCAT-DNDC, Dai et al. 2018). TFW-DNDC simulates the dynamics of carbon (C) and nitrogen (N) in LSTW thereby facilitating the assessment of the impacts of environmental stressors including soil salinity, soil water level and their interaction on plant productivity, plant and soil respiration, soil organic carbon (SOC) sequestration rate and storage, and greenhouse gas emissions (Wang et al. 2022, 2023b). TFW-DNDC incorporates critical biogeochemical processes including photosynthesis, plant and soil respiration, soil organic matter decomposition, N/P mineralization, methanogenesis, methanotrophy, nitrification, denitrification, C allocation, C storage, and C consumption. The impacts of environmental factors such as soil salinity, light/radiation, air/soil temperature, precipitation, soil moisture, redox potential, soil pH, and nutrients on these biogeochemical transformations are included in model structure (Fig. 2). TFW-DNDC was previously calibrated and validated against field data of annual litterfall, wood growth, root growth, plant respiration, soil organic carbon storage, methane, and nitrous oxide emissions collected from the Savannah and Waccamaw river sites (From et al. 2021; Krauss and Whitbeck 2012; Krauss et al. 2009; Krauss et al. 2018) with acceptable agreement between simulated values and field observations (Wang et al. 2022, 2023b). The previous model calibration and validation have shown that this model can be used to estimate if soil salinity and water level interaction can generate tipping points in ecosystem C dynamics.

In this study, TFW-DNDC was run with a series of combinations of annual average soil salinities (0.1, 0.5, 1, 2, 4, 6, 8, 10 psu) and water level relative to soil surface

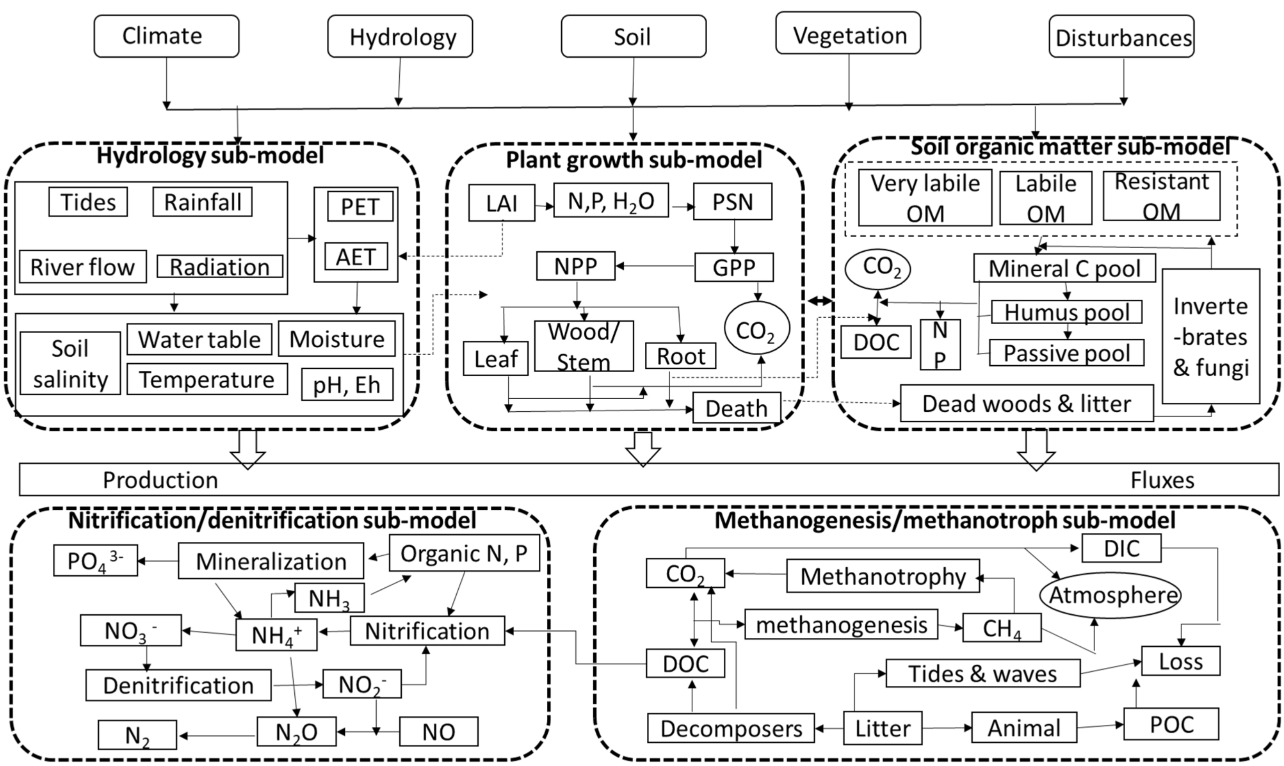


Fig. 2 Conceptualization of TFW-DNDC (Wang et al. 2022) that was modified from the MCAT-DNDC model (Dai et al. 2018). PET = potential evapotranspiration, AET = actual evapotranspiration, Eh = redox potential, LAI = leaf area index, PSN = photosynthesis, GPP = gross primary productivity, NPP = net primary productivity, DOC = dissolved organic carbon, DIC = dissolved inorganic carbon, POC = particulate organic carbon

(-30, -20, -10, -5, 0, 5, 10, 20, 30 cm) to estimate the tipping points in NPP, CO_2, CH_4, and N_2O. Simulated net primary productivity and greenhouse gas emissions under various soil salinity and water level combinations are available in Wang et al. (2023a). Water level could be either groundwater (water table) when it is below soil surface or surface water (water level) when it is above soil surface. The selection of the water level range of -30 to 30 cm was based on observed water level data in recent decades on the Savannah and Waccamaw river sites while the selection of the soil salinity range of 0.1 – 10 psu was based on the simulated soil salinities under dry and normal water level conditions for these tidal forest and oligohaline marsh sites (Wang et al. 2020). The seasonal patterns in soil salinity and water level in model experiments due to the mixing of tide and freshwater flow at each site were assumed to be the same as that for normal conditions that were identified from observed data between 2008 and 2016 (Cormier et al. 2013; Wang et al. 2020). The values of daily soil salinity and water level as input in simulation experiments with a daily time step were set by adding or subtracting the differences between the values under normal conditions and the targeted annual average soil salinity and water level. For example, the annual average soil salinity at the Savannah lower forest was 3.46 psu under the normal condition, therefore, the daily soil salinity values at this forest site in the experiments with mean annual salinity values of 0.1, 0.5, 1, 2, 4, 6, 8, and 10 psu were derived by subtracting 3.36, 2.96, 2.46, 1.46 from the daily salinity values and by adding 0.54, 2.54, 4.54, and 6.54 to the daily salinity values under the normal condition. At this forest site, the annual average water level was 4.64 cm under the normal condition, therefore, the daily water levels in the experiments with mean annual values of -30, -20, -10, -5, 0, 5, 10, 20, and 30 cm were derived by subtracting 34.64, 24.46, 14.66, 9.64 and 4.64 from the daily water levels and by adding 0.36, 5.36, 15.36, and 25.36 to the daily water levels under the normal condition. TFW-DNDC was run for four years with the first two years as a "spin-up" period (Wang et al. 2022) to obtain steady-state solutions (Thornton and Rosenbloom 2005) and mean annual values of NPP and emissions of CO_2, CH_4, and N_2O from the last two simulation years were used for threshold analysis. The environmental conditions were imposed uniformly for the entire simulation period. Soil CO_2 emissions in this study include both plant root respiration and soil microbial respiration.

Threshold Estimation

Stressor-response plots: the responses of dependent variables (NPP, CH_4, N_2O, CO_2) to stressors (soil salinity and water level) at each of the eight sites in the two coastal plain rivers were displayed using scatterplots (2 river basins × 4 sites × 4 variables × 2 stressors = 64 plots, shown in Appendix S1: Figs. S1 to S8). To detect the breakpoints, the relationships between the dependent variables and the stressors were examined to determine if there is a slope change or not. If a slope change for the relationship was discovered by visual assessments of the data scatterplots, and therefore the relationship was determined to be nonlinear, a piecewise linear regression was conducted to detect the breakpoint for the abrupt change using Statgraphics Centurion 19 (Statgraphics Technologies, Inc., The Plains, Virginia, USA). Piecewise linear regressions took the form of,

