



# Manipulating, managing and rehabilitating mangrove-dominated wetlands along Florida's east coast (USA): balancing mosquito control and ecological values

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**Abstract** In Florida, mangrove-dominated wetlands have been manipulated and managed largely for control of mosquitoes or to make way for human development since the late 1800s. More recently, many wetlands have been rehabilitated as their contributions to estuarine ecosystems became apparent and techniques that restored valuable contributions without compromising control of mosquitoes became available. This paper documents the history of manipulations largely used to control mosquito production in wetlands on the east coast of Florida, which have included ditching, filling, and impounding. It

describes the management of these environmentally sensitive habitats since World War II and approximately 40 years of effort to rehabilitate these systems and improve their management. Improvements have been accomplished via adaptive management, science-based decision making and engagement of diverse groups of resource managers and stakeholders. Interagency efforts to provide balanced management of these wetlands are discussed, and work is presented to demonstrate the outcomes from rehabilitating impoundments in the Indian River Lagoon. These strategies for management and rehabilitation should provide guidance for restoring and conserving critical ecosystem services delivered by mangrove-dominated wetlands elsewhere, including survival in the face of future environmental changes.

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## Introduction

Mangrove systems along Florida's east coast have been adversely impacted by human activities since navigational dredging in the late 1800s created the first widespread structural changes to wetlands (see timeline in Table 1). Many subsequent impacts arose from

**Table 1** Overview of anthropogenic impacts and management actions related to mosquito control and management of mangrove-dominated wetlands in Florida over the past century

Timeframe	Actions related to mangrove-mosquito management
1880–1960s	Dredging for navigation and construction of Atlantic Intracoastal Waterway
1920–1930	Early attempts at control of mosquitoes involved ditching of coastal wetlands
1940–1950	Chemical control of mosquitos was common until resistance and widespread ecological problems were identified
1950–1960	Ditching, dredge and fill, and impounding of wetlands replaced the use of pesticides for management of mosquitoes
1955–1970	192 impoundments (~ 40,000 acres) were constructed in 5 counties along IRL (Volusia, Brevard, Indian River, St. Lucie and Martin counties)
1950-present	Dredge and fill for development increased with increasing populations in coastal communities in Florida
1972	Water Resource Act passed by the state legislature
Late 1970s	First impoundment breached in MINWR to restore habitat for dusky seaside sparrow
1983	Creation of the Governor’s Working Group on Mosquito Control and Technical Subcommittee on Mosquito Impoundments by Governor Bob Graham
1983–1992	Coastal Zone Management funding for research on management of impoundments (Federal funds managed by the FDEP)
1986	FCCMC and SOMM established in Florida law
1987	SWIM Act approved
Mid-1980s-1990s	Begin reconnecting impoundments with culverts and using the RIM management for control of mosquitoes
1991	IRL designated as Estuary of National Significance and the IRL National Estuary Program established
1998	USFWS, SJRWMD, and VCMC began full impoundment restoration in MINWR
1999	National Park Service, VCMC and SJRWMD began restoration of dragline-impacted wetland in the Canaveral National Seashore
1999–2004	Wetland Initiative in MINWR guided research into impoundment management
2000–2011	Full restoration of mosquito impoundments underway in Canaveral National Seashore and MINWR
2000–2019	Restoration of dragline impacted wetlands throughout east coast of Florida
2003-present	Removal of dredge spoil and wetland restoration throughout the east coast of Florida
2005–2012	Post-restoration monitoring of fully restored mosquito impoundments
2010	NERT was established, leading to the development of additional restoration teams across Florida
2015–2017	Post-restoration monitoring of a full set of restored impoundments

Acronyms are described in Table 2

attempts to manage prolific production of “saltmarsh” mosquitoes from wetlands containing mangroves. But, scientific recognition of the value of ecological services delivered by mangroves has led to robust efforts to restore these systems. Restoration must still address management of mosquitoes, along with new issues related to climate change. Our experiences and the lessons learned in Florida may be of value to others.

The term “mangrove” describes a diverse ecological, rather than taxonomic, assemblage of plants that are adapted to coastal saline environments and occur worldwide along tropical and subtropical coasts.

Mangroves prosper on protected coasts with fine-grained sediments where the average temperature during the coldest month is greater than 20 °C (Saintilan et al. 2009). Three species of mangroves occur in North America: the red mangrove (*Rhizophora mangle*), the black mangrove (*Avicennia germinans*), and the white mangrove (*Laguncularia racemosa*; Lugo and Snedaker 1974; Tomlinson 1994). These species occur primarily in Florida, but they also can be found along the Gulf Coast of Louisiana and Texas and in other scattered locations, usually as stunted, small shrubs (Saintilan et al. 2009). Mangroves create structurally complex, biogenic,

**Table 2** Complete list of acronyms used in the text

Brevard County Mosquito Control	BCMC
Fla. Coordinating Council on Mosquito Control	FCCMC
Fla. Dept. of Environmental Protection	FDEP
Fla. Fish and Wildlife Conservation Commission	FWC
Indian River Lagoon	IRL
Merritt Island National Wildlife Refuge	MINWR
National Oceanic and Atmospheric Administration	NOAA
Nationwide Permits	NWP
North Peninsula State Park	NPSP
Northeast Florida Estuarine Restoration Team	NERT
Northern Coastal Basin	NCB
Open Marsh Water Management	OMWM
Rotational Impoundment Management	RIM
South Florida Water Management District	SFWMD
St. Johns River Water Management District	SJRWMD
Subcommittee on Managed Marshes	SOMM
Surface Water Improvement and Management Act	SWIM
United States Fish and Wildlife Service	USFWS
Volusia County Mosquito Control	VCMC

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coastal habitats that are utilized by a diverse assemblage of species from terrestrial and aquatic environments, and they provide many additional ecosystem services (Alongi 2009; Barbier 2016; Howard et al. 2017; Friess et al. 2019). In particular, mangrove forests:

1. Provide critical habitats for many plant and animal species, some of which are important ecologically, commercially or recreationally.
2. Fuel important coastal, detritus-based food webs with their high primary productivity.
3. Filter water flowing from uplands effectively.
4. Stabilize sediment and protect against erosion.
5. Store water thus providing protection from floods.
6. Sequester a large amount of carbon making them an important blue carbon resource in mitigation of climate change.

In addition to these services, significant numbers of mosquitoes can be produced in mangrove forests

(Carlson and Vigliano 1985). In many areas of Florida, a large proportion of any mangrove forest is suitable for production of mosquitoes (Provost 1973, 1976). In North America, the principal pest species reproducing in mangrove forests is the black saltmarsh mosquito *Aedes taeniorhynchus* (Wiedemann), which is an aggressive biter capable of flying relatively long distances (Rey et al. 2012a).

