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Coastal wetland management in Florida: environmental concerns and human health

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Abstract High mosquito populations have always been a part of Florida's environment. While mosquito-transmitted diseases have played a major role in Florida's history, saltmarsh mosquitoes have not been implicated in these disease outbreaks. However, the impact of high saltmarsh mosquito numbers on the well-being of residents and visitors cannot be underestimated. Coastal wetland management efforts in Florida, which date back to the 1920s, have included ditching, dredging and filling, and impounding, all having mosquito control and environmental benefits and liabilities. In the early 1980s, efforts to encourage coastal wetlands management for both mosquito control and environmental interests came to the forefront. This resulted in the Florida Legislature creating the Florida Coordinating Council on Mosquito Control and its Subcommittee on Managed Marshes. Through the efforts of these committees, a heavy investment in research, interagency cooperation, and public acquisition of coastal wetlands property, tremendous progress has been made in management of coastal wetlands. This has occurred largely by implementing management and restoration techniques that minimize environmental impacts, allow for mosquito control, and minimize the need for pesticide use. Continued efforts are needed to place into public ownership remaining privately owned coastal wetland property to allow implementation of best management practices on these important habitats.

Keywords Florida · Hydrology · Impoundment · Mangrove · Mosquito · Restoration · Salt marsh

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Introduction

Overview of Florida coastal wetlands

Florida's coastal wetlands are highly variable due to the State's geographic location, large latitudinal range, geologic history, and physiognomy. In the north, particularly along the "Big Bend" area (from Apalachicola Bay to Cedar Key), and from Jacksonville to Daytona Beach (Fig. 1), grassy salt marshes predominate. Some extensive rush-dominated marshes also exist along the Gulf in the Panhandle region (Kurz and Wagner 1957). In all these areas, smooth cordgrass

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(*Spartina alterniflora*) can form large monospecific stands at lower elevations closer to the water, but more commonly, this species only occupies narrow bands often less than 10 m wide at lower elevations along the shoreline, and is replaced by black needle rush (*Juncus roemerianus*) or other halophytic species as one moves upland (Rey 1981). Distinctive plant zonation is often evident in many Florida coastal wetlands. In some areas of North Florida, very sharp boundaries between pure *S. alterniflora* and pure *J. roemerianus* stands are clearly visible. Other distinctive plant zonation patterns can sometimes be observed, with characteristic low marsh and high marsh zones clearly delimited. Just as often, however, intricate mixtures of vegetation occur throughout large portions of a given marsh (Montague and Wiegert 1990). Other herbaceous plant species in grass/rush marshes include salt marsh hay (*S. patens*), saltgrass (*Distichlis spicata*), saltwort, (*Batis maritima*), glassworts (*Salicornia bigelovii*, *Sarcocornia perennis*), sea purslane (*Sesuvium portolacastrum*), salt joint grass (*Paspalum vaginatum*), and the sedges *Cladium jamaicense* (sawgrass), and *Fimbristylis* spp. (fringe rush).

South of Cape Canaveral in the east, and Tarpon Springs in the west (Fig. 1), cover by mangroves steadily increases becoming the dominant coastal vegetation in South Florida and the Keys. Fringes of herbaceous halophytes, however, are regularly found throughout the State. Three mangrove species occur in Florida: The red mangrove (*Rhizophora mangle*), the black mangrove (*Avicennia germinans*), and the white mangrove (*Laguncularia racemosa*). Although, not a true mangrove, the buttonwood (*Conocarpus erectus*) is often found in association with these three species. The exact geographic distribution of mangroves in Florida has varied with short-term climatic patterns (Stevens et al. 2006). Mangroves are essentially tropical species unable to thrive where average annual temperatures are below 19°C (Waisel 1972). Periods of cold weather, such as occurred in Florida in the early 1960s and late 1970s, have caused widespread mortality of mangroves and a southward retreat of red and white mangroves (Odum and McIvor 1990). The black mangrove can often persist after extreme cold episodes because of its ability to re-sprout from surviving roots (Sherrod and McMillan 1985).

