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REVIEW ARTICLE

Between a bog and a hard place: a global review of climate change effects on coastal freshwater wetlands

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Abstract

Coastal wetlands are significant components of the coastal landscape with important roles in ecosystem service provision and mitigation of climate change. They are also likely to be the system most impacted by climate change, feeling the effects of sea levels rise, temperature increases and rainfall regime changes. Climate change impacts on estuarine coastal wetlands (mangroves, saltmarsh) have been thoroughly investigated; however, the impacts on coastal freshwater wetlands (CFWs) are relatively unknown. To explore the current knowledge of the impacts of climate change on CFWs globally, we undertook a systematic quantitative literature review of peer-reviewed published literature. We found surprisingly little research (110 papers of an initial 678), the majority of which was conducted in the USA, focusing on the effects of sea level rise (SLR) on CFW vegetation or sediment accretion processes. From this research, we know that SLR will lead to reduced productivity, reduced regeneration, and increased mortality in CFW vegetation but little is known regarding the effects of other climate change drivers. Sediment accretion is also not sufficient to keep pace with SLR in many CFWs and again the effects of other climate drivers have not been investigated. The combination of unhealthy vegetation communities and minimal gain in vertical elevation can result in a transition towards a vegetation community of salt-tolerant species but more research is required to understand this process.

Keywords Coastal swamp · Sea level rise · Tidal freshwater wetland · Floodplain · Tidal marsh

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1 Introduction

Coastal wetlands, alongside alpine and arctic systems, and tropical coral reefs, are widely considered to be ecosystems most threatened by climate change (IPCC 2014; Schuerch et al. 2018). Rising sea levels can cause shifts in wetland vegetation towards dominance by more salt-tolerant species (e.g. mangroves), resulting in an inland migration of vegetation communities where an absence of physical barriers permits (Morris et al. 2002; Raabe and Stumpf 2016; Schuerch et al. 2018). Changes in rainfall patterns are also expected, with longer dry periods likely to further exacerbate impacts of saline intrusion (IPCC 2014). Additionally, anticipated increases in the frequency and intensity of extreme climatic events (e.g. cyclones, storm surges, and floods), may significantly, sometimes permanently, alter the structure and processes of many coastal wetlands along with the ecosystem services these provide (IPCC 2014; Middleton 2016a; Middleton 2016b). Furthermore, changing atmospheric gas concentrations will alter coastal wetland productivity, shifting systems from carbon sinks to sources of emissions as rates of decomposition and methanogenesis outstrip the carbon storage capacity of vegetation and soil biomass (Krauss et al. 2018). Given the significant effects of climate change anticipated, there is an urgent need to understand the responses of coastal wetlands to inform the development of effective adaptation strategies.

Most research investigating effects of climate change on coastal wetlands has focused on saline ecosystems (i.e. mangrove and salt marshes), which support many critical ecosystem services in coastal regions including habitats for fisheries, carbon sequestration, and storm mitigation (Mitsch and Gosselink 2015). Coastal freshwater wetlands (CFWs) are similarly valuable in terms of their provision of critical ecosystem services but have been relatively understudied (Saintilan et al. 2018). Given the high vulnerability of CFWs to climate change, as well as the concentrated anthropogenic pressures these wetlands typically face in the coastal fringe, there is an urgent need to better understand the risks faced by these overlooked ecosystems.

Here, we define CFWs as freshwater wetlands that exist on coastal plains which have the potential to be impacted by saline intrusion, either by overland flows (e.g. storm surges and king tides) or by rising saline groundwater (Grieger et al. 2019). Globally, CFWs are referred to using various typologies which differ according to their local hydrological and vegetation conditions. In North America, for example, CFWs are often known as tidal freshwater forested wetlands (TFFWs) or tidal freshwater marshes (TFMs), which occur in the upper tidal reaches of estuarine systems where water levels fluctuate with tides but salinity is generally less than 0.5 g/L (Cowardin 1979). TFFWs in the USA and tidal várzeas in Central and Southern America generally exist in catchments with broad flat coastal plains with large tidal ranges and high riverine discharge (Duberstein and Krauss 2016; Mitsch and Gosselink 2015; Odum 1988). Where river discharges are lower, coastal plains often support larger areas of estuarine wetlands compared to CFWs which, in such situations, are typically more dependent on rainfall and fresh groundwater than riverine freshwater or tidal flows (Rogers et al. 2017; Saintilan et al. 2018).

Ecological functions of CFWs remain poorly understood even though their importance and function has been a key research focus in North America and, increasingly, in Australia (Conner et al. 2007). In the USA, CFWs are rrecognised as important habitat for a large number of threatened and endangered species, many of which rely on wetlands for survival (Baldwin et al. 2009). Similarly, in Australia, coastal wetlands along the east coast are known to be important habitats for a wide range of protected fauna and flora (Traill et al. 2011), including many colonial and migratory waterbirds (Wilson et al. 2011). There is also growing recognition of the many important ecosystem services provided by CFWs including nutrient cycling (Ensign et al. 2008; Hopfensperger et al. 2009; Loomis and Craft 2010; Von Korff et al. 2014), carbon sequestration (Krauss et al. 2018; Loomis and Craft 2010; Marin-Muniz et al. 2014), and flood and storm mitigation (Doyle et al. 2007; Middleton 2009).

In this review, we synthesise current knowledge of the effects of climate change on CFWs globally and identify major knowledge gaps and research priorities. First, we provide a stocktake of existing scientific literature on CFWs, describing the spatial and temporal distribution of published studies and the wetland types, research focus and methods employed by these. Second, we explore the observed responses of CFWs in these studies to key climate change drivers to detect trends in reported observations. Third, we explore the findings of experimental studies that have examined responses of CFWs to key climate change drivers. We also examine the application of models to predict responses of CFWs to climate change. Finally, we provide a synthesis of key findings and highlight major management and research priorities.