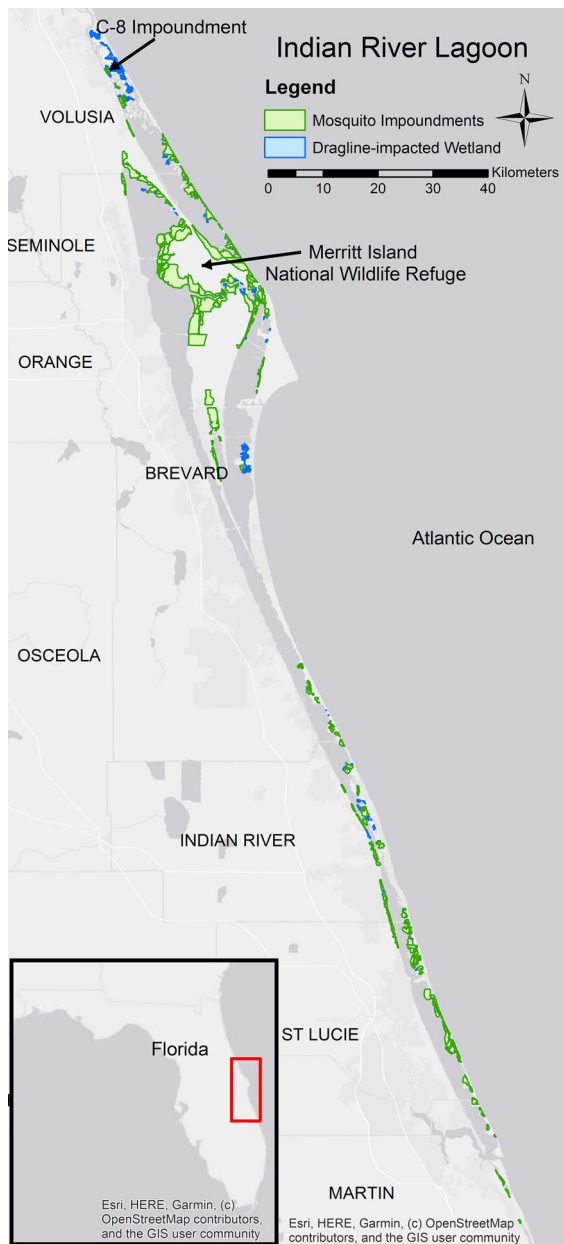
This paper examines impacts to mangrove systems in Florida, with a focus on the overlap with attempts to control mosquito production. We discuss these impacts and the consequences of that interaction from the late 1800s to the present, before giving a detailed account of the evolution of mosquito management in mangroves, as it shifted from a singular focus on mosquito eradication to a broader integration of wetland rehabilitation and management. The paper concludes with a brief discussion of two future issues, sea level rise and changes in mangrove distribution due to climate change.

### History of impacts to Florida mangroves

There have been a wide variety of direct anthropogenic impacts to coastal wetlands, including mangroves, since the late 1800s in Florida (see Table 1). Many of these impacts resulted from attempts to control the production of the mosquitoes. All impacts influenced the ecological services provided by mangroves.

#### Navigational dredging

From the 1880s through at least the 1960s, numerous navigation channels were dredged and many are still maintained as part of the Atlantic Intracoastal Waterway (Parkman 1983; Crawford 2006). In some areas, the channels were cut through pristine wetlands and large amounts of dredge spoil were deposited on adjacent wetlands. For example, in an area on the northeast coast of Florida running from Ponce de Leon Inlet to just south of the mouth of the St. Johns River, over 565 ha of essential estuarine habitat were filled by spoil from dredging (Brockmeyer, unpublished data), with additional acreage lost to the channel. Losses of this scale may be present throughout coastal areas adjacent to the intracoastal or other navigational channels.



**Fig. 1** A map of the Indian River Lagoon region along the east central coast of Florida, USA. Mosquito impoundments and dragline-impacted wetlands are shown. Merritt Island National Wildlife Refuge and the C-8 impoundment are labeled for convenience

## Mosquito control

### Ditching

Beginning in the 1920s in Florida, parallel ditches dug by hand or with dynamite were among the first

attempts to control populations of coastal mosquitoes (Rey et al. 2012b). Thousands of miles of ditches were dug throughout Florida up until World War II, in order to interrupt the life cycle of mosquitoes by removing water from the surface of the wetlands as was done in the northern coastal states of the USA. The effectiveness of ditches declined as connections to the estuary eroded and frequently closed.

### Impounding

A mosquito control impoundment is a salt marsh or mangrove forest that has been surrounded by a dike to allow control of water levels. The effectiveness of impoundments relies on the fact that saltmarsh mosquitoes will not oviposit on standing water. Thus, mosquito production was prevented by keeping the substrate flooded with even just a few centimeters of water during the warm spring/summer seasons (Carlson et al. 1999). In the Indian River Lagoon system (IRL; Fig. 1) in east central Florida, the complexity of mangrove habitats made ditching problematic while the low tidal amplitudes would limit the circulation of water through Open Marsh Water Management systems (OMWM; Ferrigno and Jobbins 1968; Lesser and Shisler 1979; Meredith et al. 1985). As a result, source reduction efforts depended heavily on impoundments constructed from the 1950s through the early 1970s to control production of mosquitoes in the large expanses of salt marsh and mangroves in the IRL (Table 1; Rey et al. 1991a; Brockmeyer et al. 1997).

### Dragline ditching

From the 1950s through the early 1970s (Fig. 1 and Table 1), draglines were used to dig ditches through wetlands throughout Florida (Rey et al. 2012b). The draglines worked from mats or were mounted on small barges, and material excavated from the wetlands was piled on either side of the newly created ditch. Extensive networks of deep, wide ditches and adjacent piles of spoil severely reduced functional acres of wetland. The purpose of the ditches and piles of spoil was to interrupt the life cycle of saltmarsh mosquitoes by eliminating suitable sites for egg-laying (oviposition) and by allowing larvivorous fish access to mosquito larvae. On average, half of any wetland ended up as ditch and spoil (Rey et al. 2012b), which

subsequently reduced the ecological services produced by the impacted area.

### *Dredge and fill*

During the 1950s and 1960s, estuarine sediments were dredged and deposited onto adjacent coastal wetlands to reduce habitats that produce mosquitoes along Florida's east-central coast. This technique to control mosquitoes proved to be too slow and costly, which led to its abandonment in the late 1960s (Rey et al. 2012b). In addition, cracks in the surface of the filled areas proved to be excellent ovipositional sites for saltmarsh mosquitoes, thus worsening the problem. Environmental regulations now restrict the filling of wetlands (Carlson and O'Meara 2009). Although constructed to control mosquitoes, some of these newly filled waterfront areas were subsequently used for urban development.