$$Y = \beta_0 + \beta_1 X if x \leq \Delta \tag{1}$$

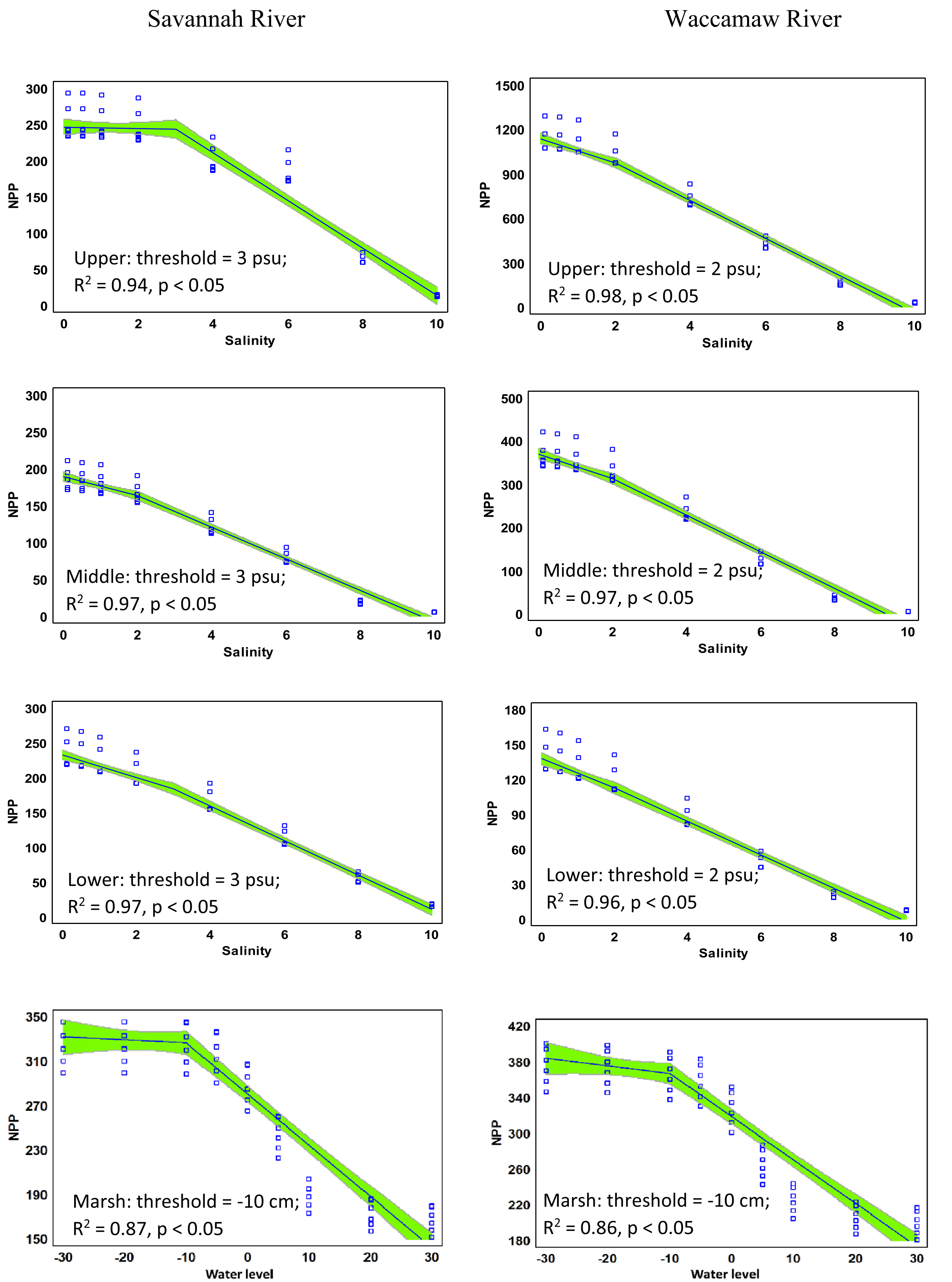
$$Y = \beta_0 + \beta_1 X + \beta_2 (X - \Delta) if x > \Delta \tag{2}$$

where Y = dependent variable (i.e., NPP, CH_4, N_2O, CO_2); X = independent variable (i.e., soil salinity, water level), β_0, β_1, β_2, and Δ are intercept, initial slope, slope change, and break point, respectively.

Combination of thresholds of two stressors: When breakpoints of soil salinity and water level were detected from the piecewise linear regression models for certain sites and certain functions (i.e., NPP, CH_4, N_2O, CO_2), we then confirmed the existence of the ecological meaningful breakpoints (or thresholds) by examining the surface contour plots and statistical analysis results (refer to "Statistical analysis" section below) when statistically significant effects were found for at least one stressor (either soil salinity or water level) or both of the two stressors regardless of their interaction significant or not.

Statistical Analysis

The impacts of soil salinity and water level on NPP, CH_4, N_2O and CO_2 were analyzed using three-way ANOVAs with *river, site, salinity or water level* and *their interaction* as explanatory variables, three-way ANOVAs with *site, salinity, water level* and *their interaction* as explanatory variables, and two-way ANOVAs with *salinity* and *water level* and *their interaction* as explanatory variables. These ANOVAs were used to determine if thresholds of soil salinity and water level vary significantly with river basin, site, and dependent variables (NPP, CH_4, N_2O and CO_2). When necessary, the simulation results were transformed using the Box-Cox method (Mateu 1997) prior to analysis to meet normality and homoscedasticity assumptions. All post-hoc tests were performed using Tukey's HSD. The SAS 9.3 software package (SAS Institute, Cary, North Carolina, USA) was used for the statistical analyses. All the tests were two-tailed based on type III sums of squares and considered significant at $p < 0.05$.


Savannah River
Waccamaw River
Upper: threshold = 3 psu;
R^2 = 0.94, p < 0.05
Upper: threshold = 2 psu;
R^2 = 0.98, p < 0.05
Middle: threshold = 3 psu;
R^2 = 0.97, p < 0.05
Middle: threshold = 2 psu;
R^2 = 0.97, p < 0.05
Lower: threshold = 3 psu;
R^2 = 0.97, p < 0.05
Lower: threshold = 2 psu;
R^2 = 0.96, p < 0.05
Marsh: threshold = -10 cm;
R^2 = 0.87, p < 0.05
Marsh: threshold = -10 cm;
R^2 = 0.86, p < 0.05
NPP
Salinity
Water level

◂**Fig. 3** Relationships between NPP (g C m^{-2} yr^{-1}) and soil salinity (psu) and water level (cm) in low salinity tidal wetlands along the Savannah River and Waccamaw River. Soil salinity thresholds were estimated for forest sites and water level thresholds were estimated for oligohaline marsh sites using piecewise linear regression model. Green areas with piecewise linear regression denote 95% confidence limits

Results

Effects of Soil Salinity and Water Level On NPP and GHG Emissions

The effect of river × site × salinity interaction was found for NPP (df = 575, $p < 0.0001$) and the effect of river × site × water level interaction was found for CH_4, N_2O and CO_2 emissions in LSTW (df = 575, $p < 0.001$) (Appendix S2: Table S1). The effects of soil salinity × water level interaction were evident for CH_4, N_2O and CO_2 emissions but not for NPP (Appendix S2: Table S2), suggesting that salinity and water level synergistically affect GHG emissions. Simulation results indicated that soil salinity plays a critical role in NPP and there is a negative and non-linear relationship between NPP and soil salinity ($R^2 = 0.94$ - 0.98, n = 72, $p <$ 0.05 for forest sites, Fig. 3). NPP is not affected by soil water level (n = 72, $p > 0.05$, Appendix S1: Figs. S1 to S8) in tidal swamp forests. In contrast, water level, but not soil salinity, negatively affected NPP in the two oligohaline marshes (R^2 = 0.86 - 0.87, n = 72, $p < 0.05$, Fig. 3). Overall, soil salinity and water level individually affected NPP in LSTW (df = 287, p < 0.0001) but not their interaction ($p = 0.65$ for Savannah sites and $p = 0.59$ for Waccamaw sites, Appendix S2: Table S2).

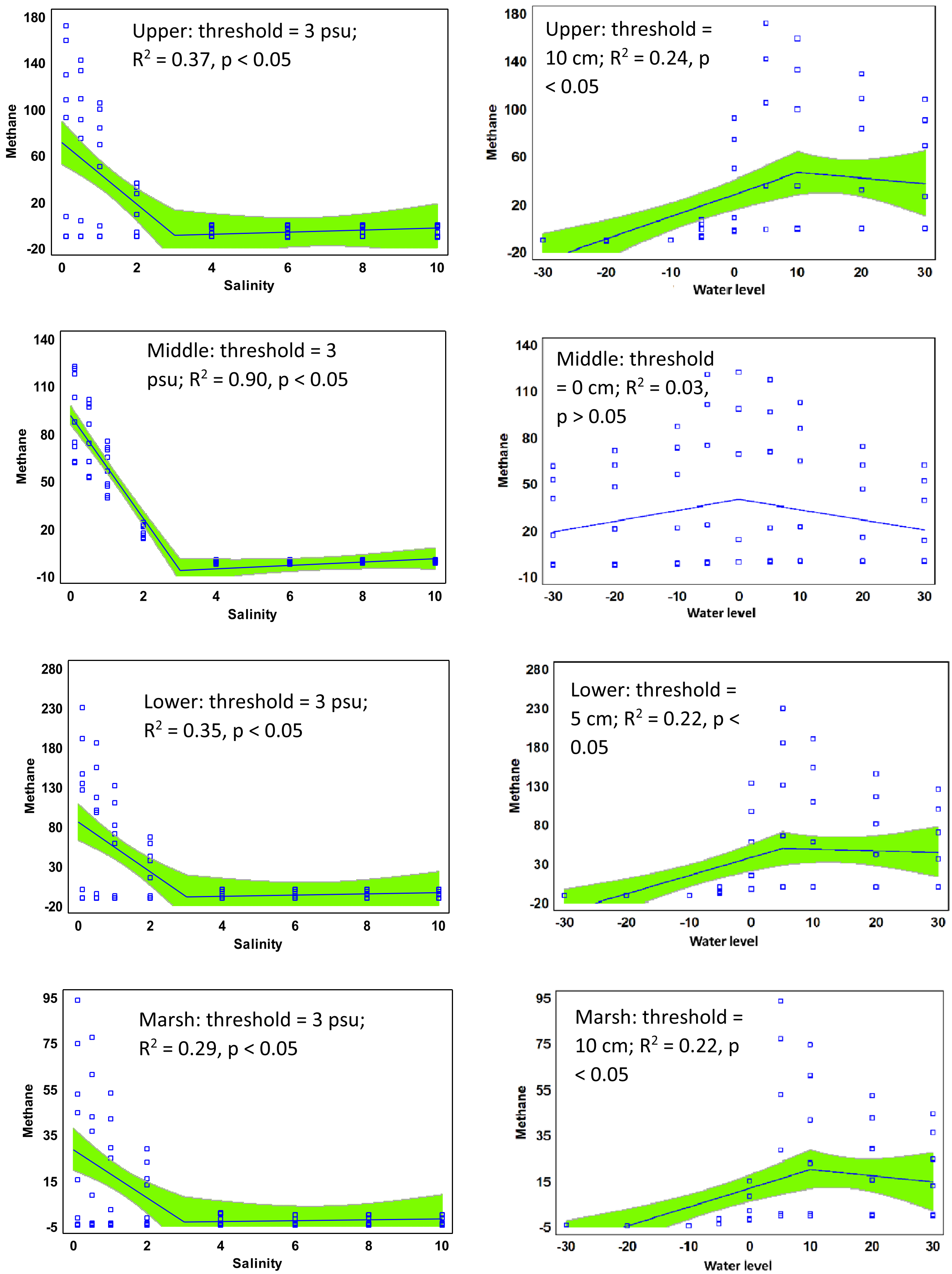
Soil CH_4 emissions were affected by both soil salinity and water level ($R^2 = 0.29$ - 0.90, n = 72, p < 0.05, Figs. 4 and 5) with a stronger effect of salinity than water level as well as their interaction ($p = 0.0085$ for Savannah sites and $p < 0.0001$ for Waccamaw sites, Appendix S2: Table S2) in LSTW. In general, salinity decreased and water level increased soil CH_4 emissions. For all tidal forest and oligohaline marsh sites, there were large variations in CH_4 emission ranging from -10 kg C ha^{-1} yr^{-1} (net CH_4 oxidation) to close to 200 kg C ha^{-1} yr^{-1} (emission) under salinity < 2 psu (Figs. 4 and 5). As shown in Figs. 4 and 5, at most of these sites, salinity explained variations in CH_4 emissions more (e.g., 28% - 38%) than water level (e.g., 19% - 24%). At the Savannah middle forest site, salinity explained 90% of the variation in methane emission whereas a small variation (< 4%) was from water level (n = 72, $p > 0.05$, Fig. 4).