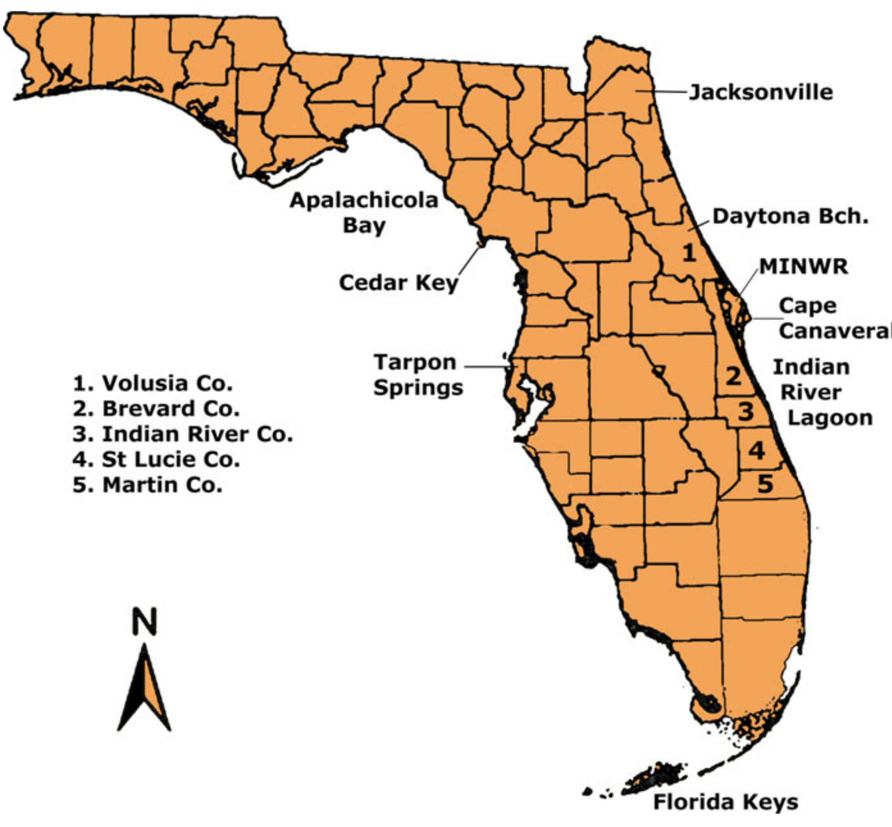

Fig. 1 Map of Florida showing some of the locations mentioned in the text. *MINWR* Merritt Island National Wildlife Refuge

Because of topography and low tidal amplitude along both coasts, a very large proportion of coastal wetlands in Florida can be considered high marsh (Provost 1973a, 1976; Rey et al. 1991b). These marshes are not flooded by daily tides, but are only flooded by spring tides, seasonal high tides, and by rainfall. This situation is ideal for the saltmarsh mosquitos *Aedes taeniorhynchus* and *A. sollicitans*, as these species will not oviposit upon standing water or overly wet substrate as would be found in low marshes that are flooded daily. Instead, these species will lay eggs upon moist soil and the eggs will hatch and develop when flooded by rainfall or spring tides (Provost 1969; 1973b). Thus, in general, a much larger proportion of the marsh acreage in Florida is suitable for mosquito production than in other coastal wetlands along the Atlantic Coast of North America. The low tidal amplitude mentioned above also complicates source reduction efforts (environmental manipulations that reduce mosquito larval habitat) as tidal energy cannot generally be relied upon to circulate water through ditches and other source reduction works.

In Florida, the presence of large expanses of mangroves is also an important difference from herbaceous salt marshes further north. In many cases, the thick mangrove canopy prevents or retards the delivery of aerially applied mosquitocides to the larval habitats. Additionally, some source reduction techniques, such as Open Marsh Water Management (OMWM) utilized successfully for mosquito control elsewhere, are difficult or impossible to implement in mangrove-dominated areas because the necessary modifications (ponds, pond radials, tidal ditches, etc.) can not be constructed through the thick tangle of mangrove roots and trunks without causing extensive environmental damage.

Florida's coastal wetlands and human health

The principal mosquito species of Florida coastal wetlands is the black saltmarsh mosquito *A. taeniorhynchus*. This species is an aggressive biter that can impact humans and animals at considerable distances from their larval habitats in the wetlands (Provost 1952; Bidlingmayer 1985; Hribar et al. 2010). The other primary coastal wetland resident is the eastern or golden saltmarsh mosquito *A. sollicitans*.

Aedes taeniorhynchus is capable of transmitting eastern equine, and St. Louis encephalitis (Nayar et al. 1986; Turell et al. 2001), but this species has not been shown to be a major vector of these diseases in nature. It can also transmit West Nile virus, but it is quite resistant to natural infection (Turell et al. 2001) and has not been implicated as a major factor in any West Nile outbreak to date. *Aedes taeniorhynchus*, however, is a major vector of dog heartworm (*Dirofilaria immitis*) and can be an important vector of Venezuelan equine encephalitis (Sudia et al. 1971; Weaver et al. 1996). Furthermore, some authors consider this species as a potentially important bridge vector for wildlife diseases (Bataille et al. 2009). Likewise, *A. sollicitans* is a competent vector of several diseases, including eastern equine encephalitis (Merrill et al. 1934; Crans 1977; Crans et al. 1986) and Cache Valley Fever (Main and Crans 1986), but as with the former congener, it has not been incriminated in any significant transmission event in nature.

Saltmarsh mosquitoes can, nevertheless, significantly impact human well-being. Reports of mosquito plagues, inferred to be saltmarsh mosquitoes, making life impossible for humans date back to the XVI century (Tebeau 1968; Harden 1997). Similar reports originate from early Florida explorers such as Jonathan Dickinson (Andrews and Andrews 1945) and William Bartram (Harper 1942). In the second half of the XIX century, yellow fever outbreaks were widespread in Florida and an epidemic in Jacksonville resulted in 5,000 cases, 400 deaths, with half the population fleeing the city, and collapse of the city's business and commerce structure (Fairlie 1940; Patterson 2004). Although the first structured efforts at mosquito control in Florida were focused at malaria and yellow fever prevention and were thus probably directed at *A. aegypti,* organized mosquito control was developed in Florida primarily as a response to the hordes of saltmarsh mosquitoes that severely impacted the quality of life for residents and made outdoor activities impossible during the summer (Connelly 2009). By the 1950s, hundreds of miles of coastal wetland ditches and countless gallons of pesticides had been employed in attempts to provide some relief to Florida residents from these aggressive mosquitoes. Quality of life and human welfare along coastal Florida would be severely lessened without effective mosquito control.