### Development

Similar to the dredge and fill approach to controlling mosquitoes, wetlands were filled with spoil to create dry areas for commercial and residential development separated by deep channels for docks and boats. These "finger canal" developments typically have bulk-headed shorelines, and poor water circulation in dead-end canals can create poor water quality. In addition to loss of wetlands and reduced water quality, increases

in human populations near prolific mosquito producing areas necessitates additional mosquito control activities that may further impact the lagoon and associated wetlands. Areas filled for development can be identified easily in aerial imagery due to parallel canals or prominent, regular geometric shapes that protrude into the estuary (Fig. 2). Though this type of development occurred throughout Florida, the rate of filling for development around the IRL increased rapidly beginning in the 1950s (Table 1). Much of the increase was due to the expanding presence of the National Aeronautical and Space Administration at Cape Canaveral. This coastal development combined with alterations to manage mosquitoes resulted in significant loss of mangrove habitat throughout the Lagoon.

### Recovering functions of impacted wetlands

The value of coastal wetlands was recognized in the 1950s and 1960s (Provost 1968, 1969; Odum and Heald 1972), but the first efforts in east-central Florida to address lost functions occurred in the early 1970s. In this section, we will describe research from the 1960s through the 1980s that documented impacts from impounding and isolating wetlands but also revealed the benefits from even minimal reconnection via culverts. With interagency coordination, efforts began to rehabilitate the 16,200 ha of impounded wetlands in



**Fig. 2** Aerial imagery from 1943 (left) and 2009 (right) illustrating the impact of development in Indian River County, FL. Note the numerous mangroves scattered in the wetlands in 1943

the IRL (Rey et al. 1991a; Brockmeyer et al. 1997). Full restoration of impoundments and of a variety of other impacted wetlands followed. Other key issues include evaluating restoration and management to confirm their success, expanded coordination to advance restoration and concerns surrounding permitting.

### Impoundment research

Impounding was effective at controlling mosquitoes and reducing the use of pesticides, but it had many negative consequences for the ecological function of these systems (Carlson et al. 1989; Rey et al. 1992; Brockmeyer et al. 1997). Impacts included decreased dissolved oxygen, wildly fluctuating salinities, high sulfide concentrations, high water temperatures, and uncharacteristically high levels of compounds containing nitrogen and phosphorous. Deep flooding eliminated wetland vegetation in some impoundments resulting in barren and usually hypersaline flats. In other high marshes, the natural vegetation of black mangroves mixed with herbaceous halophytes was replaced by red mangrove monocultures because their arching prop roots helped them cope with high water levels (Lahmann 1988). In some impoundments flooded by artesian wells or upland drainage, vegetation shifted to freshwater systems usually dominated by cattails (*Typha* spp.; Clements and Rogers 1964; Brockmeyer et al. 1997). Impounding interfered with the exchange of organisms and materials between the wetland and the estuary, and the isolation drastically reduced the diversity of fish utilizing these wetlands (Harrington and Harrington 1961, 1982). Invertebrates also were affected, with research documenting impacts to zooplankton and other aquatic and terrestrial invertebrates (Gilmore et al. 1982; Rey et al. 1991b; Tunberg 2009).

One of the first efforts to address the negative effects of impounding occurred in Brevard County in the early 1970s with the construction of one of the last impoundments. The impoundment included water control structures and spillways to allow effective management of water levels during initial construction (Provost 1977; Brockmeyer et al. 1997). Subsequent work focused on identifying and quantifying deleterious effects of impoundments upon marsh and estuarine systems, and on developing strategies to mitigate these effects. Studies addressed fish (Gilmore

et al. 1982; Rey et al. 1990a, b), zooplankton (Rey et al. 1991b), other invertebrates (Tunberg 2009), mangroves and other halophytic vegetation (Lahmann 1988; Rey et al. 1990c, d; Rey 1994), water quality (Rey et al. 1992), soil chemistry (Parkinson et al. 1993; Rey and Kain 1993), and birds (Schikorr and Swain 1995; Smith and Breininger 1995). A common finding was that isolating the wetland from the adjoining estuary was a major driver for adverse impacts. This research provided the framework for several management techniques currently used in Florida (described below) that emphasize re-establishment of marsh-estuary tidal connections while maintaining the ability to control mosquitoes with minimal use of pesticides. During the mid-1990s, research priorities shifted away from mosquito control issues. Federal funding became difficult to obtain because impounded wetlands were considered a “local” problem. Most scientific data resulted from ecological monitoring and evaluation of wetland rehabilitation or restoration projects, primarily conducted by local universities (Lin and Beal 1995; Taylor et al. 1998; Faunce and Paperno 1999; Faunce 2000; Poulakis et al. 2002; Donnelly 2014; Donnelly and Walters 2014).

Beginning in the late 1990s, conflicts between management priorities (e.g., aquatic ecosystem functions vs migratory bird management) at Merritt Island National Wildlife Refuge (MINWR) led to a multi-year, multi-disciplinary study entitled the Wetlands Initiative, which examined the benefits and impacts associated with managing impoundments in the Refuge (Brockmeyer et al. 2005). The work identified many issues related to use of impounded wetlands by fish and wildlife and the critical role that stable emergent vegetation played in the survival of these same wetlands. Publications resulting from this work dealt with shorebird habitats (Collazo et al. 2002), historical rate of sediment accretion (Parkinson et al. 2006), the ecology of waterfowl/lesser scaup (Herring and Collazo 2004, 2005, 2006, 2009), habitat selection by wading birds (Stolen et al. 2007) and associations between fish and vegetation (Stolen et al. 2009). The wide-ranging ecological results of this initiative were integral in developing the Comprehensive Conservation Plan for MINWR (USFWS 2008), which also identified the impoundments designated for full restoration (see below).

## Coordination

Watershed management has a long history in Florida. With the passage of the Water Resources Act by the Florida Legislature in 1972 (Table 1), the state was divided into 5 watershed-based water management districts. Within those districts, smaller surface water basins were identified as management units. Some of these basins were identified for special planning and management through the Surface Water Improvement and Management (SWIM) Act (1987) under which, the IRL was included to receive special protection and restoration. In 1991, the IRL was designated as an Estuary of National Significance and became part of the National Estuary Program managed by the United States Environmental Protection Agency. Both programs generated basin-specific plans to address a wide array of issues that included restoration of coastal wetlands.

Improved management of coastal wetlands in Florida benefitted greatly from increased interaction and cooperation among regulatory agencies, mosquito control programs, stakeholders, and researchers. These improvements were fostered by 2 committees codified by the Florida Legislature in 1986, the Florida Coordinating Council on Mosquito Control (FCCMC) and its Subcommittee on Managed Marshes (SOMM; Carlson 1987). The FCCMC's role is to foster efficient use of resources, advise and assist arthropod control agencies in implementing best management practices, capitalize on sources of research funding, and enhance interagency communication. SOMM's role is to provide technical review and guidance on management plans for coastal wetlands and serve as a source of information on issues surrounding coastal wetland management (Carlson et al. 1991). In the mid-1980s, SOMM compiled research-based recommendations for managing coastal impoundments into a set of guidelines known as Rotational Impoundment Management (RIM). RIM provides adequate control of saltmarsh mosquitoes via flooding during the spring/summer months and open access to the adjacent estuary through culverts during the remainder of the year. Water levels are controlled during the summer to prevent damage to marsh vegetation (Brockmeyer et al. 1997; Rey et al. 2012b).