Soil N_2O emissions were largely controlled by water level ($R^2 = 0.41 – 0.98$, n = 72, p < 0.05, Fig. 6) rather than soil salinity, and also by their interaction ($p < 0.0001$ for both Savannah and Waccamaw sites, Appendix S2: Table S2) in LSTW. In general, for tidal forest and marsh soils, N_2O emissions declined greatly with rising water level when soils were not inundated, and emissions were low when soils were inundated (Fig. 6). These results suggest that threshold on N_2O emissions is mainly water level driven rather than salinity driven. The exception is the Savannah middle forest where salinity explained a slightly larger variation in N_2O emission (45%) than water level (41%) as shown in Fig. 6. At this site, N_2O emissions increased when soils were driest and decreased when soils were inundated with maximum N_2O emissions occurring when water level was right at or close to soil surface (Fig. 6). At the Savannah middle forest site, thresholds on N_2O emissions were estimated from both salinity and water level and their synergistic effects as indicated by the relationships ($R^2 = 0.45$, n = 72, $p < 0.05$ for salinity and $R^2 = 0.4$, n = 72, $p < 0.05$ for water level) between N_2O emissions and both soil salinity and water level (Fig. 6).

For tidal swamp forest soils along all upper, middle and lower sites, more than 80% of the variation in soil CO_2 emissions was explained by soil water level ($R^2 = 0.81 – 0.99$, n = 72, $p < 0.05$, Fig. 7) whereas less than 20% of the variation was explained by soil salinity (Appendix S1: Figs. S1 to S8). Soil CO_2 emissions decreased considerably with rising water level and such that soil CO_2 emissions were generally low when soils were inundated (Fig. 7). Soil CO_2 emissions also decreased ($p < 0.05$) with increasing salinity at these tidal swamp forests (Appendix S1: Figs. S1 to S8). For oligohaline marsh sites, soil water level explained > 95% of the variation in soil CO_2 emissions with decreasing emissions with greater water levels ($R^2 > 0.98$, n = 72, $p < 0.05$, Fig. 7) whereas soil salinity showed no impact on soil CO_2 emissions ($p > 0.05$). The interaction between salinity and water level also affected soil CO_2 emissions in LSTW (df = 387, $p < 0.0001$ for both Savannah and Waccamaw sites, Appendix S2: Table S2).

Detected Thresholds of Soil Salinity and Water Level On NPP and GHG Emissions

The results of the statistical analyses indicate that thresholds of soil salinity and water level vary with river, site (i.e., plant community type with different species compositions) and depends on the specific ecosystem process (e.g., plant production, soil organic matter decomposition, methanogenesis, nitrification and denitrification). For NPP in tidal swamp forests a soil salinity threshold at 2-3 psu was detected by the piecewise linear regression, with no influence from soil water level (Table 1, Fig. 3). In contrast, oligohaline marsh NPP had a water level threshold of 10 cm below the soil surface without influence of salinity (Table 1, Fig. 3). For N_2O emissions in tidal swamp forest and marsh soils (except the Savannah middle forest) thresholds of water level rather than salinity were detected. Water level thresholds for soil N_2O emissions occurred at 10 cm below the soil surface at


Upper: threshold = 3 psu; R² = 0.37, p < 0.05
Upper: threshold = 10 cm; R² = 0.24, p < 0.05
Middle: threshold = 3 psu; R² = 0.90, p < 0.05
Middle: threshold = 0 cm; R² = 0.03, p > 0.05
Lower: threshold = 3 psu; R² = 0.35, p < 0.05
Lower: threshold = 5 cm; R² = 0.22, p < 0.05
Marsh: threshold = 3 psu; R² = 0.29, p < 0.05
Marsh: threshold = 10 cm; R² = 0.22, p < 0.05
Methane
Salinity
Water level

◂**Fig. 4** Relationships between CH_4 emission (kg C ha^{-1} yr^{-1}) and soil salinity (psu) and water level (cm) in low salinity tidal wetlands along the Savannah River. At all tidal forest and oligohaline marsh sites except Savannah middle forest site, thresholds of both soil salinity and water level were estimated using piecewise linear regression model. Green areas with piecewise linear regression denote 95% confidence limits

upper forest sites, 5 cm for lower forest sites, and 0 cm for oligohaline marsh sites (Table 1, Fig. 6). This result suggests that for most LSTW soils, N_2O emissions can be assessed based on soil water level conditions. The only exception is the Savannah middle forest where a soil salinity threshold of 2 psu was estimated for N_2O emissions in addition to a water level threshold of 0 cm (Fig. 6).

Contrary to single stressor thresholds on NPP and N_2O emissions, thresholds for both soil salinity and water level were found for CH_4 emissions, implying that salinity impact on CH_4 emissions is dependent upon water level and vice versa. A soil salinity threshold of 3 psu was estimated, below which CH_4 emissions increased with decreasing soil salinity (Figs. 4 and 5). CH_4 emissions increased greatly with rising water level up to 10 cm above the soil surface and then remained constantly high (Figs. 4 and 5). Although soil salinity was found to affect soil CO_2 emissions in tidal forest sites along the two rivers ($p <$ 0.05), clear salinity nonlinear thresholds were not detected due to the absence of slope change of the piecewise linear regression line. Nevertheless, the interactions between soil salinity and water level on soil CO_2 emissions for the tidal forest sites along the two rivers especially Savannah middle and Waccamaw lower sites were evident from the contour plots (Appendix S3: Figs. S9 and S10). A water level threshold of 5 cm above the soil surface was estimated for soil CO_2 emissions in tidal swamp forest soils, except -10 cm for Savannah upper forest site, with greater declines of CO_2 emissions with rising water level up to 5 cm of inundation, and stable CO_2 emissions with further increasing water level (Table 1, Fig. 7). A water level threshold of 5 cm above the soil surface was also detected for oligohaline marshes where CO_2 emission was not inhibited by salinity.

The relationships between soil CO_2/CH_4 ratio (mass-based) and soil salinity and water level at the forest and oligohaline marsh sites along the two rivers are shown in the surface plots in Fig. 8. Soil CO_2/CH_4 ratios ranged greatly from 5 to 1887. For all forest and oligohaline marsh sites, soil CO_2/CH_4 ratios were less than 40 under inundation (water level > 0 cm) and very low salinity (< 2 psu) conditions (Fig. 8). The ratios rose as the water level fell at or below soil surface and when soil salinity increased from freshwater salinity of < 0.5 psu to 2 psu at all the sites (Fig. 8). Water level thresholds for soil CO_2/CH_4 ratios from -5 cm to 5 cm above surface were estimated using the piecewise linear regression model for tidal forest and oligohaline marsh sites except Savannah lower and marsh sites where a soil salinity threshold of 2 psu was estimated (Fig. 9).