Saltmarsh mosquitoes can also be a significant health risk for persons with allergic reactions to mosquito bites (Simmons and Peng 1999). Severe reactions to mosquito bites, often generically referred to as "mosquito syndrome" or "skeeter syndrome" (Sabbah et al. 1999; Simmons and Peng 1999) can be local or systemic and can cause severe necrotic lesions, urticaria, swelling of the mucous membranes including the larynx, fever, decreased blood pressure, loss of consciousness, and other symptoms (Peng et al. 2004). Reactions may involve specific IgE and IgG responses to mosquito salivary antigens, some of which are species-specific and others widely shared among groups (Simmons and Peng 1999). The prevalence of the condition is probably underestimated because the syndrome is often misdiagnosed as an "infection" at an insect bite site.

Although, not exclusively related to wetlands, human health risks from pesticides used for mosquito control also need to be considered. Unfortunately, most pesticide exposure health effect assessments have been done with agricultural pesticides, which tend to be applied at much greater amounts and dosages than those for mosquito control (Hribar and Bryan 2009), or directly to food. Recent work related to current emerging disease outbreaks, such as West Nile virus indicate that human health risks from pesticide use from mosquito control are low (Peterson et al. 2006). Nevertheless, acute effects from pesticide exposure, such as allergic reactions, neurological impairment and infertility (Savage et al. 1988) and adverse effects on individuals suffering from idiopathic environmental intolerance, whether physiological (Schnakenberg et al. 2007) or somatoform (Bailer et al. 2005), are of concern. Furthermore, our inability to predict long term effects of exposure to some of the newer synthetic insecticides demands caution in their use.

In addition to mosquitoes, Florida's coastal wetlands can produce prodigious numbers of biting midges of the genus *Culicoides* (sandflies, no-seeums, punkies). There are 47 species in Florida, of which seven are human pests. Some common *Culicoides* species can transmit the nematode *Mansonella ozzardi*. Infection with this nematode is rather benign with very few symptoms, but the impacts of sandfly bites on humans and animals can be as severe as those of mosquitoes. Control of these pests is very difficult because of the extensive habitat that they occupy, and direct funding for sandfly control is almost nonexistent in Florida (Connelly and Day 2005).

Coastal wetland management history in Florida

Early history

Perhaps the earliest mention in the literature of mosquitoes in Florida dates back to the mid-XVI century. It was written by a Jesuit Missionary, Brother Francisco, who was assigned to a mission in Biscayne Bay. In 1565 he stated "…about a plague of mosquitoes of 3 months duration during which the only relief was to remain close of the fire smothered by smoke." It is likely that Brother Francisco was being bitten by the saltmarsh mosquito *A. taeniorhynchus* (Harden 1997). In *The Mosquito Wars: A history of mosquito control in Florida*, Patterson (2004) points out that in the late 1500s European travelers to the Florida coast reported that "the native people buried themselves to protect against mosquito bites".

Beginning in the 1920s, parallel ditching done by hand or dynamite, was the first major attempt in Florida to control coastal mosquito populations. This method was adapted from the northern coastal states and was outlined in Hardenburg (1922). He describes ditching utilizing a "parallel plan" as being considered the "best practice" in New Jersey. Further, he describes effective parallel ditching as being "sufficiently close together to remove surface water." While not considered as effective, Hardenburg also describes a competing ditching method that may be considered the precursor to the modern OMWM. This method known as a "pool-connecting system" calls for the interconnection of pools with one or more outlets to tidal waters.

During the Great Depression of the 1930s, this ditching effort was greatly expanded utilizing federal funding through programs like the Civilian Works Administration and Works Progress Administration (Patterson 2004). Thousands of miles of hand- and dynamite-dug ditches were constructed throughout Florida. This source of funding and much of the ditching effort faded with the approach of World War II. The effectiveness of these ditches declined as connection to the estuary eroded and closed.

In Florida, early attempts at wetland impounding occurred in St. Lucie Co. in 1935, when after attempts at draining a marsh using pumps failed, the pumps were reversed and used to flood the marsh instead, resulting in cessation of mosquito production from the flooded marsh (Hull and Dove 1939). However, as with ditching, funding declined as WWII approached.

In 1942, the U.S. Department of Agriculture established their Insects Affecting Man and Animals research group in Orlando. It was charged with the responsibility to develop means for controlling insects of medical importance for military personnel serving around the world. Near the end of WWII, this laboratory began testing the organochlorine chemical dichloro-diphenyl-trichloroethane (DDT) as an agent to control human lice, which transmit typhus. The scientists learned that this material also served as a mosquitocide. At the end of the war, DDT became the material of choice for larval and adult mosquito control in Florida, much of it being applied aerially. While it initially provided tremendous mosquito control benefits, within several years, many mosquito species became resistant to it along with several other organochlorine insecticides (Wassmer and Royals 2009).

In the 1950s, with the decline in the effectiveness of these WWII-era chemicals, alternative methods of control were needed. Many of these alternatives involved physical alteration of the high marsh that reduced the available habitat for mosquito reproduction. A variety of these source reduction methods were used in Florida.

Dredge and fill

During the 1950s and 1960s primarily along the central east coast of Florida, dredging of estuarine sediments and depositing them onto coastal wetlands was a common practice. The goal was to eliminate coastal wetlands, which produce large numbers of mosquitoes. A secondary 'benefit' was the production of waterfront uplands amenable to development; in fact, some of the marsh filling projects at the time were actually undertaken or financed by developers. This technique proved to be too slow and very costly; a mosquito control agency using a 10-inch dredge and working two 8-h shifts per day, was only able to fill about 50 acres per year (J. Beidler, personal communication, 2011). Consequently, this approach was abandoned in the late 1960s. Also, cracks in the dried dredge material proved excellent ovipositional sites for saltmarsh mosquitoes, thus exacerbating the mosquito problem. Today this type of estuarine sediment disturbance and wetland filling is not allowed due to environmental restrictions (Carlson and O'Meara 2009).