## Impoundment rehabilitation

Following the guidance outlined by SOMM, structural features that would facilitate RIM in existing impoundments (e.g., culverts, pumps, weirs and spillways) began to be added. The major focus of this rehabilitation effort was re-establishing and enhancing hydrological connections between wetlands and the estuary (Brockmeyer et al. 1997). In the mid-1980s, local funding was used to reconnect impoundments via culverts with state and regional funding following. The IRL SWIM Plan, developed jointly by the St. Johns River and South Florida Water Management Districts (SJRWMD and SFWMD), set natural productivity and biodiversity as primary objectives for impounded coastal wetlands (Steward et al. 1994, 2003; Brockmeyer et al. 1997). The SJRWMD implemented work through contracts with local entities responsible for control of mosquitoes and regional land managers. Later, some of this work was funded through state and federal grants (Brockmeyer et al. 1997; Rey et al. 2012b). To date, 11,165 ha of impounded wetland have been reconnected via culverts to the adjacent IRL by ongoing efforts.

Research along with increased management experience, resulted in the development and application of new strategies for managing impounded wetlands that took advantage of the enhanced control of hydrology provided by new structural features. Guidelines were developed for culverts (e.g., invert elevation, size, number per linear feet of dike, etc.), as well as alternatives for management of water based upon RIM principles (Brockmeyer et al. 1997; Rey et al. 2012b). These techniques included bottom water release, enhancement of circulation, opening/closing of culverts, and permanent pumps (Rey et al. 2012b).

## Impoundment restoration

During the mid to late 1990s, a partnership developed to restore impounded wetlands more fully by grading impoundment dikes to elevations near those of natural wetlands and partially filling the adjacent borrow ditch to maximize the area at natural marsh elevation. In 1998, the United States Fish and Wildlife Service (USFWS), SJRWMD, and Volusia County Mosquito Control (VCMC) entered into a cooperative agreement to restore/rehabilitate six impoundments in the Volusia County portion of MINWR (Table 1; Rey

et al. 2012b). Since this first project, the partnership has removed nearly 69 km of dike to restore natural hydrology to 940 ha of coastal wetland in areas where mosquito control is handled by other means or is not a primary concern with funding from a variety of sources (Rey et al. 2012b). The most ambitious effort was a large-scale implementation (~ 32 km of dike) at MINWR funded by the National Oceanic and Atmospheric Administration's (NOAA) American Recovery and Reinvestment Act restoration program. Because the work had been ongoing and the partnership had state and federal permits in hand, it was deemed "shovel ready." This large effort allowed the contractors implementing the project to refine their techniques over time to increase efficiency, and to improve the quality of the finished product (Brockmeyer, unpublished data). Dikes also have been removed around more than 360 ha of wetland as part of regulatory mitigation. (Rey et al. 2012b; Brockmeyer, unpublished data). Based on the evaluation of recovery at restored impoundments as outlined below, planning for additional projects that would use these methods is underway, including more work at MINWR.

#### Evaluation and validation of methods

Agency partners used an adaptive management framework to establish goals, implement restoration, evaluate the effectiveness of methods, disseminate the results of monitoring to partners and stakeholders, and adjust methods to increase the quality of restored habitat. Evaluations of projects over time are critical to determine if long-term objectives are achieved, to provide guidance that improves the outcomes of future restoration, and to ensure accountability for use of resources (Zedler 2017; Saunders et al 2020). Below, we present monitoring protocols, general results, and management applications from the evaluation and validation of methods to restore mosquito impoundments in the northern IRL system, Brevard and Volusia counties, FL (Donnelly 2014; Donnelly, unpublished data). This work provides a good example of how evaluations of restoration methods can improve outcomes.

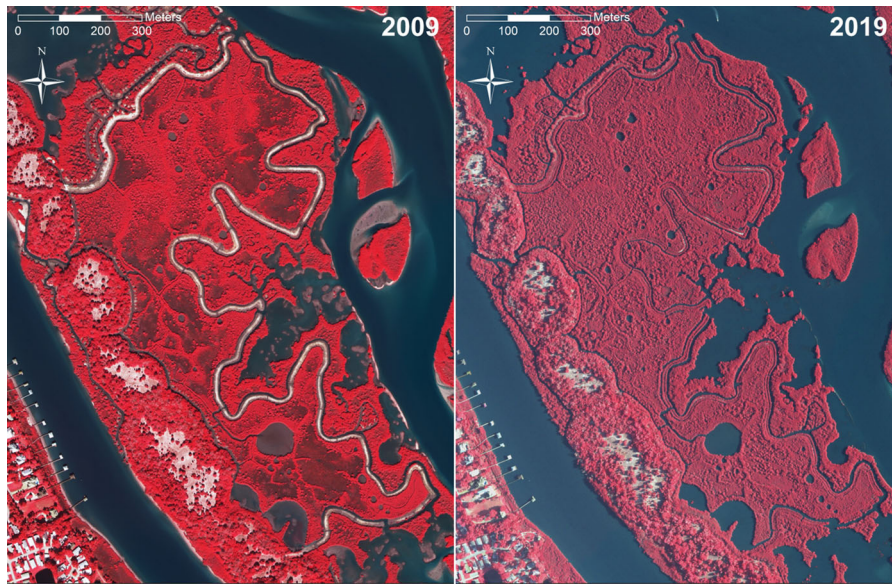
Hydrology is a critical determinant of wetland diversity, community structure and ecosystem function (Alongi 2009), and restoring hydrology in human-altered wetlands is the first step in restoration of the

system (Lewis 2005). The goals of restoring impoundments were to return the dikes to wetland elevations, reestablish natural hydrological conditions and initiate natural regeneration of wetland communities (Lewis 2005; Rey et al. 2012b). Initial monitoring began in 2005 at three restored impoundments and two reference marshes and monitoring protocols were established to evaluate response variables directly tied to the project's goals (Table 1). Effects of dike removal on abiotic characteristics of natural wetland hydrology was evaluated by establishing a permanent transect and measuring relative changes in elevation (referenced to lowest observed mean water level) using a laser level and stadia rod and by measurement of soil salinity and soil moisture. Biotic characteristics were evaluated in twenty 0.25-m<sup>2</sup> quadrats arranged in a grid pattern in the restored area and five 0.25-m<sup>2</sup> quadrats placed in the interior marsh. Within each quadrat, diversity, density, and percent cover of plants were recorded, along with numbers of fiddler crab burrows. This same monitoring protocol was utilized for impoundments restored between 2007 and 2010, with monitoring continuing through 2012. Another phase of monitoring to evaluate long-term effects of dike removal was undertaken from 2015 to 2017 at 20 impoundments that had been restored 5 to 18 years earlier (Table 1).