2 Methods

2.1 Search methodology

We conducted a systematic quantitative literature review to synthesise current knowledge of climate change effects on CFWs. This rigorous, comprehensive method allows reproducibility with clearly defined rules for inclusion and exclusion of literature (Pickering and Byrne 2014). Searches of peer-reviewed literature in English were conducted in the online repositories *Thompson ISI Web of Science* and *Scopus* in November 2017 and updated in February 2020 to capture all relevant research published before 2020. The following search terms were used to capture literature relating to coastal freshwater wetlands; “coastal wetland”, “coastal marsh”, “coastal swamp”, “coastal forest”, “coastal floodplain wetland”, “tidal freshwater marsh”, “tidal freshwater wetland”, and “tidal freshwater forest”. The specific term “coastal freshwater wetland” was not included in this list as there is not currently a clear definition of CFWs which is used globally. Hence, a broader search was conducted to identify papers specifically relating to CFWs as well as papers examining a range of wetlands including CFWs. A second set of search terms, separated from the first by the AND operator, was used to identify literature within the first set specifically relating to climate change; “climate change”, “global warming”, and “sea level rise”.

Publications returned from searches were then screened for inclusion in a shortlist based on the abstract. Papers were excluded if they were solely literature reviews or methodological studies, did not relate to contemporary climate change (i.e. papers examining responses to SLR in the geological past), or only concerned saline/estuarine systems (i.e. papers which included brackish marshes along a gradient from fresh-to salt-water were included). Reference lists of review papers were also searched so that any relevant literature not captured in previous searches was also included in the database.

2.2 Data classification

The remaining short-listed papers were read in their entirety, with specific information entered into an Excel database on (I) citation information, (II) study location, (III) study duration, (IV) wetland type, (V) methods used, (VI) attribute of CFWs examined, (VII) aspect of climate change investigated, and (VIII) response of attribute to climate change (Supplementary Material 1).

2.3 Data synthesis and visualisation

To identify the spatial distribution of global CFW research, the location of each reviewed study was plotted on a world map and the percentage of publications from each continent was calculated. To visualise publication output over time the number of annual publications regarding key components of climate change (i.e. temperature increase, extreme events, altered rainfall patterns) was calculated and plotted as a stacked bar graph. Variation in research methodologies was investigated by calculating the number of papers in each broad methodology category (observational, experimental, modelling) and identifying the most common methods used within these. To identify which key aspects of climate change current research has concerned, the sum of publications in each category was calculated and visualised this using an area proportional Euler diagram (eulerr package in R; Larsson (2018)). Finally, the major research findings of each aspect of climate change were also synthesised within each broad methodology category.

3 Results

Note: Short-listed papers will be referenced by numbers throughout the results section with the full references included in supplementary material 2 (S2).

3.1 Stocktake of research into climate change effects on CFWs

From an initial list of 678 papers, we identified 110 peer-reviewed original research papers that fit the search criteria. Of these, the majority of studies were conducted in the subtropics (78.4%), specifically in the USA (77.4%) where majority was from the east coast (Fig. 1.), with only 7.2% from Europe, 5.4% from Asia and 4.5% each from Australia, and South America (Fig. 1), and only one study (S2 61) conducted across multiple continents.

Publication output was greatest between 2010 and 2019 inclusive (~ 82%), after the first publication appeared in 1992 (Fig. 2.). Significantly, the greatest publication output occurred in 2019 with 20 papers published. Most studies (~ 66%) reported on research conducted over short time scales, i.e. < 1-year up to 3 years. Only 33% of papers investigated CFW responses to climate change over longer time frames (3–10 years and > 10 years), mostly within the USA (29 papers) but with some longer term studies from Australia (S2 10; 13), the Netherlands (S2 90; 91), Puerto Rico (S2 72; 108), and China (S2 93; 110). Papers presenting long-term data are identified in the supplementary material by an asterisk (S2).

Research on CFW responses to climate change generally focuses on three attributes: (I) soil processes, such as nutrient cycling and microbial dynamics (47 papers); (II) sediment accretion and carbon sequestration (39 papers); and (III) vegetation distribution and function (73 papers). Much less research attention is given to fauna (S2 15; 18; 45; 85) and hydrological responses to climate change (eight papers).

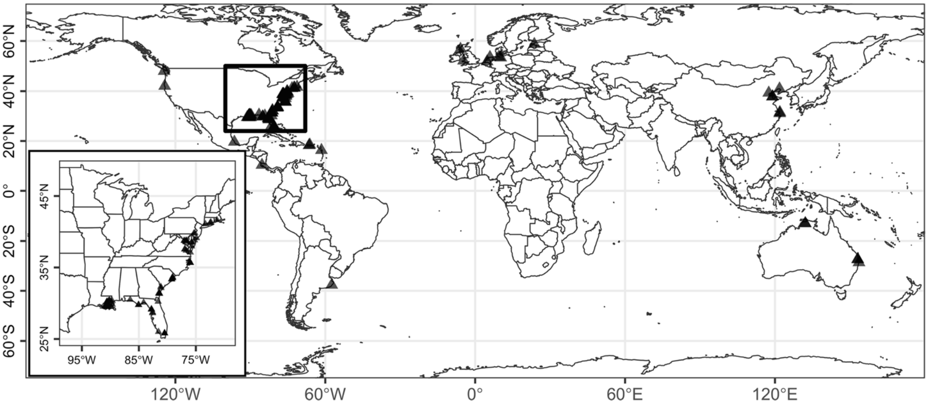

Fig. 1 Map showing study location of reviewed papers. Inset map of eastern USA, no data is lost under inset map

3.1.1 Aspects of climate change

Five main aspects of climate change are examined in the short-listed studies: (1) SLR, (2) altered rainfall regimes, (3) temperature changes, (4) extreme events, and (5) changes in atmospheric greenhouse gases (CO_2 and CH_4). Amongst papers only considering a single aspect of climate change, effects of SLR on CFWs have received significantly greater research attention (68 papers) compared to altered rainfall (six papers), extreme events (four papers; S2 57; 58; 79; 87), greenhouse gasses (S2 60), and temperature (Fig. 3, S2 86; 110). Twenty-eight papers considered combined threats of climate change, most commonly the interaction between SLR and altered rainfall regimes (Fig. 3). Eight papers investigated the effects of