Dragline ditching

In the 1950s and 1960s, large excavators called draglines were used to cut through the wetlands. The draglines worked from mats or were mounted on small barges, and material excavated from the wetlands piled on either side of the created ditch. The barge-mounted draglines moved by pulling themselves along through ditches as they were created and proved to be much more cost effective (unpublished data, Volusia County Mosquito Control (VCMC)). Extensive networks of deep, wide ditches and spoil piles were created that cut through historical coastal wetland habitat, and severely reduced wetland acreage (Fig. 2). The purpose of the ditches was to interrupt the life cycle of saltmarsh mosquitoes by altering their egg-laying (oviposition) sites and allowing larvivorous fish access to mosquito larvae.

While dragline ditching effectively reduced the mosquito population in coastal wetland areas, an unintended result was a severely altered wetland ecosystem. The wetland habitat reductions were widespread, with the amount of habitat lost varying with the intensity of ditching. In the most extensively ditched areas, up to 80 percent of wetlands was replaced with ditches and spoil piles. On average, half of an impacted area is ditch and spoil (Brockmeyer unpublished data). This reduces wetland ecosystem services, which in turn may reduces the fish and wildlife populations and diminish storm protection. Spoil areas are at a substantially higher elevation than the surrounding wetland (R. Brockmeyer, unpublished data) thus allowing the colonization of upland plant species, including invasive exotics, such as Brazilian peppers (*Schinus terebinthifolius*). The mangroves that remain inhabit a narrow intertidal zone along the edges of spoil piles (R. Brockmeyer, personal observation), but can be out-competed by terrestrial and exotic species on the elevated portion of the pile. The most extensive ditching occurred in Mosquito Lagoon where nearly 485 ha were impacted in this northern Indian River Lagoon (IRL) basin, though ditching is also present elsewhere in the IRL (IRL total is approximately 810 ha; Steward et al. 2003) and in northeast Florida coastal basins. In northern Volusia County, approximately 160 additional ha of coastal

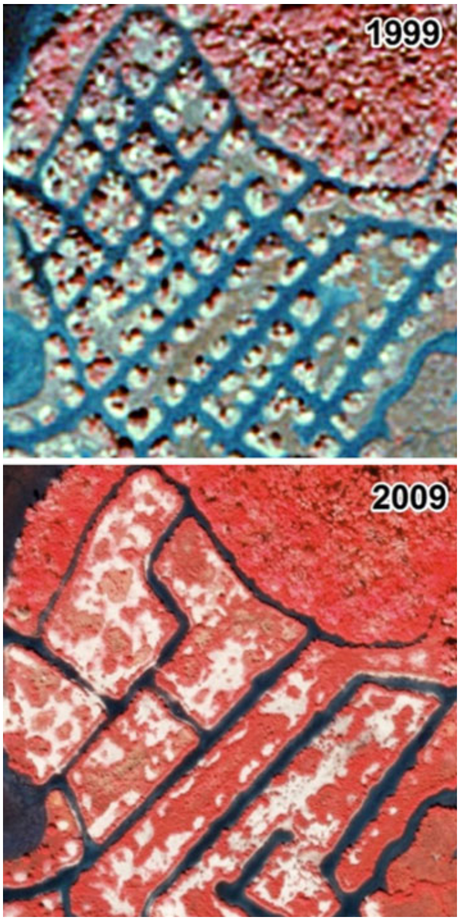

Fig. 2 Aerial view of dragline ditches on orange island in mosquito lagoon, Florida, before (*top*) and after (*bottom*) restoration

wetland were dragline ditched in the Tomoka River/Halifax River/Spruce Creek drainages.

Impounding

Due to the previously mentioned issues with physical complexity of mangrove habitats, low tidal amplitude, and the large expanses of mosquito-producing high marsh in the area, source reduction efforts in east-central Florida depended heavily on impoundments (Rey et al. 1991b). A mosquito control impoundment is a salt marsh or mangrove forest that has been diked to allow control of water levels. Impoundments rely upon the fact that saltmarsh mosquitoes will not oviposit upon standing water. Thus, mosquito production is prevented by keeping the substrate flooded by even just a few centimeters of standing water during the mosquito producing season, approximately May to October in this area (Carlson et al. 1999).

With development of DDT resistance by a large proportion of saltmarsh mosquitoes in the 1950s, impounding for mosquito control resumed in Brevard and Indian River counties. Additional work quickly followed in Volusia, St. Lucie and Martin counties (Fig. 1). The development of the Space Center in Cape Canaveral during the early 1960s provided a boost to mosquito control and impounding in the area, as work by technicians and engineers was greatly impacted by the pestiferous conditions (Patterson 2004). By the 1970s, over 16,000 ha of coastal marshes and mangal had been impounded for mosquito control. A large proportion of the area impounded lies within the Merritt Island National Wildlife Refuge (MINWR, Fig. 1), overlaying the Kennedy Space Center.

Structure

The typical mosquito control impoundment is bordered by an earthen dike constructed via dragline close to the mean high water mark, and which may encircle the whole marsh or may stop at the upland edge. A perimeter ditch (borrow pit), from which material for dike construction is obtained, parallels the dike, typically on the inside of the dike. Several water control structures such as culverts, spillways, tide gates and others are used to manipulate water levels and impoundment–lagoon exchange (Provost 1977). In some cases, artesian wells were utilized to keep the impounded marsh flooded, but currently, most impoundments have dedicated diesel or electric pumps to allow precise control of flooding elevations.