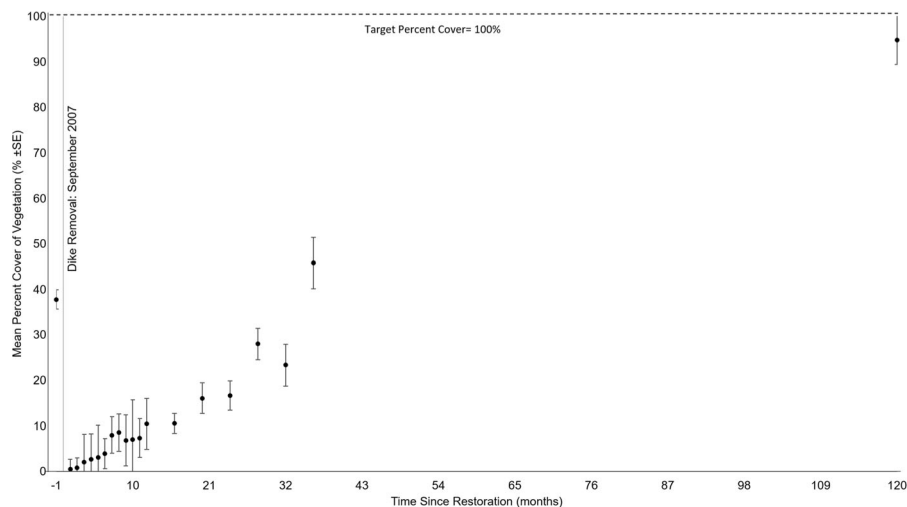
Initial results documented the need for hydrological restoration to recover ecological structure and function of these wetlands that had been altered for mosquito management. Before restoration, tidal inundation was rare at the highest elevations on the dike, with soil moisture and soil salinity at least 50% less than at reference marshes. Impoundment dikes had a mix of terrestrial and wetland plants, including mangroves at low elevations and exotic *Schinus terebinthifolius* in the higher and drier elevations. In comparison, removal of dikes created elevations similar to reference marshes and allowed for complete submersion during high tides. Hydrological restoration led to subsequent increases in soil moisture and soil salinity and colonization of restored area by wetland plants within one month of dike removal.

Results from the first phase of monitoring (2005–2006) identified extensive halophytic vegetation along the shoreline of the dike that could be conserved during leveling and target elevations that limited recruitment of non-native species. These management recommendations were implemented





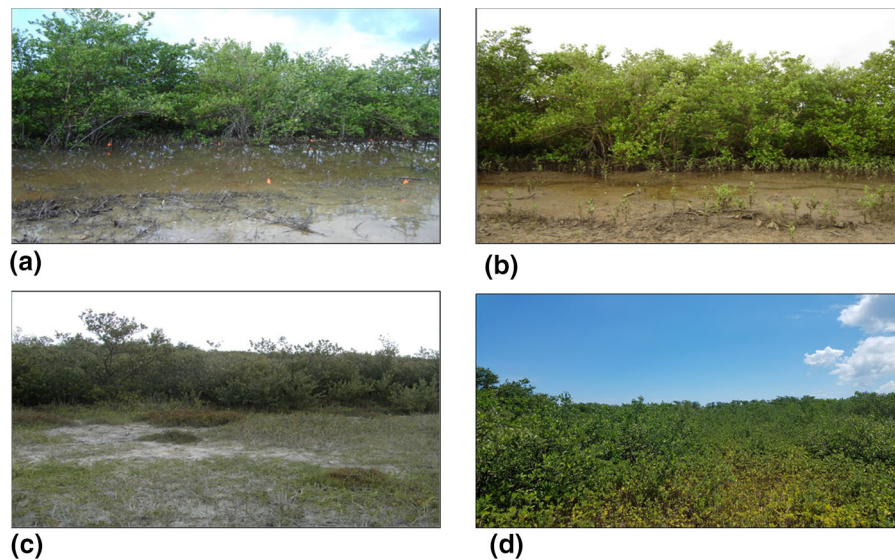
**Fig. 3** Aerial images of the C-8 impoundment shortly after restoration (2009) and 10 + years post restoration. Note how the restored dike surface revegetates in the period between images



**Fig. 4** Mean percent cover of vegetation ( $\% \pm SE$ ) at the C-8 impoundment from one month before restoration in September 2007 to 10 years post-restoration (2017). The target for percent cover of vegetation (100%) was based on data collected at the reference marsh

by VCMC during the next phase of impoundment restoration in 2007, starting with the C-8 impoundment (Fig. 3; Mosquito Lagoon, Volusia County, FL). Pre- and post-restoration monitoring at the C-8 impoundment documented an increased recovery for plant communities where conserved vegetation along the shoreline acted as a source of native wetland plants directly adjacent to restored habitat (Figs. 4 and 5). Because natural regeneration relies on recruitment

from nearby areas (Field 1999; Lewis 2005), the conservation of reproductively mature mangroves and other halophytic vegetation along the shoreline and in the interior marsh provided a readily available source of propagules, vegetative fragments, and seeds. Recruitment of native vegetation is the initial phase of restoration for this biogenic habitat (McKee and Faulkner 2000; Alongi 2009) and recovery of



**Fig. 5** Recovery of vegetation after restoration at the C-8 impoundment after one month of dike leveling (a), one year post-restoration (b), three years post-restoration (c) and ten years post-restoration (d)

vegetative cover and structure will directly affect the quality of restored areas.

Plant communities after restoration were comprised of only obligate and facultative wetland species similar to reference marshes. Dominant species in restored areas were black mangroves (*A. germinans*), saltwort (*Batis maritima*), perennial glasswort (*Salicornia ambigua*), sea purslane (*Sesuvium portulacastrum*), and saltgrass (*Distichlis spicata*; taxonomic names based on Wunderlin et al. 2021). These five species were initial colonizers of restored areas following removal of dikes through recruitment of seeds and propagules and vegetative propagation from plants conserved along the shoreline and interior marsh. Over the first year, percent cover of vegetation increased to 10% and included recruitment of additional species of mangroves (*R. mangle* and *L. racemosa*; Fig. 5b). Three years after restoration percent cover of vegetation had increased to over 45% (Figs. 4 and 5c), and, after ten years, vegetative cover was approaching 100%. All three mangrove species increased in abundance, and densities of halophytic shrubs and grasses decreased as mangroves became dominant in restored areas. Mangroves have been increasing in wetlands throughout Mosquito Lagoon during this timeframe, with similar decreases in abundance of shrubs and grasses also observed at reference sites.

Hydrological restoration of mosquito impoundments has resulted in the development of functional wetlands in the IRL and reversed some of the extensive habitat loss caused by construction of impoundments. This work also identified several important influences on recovery of restored habitat and provided recommendations to guide future restoration of coastal wetlands, including: (1) target elevations for promoting natural hydrological properties, (2) effectiveness of natural regeneration following removal of a dike, (3) benefits of conserving shoreline wetland vegetation to enhance the rate of recovery, and (4) importance of abiotic conditions for preventing recruitment of non-native plants. For example, achieving optimal elevations restricted the diversity of plants to mangroves and halophytic wetland species. We observed complete removal of the non-native *S. terebinthifolius* after hydrological restoration, which highlights the importance of natural environmental barriers in reducing invasion by non-native plants that had exploited the altered conditions on dikes. Methods for hydrological restoration validated for impoundments were applied to other impacted and degraded wetlands in Florida with the common goal of balancing management of mosquitoes with ecological function of mangrove wetlands.