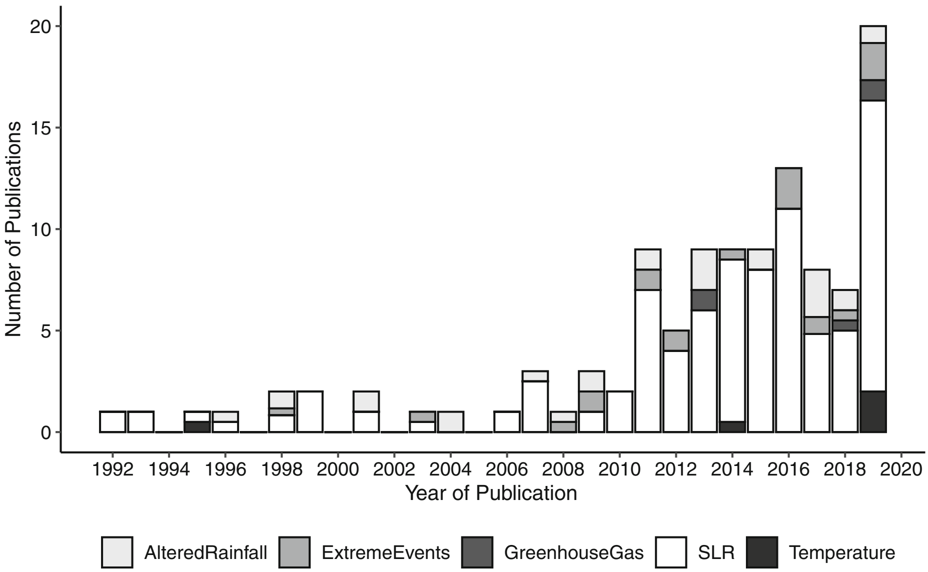

Fig. 2 Number of publications per year of coastal freshwater wetland literature showing the temporal distribution of research into each aspect of climate change

SLR and extreme events, while three papers investigated the triple threat of SLR, altered rainfall, and extreme events (S2 9; 96; 104). Authors rarely investigated the combination of SLR and changes in temperature (S2 35; 56), greenhouse gas changes and SLR (S2 29; 43; 51), and altered rainfall and extreme events (Fig. 3, S2 47; 69).

3.1.2 Research methodologies

Methods used to investigate climate change impacts on CFWs are commonly (I) observational, i.e. field surveys, long-term monitoring (43 papers); (II) experimental, i.e. in-situ manipulations, mesocosms, laboratory soil analysis, etc. (58 papers); or (III) modelling, i.e. distribution change over time, future projections based on current data (30 papers). Twenty-four shortlisted papers used a combination of methods. Observational studies mainly assessed changes in vegetation distribution, structure, and composition over time in response to SLR (30 papers). Experimental methods generally assessed responses of vegetation and soil processes to a range of flooding, salinity, warming, nutrient enrichment, or disturbance treatments (26 papers). Projections of vegetation distribution and wetland coverage were explored through various modelling methodologies (18 papers). A list of all review publications grouped by research methodology is provided in Table 1.

3.2 Observed effects of climate change on CFWs

3.2.1 Sea level rise

Long-term effects of SLR on CFWs are not thoroughly investigated for systems outside of southeastern USA. Within this area, however, effects of rising sea levels have been observed for several decades through long-term vegetation monitoring programs and SET monitoring systems, investigating the influence of SLR on multiple aspects of wetland systems including

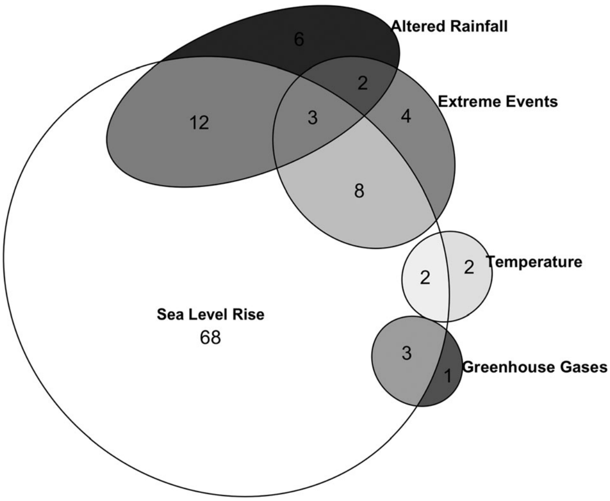

Fig. 3 Area proportional Euler diagram showing the number of papers reviewed for each aspect of climate change with the number of papers investigating multiple aspects shown where the circles overlap

Table 1 Summary of short-listed publications grouped by broad methodology and its variations

Data collection method (number of papers)	Study focus	Reference (publication number in supplementary material 2)
Observational (21)	Vegetation	Anderson and Lockaby (2013; 3), Canepuccia et al (2009; 18), Cormier et al (2013; 22), Delgado et al (2018; 26), Ensign et al. (2014; 31), Hoeppner et al (2008; 47), Langston et al. (2017; 52), Liu et al (2017; 54), Wang et al (2019; 94), Weston et al (2014; 97), Williams et al. (1999; 103), Williams et al. (2003; 104)
	Birds	Brittain and Craft (2012; 15), Taillie et al (2019b; 85)
	Fish	Hitch et al (2011; 45)
	Invertebrates	Canepuccia et al (2009; 18)
	Surface elevation monitoring	Cadol et al (2014; 17), Graham and Mendelssohn (2014; 40), Wang et al. (2016; 93)
Experimental (46)	Soil seed bank	Baldwin et al (1996; 8), Middleton (2016; 59), Osland et al (2011; 69), Peterson and Baldwin (2001; 71)
	Vegetated sod	Baldwin and Mendelssohn (1998; 9), Flynn et al (1995; 33), Gao et al (2018; 34), Howard and Mendelssohn (1999; 49), Howard et al (2016; 48), Li and Pennings (2018; 53), Markus-Michalczyk et al (2019; 55), Sharpe and Baldwin (2012; 76), Spalding and Hester (2007; 78), Watson et al (2015; 96), Wilson et al (2019; 105)
	In situ manipulations	Osland et al (2011; 69), Sánchez-Garcia et al (2017; 73), Sutter et al (2015; 83), Sutter et al (2014; 82), Tate and Battaglia (2013; 87), Visser et al (2015; 92)
	Sediment accretion	Beckett et al. (2016; 11), Boyd et al (2016; 14), Charles et al (2019; 19), Craft (2012; 24), Graham and Mendelssohn (2014; 40), Hill et al (2015; 44), Noe et al. (2016; 65), Nyman et al (1993; 67), Nyman et al (2006; 68), Palinkas and Engelhardt (2016; 70)
	Soil chemistry	Ardón et al. (2017; 5), Choi et al. (2001; 21), Craft et al. (2009; 23), Gao et al (2014; 35), Neubauer et al (2018; 64), Noe et al (2013; 66)
Modelling (19)	Sea level affects marshes model	Akumu et al (2011; 1), Geselbracht et al (2011; 36), Geselbracht et al (2015; 37), Glick et al (2013; 38), Traill et al. (2011; 89), Wu et al (2017; 107)
	Digital terrain models and digital landscape elevation models	Bayliss et al (2018; 10), Zhong et al (2011; 109)
	Bayesian belief networks	Field et al (2016; 32)
	Sea level over proportional elevation model	Doyle et al (2010; 30)
	Generalised linear models	Bowman et al (2010; 13), Smith (2013; 77) Van Dobben and Slim (2012; 90)
		McCarthy et al. (2018; 56), Mo et al (2019; 62)