Impacts

Originally, many impoundments had no connection to the adjoining lagoon, and were flooded by wells or portable pumps that were shared among many impoundments. Impoundments were flooded to much higher levels than necessary to assure that enough water remained to maintain mosquito control during the mosquito producing season after losses to seepage and evaporation between pump visits. During the rest of the year, water was allowed to fluctuate depending upon rainfall and evaporation. These early impoundment management practices had serious negative impacts upon these systems. Water quality in impoundments was severely impacted (Carlson et al. 1989; Rey et al. 1992). Among common effects observed were decreased D.O. levels, wildly fluctuating salinities, high sulfide concentrations, high water temperatures, and uncharacteristic levels of nitrogen and phosphorous compounds. Lack of circulation and flushing, vegetation mortality, and abnormal water levels were mainly responsible for the declines in water quality.

Most obvious were the effects on the marsh vegetation. Because of the deep flooding, marsh vegetation in some impoundments was completely eliminated. Herbaceous halophytes such as *Batis* and *Salicornia* cannot tolerate extended submergence, and black mangroves are also killed after prolonged submergence of their pneumatophores (Provost 1973b). Vegetation damage due to extreme salinities and poor water quality was also pervasive (Rey et al. 1990b). In some areas, the typical high marsh vegetation (black mangroves interspersed among *Batis* and *Salicornia* meadows) was replaced by monospecific stands of red mangroves, which are better adapted to high water levels because of their high, arching prop roots. Vegetation in some impoundments that were flooded by artesian wells or by upland drainage shifted to assemblages more characteristic of freshwater systems, usually dominated by cattails (*Typha* spp.) (Clements and Rogers 1964; Brockmeyer et al. 1997).

Impounding drastically reduced the numbers of fish species utilizing the marsh habitat. Harrington and Harrington (1961, 1982) noted elimination of all but a few small resident species that completed their entire life cycle in the marsh after impounding. Many important fishery species that utilize this habitat during part of their life cycle including tarpon (*Megalops atlanticus*), mullet (*Mugil cephalus*, *M. curema*), snook (*Centropomus undecimalis*), ladyfish (*Elops saurus*), and others were eliminated from this very critical habitat by impounding (Snelson 1976, 1983; Gilmore et al. 1982; Rey et al. 1990b). Marsh invertebrates were not immune to adverse effects and early on, research documented impacts to zooplankton and other aquatic and terrestrial invertebrates (Rey et al. 1991a; Gilmore et al. 1982; Tunberg 2009). Impounding, on the other hand, was found to be beneficial to some species of wading birds (Provost 1969).

As impacts from early impoundment design and management protocols became known, controversy arose about the use of this technique for mosquito control. However, strong opposition to the use of pesticides, particularly over aquatic systems, was also growing, so that by the 1970s, mosquito control and environmental interests were poised for what Patterson aptly called “The Mosquito Wars” (Patterson 2004). Details of the controversy are beyond the scope of this paper, but are described in detail in Patterson’s (2004) work. The creation of the Subcommittee on Managed Marshes (SOMM) of the Florida Coordinating Council for Mosquito Control (FCCMC; both described below), and the allocation of funds for research on wetlands management by various entities including the Florida coastal management program proved to be critical in advancing ecologically sound wetlands mosquito control in Florida without reverting to heavy reliance on pesticides.

Impoundment management research

Early experiments in Florida had shown that flooding the wetlands only during the summer provided acceptable mosquito control (Clements and Rogers 1964), and seasonal flooding experiments in the early 70s demonstrated the effectiveness of the technique and the importance of water level control and maintenance of marsh-lagoon connections for reducing environmental impacts of impounding. The latter was a collaboration between Maurice Provost of the Florida Medical Entomology Laboratory and Jack Salmela of the Brevard Mosquito Control District that incorporated most of the elements of current impoundment management techniques, including a pump, riser and flapgated culverts (Provost 1973b; 1977).

This early success, led to a movement towards reconnection of wetlands previously isolated by impounding. Culverts with flashboard risers to prevent excessive water levels were installed through impoundment dikes. The use of dedicated pumps eliminated the need to overflood the marsh, and the management protocols changed to flooding for mosquito control only during the summer mosquito production season, and re-establishing tidal exchange through culverts during the rest of the year. This technique, now called Rotational Impoundment Management (RIM), and various modifications for specific purposes such as waterfowl management, is the primary impoundment management strategy used by mosquito control programs along Florida’s IRL

(Carlson et al. 1991; Carlson 2006; Brockmeyer et al. 1997). With local, Water Management District (WMD), state, and federal partnerships, the reconnection effort has progressed to include over 9,300 ha of impoundments lagoon-wide that have culverts in place to allow active management. If compensatory mitigation activities are included, the total area under active management climbs to 10,830 ha. (Steward et al. 2003; R. Brockmeyer, unpublished data). A great deal of research accompanied the reconnection movement, which led to fine tuning of RIM, and documentation of the benefits of marsh restoration through hydrologic reconnection. Some of this research demonstrated that if tidal exchange is restored, recovery of herbaceous vegetation is often rapid, followed by a slower mangrove recovery (Rey et al. 1990a). Furthermore, the enhanced water management capabilities provided by RIM became an important tool for management of exotics and nuisance vegetation in impoundments (Schmalzer 1995). Primary production and growth rates of mangroves and herbaceous species from reconnected impoundments compared favorably with those from unimpounded areas (Rey et al. 1986, 1990c; Lahmann 1988). Although, the summer flooding does appear to curtail above-ground primary production, it has little effect on yearly production because in this area production is normally at a minimum during the summer because of high temperatures and interstitial salinities (Rey et al. 1990c; Brockmeyer et al. 1997).