## Development and implementation of other restoration methods

As reconnecting and restoring of impoundments continued, a review of other impacted wetlands demonstrated the need for additional efforts (Steward et al. 2003). Collaboration between mosquito control entities and restoration practitioners was critical to addressing issues as planning and implementation of projects progressed. Here, we will discuss three examples of methods developed to deal with specific impacts to wetlands in east central Florida, with notes on progress in implementing them and lessons learned.

### *Dragline-impacted wetlands*

In 1999, a partnership that included the National Park Service, VCMC and SJRWMD developed a pilot project to restore an area of dragline-impacted wetland in the Canaveral National Seashore (Table 1). A 22.5-ha area that included Porkchop Island and parts of Orange Island were targeted with the objective of maximizing the amount of area returned to the elevation of adjacent wetland by placing spoil back into the ditches (Rey et al. 2012b). With implementation by VCMC, remnant ditches continue to control mosquitoes, eliminating the need for alternative methods. The success of this pilot project led to expanded efforts with subsequent work addressing a total of over 350 ha of dragline-impacted wetland and returning well over 100 ha to wetland elevation to date. With most of this work being implemented by just a few equipment operators employed by VCMC, a consistent quality was maintained. These efforts were supported by variety of funding sources including, SJRWMD, Florida Fish and Wildlife Conservation Commission (FWC), VCMC, and USFWS's National Coastal Wetland Conservation Grants Program.

### *Subsided wetland*

As part of the Wetlands Initiative at MINWR, areas of historical coastal wetlands that had eroded or subsided below the elevation where wetland vegetation can survive were identified. After repeated efforts to transplant vegetation failed, a pilot project to raise the elevation of the substrate was considered. A partnership of MINWR, Brevard County Mosquito Control (BCMC) and SJRWMD developed and

implemented a plan to address this issue. Two phases of work were funded through a NOAA grant.

Phase 1 compared containment materials and various sources of fill in small test plots. This first phase pointed out shortcomings in the several types of wattles used as containment when receiving pumped fill. As test plots were filled, containment was breached when the slurry flowed under or between wattles. A coconut-fiber “block” with a rectangular cross-section (BioD-Block™ 16–300; RoLanka International, Inc.) was selected for subsequent work because it had a larger surface in contact with the substrate and a panel of woven coir fabric attached on three sides. The ends of the fabric panels were buried in a trench paralleling the containment line. These features greatly reduced undermining when fill material was pumped into a contained area.

Phase 2 used a small dredge to move eroded soils that had settled in a pond within an impoundment at MINWR into a larger containment cell (~ 5 ha) surrounded by blocks on the subsided surface of the wetland. This phase successfully pumped and contained fill, and it raised the elevation in most of the containment cell (Brockmeyer, unpublished data). It, however, had limited success in raising large areas of the wetland surface high enough to support wetland vegetation. Factors limiting success included optimistic sizing of the containment cell, underestimating the water content of the organic fill material, and underestimating the cost of the dredging operation. The project has provided valuable information for the design and implementation of future work. BCMC participation insured that their concerns were considered in the planning and execution of the project. This method could be valuable in addressing sea level rise (Cornwell et al. 2020; Howard et al. 2020), and planning for similar projects is underway.

### *Removal of dredge spoil*

The SJRWMD's Northern Coastal Basins (NCB) SWIM Program, with assistance and endorsement from managers of local estuarine resources, developed a document to identify the need for estuarine restoration and guide cooperative efforts in the NCB watersheds. In the North Peninsula State Park (NPSP) in Volusia County, the SJRWMD and Florida Department of Environmental Protection's (FDEP) State Parks District 3 identified an initial area of historical

wetland that was covered with spoil and suitable for restoration and enhancement. While similar work had been done at Pine Island Conservation Area in Brevard County (25.4 ha; Taylor 2012), this effort was the first grant-funded restoration of its kind within a Florida state park. Restoration at the initial site included clearing a 1.7 ha restoration site, removing spoil, leveling of the site to target elevation based on adjacent undisturbed wetlands, and planting according to an approved restoration plan. After several subsequent projects at NPSP demonstrated that successful restoration was feasible, over 35.7 ha have been completed. Most sections of the work were designed to include a “creek” feature that was graded to allow tidal exchange. The Floridan Resource Conservation and Development Council, a Florida non-profit corporation, has worked to implement these restoration projects under an agreement with NPSP. This consistent oversight increased efficiency and the quality of the final product. At present, the last 2.7 ha of accessible dredge spoil at NPSP are being removed. Several similar projects are under consideration. This method can be used to restore areas filled for development when they become available. As with all the previous efforts, future projects should be coordinated with mosquito control professionals and consider sea level rise in the design and grading of the project.

#### Continued and expanded coordination

The SOMM has continued to address issues related to mosquito control and protection of wetlands while considering impacts or benefits to salt marsh and mangroves throughout Florida. Subjects for meetings have included pesticide use on conservation lands, impacts on wetlands related to development, impacts to wetland management related to changes in sea level, and the effects of climate change on the distribution of mosquito-borne tropical diseases. These subjects inform decisions related to mosquito control while planning methods and projects to restore wetlands.

After years of successful rehabilitation and restoration in northeast and east central Florida, some of the agencies and groups working on restoration developed a framework to facilitate and enhance implementation of rehabilitation and restoration projects. These efforts began in 2010, and they were, in part, designed to enhance the competitiveness of projects submitted to

national funding programs. The first of these efforts resulted in the Northeast Florida Estuarine Restoration Team (NERT) whose mission is “To create healthy, thriving estuarine habitats of sufficient quantity and quality throughout northeast Florida.” This team developed a NE Florida Estuarine Restoration Plan and a planning guide to assist similar teams throughout Florida (Frazel 2013). This latter document identified numerous references related to planning and outlined consultations needed as planning progressed. One of these recommendations specifically calls for the inclusion of local/regional mosquito control entities. At this point, similar groups have formed in at least five regions along Florida’s coasts.

#### Permitting

Permitting is one of the initial steps in implementing restoration. In Florida, permitting for these types of projects has fallen mainly within the jurisdiction of the FDEP (or by delegation to water management districts) and the U.S. Army Corps of Engineers (Sect. 404 of the Clean Water Act). Recently, responsibility for Sect. 404 permits was delegated to the State of Florida (FDEP 2021a). In addition, some local jurisdictions (cities or counties) may have wetland protection programs that require permits. Regardless of the type of permit being sought for the project, early consultation with regulatory staff is critical. Consultation is especially valuable when proposed methods have not been used widely in the past. There are two primary paths to permitting a restoration project in the state of Florida. The first and simplest is the direct permitting of a project to restore or enhance natural resource values in an area of disturbed coastal wetland. Historically, this process could be long and complicated as these projects were reviewed with the same criteria as those for urban development. More recently, state and federal regulatory agencies have simplified the permitting process for such projects. The state agencies have general permits with simplified applications and standard conditions. On the federal side, the Army Corps of Engineers has a series of Nationwide Permits (NWP) that can be accessed for specific types of restoration, with the most applicable being the NWP #27 for Aquatic Habitat Restoration. When securing these permits for restoration activities, our experience suggests that you permit more area than you have funding to complete as it is typically

easier to secure additional funding for an ongoing effort.