Table 1 (continued)

Data collection method (number of papers)	Study focus	Reference (publication number in supplementary material 2)
	Normalised difference variation index	
	Swamp individual-based tree model	Hoeppner and Rose (2011; 46)
	Hydrodynamic marsh equilibrium model	Alizad et al (2016; 2)
	Wetland accretion rate model of ecosystem resilience	Throne et al (2018; 88)
Mixed–combination of observational, experimental, and modelling methods (24)		Ardon et al (2013; 6), Baldwin et al (2001; 7), Brittian and Craft (2012; 15), Cadol et al (2014; 17), Craft et al (2009; 23), Desantis et al. (2007; 28), Field et al (2016; 32), Grenfell et al (2016; 41), Grieger et al. (2019; 42), Kearney et al. (2019; 50), Krauss et al. (2018; 51), Middleton (2009; 58), Mitsch et al (2013; 60), Neubauer et al (2018; 64), Rivera-Ocassio et al (2007; 72), Smith (2013; 77), Stagg et al (2017a; 80), Stagg et al (2017b; 81), Taillie et al (2019a; 84), Taillie et al (2019b; 85), Van Dobben et al (2012; 90), Whittle and Gallego-Sala (2016; 99), Widney et al (2019; 100), Yu et al (2019; 108)

vegetation composition, structure and function, sediment accretion, nutrient sequestration, and microbial function (e.g. S2 52).

Effects of SLR on accretion Accumulation of organic matter in soil and accretion of sediment is a key factor limiting the capacity of wetlands to maintain position with rising sea levels. For CFWs in the USA, especially TFFWs, observed accretion rates are not sufficient to keep pace with current and projected SLR (Fig. 4, S2 24; 31; 65; 81). Accretion rates in TFMs are slightly higher due to greater belowground biomass of marsh species; however, rates of accretion are still insufficient in the face of current and projected SLR rates (Fig. 4, S2 11; 14; 17; 27; 68; 70). Migration of salt marsh into freshwater marsh areas can raise accretion rates closer to those of SLR; however, this comes at the loss of freshwater marsh vegetation (S2 24; 68). Reported accretion rates within the USA and globally vary based on local SLR rates and climate (Fig. 4.). Accretion rates are generally higher in brackish wetlands or salt marshes compared to TFFWs or TFMs (Fig. 4), and are up to 70% higher in the tidal marshes of Elbe Estuary, Germany, where tidal marshes, but not freshwater wetlands, appear to be keeping pace with local SLR (Fig. 4, S2 16). Historic rates of sedimentation in Estonian coastal wetlands show varied responses to atmospheric pressure and storm surges with increasing sedimentation rates since the 1960s, most likely in response to SLR, recent climate change and loss of sea ice but are also considered to be keeping up with local SLR (S2 95). Freshwater *Phragmites* and *Saueda* wetlands in the Liaohe Delta, China, exhibited overall net increases in accretion rates (0.3 mm year^{-1} to 6.9 mm year^{-1}, compared to SLR 2.4–5.5 mm year^{-1}), suggesting that they could also keep pace with higher sea level conditions, especially for *Phragmites* wetlands which might continue to gain elevation at rates higher than

SLR (S2 93). Comparing accretion rates to rates of global SLR predicted by the IPCC under RCP 8.5 scenario we see that only brackish marsh accretion rates are sufficient to keep pace (IPCC 2013; Fig. 4.).

SLR effects on soil chemical processes and carbon sequestration Most of the papers investigating the effects of SLR on soil chemical processes and carbon sequestration (11 of 13 papers) come from studies in freshwater marshes in the USA. In both TFMs and TFFWs, more frequent and longer saline periods have led to increased nitrogen and phosphorous export (S2 5; 6; 66), stimulated decay of available carbon (i.e. cellulose from litterfall; S2 79), reduced amounts of available litter (S2 22), and increased sulfidization in high iron wetland soils (S2 74). In coastal Scotland, SLR-induced migration of saline communities into coastal peatland areas have reduced carbon accumulation and lowered recent carbon sequestration (S2 99).

The carbon sequestration potential of CFWs is a current research priority globally, receiving significant research attention since 2018. However, the influence of SLR on this capacity is relatively unknown. Krauss et al. (2018; S2 51) highlighted the sequestration importance of TFFWs and oligohaline wetlands which can store an average of 721 Mg C ha^{-1}. Significantly, this is higher than the global estimates for seagrasses (140 Mg C ha^{-1}; Fourqurean et al. 2012) and saltmarshes (162 Mg C ha^{-1}; Duarte et al. 2013) but lower than those for mangroves (856 ± 32 Mg C ha^{-1}, global estimate; Kauffman et al. 2020). Similarly, Weston et al. (2014; S2 97) noted that TFMs can be equally or more productive than salt marshes but exhibit large interannual variability in plant productivity. With an expected expansion of freshwater marshes into inland forested areas in response to climate change, Krauss et al. (2018; S2 51) suggest that carbon sequestration will increase in coastal landscapes overall due to the greater soil carbon