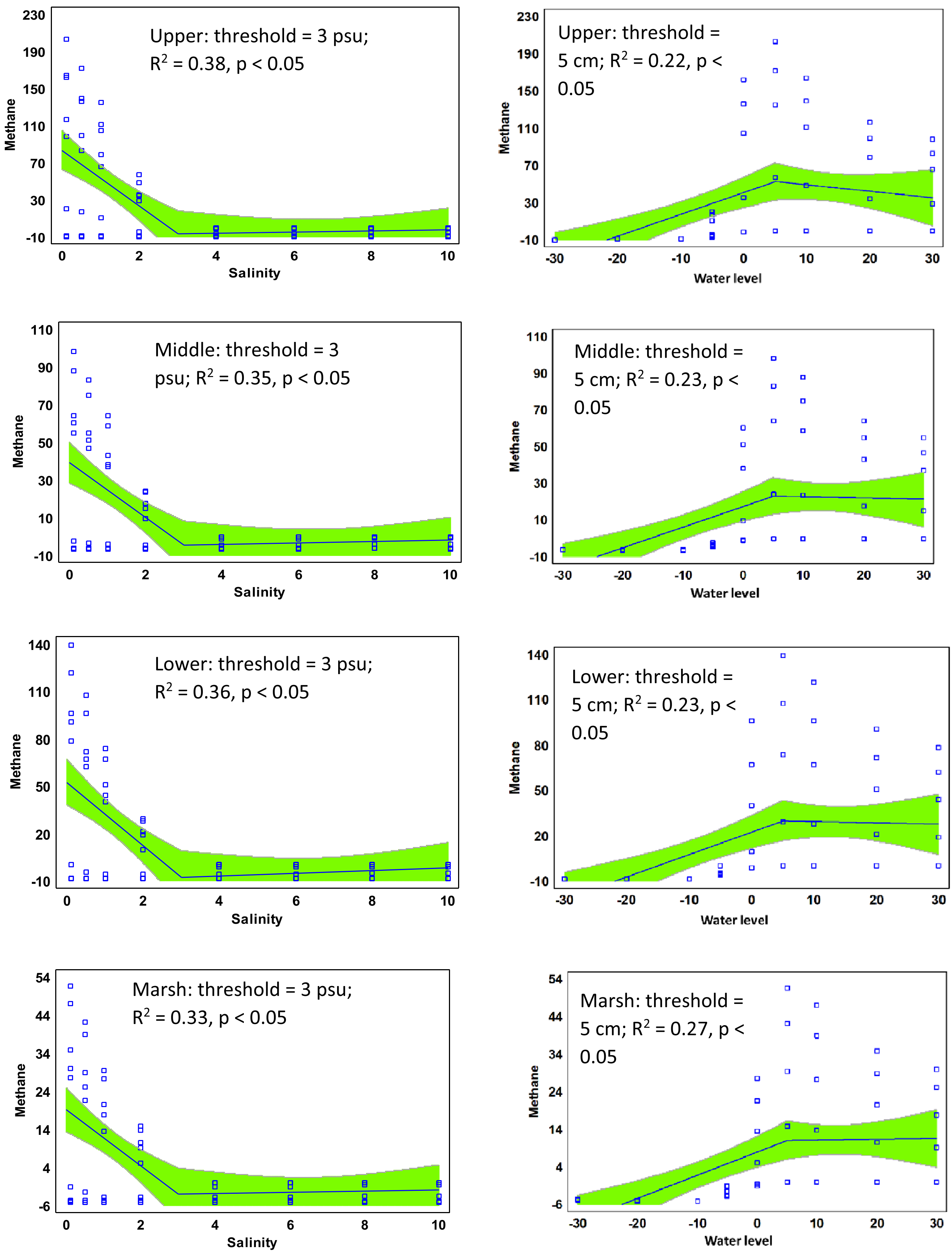
Discussion

Interactive Effects of Soil Salinity and Water Level

Our first key finding is that in addition to nonlinear effects, the synergistic (enhancing) or the antagonistic (inhibiting) interacting effects between soil salinity and water level could be critical in the determination and establishment of stressor thresholds in low salinity tidal wetlands. In the present study, soil salinity and water level were found to have antagonistic effects on CH_4 emissions and synergistic effects on CO_2 release. The responses of CH_4 to soil salinity change are conditional upon soil water level conditions. Thresholds of both soil salinity and water level on CH_4 emission were estimated from piecewise linear regression. CH_4 emissions were increased by more than 82% when soil salinity was less than the 3 psu threshold and when soil water level increased up to 5 cm above the soil surface.

We identified a 3 psu threshold for declining CH_4 emissions in soils of LSTW. Limited previous studies of salinity thresholds on CH_4 emission in LSTW including tidal freshwater forest and marsh soils found either no thresholds (e.g., Wang et al. 2017a) or varying thresholds (e.g., 2 - 5 psu, Chambers et al. 2011; Marton et al. 2012). However, water level impacts were not explicitly considered at the same time with salinity impacts in these salinity threshold studies using incubation methods, therefore, the interaction between salinity and water level was ignored, likely leading to the identification of different thresholds among studies of tidal wetlands. In fact, there are synergistic and antagonistic effects between salinity and water level on GHG emissions from our study and other studies (e.g., Krauss and Whitbeck 2012; Liu et al. 2017; Ardón et al. 2018; Luo et al. 2019). Future studies of methane emissions from coastal wetlands clearly need to consider both salinity and water level.

Since our threshold detection is based on a process-driven biogeochemistry model, thresholds of salinity and water level, both detected individually or interactively, if determined, reflect the tipping points at which the shift in metabolic pathways occurs in tidal wetlands. Moreover, Poffenbarger et al. (2011) found that oligohaline (0.5 - 5) marshes have the highest and most variable CH_4 emissions (155 ± 221 g m^{-2} yr^{-1}). Our study also showed a larger variation in CH_4 emission with salinity < 3 psu than salinity > 3 psu not only for the oligohaline marsh sites (-10 to 94 kg C m^{-2} yr^{-1}) but also for the tidal freshwater forest sites (-10 to 230 kg C m^{-2} yr^{-1}). Such large variations in CH_4 emission could result from the high diversity of plant species in these low salinity wetlands since plants are the sources of both organic carbon and certain electron donors for methanogenesis (Krauss and Whitbeck 2012). Plant communities can also have a large impact on the emission of CH_4 emissions via transport that bypasses oxidative layers of soil or water columns (e.g.,



Upper: threshold = 3 psu; R^2 = 0.38, p < 0.05
Methane
Salinity
Upper: threshold = 5 cm; R^2 = 0.22, p < 0.05
Methane
Water level
Middle: threshold = 3 psu; R^2 = 0.35, p < 0.05
Methane
Salinity
Middle: threshold = 5 cm; R^2 = 0.23, p < 0.05
Methane
Water level
Lower: threshold = 3 psu; R^2 = 0.36, p < 0.05
Methane
Salinity
Lower: threshold = 5 cm; R^2 = 0.23, p < 0.05
Methane
Water level
Marsh: threshold = 3 psu; R^2 = 0.33, p < 0.05
Methane
Salinity
Marsh: threshold = 5 cm; R^2 = 0.27, p < 0.05
Methane
Water level

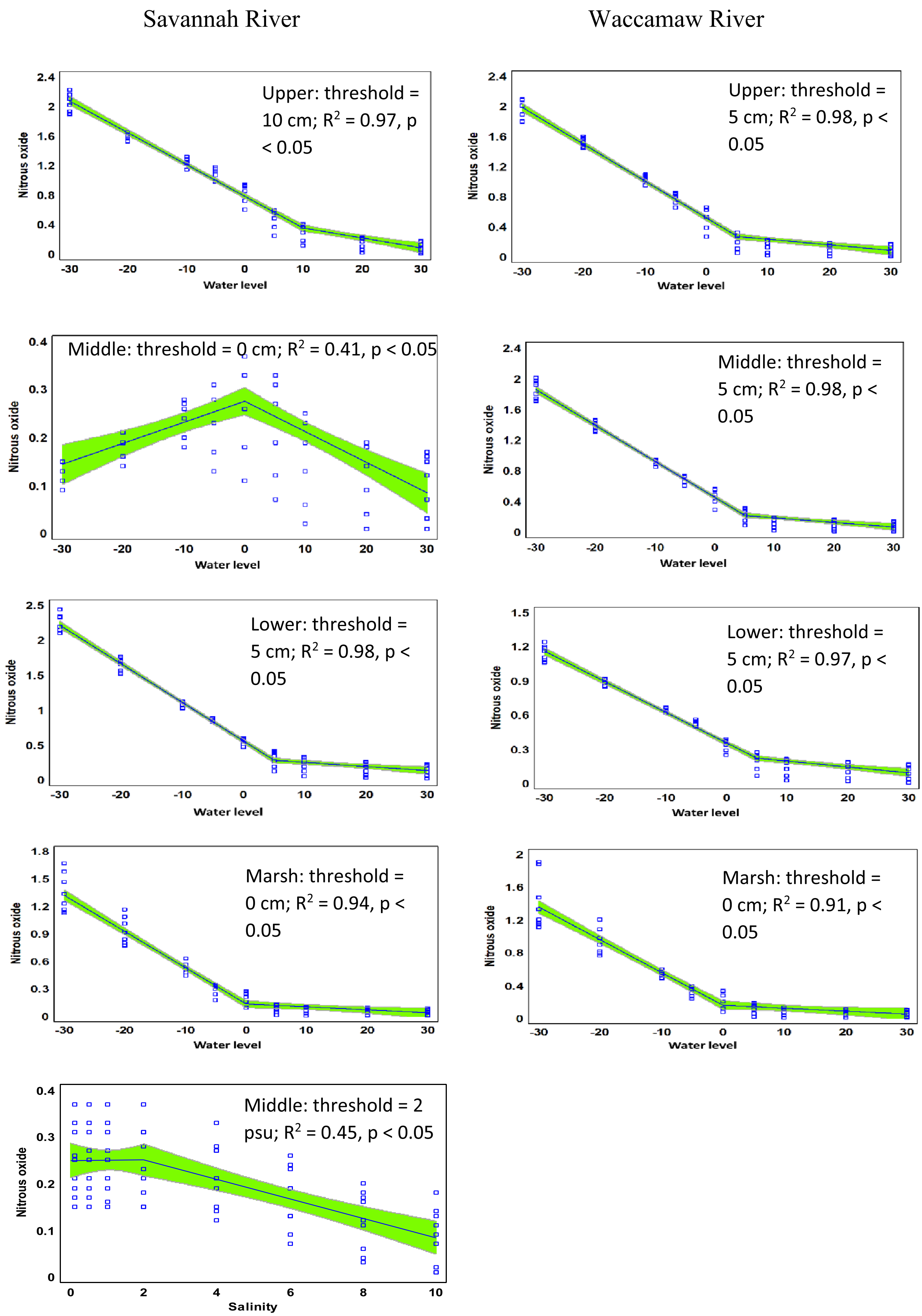
◂**Fig. 5** Relationships between CH_4 emission (kg C ha^{-1} yr^{-1}) and soil salinity (psu) and water level (cm) in low salinity tidal wetlands along the Waccamaw River. At all Waccamaw tidal forest and oligohaline marsh sites, thresholds of both soil salinity and water level were estimated using piecewise linear regression model. Green areas with piecewise linear regression denote 95% confidence limits