The second path is one that may be used for large-scale restoration projects whose investors are reimbursed from clients that need mitigation. In Florida, this process is called mitigation banking. This more complex method requires the project to meet predetermined success criteria before release of marketable mitigation credits. In the field of compensatory mitigation, these banking projects with their predetermined success criteria are seen as being beneficial because of the mixed success of smaller-scale, on-site mitigation (Crewz and Lewis 1991; Allen and Feddema 1996). Florida Statutes Sect. 373.4136 (State of Florida 2021) requires mitigation banks to have provisions for perpetual management and maintenance. However, meeting success criteria in a permit does not always mean achieving full functional equivalence (e.g., Reiss et al. 2009).

### Current and future issues

Our review of past changes to mangrove-dominated wetlands in Florida has focused primarily on direct anthropogenic impacts and related management of mosquito. Moving forward, restoration and conservation of wetlands and mosquito control will need to incorporate synergistic effects of changes in climate into management plans. It will require support from all levels of government.

#### Sea level rise and resilience

Resilience, in the context of this paper, refers to resistance to loss of habitat (including mangroves) and the adaptation of these habitats to changing conditions. To a lesser extent, it includes the ability of infrastructure that controls mosquitoes to withstand these changes. In addition to direct anthropogenic changes discussed above, one of the most significant threats to coastal wetlands over the next century is increased rates of sea level rise (Gilman et al. 2008). Erosion of shorelines and loss of intertidal habitat is expected to worsen with continued sea level rise and increased extreme weather events (Pachauri et al. 2014). Mangroves and other coastal wetland vegetation can mediate the effects of rising sea levels through direct and indirect biotic processes that maintain sediments

at elevations that support survival and growth of plants (Morris et al. 2002; Cahoon et al. 2006, 2021; McKee et al. 2007; Krauss et al. 2014). Wetlands also increase resilience of coastal communities and infrastructure through protection from flooding and waves from severe storms (Hochard et al. 2019; Menendez et al. 2020). This connection highlights the importance of developing suitable plant communities following restoration to support long-term sustainability of restored wetlands as well as the importance of conserving existing wetlands to protect critical ecosystem functions in the future. In Florida, a program sponsored by the FWC called the “Coastal Habitat Integrated Mapping and Monitoring Program” (CHIMMP; FWC 2021) has been organized to compile relevant information. Through a series of workshops and other collaborations, CHIMMP has produced maps and a regularly updated, statewide technical report that supports management and conservation goals by documenting the status of saltmarsh and mangrove habitats in regions around Florida. These efforts will be critical in identifying losses of coastal wetland due to inundation. Areas of drowning may be suitable for restoration through placement of material that raises their elevation (e.g., Subsidized Wetland, above or thin layer placement; Cornwell et al. 2020; Howard et al. 2020).

If rates of sea level rise are greater than natural processes, coastal wetlands can adapt by migrating landward to maintain optimal elevations, if suitable habitat is available and barriers to migration are absent (i.e., bulkheads or steep slopes). These new wetland areas may require efforts to control mosquitoes. However, alterations to wetlands, such as those described here, have changed the structure of natural communities, and such changes threaten the ability of coastal wetlands to adapt to future changes in sea level (Romanach et al. 2018). This situation highlights the crucial need for science-based restoration, management, and conservation of mangroves and salt marsh to increase resilience in these critical habitats and preserve ecosystem function. To address this need, future environmental conditions must be considered during planning for restoration, so the outcome maximizes the long-term effectiveness of the restored systems. For example, hydrological restoration can include a range of elevation targets to support current wetland plant communities and support migration to higher elevations under future environmental

conditions. In areas where full wetland restoration is not possible, implementation of living shorelines that incorporate mangroves to stabilize sediments has been used as an alternative to hard-armoring, such as riprap or bulkheads. Living shorelines effectively reduce erosion in addition to providing additional ecosystem services and maintaining an ability to adjust to future sea level rise (Gittman et al. 2016; Donnelly et al. 2017; Kibler et al. 2019; McClenachan et al. 2020).

Recently, all levels of government have recognized the issues that climate change, and particularly sea level rise, generate with regard to the resilience of infrastructure, habitats, and communities. For example, NOAA has been funding coastal community projects that address resilience to sea level rise and other climate related changes (NOAA 2018). In Florida, the state's Aquatic Preserves are now part of FDEP's Office of Resilience and Coastal Protection (FDEP 2021b), and regional and local governments are hiring staff and developing resilience programs (SJRWMD 2020). At this time, most efforts focus on accommodation to the changing conditions.

In estuarine wetlands, an often-raised question is how climate change, and in particular rising water levels, might impact populations of saltmarsh mosquitoes (*Ae. taeniorhynchus* and *Ae. sollicitans* (Walker)). Saltmarsh mosquitoes lay their eggs on moist soil and not on standing water. The eggs then hatch when flooded by high tides or rainfall. Consequently, with rising water levels due to climate change, it is likely that wetlands that are currently intertidal, at some point will become constantly inundated so they will not produce these mosquitoes. Correspondingly, upland habitats that are adjacent to wetlands but currently not flooded by tides likely will be inundated more regularly in the future thus becoming locations that produce mosquitoes. Fortunately, significant effects on human health are unlikely because *Ae. taeniorhynchus* in our area is not a vector of pathogens to humans, but they are capable of transmitting dog heartworm.