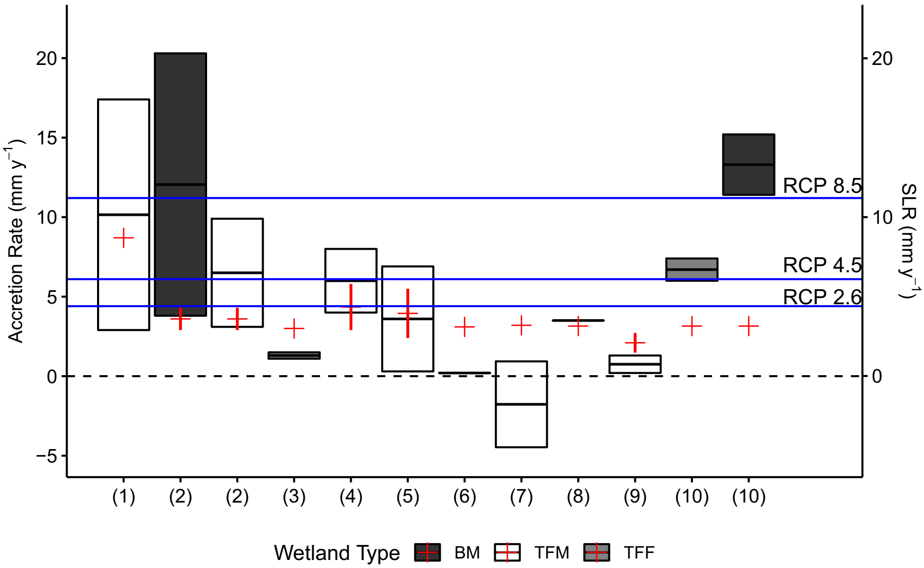

Fig. 4 Reported accretion rates of CFWs and brackish marshes showing mean, min, and max as boxplot. Local rate of mean SLR shown as red + extended to show min and max local SLR, where mean accretion below mean local SLR suggests higher likelihood of wetland submergence. Blue horizontal lines show global rates of SLR under RCP scenarios (IPCC 2013). (1) Palinkas and Engelhardt (2016), (2) Beckett et al. (2016), (3) Craft (2012), (4) Delgado et al. (2013), (5) Wang et al. (2016), (6) Stahl et al. (2018), (7) Beckett et al. (2016), (8) Noe et al. (2016), (9) Ward et al. (2014), and (10) Ensign et al. (2014)

stock observed in marsh sites; however, this prediction does not account for marsh losses from SLR inundation (S2 21).

Effects of SLR on vegetation of CFWs In general, rising sea levels negatively affect vegetation cover, structure, composition, and function in CFWs. In the USA, increasingly saline and more frequently flooded conditions have negatively affected coastal forested wetland areas, causing declines in forest health and productivity (S2 52; 56), basal area and tree density (S2 22; 54), species diversity (S2 3; 28; 52), and seed germination and regeneration (S2 28; 52; 103; 104), along with increased plant mortality (S2 3; 22; 52). Similarly, altered salinity led to reduced recruitment and tree growth in Puerto Rico (S2 72). Declines in Melaleuca forest area of Kakadu National Park, Australia, are associated with SLR impacts, exacerbated by feral water buffalo (S2 13). Conversely, soil subsidence, not SLR, attributed to changes in species composition of island marsh wetlands over 15 years of SLR in the Netherlands (S2 90). Kearney et al. (2019; S2 50) referred to the transitional zone between healthy forest and marsh as a "persistence zone" where live mature trees persist but regeneration is limited, and saltmarsh species start to appear. Collapse of these systems, triggered by a large disturbance such as fire, results in "ghost forests" (Kirwan and Gedan 2019).

Dieback of freshwater forested wetlands and subsequent migration of salt and brackish marsh into "ghost forest" areas is a common response to SLR (see Kirwan and Gedan 2019 and references) and transition can be accelerated under the influence of extreme events such as fire and hurricanes (S2 84). In other cases, however, dominant wetland species constrain the migration of saline vegetation into CFWs (S2 77). In the Delaware Estuary (Delaware, USA), for example, *Phragmites australis* expanded into areas of SLR-related forest dieback which restricted transition to saltmarsh (S2 77). Lower canopy cover and greater light availability at the marsh-to-forest boundary of SLR affected forested wetlands in Connecticut enhanced tree growth and minimised landward migration of saltmarshes (S2 32). These results highlight the ecological complexities of landward ecosystem migration which can be influenced by local geomorphology and hydrology (Brinson et al. 1995; S2 32; 77).

3.2.2 Altered rainfall regimes and extreme events

Only six of 40 observational papers in our short-list investigated responses of CFWs to effects of climate change other than SLR, specifically altered rainfall regimes and extreme events. Drought can have significant effects on CFWs by reducing freshwater supply and increasing saltwater intrusion (S2 47). Often in conjunction with saline intrusion, drought has resulted in observable negative effects on CFWs, particularly for vegetation structure and productivity (S2 47; 104). Drought and salinity resulted in tree mortality, reduced recruitment, increased leaf litter biomass, and decreased annual net primary productivity in forested wetlands of Louisiana and Florida (S2 47; 104). Drought also resulted in delayed and shortened growth periods for coastal marsh species, suggesting that growth inhibition and dieback could occur over extended periods (S2 61). For seasonally flooded CFWs in wet/dry tropical regions, an extended dry season and reduced rainfall at the start of the wet season could reduce vegetation species richness and facilitate a transition towards drought tolerant species (S2 69).

Extreme events such as hurricanes often exacerbate the effects of drought and salinity in CFWs. Hurricane impacted wetlands of the Gulf of Mexico exhibited reduced vegetation regeneration, recruitment, and increased tree dieback in areas of storm surge-induced saline intrusion (S2 58; 104). Physical removal of standing trees in these wetlands by hurricanes has led to a significant change in vegetation structure in a coastal forested wetland of western Florida (S2 104).

3.2.3 Climate change effects on fauna

Only two papers observed effects of climate change on faunal communities of CFWs. In both cases, climate change decreased species richness and habitable area. Increased salinity and relative sea level correlated with increased fragmentation and decreased cover of submerged aquatic vegetation which resulted in lower fish densities in Louisiana coastal marshes, USA (S2 45). Increased rainfall and flooding in Argentina, attributed to climate change, reduced habitat diversity for arthropod assemblages, impacting species with poor dispersal abilities and specific habitat requirements (S2 18).