Villa et al. 2020). But water level (flooding and non-flooding) is found to be another critical factor in controlling wetland CH_4 emissions (Wang et al. 2017a; Gutenberg et al. 2019; Wang et al. 2021) and should be considered in explaining CH_4 variations and determining thresholds in low salinity tidal wetlands. Alternatively, the lower magnitude and large range of CH_4 emissions found in this study compared to others could be due to the slightly higher elevation in the tidal frame that tidal freshwater forests occupy, compared to tidal marshes that occur 10-20 cm lower at the same locations in tidal rivers (Kroes et al. 2023). Tidal freshwater forests are less often inundated by tides than tidal marshes, generating high variability in GHG emissions. Additionally, our modeling study confirms that there is less CH_4 variation in tidal wetlands with salinity 5-10 psu. Furthermore, the combined effects of soil salinity and water level tended not to be additive and subtractive of individual effects due to the nonlinear relationships between soil organic matter carbon mineralization and at least one stressor from soil salinity and water level (Wang et al. 2023b).

For soil CO_2 emissions, water level thresholds in the range of -10 (groundwater) to 5 cm above surface were estimated for the tidal forest and oligohaline marsh sites. Water level played a more important role (> 80%) than soil salinity on soil CO_2 emissions. This study is consistent with previous studies in which water level was found to affected CO_2 emissions more than salinity with decreased CO_2 emissions under flooded condition resulting from decreased oxygen and low redox potential (Krauss and Whitbeck 2012; Liu et al. 2017; Zhao et al. 2020). Reduced CO_2 emissions with increasing salinity could be explained by the reduced microbial activity and metabolism as well as the decrease in microbial community size and soil enzyme activity (Marton et al. 2012; Chambers et al. 2011). Although soil CO_2 emissions decreased with increasing soil salinity and there is a salinity × water level interaction (df = 287, $p < 0.0001$, Appendix S2: Table S2), thresholds of salinity were not detectable for tidal forest and oligohaline marsh sites along the two rivers, suggesting that interactions of two stressors do not necessarily lead to threshold detection of both stressors. Our modeling simulation results indicate that soil salinity indeed affects the magnitude of the responses and the thresholds of water level on soil CO_2 emissions.

Production of CO_2 and CH_4 together from tidal wetland soils is the result of total anaerobic carbon mineralization in which CO_2 production is dominant (Neubauer et al. 2013). Water level thresholds from -5 cm (groundwater) to 5 cm above surface influenced soil CO_2/CH_4 ratios at six of the eight tidal forest and oligohaline marsh sites, with increasing CO_2/CH_4 ratios when water level falls below that threshold near the soil surface, suggest that water level plays an important role in controlling carbon dioxide and methane emissions from LSTW as its role in other types (e.g., non-tidal peat soils) of wetland soils (e.g., Moore and Knowles 1989). In this study, soil CO_2/CH_4 ratios at Savannah lower and Marsh sites could reach as high as 1887 (mass-based ratio, = 686 molar-based ratio) under a soil salinity of 4 psu, suggesting that CO_2 production is the dominant gas emitted from LSTW soils under anaerobic condition with increasing salinity > 2 psu. Previous studies also found that even modest increases in salinity (at 2 psu) for freshwater marsh soils increased CO_2 production and decreased CH_4 production in tidal freshwater marshes with highest soil CO_2/CH_4 ratio of 1626 (molar-based) (Neubauer et al. 2013). Soil CO_2/CH_4 ratio is highly indicative of overall redox status and presence of alternative electron acceptors. Soil CO_2/CH_4 ratios larger than 1000 at Savannah Middle forest site could be explained by the larger available soil organic carbon at this site than other sites (Wang et al. 2022) as terminal electron acceptors for hydrolysis, fermentation, and methanogenesis (Neubauer et al. 2013). Clear soil salinity thresholds for CO_2/CH_4 ratio at Savannah middle and marsh sites could be attributed to relatively higher soil $NH4^+$-N and pH at these two sites ($NH4^+$-N: 0.136 and 0.079 µmol N cm^{-3}; pH: 5.0 and 4.7) than other forest and marsh sites (e.g., $NH4^+$-N: 0.066 and 0.058 µmol N cm^{-3}; pH: 4.6 and 4.0 at Waccamaw middle and marsh sites) (Noe et al. 2013). It was found that for tidal wetland soils, both CH_4 and CO_2 emissions were negatively correlated with $NH4^+$-N, but positively correlated with soil pH (e.g., Wang et al. 2017a). In conclusion, C metabolic pathways and CO_2 and CH_4 emissions clearly, and not surprisingly, depend on both water level and salinity in LSTW.

In this study, N_2O emissions were found to be affected by both water level and soil salinity only at the Savannah middle forest site ($R^2 = 0.41$, $p < 0.05$ for water level and $R^2 = 0.45$, $p < 0.05$ for salinity, Fig. 6). Under flooding conditions, high salinity reduced the peak of N_2O emission rate (e.g., Liu et al. 2017). But for most of the tidal forest and oligohaline marsh sites, there tended to be no clear relationship between salinity and N_2O emission that is consistent with other studies and can be explained by both enhancement and inhibition of nitrification and denitrification by salinity (e.g., Krauss and Whitbeck 2012; Wang et al. 2017a; Ardón et al. 2018; Korol and Noe 2020). Instead, soil water level is a critical limiting factor on N_2O emission. Continuous flooding limited the availability of oxygen in soils, reducing nitrification (e.g., Liu et al. 2017). Under drier conditions, oxygen can penetrate into soils, influencing microbial processes, including substrate availability and microbial cell


Savannah River
Waccamaw River
Upper: threshold = 10 cm; R2 = 0.97, p < 0.05
Upper: threshold = 5 cm; R2 = 0.98, p < 0.05
Middle: threshold = 0 cm; R2 = 0.41, p < 0.05
Middle: threshold = 5 cm; R2 = 0.98, p < 0.05
Lower: threshold = 5 cm; R2 = 0.98, p < 0.05
Lower: threshold = 5 cm; R2 = 0.97, p < 0.05
Marsh: threshold = 0 cm; R2 = 0.94, p < 0.05
Marsh: threshold = 0 cm; R2 = 0.91, p < 0.05
Middle: threshold = 2 psu; R2 = 0.45, p < 0.05
Nitrous oxide
Water level
Salinity

◂**Fig. 6** Relationships between N_2O emission (kg N ha^{-1} yr^{-1}), soil salinity (psu) and water level (cm) in low salinity tidal wetlands along the Savannah River and Waccamaw River. Water level thresholds were estimated for all tidal forest and oligohaline marsh sites using a piecewise linear regression model. Soil salinity threshold was estimated for only Savannah middle site. Green areas with piecewise linear regression denote 95% confidence limits