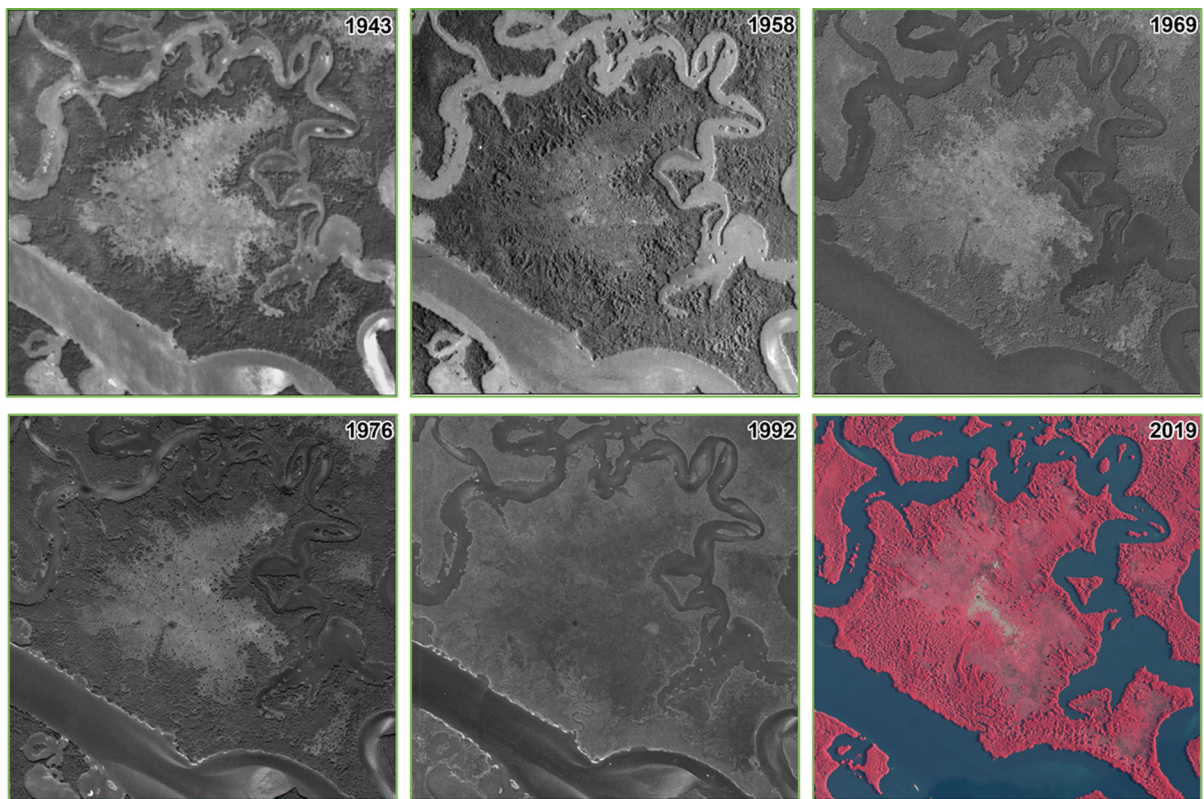
#### Northward migration/expansion of mangroves

Assemblages of plants in coastal wetlands vary with climate on a global scale, exhibiting a latitudinal gradient from the temperate coastlines at higher latitudes to the tropical coastlines around the equator (Pennings and Bertness 2001). Mangroves dominate in

tropical climates, with the extent of mangroves largely controlled at any given time by the frequency of freezing events (Odum and McIvor 1990; Tomlinson 1994; Cavanaugh et al. 2019). Coastal wetlands at the temperate-subtropical climate boundary often have a mix of both temperate and tropical plants (Odum and McIvor 1990; Cavanaugh et al. 2019). In the last few decades, mangroves have progressed northward along the southeast coast of the US (Cavanaugh et al. 2019). There are also indications that mangroves are expanding their presence and extent on oyster reefs in Mosquito Lagoon (McClenachan et al. 2021). To evaluate these situations, it will be valuable to have some historical context for such movement. This context can be provided by a comparison to the citrus industry (Stevens et al. 2006) and, more recently, historical aerial imagery.

From a Florida perspective, parallels between mangroves and the citrus industry are hard to miss. Citrus and mangroves both appear to be more sensitive to extreme cold events than to average temperatures. In Florida, citrus industry altering or "impact" freeze events had occurred infrequently from 1835 through 1962 (3 events with circa a 60-year return frequency), with each event pushing the industry further to the south on the Florida peninsula (Attaway 1997). However, the 13-year period from 1977 through 1989 contained a snow fall event (1977; Brockmeyer, pers obs.) and 2 "impact" freezes among the 5 freeze events. The event in 1989 completely changed the landscape of coastal wetlands in the IRL system, with many areas completely devoid of large mangroves well into south Florida (Brockmeyer, Rey, Carlson; pers obs.). The importance of this period also was identified by Stevens et al. (2006); Cavanaugh et al. (2019) and McClenachan et al. (2020). No similarly severe freeze events have occurred in subsequent years.

The effects of some of these freeze events can be illustrated by examining a fixed location within the transition zone between mangroves and saltmarsh. The typical vegetation on coastal wetland islands in Mosquito Lagoon consists of saltwort (*B. maritima*) and glassworts (*S. ambigua* and *Salicornia bigelovii*) mixed with some saltgrass (*D. spicata*). Smooth cordgrass (*Spartina alterniflora*) may be present at the edges of the marsh islands. Black mangroves (*A. germinans*) are an ephemeral component of this wetland community, becoming more prominent as



**Fig. 6** Selected images from numerous sources showing relatively unimpacted islands near the C-8 impoundment in Mosquito Lagoon, Volusia County, Florida, USA. The darker textured areas around the perimeter of the larger central island are mangroves

the period between freeze events increases. Figure 6 depicts a group of wetland islands in Mosquito Lagoon in 6 different years beginning in 1943. Note the dark textured areas around the periphery representing the extent of mangrove cover in the imagery. These images were selected from 21 separate years from 1943 to 2019 (presented with freeze information in Online Resource 1). The 1958 image may have the largest cover of mangroves. Note the extent of mangroves in the pre-freeze period represented by the 1976 image and the change depicted in the image from 1992 that shows a much-reduced footprint for mangroves. The 2019 image shows increased mangrove cover; however, they have not reached the extent seen in the pre-1977 imagery. Thus, severe freezes alter the distribution of mangroves for multiple years.

## Conclusion

Over the past century, mangrove-dominated wetlands have undergone tremendous changes in Florida largely due to anthropogenic influences, with mosquito control and development being primary factors. As described in this paper, these influences have included ditching through densely vegetated wetlands, filling these habitats when they were considered “wastelands,” impounding them to control saltmarsh mosquitoes and manage waterfowl, and later, working to better manage and rehabilitate degraded wetlands as their ecological significance became apparent. Improved management largely has occurred over the past 40 years, with continued focus on balancing integrity of mangrove wetlands with the need for mosquito control. Management strategies have been supported through on-going research, with results providing science-based information to guide decision-making and support adaptive strategies to improve ecological outcomes and maintain mosquito

control. The restoration work in Florida contributes to the growing knowledge of mangrove rehabilitation globally and supports the use of proven techniques to increase success of projects (Friess et al. 2020). Some key lessons learned from these rehabilitation and restoration efforts include: work with land owners/managers, stakeholders, and partners to plan restoration projects; consult regulatory staff early and permit more area than you currently have funds to restore; find and repeatedly use professional construction contractors or implementation partners that can execute your restoration plan effectively and efficiently; and monitor and correct issues that arise during and after completion of your project. Interagency cooperation at the federal, state, and local levels can address the diverse interests in wetland management and integrate the needs of diverse stakeholders. Creation of interagency working groups can facilitate the dissemination of knowledge generated through research and experience. The future of these efforts undoubtedly will have to consider climatological factors along with continued efforts to make certain these mangrove systems are performing their important ecological functions.

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