Nekton species utilizing these marshes can be divided into resident and transient. The former species tend to be small and physiologically adapted to variably rigorous environmental conditions. The later tend to be larger species, most of sport and commercial fishery value that recruit during specific portions of their life history. Studies on fish and crustacean utilization of impounded wetlands demonstrate a significant increase in diversity and abundance of transient species after hydrological reconnection (Harrington and Harrington 1982; Gilmore et al. 1982; Taylor et al. 1998; Poulakis et al. 2002). These studies also indicate that culverts provide adequate nekton access between marsh and estuary as long as they are installed at the correct elevation and open at the right time (Brockmeyer et al. 1997). However, summer closure for mosquito control still interferes with recruitment of certain species such as tarpon (*M. atlanticus*) and silver mullet (*M. curema*, Gilmore et al. 1982) and adjustments to management schedules may be necessary in areas with heavy utilization by these species.

Zooplankters are important components of marine and estuarine food webs and often excellent indicators of overall ecosystem health. Natural marsh zooplankton communities in this area resemble those of nearshore areas of the lagoon, and are dominated by copepods such as *Acartia tonsa* Dana and *Oithona nana* Giesbrech (Rey et al. 1987). Isolation through impounding can cause a transition towards more freshwater-like communities dominated by rotifers and with very low copepod densities (J. Rey, unpublished data), but hydrological reconnection quickly brings about a return to a more typical near shore estuarine community (Brockmeyer et al. 1997). Studies on surface and pore water quality (e.g., Rey et al. 1991b, 1992; Carlson et al. 1983) and marsh sediments (Rey and Kain 1993) after reconnection report smaller fluctuations in various water quality variables, particularly salinity and dissolved oxygen, but the large temporal and spatial variability characteristic of coastal wetlands make evaluation of the effects of reconnection very difficult. Certain impoundment-related structures, such as perimeter ditches and culverts, the specific management protocols employed at each impoundment, and the resulting hydrological regime all had important influence on water and sediment dynamics (Brockmeyer et al. 1997). More recently, a multi-year multi-disciplinary study called the Wetlands Initiative at MINWR examined the benefits and impacts of wetland management utilized there. This study pointed out important issues relating to fish and wildlife utilization as well as the critical role of emergent vegetation in the long-term survival of the wetlands themselves (Brockmeyer et al. 2005). So far, published results of the Initiative have dealt with accessibility of shorebird habitats (Collazo et al. 2002), sediment accretion rates (Parkinson et al. 2006), waterfowl/lesser scaup (Herring and Collazo 2004, 2005, 2006, 2009), wading birds (Stolen et al. 2007) and vegetation/fish associations (Stolen et al. 2009).

Impoundment management alternatives

Bottom water release

This variant of RIM was developed to resolve water quality issues that caused dissolved oxygen stress in fish inside closed, managed impoundments. Sulfides in the system can reach high levels in the water of the perimeter ditch, and due to water column stratification tend to accumulate near the bottom. Bottom water release is utilized primarily by the St. Lucie County Mosquito Control District (SLCMCD) to improve water quality in the perimeter ditches of managed impoundments (Carlson et al. 1989; David and Vessels 1989). During the summer, water is continuously pumped into the impoundment and water levels are balanced by releasing water through one or more culverts with bottom-water release structures. These systems sometimes include aerators to supplement oxygen levels. This method is very successful at improving perimeter ditch water quality, but is more energy and labor intensive than standard RIM (David 2001).

Wildlife/aquatic management (WAM)

Wildlife/aquatic management was designed to provide submerged aquatic vegetation (SAV; *Ruppia* or *Chara*) for consumption by migratory waterfowl, primarily dabbling ducks (Gordon et al. 1989; Collazo et al. 2002). If the appropriate amount of substrate without emergent vegetation is available, the hydrologic regimes calls for gradually increasing water levels from spring through fall reaching a peak in October or November. From this point, water levels are reduced in stages to provide continued access to SAV for grazing by waterfowl through the spring. There may be a short spring open period to consolidate sediment and germinate seeds. Because under WAM, the wetland is flooded during the summer mosquito-producing season, it is also effective at controlling saltmarsh mosquitoes. The prolonged inundation and isolation, however, can damage wetland vegetation and does not allow access for fish most of the year.

Impoundment breaching and restoration

For impoundments where mosquito control is no longer an issue or where mosquito control is maintained by other means (e.g., OMWM), further steps beyond reconnection via culverts can be taken to restore wetland functions. Impoundment work in Volusia County initially concentrated on dike breaching. Three impoundments were permanently breached with explosives by VCMC during the 1990s. Mosquito control in these permanently open systems was accomplished by the installation of rotary ditch systems. Because of the design of the rotary ditching equipment, spoil is dispersed widely leaving no "spoil mounds" like those found in dragline-ditched areas, and the low bearing weight of the ditching equipment, does not produce ruts or permanent impacts to the marsh surface (Duhring 1989). This technique eliminated the need for pesticides; allowed marshes to remain open and tidal throughout the year; promoted a more natural exchange of water, fish, and wildlife; and maintained mosquito control benefits. Local and St. Johns River Water Management District (SJRWMD) funds were used to breach these impoundments. A total of more than 465 ha of impoundments have been breached by a number of entities.