3.3 Experimental responses of CFWs to climate change

3.3.1 Sea level rise

SLR and soil processes Effects of SLR on soil processes associated with greenhouse gas production are explored experimentally by applying saline flooding treatments to soil cores collected from CFWs. Saline intrusion in CFWs can shift microbial community compositions increasing CH_4 and CO_2 production (S2 25), especially in intermittently flooded soils where CH_4 emissions were almost double those of permanently inundated soils (S2 43). However, net reductions in greenhouse gas emissions occurred in permanently flooded soils (S2 43), urban pollutant impacted wetlands (S2 29), and in phosphorus enriched wetlands (S2 105). CFWs experiencing marine incursion may therefore exhibit transitional periods in which their greenhouse gas emissions exceed those of saltmarsh (S2 25) or act as short- (S2 29) or long-term carbon sinks (S2 43; 105), depending on their geographical setting.

Rising salinity reduces soil stability in marshes associated with higher decomposition of soil organic carbon (SOC; S2 99; 102), contributing to elevation decline and further submergence due to reduced plant productivity and root biomass (S2 19; 98; 105). Saline intrusion also affects soil microbes involved in denitrification, reducing rates by up to 70% (S2 64). In wetlands experiencing early stages of SLR, dry periods allow for nitrification to occur between periods of saline inundation, however, under permanent inundation ammonium is released and macrophyte N storage is reduced (S2 100). Saline conditions in combination with warming, however, can increase denitrification and ammonium availability (S2 35). Decomposition of leaf litter increased with initial saline intrusion in Louisiana and South Carolina freshwater marshes, however, with more permanent saline flooding rates of litter decay could decline, resulting in greater carbon storage (S2 79; 80). Saltwater intrusion greatly increased the release of bioavailable phosphorous (PO_4^{3-}) from salt- and brackish marsh soils in northern Florida but not in the freshwater marsh where PO_4^{3-} remained available for plant uptake (S2 101).

SLR and vegetation Responses of CFW vegetation to SLR are commonly explored through experimental applications of salinity and water to TFM mesocosms and soil seed bank samples. Reduced seed germination and vegetative regeneration typically occur in response to saline flooding (S2 8; 9; 33; 42; 73; 96), except amongst species commonly found in higher salinity environments (S2 33; 42; 76; 83). Experimental saline flooding also tends to reduce biomass and productivity of emergent seedlings and standing vegetation in mesocosms, causing mortality in some species (S2 9; 26; 33; 34; 39; 42; 49; 76; 83; 92; 96; 100). Net ecosystem productivity fell by up to 55% under in situ treatments of elevated salinity, and up to 75% in flooding treatments, in a TFM in South Carolina (S2 63). Freshwater and brackish marsh species (e.g. *Panicum hemitomon*, *Sagittaria lancifolia*, *Distichlis spicata*, and *Spartina bakeri*) commonly exhibit reduced plant growth and higher mortality in response to SLR. In contrast, species which are more commonly found in saltmarshes (e.g. *Spartina alterniflora*, *Juncus roemerianus*, and *Sporobolus virginicus*), are not negatively affected (S2 42; 48; 49; 53; 78). Saline conditions increase the dominance and proportion of salt-tolerant species in mesocosm and soil seed bank germination trials (S2 33; 76; 83), suggesting that these species will likely become more common in CFWs as saline intrusion occurs. Significantly, Bompy et al. (2015; France; S2 12) records that seedlings of the common freshwater forested wetland tree species *Pterocarpus officinalis* are able to gradually adapt to increasing salinity over a short period, especially when sporadic flushing with freshwater allowed for desalination of leaves. Similarly, juvenile individuals of floodplain willows (*Salix alba*, *Salix viminalis*) were resilient to low levels of salinity (up to 2 ppt), however, increased saline flooding negatively affected morphological traits and reduced breaking resistance (S2 55). Numerous experimental studies further suggest that the overall negative effects of experimental SLR are likely to be exacerbated by other biological disturbances such as herbivory (S2 9; 39).

3.3.2 Altered rainfall and extreme events

Experimental treatments of water levels examine the effects of rainfall changes on biotic and abiotic responses of CFWs. Drought conditions, for instance, increased nitrogen (NH_4^+) export from sediments of wetlands undergoing restoration, and to a lesser degree, from forested wetlands (S2 6). In contrast, experimental flood conditions reduced germination and species richness of freshwater marshes (S2 7; 42; 71), suggesting likely biodiversity loss and vegetation change in response to more frequent and severe floods.

Effects of hurricanes on CFWs are experimentally investigated through treatment applications representing storm surge conditions and debris deposition (wrack). Storm surge–induced saline intrusion reduced seed germination in several wetland types (S2 58; 59). Similarly, in CFWs of eastern USA, storm surge conditions reduced vegetation biomass and cover, and increased mortality, where wrack application also led to further reductions in cover (S2 59; 87). Salinity from a storm surge event can penetrate wetland soils at a rapid rate and can persist up to 6 months (S2 57; 87), with potential implications for soil microbial function and vegetation productivity due to the exposure of the rhizosphere to elevated salinity and increased availability of soil nitrogen (S2 57; 87).

3.3.3 Temperature

Only two short-listed papers investigate the influence of increased temperatures on CFWs through soil cores and temperature manipulations. Both studies, conducted in *Phragmites* reed dominated wetlands from temperate coastal regions of China, find that increases in temperature influences wetland function (S2 86; 110). Increases in vegetative litter decomposition, total organic carbon, soil enzyme activity, microbial nitrogen and phosphorus, and total nitrogen all occur under warming conditions, suggesting that these wetlands will continue to play important carbon and nitrogen processing and storage roles in a warmer world (S2 86; 110).