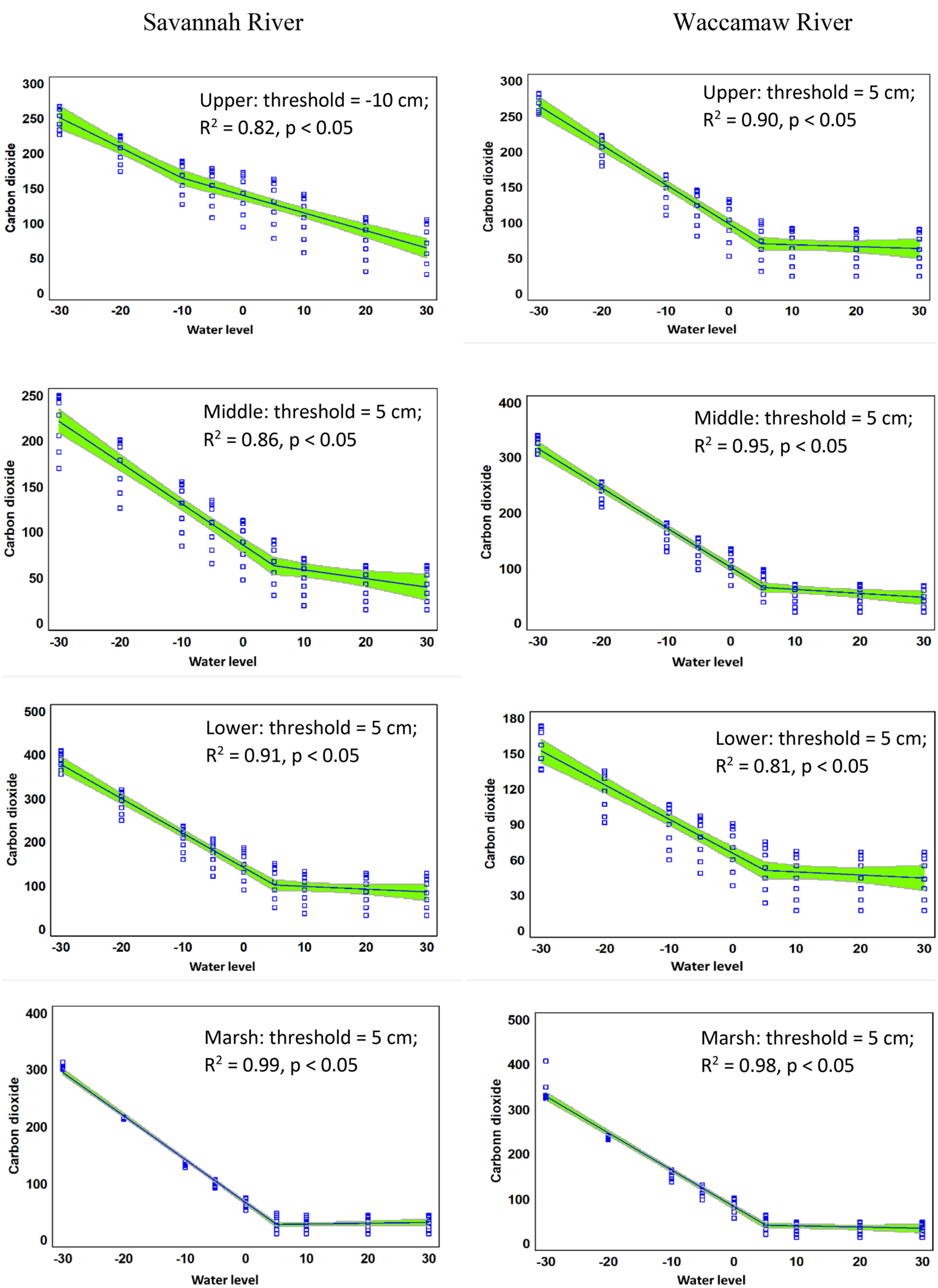
physiology, and soil physical properties, thus enhancing N_2O emission and increasing soil N losses (Liu et al. 2017).

Soil Salinity Thresholds for Both Structural and Functional Changes

Our second key finding is that a soil salinity of 2-3 psu is the tipping point for ecosystem level functional changes in low salinity tidal swamp forests. Our study showed that salinity is the most limiting factor for tree growth with an inverse relationship with NPP at TFFW forest sites along the Savannah and Waccamaw Rivers that is consistent with prior studies (e.g., Krauss et al. 2009; Cormier et al. 2013; Pierfelice et al. 2015; Thomas et al. 2015; Liu et al. 2017). For example, Pierfelice et al. (2015) found that litterfall, woody biomass, and fine roots all decreased from the swamp forest sites along the Waccamaw River with an increasing salinity gradient. Although dominant species in the middle and lower forest locations along tidal rivers in the South Atlantic coast (e.g., baldcypress) can tolerate salinity up to 5 psu (e.g., Day et al. 2007), the NPP thresholds were estimated to be 3 and 2 psu for the Savannah and Waccamaw forested sites, respectively, suggesting that their NPP will be reduced dramatically when salinity > 2 psu. For tidal swamp forests along the Savannah River, once the soil salinity threshold of 3 psu is exceeded, NPP decreased by 21%, 35%, and 30% relative to salinity = 0 condition for the upper, middle, and lower forests, respectively. NPP could decline by > 75% for the middle and lower forests where soil salinity was predicted to be > 7 psu under drought conditions (Wang et al. 2020). NPP decreased by 11%, 12%, and 16% relative to salinity = 0 condition when soil salinity threshold of 2 psu was exceeded for the upper, middle, and lower forest along the Waccamaw River. For the Waccamaw tidal swamp forest, NPP could decline by > 60% for the middle and lower forests where soil salinity was predicted to be > 6 psu under drought conditions (Wang et al. 2020). The dramatic decrease in NPP in forest sites with soil salinity in exceedance of the 2-3 psu thresholds can be explained by reduction in photosynthesis as reflected by reduction of sapflow under salinity stress (Krauss and Duberstein 2010) and nutrient stress particularly of P when salinity exceeds the salinity threshold, resulting in inhibition of nutrient uptake (e.g., Zhai et al. 2018). A lower salinity threshold (2 psu) at Waccamaw forest sites than that (3 psu) of Savannah forest site is likely attributed to the higher sensitivity of litterfall and root growth to salinity stress at the Waccamaw forest sites. For example, litterfall values were 334 and 304 g C m^{-2} yr^{-1} under 0.63 and 1.91 psu at Waccamaw middle and lower forest sites whereas litterfall values were 273 and 260 g C m^{-2} yr^{-1} under 1.09 and 3.46 psu at Savannah middle and lower forest sites (Wang et al. 2022). Salinity thresholds for the two oligohaline marsh sites were not detected and mainly due to the relatively high salt tolerance of oligohaline marsh species (e.g., Wang et al. 2022).

The 2-3 psu salinity threshold has an ecological importance for structural changes in tidal swamp forests under increased salinity conditions due to saltwater intrusion from droughts and sea level rise. It was found that mean salinity levels approaching 2 psu represent an important threshold for vegetation community type change from the freshwater tidal forests to oligohaline marsh (Hackney et al. 2007; Cormier et al. 2013; Thomas et al. 2015). Significant ecological functional changes (here NPP reduction) tended to be a prerequisite for structural changes. It was found that salinity could substantially reduce dissolved organic carbon export from TFFW to nearby estuaries through changes in plant productivity under drought-induced salinity increase before major changes in plant community composition occur (Ardón et al. 2016). Salinity of > 3 psu with duration > 20 days was found to change species composition shifting to more salt-tolerant species, reducing species richness and aboveground biomass of freshwater marshes (Li and Pennings 2019). Baldwin and Mendelson (1998) found that biomass of *Sagittaria lancifolia*, a common species in fresh and intermediate marshes and a major species in herbaceous communities of the middle and lower forest sites, and the species richness of the marsh community were both substantially reduced by salinity in disturbed mesocosms (i.e., clipped aboveground vegetation), but not in the absence of disturbances. It was concluded that disturbance is an important component of vegetation change in response to rising sea level, catalyzing rapid shifts in vegetation structure (Baldwin and Mendelson 1998). For tidal swamp forests, it is the dramatic decline in NPP when soil salinity exceeds the 2-3 psu salinity threshold that triggers a reduction in the number of species present and their flood tolerance, and from live tidal freshwater forest to a ghost forest of dead trees (Kirwan and Gedan 2019). On the other hand, plant community composition changes lead to changes in NPP and GHG emissions via changes in biogeochemical processes as shown in the different responses of NPP and GHG emissions with various thresholds of soil salinity and water level in the forest and marsh sites from this study, confirming the interdependencies between compositional and functional stability of ecosystems (Hillebrand et al. 2020).

In this study, a salinity threshold of 3 psu was also estimated for CH_4 emissions at all sites and 2 psu for CO_2/CH_4 ratios at Savannah lower and marsh sites. Together with the 2-3 psu threshold for NPP, our findings indicate that 2-3 psu is a


Savannah River
Waccamaw River
Upper: threshold = -10 cm;
R^2 = 0.82, p < 0.05
Upper: threshold = 5 cm;
R^2 = 0.90, p < 0.05
Middle: threshold = 5 cm;
R^2 = 0.86, p < 0.05
Middle: threshold = 5 cm;
R^2 = 0.95, p < 0.05
Lower: threshold = 5 cm;
R^2 = 0.91, p < 0.05
Lower: threshold = 5 cm;
R^2 = 0.81, p < 0.05
Marsh: threshold = 5 cm;
R^2 = 0.99, p < 0.05
Marsh: threshold = 5 cm;
R^2 = 0.98, p < 0.05
Carbon dioxide
Carbonn dioxide
Water level

◂**Fig. 7** Relationships between CO_2 emission (g C m^{-2} yr^{-1}) and soil water level (cm) in low salinity tidal wetlands along the Savannah River and Waccamaw River. Water level thresholds were estimated using a piecewise linear regression model. Although soil salinity affects CO_2 emission, no salinity thresholds were estimated due to the absence of slope change. Green areas with piecewise linear regression denote 95% confidence limits

tipping point for not only plant community type or composition change (e.g., Hackney et al. 2007; Krauss et al. 2009; Liu et al. 2017), but also for forest productivity reduction and shifts in allocation of primary productivity among different components (trees, herbaceous and roots under salinity stress within that community through altered protein synthesis, photosynthesis and lipid metabolism) (Pierfelice et al. 2015), and thus the carbon biogeochemical processes in LSTW. In the present study, we used simulated annual soil salinity and water level (not acute salinity and water level pulses) to explore the thresholds of soil salinity and water level on NPP. We found that water level is not a critical limiting factor on NPP at forest sites that is consistent with Thomas et al. (2015) who found that soil moisture is generally not a limiting factor for swamp trees. It should be noted that within-year hydrological variations are not included in the threshold detection. It was found that flood duration and frequency play important roles in maintaining forest productivity during drought by interacting with soil salinity (Cormier et al. 2013). Cormier et al. (2013) found that litterfall was highest on sites with lowest flood durations along with lowest flood frequency. Given the understanding from the present study on thresholds of annual soil salinity and water level in LSTW, thresholds of seasonal soil salinity and water level on ecosystem processes including productivity and CH_4 emissions warrant further study. It should be noted that our thresholds were estimated based on annual mean soil salinity and water level from two years of simulations of ecosystem processes in responses to changes in hydrology and salinity and their interaction. Therefore, the long-term (multiple year) effects of salinity and water level conveyed in these simulation results may not be consistent with the effects of shorter-term (seasonal, monthly, or daily) variations in the same variables. For example, our finding of decreased CH_4 with increasing salinity for oligohaline marsh sites is consistent with the results of a 3.5-year field experiment in Neubauer et al. (2013) but different from others who found increased CH_4 fluxes from short-term lab incubation experiments from accelerated sulfate reduction (Chambers et al. 2011; Weston et al. 2011; Ardón et al. 2018) in which vegetation was excluded in the experimental design (Weston et al. 2011).