Restoring the shoreline of previously impounded wetlands by backfilling the perimeter ditch, while more costly, provides the most natural condition possible and removes these wetlands from active hydrological management. In 1998, the SJRWMD, VCMC, and U.S. Fish and Wildlife Service (USFWS) entered into an agreement to restore the shorelines (7.7 km) of four impounded coastal wetlands totaling 93 ha at the MINWR while maintaining effective mosquito control through a combination of directed rotary ditching and OMWM. This successful project led to additional impoundment restoration work and significant reduction in the use of pesticides.

In summary, a more natural hydrology has been restored to over 940 ha of previously impounded wetlands through the removal of nearly 69 km of dike. Throughout the IRL, the total area restored by all entities is over 1,307 ha. Of the original 16,185 ha of IRL impoundments, over 12,605 have been rehabilitated in some manner (i.e., reconnected, breached, or restored; Brockmeyer unpublished data).

Open marsh water management

OMWM is an updated version of some of the previous ditching methodologies with a much more limited impact to wetland systems. It is similar to the "pool-connecting systems" mentioned by Hardenburg (1922). It has been utilized and refined in states like New Jersey, Delaware, and others (Ferrigno and Jobbins 1968; Shisler and Jobbins 1977; Lesser and Shisler 1979; Resh and Balling 1983; Meredith et al. 1985).

In areas of Florida without large concentrations of mangroves, rotary ditching has been used to connect known mosquito-producing areas (depressions or shallow ponds) to permanent water sources (tidal or deep pond/pothole). This connection can change flooding frequency and duration while providing larvivorous fish access to immature mosquitoes. Use of this method in the IRL is typically limited to previously impacted wetlands like impoundments or hand-ditched areas.

Restoration of dragline ditch-impacted coastal wetlands

Rehabilitation of dragline ditch-impacted coastal wetlands was initiated in 1999 as a pilot project with the cooperation of VCMC, SJRWMD, and Canaveral National Seashore. The project was designed to evaluate several equipment and technique options on 22.5 ha of ditched wetland. Successful techniques developed in the pilot project have been applied to ongoing work in Mosquito Lagoon. These techniques were also implemented in Tomoka State Park.

Dragline ditch restoration requires the use of an amphibious excavator. An excavator is mounted on tracked pontoons, enabling it to cross submerged areas. Two of these low bearing weight machines (less than 2 lbs/sq. in.) are owned and operated by VCMC. Vegetation is cleared from the spoil area and placed in the adjacent ditch. This process avoids burning the plants and permanently sequesters the carbon they contain. Spoil material is first moved to the small side ditches (as seen in the top image of Fig. 2, between the spoil piles). If additional material remains, the main ditch is narrowed. The area of the spoil pile and the newly filled ditch are carefully graded to the adjacent remaining wetland elevation. The result is that substantially more area is at coastal wetland elevation without the return of substantial mosquito production (Fig. 2).

Fiddler crabs (*Uca* spp.) are the first animals to recruit to the newly restored surface within days. This semi-terrestrial wetland native can reach very high numbers and is food for numerous other animals, such as wading and shorebirds, fish and mammals (Montague 1980). Mangroves and other wetland plants quickly colonize the area, though it will take several years to reach near full coverage (M. Donnelly, personal communication, 2011).

Restoration work has been restricted to public lands with management objectives that include restoration of impacted wetlands. Experience has shown that focusing on public lands greatly simplifies permitting issues. Restoration priorities outlined in a State-approved plan (e.g., Surface Water Improvement and Management (SWIM) Plans) are eligible for Noticed General Permits from the State. These projects are also eligible for Nationwide Permits from the Army Corps of Engineers. To date, more than 132 ha of dragline ditch-impacted wetlands in the IRL system have been addressed, returning approximately 49 ha to wetland elevation.

Other wetland uses

Historically, salt marshes along the IRL have been used to achieve several different management objectives. One example no longer in use is for saltmarsh impoundments to retain and treat secondarily treated wastewater. This use was compatible with mosquito control objectives and was found to lower pumping and larvicide costs (Carlson 1983). Another option is using a coastal wetland to receive waste brine water generated by a reverse osmosis plant which produces potable water. Typically brine water is disposed via deep well injection but this alternative discharge method into coastal wetlands is under investigation with the possibility of using it elsewhere in Florida if the benefits outweigh the risks.

Integrated pest management

Integrated pest management (IPM) incorporates a combination of the best parts of all control methods applicable to a pest problem (Ware and Whitacre 2004). For mosquito control, this typically includes source reduction, the application of pesticides based on adequate surveillance, and public education. Since the 1950s, several insecticides have been used for larval saltmarsh mosquito control, including primarily methoprene (insect growth regulator), *Bacillus thuringiensis israelensis* (*Bti*, a bacterial byproduct), temephos (an organophosphate), and oils. The organophosphates malathion, fenthion, and naled, as well as several pyrethroids, have largely served as adulticides. These materials have been used as part of an IPM approach to controlling saltmarsh mosquito populations (Hribar and Bryan 2009).

Political considerations

Establishment and role of FCCMC & SOMM

Because of the above-mentioned controversies between mosquito control programs and agencies responsible for natural resources, Governor Bob Graham created the FCCMC and SOMM in 1983. The FCCMC is an advisory body made up of wide representation among environmental regulatory agencies, the Fla. Dept. of Health, research laboratories, mosquito control officials, and private citizens. Currently there are 15 members on the Council who participate in developing and implementing guidelines to assist The Florida Department of Agriculture and Consumer Services (FDACS) in resolving disputes arising over the control of arthropods on publicly owned lands. The Council also identifies and recommends research priorities and possible funding sources to carry out such work.