3.4 Modelled responses of CFWs to climate change

Eighteen short-listed papers predict the effects of climate change on CFWs using models. Most of these explore changes in the spatial distribution of coastal wetland types in response to SLR. Thirteen papers predict declines in the total area of freshwater forest and freshwater marsh (S2 1; 10; 15; 18; 23; 30; 36; 37; 38; 76; 89; 107; 108) while six papers predict an expansion of saline wetlands into areas of CFW (S2 1; 23; 30; 36; 37; 89). An overall decrease in all wetland types (freshwater and saltwater) is predicted for western USA coastal estuaries and areas of coastal Louisiana, due to low local accretion rates and a lack of upland space available for wetland migration (S2 38; 88). Similarly, Kearney et al. (2019; S2 50) identified that up to 20% of TFFFs on the Delmarva Peninsula lie within a "persistence zone" where trees do not regenerate and are liable to forest collapse with future SLR and storminess (S2 50). Furthermore, in coastal Louisiana, USA, predicted accretion rates are not sufficient to maintain stable coastal marshes, leading to submergence of brackish and freshwater wetlands (S2 20; 30; 91).

Predicted effects of SLR on CFWs have focused on overall changes in wetland area with trajectories of change and degradation of wetlands through time receiving comparatively little attention. Model simulations of forest decline in response to salinity and flooding over 500 years for *Taxodium distichum* and *Nyssa aquatica* trees suggests that even small changes in elevation and salinity (− 0.23 m and ~ 1–6 psu) can increase flood duration, decrease swamp function, reduce tree basal areas, and induce tree mortality (S2 46).

Changes in CFW habitat for threatened animals in response to SLR can have significant impacts on their populations. Modelled declines of herbaceous wetland communities, and expansion of mangrove areas, in south-east Queensland, Australia, suggest greater habitat availability for an increased population of *Xeromys myoides* (False Water Rat). However, model runs revealed that simultaneous expansion of urban areas and feral cat predation are likely to dramatically reduce, or even eradicate, the population by 2100 (S2 89) Losses, predicted by Brittian and Craft (2012), of shrub habitat, salt marsh and tidal forest from SLR, and of oak and pine forests from urban development, highlight the importance of tidal forests as a refuge for avian forest species (S2; 15). Significantly, the effect of climate-induced wetland restructuring is dependent on the habitat structural requirements of each bird species, where the transition to ghost forests benefits species which favour shrubby areas (e.g. common yellowthroat, northern bobwhite), while canopy-dwelling species are negatively affected (S2 85).

Only four short-listed studies model the influence of climate change on ecological functions of CFWs. Reductions in ecosystem service delivery, such as productivity and wastewater treatment, are predicted in response to reduced macrophyte biomass, decreased denitrification, and nitrogen sequestration under low level SLR predictions (0.52–0.82 m; S2 23). Soil organic carbon and organic nitrogen storage potential of Louisiana coastal wetlands will be significantly impacted by SLR as projections of up to 6000 km^2 of CFWs are likely to be inundated (up to 100 cm elevation) corresponding to the area of greatest soil organic carbon storage (S2 109). Mitsch et al. (2013; S2 60) reported that freshwater wetlands in temperate regions had the highest carbon sequestration rate (278 g C m^{-2} $year^{-1}$; S2 60). Despite this, tropical and subtropical wetlands have a greater global area and therefore have greater total carbon stock potential (0.56×10^{15} g C $year^{-1}$; S2 60). Louisiana coastal marshes are also predicted to increase their CO_2 uptake and storage with increases in atmospheric CO_2 due to the increased length of marsh growing periods (S2 62).

4 Discussion

Climate change can affect CFWs via multiple pathways due to their low-lying topography and position within the coastal plain, but surprisingly little is known of what the effects and outcomes will be (Conner et al. 2007; Saintilan et al. 2018). Most research to date examines effects of SLR, with the bulk of the knowledge generated over the last 9 years (Fig. 1) and mainly in the USA (Fig. 2). More broadly, however, we identified three broad aspects of CFWs that global research has focused on (I) sediment accretion and changes in elevation; (II) carbon accumulation, nutrient cycling and, sediment processes; and (III) vegetation structure, function, and distribution. Despite a diversity of study areas and methodologies, major learnings have emerged from each of these broad research areas. First, multiple lines of evidence indicate that current sediment accretion rates are not sufficient to keep pace with current rates of SLR. As a result, the persistence of CFWs is dependent upon their capacity to migrate into new available areas, as dramatic changes in ecological function are likely to occur due to saline inundation and peat collapse. Second, CFWs are increasingly recognised as important sites for carbon sequestration, sediment accumulation, and nutrient cycling but the influence of SLR on these processes is relatively unknown. Third, vegetation in CFWs is negatively impacted by SLR, the effects of which are exacerbated by drought or extreme storm events. Our review has highlighted the lack of integrated research exploring the effects of combined effects of multiple climate change drivers. Very few studies explore the impacts of more than a single axis of climate change; yet, we know that the drivers do not operate in isolation and the synergistic impacts will likely drive dramatic changes in CFW ecosystems. More work is also needed to understand the cumulative impacts of climate change drivers on CFW structure and functioning, including the sequential impacts of extreme events and changes in temperature.

4.1 Knowledge gaps

In this review, we have synthesised a significant body of research regarding the effects of climate change on CFWs. However, even within USA, where most of the reviewed research comes from, there are still gaps in the literature, especially concerning the effects of increased temperatures on CFWs and how interacting climate drivers will influence CFWs. Globally, there is a need for research into all aspects of CFWs as this basic information is critical to be able to make reliable projections regarding their future with climate change. Landward migration away from the saline influence is a widely recognised mechanism for resilience to climate change in coastal wetland vegetation literature (Morris et al. 2002). However, this migration has not been observed in CFWs and there is a lack of knowledge regarding the mechanisms of potential migration in CFW species, making it difficult to predict the future distribution of species if they were able to migrate. While the effects of temperature changes will likely influence the function and productivity of CFWs, research is greatly lacking on this topic (only two papers in this review). Although CFWs are becoming increasingly recognised as important sites for carbon sequestration, this research is still emerging and is focused on CFWs in the USA. Significant further knowledge is required to quantify carbon sequestration in CFWs globally. Also, the impacts of climate change on carbon sequestration and other soil nutrient processes are relatively unknown, adding to the uncertainty of the future of CFWs. Impacts of climate change on fauna which inhabit CFWs is also under-represented in this review suggesting that further research is warranted.