Critical Water Levels for Ecosystem Functional Changes

Our third key finding is that a soil water level from 10 cm below soil surface (groundwater) to 10 cm above the soil surface is a critical range in which biogeochemical processes respond strongly to hydrological regime changes, generating water level tipping points on ecosystem functions for LSTW. In the present study, CH_4 emissions were found to increase dramatically (2 -19 times) with water level from -5 to 0 cm relative to soil surface (or 5 cm below surface to soil inundation at surface), maximum CH_4 emissions occurred when soil was inundated between 5- 10 cm (also required low salinity close to 0.1 psu), and CH_4 emissions were reduced when soil water level was 10 cm above surface, but completely suppressed when soil water level was 10 cm and 5 cm below surface for tidal swamp forests and oligohaline marshes. The water level threshold for CO_2 emissions was estimated to be 5 cm above soil surface (except the -10 cm for the Savannah upper forest site) and CO_2 emissions declined dramatically (- 65% to - 90%) once the threshold was exceeded. In addition, 10 cm below soil surface was estimated to be the water level tipping point for NPP at oligohaline marshes and water level thresholds for N_2O emissions were in the 0-10 cm above soil surface.

Previous studies also found that soil water level 10 cm below and 10 cm above the soil surface is a critical range for GHG emissions in LSTW. Kelley et al. (1995) found that CH_4 flux peaked at around 80 mg CH_4 m^{-2} day^{-1} just as incoming tidal level reached the soil surface and decreased considerably as soil surface water depths increased to 20 cm (to ~45 mg CH_4 m^{-2} day^{-1}) along the White Oak River, North Carolina, USA. The water level of -5 to 0 cm relative to soil surface is consistent with other studies (Gutenberg et al. 2019; Zhao et al. 2020; Wang et al. 2021). For example, highest CH_4 emissions were found when water level stayed above -5 cm in non-tidal swamps (e.g., the pocosin site in the Great Dismal Swamp in the Coastal Plain region between southeastern Virginia and northeastern North Carolina, Gutenberg et al. 2019) and in Pocosin Lakes National Wildlife Refuge in the east coast of North Carolina, Wang et al. 2021). It was found that 5-10 cm below soil surface is a zone of low rates of methane production and deep oxidizing leading to high CH_4 oxidation efficiency and rapid decline in CH_4 emissions in tidal swamp forest soils (Megonigal and Schlesinger 2002). The water level threshold for CH_4 emissions (-5 to 0 cm below soil surface) can be explained by the downward infiltration of fresh carbon and substrate for methane production, transport, and oxidation that are affected by plant community, root depth, root exudates and the upward moving of dissolved humic substance as an alternative electron acceptor when water level rises (e.g., Luo et al. 2019; Wang et al. 2021). The methanogens become active and more CH_4 is produced by methanogens than consumed by methanotrophs when the water levels exceed a depth threshold (Wang et al. 2021). Zhao et al. (2020) found that cumulative soil CH_4 emission was positively correlated to soil organic carbon and total carbon, suggesting that carbon component can supply energy and nutrients and benefit for soil CH_4 production.

Table 1 Thresholds of soil salinity and water level on NPP and GHG emissions in tidal freshwater forest and oligohaline marsh sites along the Savannah and Waccamaw Rivers

Thresholds	**NPP**	**CH_4**	**N_2O**	**CO_2**
Salinity thresholds	For Savannah tidal swamp forests: **3** psu; for Waccamaw tidal swamp forests: **2** psu. NPP is reduced when salinity is in exceedance of thresholds. NPP is not affected by salinity at oligohaline marshes.	For all tidal swamp forest and oligohaline marsh sites: **3** psu. CH_4 emission is inhibited when salinity exceeds threshold.	Only for Savannah middle forest: **2** psu. N_2O emissions is inhibited when salinity exceed threshold. N_2O emissions are not affected by salinity at other forest and oligohaline marsh sites.	For all tidal swamp forest sites: CO_2 release is inhibited with increasing salinity, but a clear threshold is not detected. CO_2 is not inhibited by salinity for oligohaline marshes.
Water level thresholds	Only for oligohaline marshes: **10 cm** below soil surface (when soil water level below soil surface is less than **10** cm, NPP is significantly reduced). NPP is not affected by water level for tidal swamp forests.	For all tidal swamp forest and oligohaline marsh sites except Savannah middle forest: **-5 to 10 cm** below soil surface. CH_4 emits when soils are close or at inundation. When water level below soil surface is larger than **10** cm, no CH_4 emissions occur.	For upper forest sites: **10** cm, for lower forest sites: **5** cm, for oligohaline marsh sites: **0** cm from soil surface, N_2O emissions are inhibited. For Savannah middle forest site: **0** cm, for Waccamaw middle forest site: **5** cm.	For all tidal swamp forest and oligohaline marsh sites: **5** cm except Savannah upper forest site (**-10** cm).
Salinity × water level thresholds	There is no interaction between salinity and water level for NPP thresholds	Salinity threshold on CH_4 emission is dependent on soil water level and is active only when water level below soil surface is less than **5** cm (or towards inundation). Maximum CH_4 emissions occur when soil salinity is close to **0.1** psu and soil is inundated around **10** cm depth. Salinity affects CH_4 emission more than water level.	Only for Savannah middle forest: inhibition of N_2O when salinity exceeds **2** psu occurs at water depth between **-5** and **5** cm.	For tidal swamp forests, reduction of CO_2 at soil inundation depth is larger than **5** cm, synergistic effects from both water level and soil salinity. Water level affects CO_2 release more than salinity. There is no interaction between salinity and water level for oligohaline marshes.

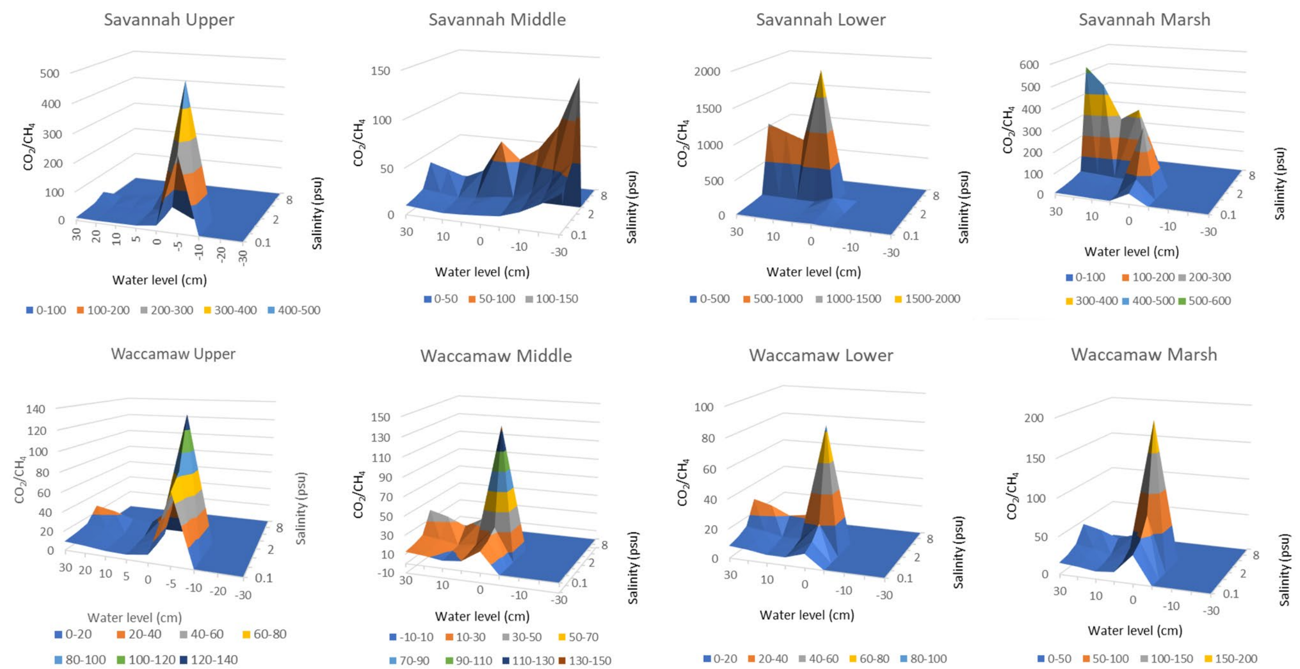


Fig. 8 Surface plots between soil CO_2/CH_4 ratio and soil salinity and water level in low salinity tidal wetlands along the Savannah River and Waccamaw River. Note: conditions with methane uptake (CH_4 emission < 0) were not included in the estimates of the CO_2/CH_4 ratios

Cumulative CH_4 emissions from tidal wetland soils had a positive relationship with soil moisture at 0-10 cm depth, whereas for CO_2 the relationship was inverse (Zhao et al. 2020). Cumulative soil CO_2 emission was correlated with soil microbial biomass carbon, suggesting that microbial activity played an important role in CO_2 emissions in coastal wetlands (Zhao et al. 2020). The determination of soil water level thresholds for GHG emissions regardless of its interaction with soil salinity thresholds has an important management implication. Although coastal managers could control soil salinity in tidal wetlands by blocking saltwater intrusion with infrastructures such as tidal gates (e.g., Krauss et al. 2009), freshwater diversion from rivers and upper watershed streams and creeks (e.g., Wang et al. 2017b), it is difficult if not impossible to control accurately surface water and soil water salinity within targeted magnitude and duration. In contrast, managers could control water level relatively well to achieve targeted water level through impoundments and other hydrological alterations (e.g., Drexler et al. 2013). Thus, managing water level may be more practical for ecosystem-based management towards enhancing productivity and carbon sequestration and reducing GHG emissions and carbon loss for climate change mitigation in low salinity tidal wetlands.