SOMM plays an advisory role designed to ensure that source reduction projects, whether being implemented by private or governmental entities, take into account both mosquito control and natural resource interests. SOMM currently includes 13 members from agencies responsible for natural resources, research institutions, and government agencies. SOMM meets 3–4 times per year at different locations around Florida, with the business meeting typically including a field trip to representative wetland habitats of the area visited. Based on research conducted since the early 1980s, SOMM has determined that RIM and OMWM best meet the dual roles of providing mosquito control with a minimum of pesticide use, while allowing the marsh to function as naturally as possible (Carlson et al. 1999). Most of the coastal wetland projects reviewed by SOMM during the 1990s and early 2000s have proposed either RIM or OMWM.

Both of these committees have been successful in establishing and maintaining an effective dialogue amongst organizations with an interest in mosquito control and the environment. On a number of occasions, SOMM has been pointed to as one of the finest examples of an interagency committee working together to achieve multipurpose objectives.

Environmental rules and regulations

The application of mosquito control pesticides as part of a saltmarsh mosquito management program is regulated at the Federal level through the insecticide labeling process. This is carried out by the U.S. Environmental Protection Agency (U.S. EPA) administering the Federal Insecticide, Fungicide & Rodenticide Act (FIFRA). Under FIFRA, all applications must follow the insecticide label directions. This authority is administered at the state level by FDACS which oversees Florida mosquito control programs. FDACS determines which chemicals can be applied in Florida and verifies that these materials are applied properly. FDACS also administers Florida's Public Health Pest Control certification program which allows a certified applicator to apply restricted use pesticides.

Environmental permits are routinely required for coastal wetland source reduction projects. This frequently includes permitting to install water control structures in impoundments, to create ditch systems and to restore impacted coastal wetlands. At the Federal level, these permits are issued by the U.S. Army Corps of Engineers. At the state level, permits are typically issued by a regional WMD. Under certain circumstances they are provided by FDEP. Several of these WMDs have been influential in the improved management of coastal wetland impoundments. Permission to make wetland habitat improvements as part of a governmental mosquito control project is typically approved through a streamlined permit process (Dale et al. 2008).

Land ownership

Typically, mosquito control agencies do not own the wetlands that they manage. Examples of private ownership of these environmentally-sensitive areas include individuals, corporations and not-for-profit organizations (e.g., Indian River Land Trust). Publicly owned coastal wetlands include U.S. Dept. of Interior properties operated by USFWS (e.g., national wildlife refuges) or the National Park Service. State-owned lands include state parks and aquatic preserves. Local environmentally-sensitive parks, nature trails and preserves may also be managed for mosquito control and natural resource protection.

Carlson et al. (1991) described the importance of having coastal wetlands in public ownership in order to expedite the implementation of optimal management practices. Significant efforts have been underway for the past 20+ years to publicly purchase privately owned coastal wetlands. When such properties are placed under public ownership, they typically can be more appropriately managed. In Florida, in order to conduct mosquito control on publicly-owned State lands, an "arthropod control plan" must be approved by the FDEP. FDEP is generally supportive of source reduction using RIM or OMWM, and of larviciding using *Bti* or methoprene.

Funding of wetlands restoration

Funding for coastal wetland reconnection and restoration efforts has come from a variety of sources from all levels of government. The first efforts to reconnect impoundments were funded by the local mosquito control programs themselves. The best example of this was the SLCMCD work conducted in the 1980s reconnecting isolated impoundments via RIM.

The regional WMDs have also provided substantial support for these efforts, mostly after passage of the 1987 SWIM legislation. Funding provided by the Districts to support local efforts has come from a variety of sources. South Florida Water Management District and SJRWMD initially provided primarily SWIM program money that was a mixture of State of Florida and District ad valorem funds. As SWIM program money from the State was reduced, a larger percentage of the funding was from District sources. By the late 1990s and 2000s, other State programs (e.g., Saltwater Fishing License funds, Florida Forever restoration funds) became available to support reconnection and restoration efforts through the Districts. Also available through the Districts is the funding from the IRL License Plate. The "Snook Tag" has been available statewide since 1995 with proceeds supporting habitat restoration and education.

SJRWMD has also been successful at channeling federal funding to coastal wetlands work through a variety of pathways. The IRL Comprehensive Conservation and Management Plan (CCMP) calls for a variety of measures to enhance and restore the natural functions of coastal wetlands. Federal EPA CCMP implementation money has been used to support these efforts. SJRWMD with its state and local partners has also been successful at securing project specific grant funding from several federal programs including NOAA Recovery Act grants and USFWS National Coastal Wetland Conservation Grant Program. All partners (state, regional, and local) are providing matching funds for restoration work under these grants.

Summary

Even though mosquito-transmitted diseases have played an important role in Florida's history, saltmarsh mosquitoes have not been implicated in these sometimes deadly disease outbreaks. Nevertheless, high saltmarsh mosquito numbers have significantly impacted the health and well-being of residents and visitors. Wetland management efforts along Florida's coastal areas date back to the 1920s and have included ditching, dredging and filling, and impounding. The FCCMC and SOMM have been at the forefront of efforts to develop and implement environmentally sound mosquito control through research, interagency cooperation, and public acquisition of coastal wetlands. Continued efforts are needed to publicly acquire coastal wetland property remaining in private ownership to assure that health impacts to the public from high mosquito numbers are minimal while still allowing for the implementation of best management practices on these environmentally sensitive areas.

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