4.2 Assessing impacts of multiple drivers

Compounding effects on CFWs by multiple climate drivers have received minimal research attention to date. This knowledge is valuable in understanding the processes and responses of CFWs, enabling the development of more robust predictions of future changes and responses. Only 20% of papers reviewed here investigate the effects of two or more climate drivers. Research which only considers one climate driver is valuable in understanding the specific responses to that driver, but it is important that these responses be considered in the wider context of climate change given that it impacts many aspects of an ecosystem's structure and function. McCarthy et al. (2018), for example, observed forest decline in Florida, USA over four decades and attributed gradual decline to increased saline intrusion and flooding as a result of rising sea levels. However, to understand the recent rapid decline in forest cover, they learnt that temperature patterns were more informative, as a recent period of extended cold snaps helped to explain the decline (McCarthy et al. 2018).

Observing the effects of multiple climate drivers is difficult in the field, where changes can be gradual and take longer to result in a significant quantifiable outcome, and generally longer than most funding allows. However, for some organisms and ecosystems, the effects of multiple climate drivers could work synergistically to drive fast and dramatic changes. We rrecognise the challenges of field-based observations of multiple climate drivers and responses and highlight the role here of experimental and modelling methods which can have more intense treatment applications and include predictions over long-time scales. Ideally, research programs should use local field observations to guide the development of an experiment, with data from both used to inform the development and validation of a predictive model. This integrated approach, while resource intensive and requiring a large interdisciplinary team, would result in a significant increase in knowledge enabling better management of CFWs in the face of a rapidly changing climate.

Non-climate change threatening factors, like urban expansion, excess nutrients, and feral animals, were not commonly addressed in conjunction with climate change threats in the research reviewed (just six studies of the 110 reviewed). Although these non-climatic drivers of change were not the focus of this review, they can contribute to greater loss and decline of ecosystems when considered in conjunction with climate change threats. Future work should couple examination of climatic and non-climatic threats, as the expansion of urban developments in coastal areas continues to threaten coastal wetlands, and in many locations around the world there is no space available between them and the built urban environment or unfavourable topographies, largely reducing the potential migration area (Thorne et al. 2018). Encroachment into CFWs by salt marsh and mangrove systems as they migrate inland results in coastal squeeze.

4.3 Management considerations

Conservation of CFWs under climate change requires a significant increase in the global knowledge base for adequate management and policy decisions to be made. This requires a far-reaching research initiative to encompass all aspects of CFWs but also site-specific investigations due to the inherent differences in hydrology, topography, and species composition between CFWs. Long-term monitoring of CFWs is required to understand the processes of vegetation migration, impacts of climate change on species productivity and regeneration and, the anticipated change in functioning of CFWs.

Many CFWs which are currently affected by SLR likely exist in a 'relic' state, or what Kearney et al. (2019) have termed a persistent state, not able to reproduce or regenerate, and liable to collapse if a disturbance event, such as a hurricane or fire, removes the standing vegetation, resulting in 'ghost forests' where trees have been replaced by intertidal vegetation (Baldwin and Mendelssohn 1998; Kirwan and Gedan 2019; Langston et al. 2017; Williams et al. 1999; Williams et al. 2003). This collapse has been observed in freshwater forested swamps of Chesapeake Bay and coastal Florida, USA, where standing trees in SLR affected areas died and were uprooted after the wind, storm surge, and saline intrusion of recent hurricanes (Desantis et al. 2007; Langston et al. 2017; Middleton 2016a; Williams et al. 2003). Regeneration post hurricane in these sites has been dominated by salt-tolerant species (Desantis et al. 2007; Langston et al. 2017; Middleton 2009; Williams et al. 2003). These studies signal a significant imminent threat to the future of CFWs. Many CFWs may not be able to exist in their current state for much longer, with a transition to species which are salt-tolerant already observed and likely to continue. CFWs often lack space for migration and are directly affected by encroachment of large urban developments in coastal regions and to date there have been no observations of landward migration, highlighting their vulnerability to encroachment. Recognising the squeeze on CFWs, we suggest that it is important to leave space for wetland migration through the expansion of existing coastal protected areas and for research to be conducted into the migration potential and dispersal mechanisms of CFW species. The conversion of coastal agricultural lands to CFWs in areas which have reduced agricultural productivity due to increased inundation and salinity is an emerging opportunity which could provide space for wetland migration and regeneration, as well as reduce runoff of agricultural fertilizers and chemicals into coastal and nearshore environments (Waltham et al. 2019).

The other mechanism which could contribute to wetland persistence is sediment accretion. However, accretion rates in CFWs reviewed here were generally found to be outstripped by SLR. To aid in sediment accretion processes and increase rates of vertical elevation gain, sediment remediation could be implemented as sufficient sediment supply was found to be a contributing factor to elevation gain. The restoration of flow regimes in highly modified rivers could also help to reduce the impact of saline intrusion facilitated by minimal freshwater flows and deliver sediment supplies for accretion processes. Similarly, providing periodic freshwater flushing of salt impacted CFWs could improve the resilience of species which are not salt-tolerant, providing short periods in which regeneration and migration could occur (Mauchamp and Mesleard 2001).

Active restoration and mitigation actions can lead to further impacts on the coastal region, and therefore require careful consideration, planning, and consultation with the relevant stakeholders to achieve an optimal outcome of enhanced wetland resilience while maintaining the services and function of CFWs and surrounding lands. The impacts of salinity, temperature, and water regime on sediment accretion processes all require further investigation to be able to accurately predict the future of CFWs. Implementing further widespread long-term monitoring programs which quantify accretion rates during periods of climatic change would also help untangle this process.

5 Conclusion

Coastal freshwater wetlands are key components of the coastal landscape which are significantly threatened by global climate change. While there has been strong growth in research from 2010 to 2020 exploring SLR effects on CFWs, very little attention has been given to other aspects of climate change. Furthermore, there is a lack of studies which investigate the impacts of compounding climate threats to CFWs. The key findings of our review are that (I) current sediment accretion rates are not sufficient to keep pace with current rates of SLR; (II) the effect of climate change on carbon sequestration, sediment accumulation, and nutrient cycling processes are unknown; and (III) vegetation is negatively impacted by the effects of SLR which are further exasperated when combined with drought or extreme storm events. We suggest that future research attention should be given to CFWs in areas outside of the USA (but not to their exclusion) and that research should focus on the effects of temperature changes on CFWs, the carbon sequestration potential of these wetlands, and the impacts of multiple climate drivers on CFWs.

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