Absence, Presence, and Variance of Salinity and Water Level Thresholds

It is surprising that soil salinity thresholds could not be detected for CO_2 emissions at the tidal forest sites although CO_2 emissions decline with increasing soil salinity. The absence of salinity tipping points for soil CO_2 emissions in this study is not evidence of absence of salinity threshold in all LSTW. The setting of 0.1, 0.5, 1, 2, 4, 6, 8, 10 psu especially the low range < 2 psu may not be fine enough to detect rapid changes in soil respiration and associated CO_2 emissions for LSTW with low level of salinity impact. It was found that the responses of CO_2 emissions to salinity and water level varied greatly in this study (Appendix S1: Figs. S1 to S8) and such highly variable responses could preclude the detection of ecological thresholds even they exist due to the variance noise (Hillebrand et al. 2020). For the same reason, the presence and magnitudes of detected salinity and water level thresholds in this study may not be generalized for all LSTW. In this study, we used breakpoint-based, nonlinear (but can be piecewise linear), continuous relationships between response and explanatory variables with slope change approach to detect tipping points in soil salinity and water level. On one hand, the model simulation results did not provide within-site variances in NPP and GHG emissions under one set of salinity and water level combinations (or no replicates). Under laboratory experiment and field conditions, variances in the responses of NPP and GHG emissions to the same salinity × water level treatment/set are expected. On the other hand, the changes in the relationships between environmental stressors and ecosystem functions can also be discontinuous (e.g., a step function), or the changes can occur in a narrow transition zone (e.g., Toms and Villard 2015). Therefore, a narrow range

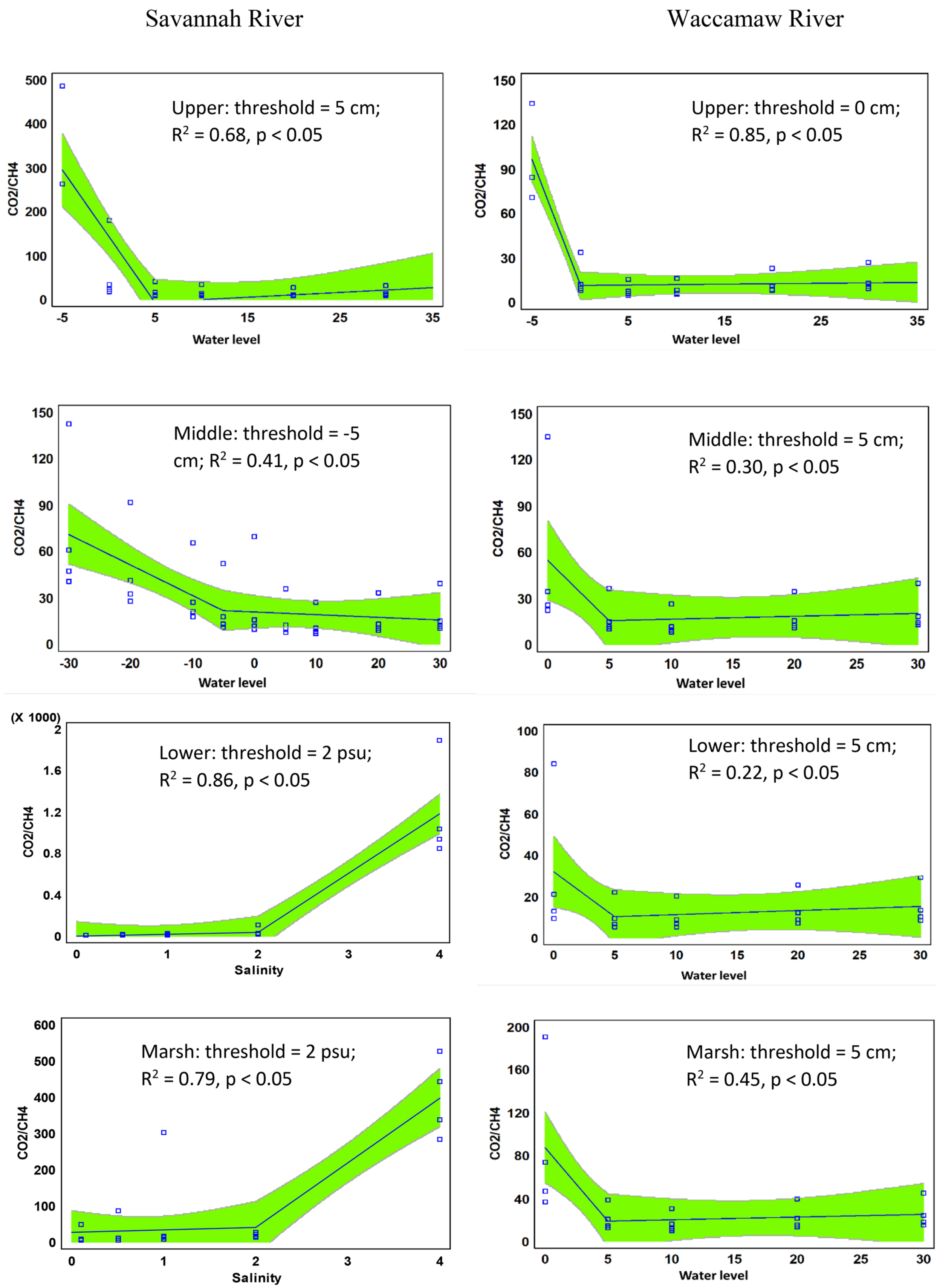

Savannah River
Waccamaw River
Upper: threshold = 5 cm;
R² = 0.68, p < 0.05
Upper: threshold = 0 cm;
R² = 0.85, p < 0.05
Middle: threshold = -5 cm; R² = 0.41, p < 0.05
Middle: threshold = 5 cm;
R² = 0.30, p < 0.05
Lower: threshold = 2 psu;
R² = 0.86, p < 0.05
Lower: threshold = 5 cm;
R² = 0.22, p < 0.05
Marsh: threshold = 2 psu;
R² = 0.79, p < 0.05
Marsh: threshold = 5 cm;
R² = 0.45, p < 0.05
CO2/CH4
Water level
Salinity
(X 1000)

Fig. 9 Relationships between soil CO_2/CH_4 ratio and soil salinity (psu) and water level (cm) in low salinity tidal wetlands along the Savannah River and Waccamaw River. Soil salinity and water level thresholds were estimated using piecewise linear regression model. Green areas with piecewise linear regression denote 95% confidence limits

rather than a single point as ecological thresholds could be more valuable for understanding ecosystem processes and decision-making of best ecosystem-based management actions. Field or laboratory studies on the responses of plant productivity and GHG emissions to salinity, water level and/or other critical stressors could help to confirm the detected salinity and water level thresholds in LSTW by this study.

Conclusions

The thresholds of soil salinity and water level on NPP and GHG (CH_4, N_2O, CO_2) emissions were estimated using a process-driven biogeochemistry model, TFW-DNDC for low salinity tidal wetlands (salinity < 10 psu) which encompasses TFFW and oligohaline marshes. Our results showed that soil salinity and water level interact and work synergistically to determine the responses of CH_4 emissions whereas NPP in tidal swamp forests was mainly influenced by soil salinity and N_2O and CO_2 emissions were mainly influenced by soil water level. Soil salinity and water level were found to have antagonistic effects on CH_4 emissions and synergistic effects on CO_2 release, but soil salinity thresholds could not be determined for CO_2 emissions. The responses of CH_4 to soil salinity change are conditional upon soil water level. Therefore, both soil salinity and water level needed to be included in detecting thresholds for CH_4 emissions and CO_2/CH_4 ratio (at the Savannah lower and marsh sites) whereas single stressor could be used for NPP (salinity) and N_2O and CO_2 (water table) threshold detection. Moreover, it was found that a soil salinity of 2-3 psu is the tipping point for not only the structural change (e.g., community type switch), but also the ecosystem level functional changes (e.g., NPP and CH_4 emissions) in low salinity tidal swamp forest. Furthermore, a soil water level from 10 cm below soil surface (groundwater) to 10 cm above the surface is a critical soil water level range in which biogeochemical processes respond strongly to hydrological regime changes, thus water level tipping points on ecosystem functions could be found from this range for LSTW. Data and information on these specific, nonlinear tipping points of salinity and water level from this study can be used for ecosystem-based management of LSTW that targets enhancement of ecosystem services including carbon sequestration and carbon credit.

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Data Availability The data on which this article is based are available from the following cited reference and URL: Wang, H., K.W. Krauss, G.B. Noe, Z. Dai, and C.C. Trettin. 2023a. Simulated net primary productivity and greenhouse gas emissions under various soil salinity and water table depth combinations in low salinity tidal wetlands. U.S. Geological Survey data release, https://doi.org/10.5066/P9UR522Z.

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