Chapter 2
The Evolution of the Everglades as a Perturbed Ecosystem

Darren G. Rumbold

Abstract Much has been written about the origin and evolution of the Everglades (for review, see Chap. 1, this volume). The objective here is not to restate what has already been written but instead to highlight the environmental features and processes, both natural and those altered by humans that combine to make the Everglades extraordinarily susceptible to mercury.

Keywords Altered hydrology · Agriculture · Soil amendments · Eutrophication · Biogeochemistry

2.1 Natural System

The historic Everglades extended over an area approximately 60–80 km wide by 145 km long, from the south shore of Lake Okeechobee to the mangrove estuaries of Florida Bay (Chap. 1, this volume). Yet, to understand the Everglades, one must also consider Lake Okeechobee and its source waters, e.g., Kissimmee River and several creeks (which have a combined drainage area of over 1 million ha; Jones 1948). This is sometimes termed the Kissimmee-Lake Okeechobee-Everglades (KLOE) Watershed (Chap. 1, this volume).

The Everglades has been described as a depression in the limestone comprising the surficial geology of the region that has filled with organic matter and sedimentary deposits (for review of processes creating basin, see Gleason and Stone 1994). The formation of the Everglades peatland from partly decayed plant materials began about 5000 years before present (YBP) following a change in climate leading to a more stable sea level (Gleason and Stone 1994). The various peat types and the specific plant materials they arose from is reviewed by Jones (1948) and summa-

D. G. Rumbold (✉)
Department of Marine and Environmental Sciences, Florida Gulf Coast University, Fort Myers, FL, USA
e-mail: drumbold@fgcu.edu

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rized in Chap. 1 (this volume). Not surprisingly, materials leached from this accumulating plant material also generated dissolved organic matter (DOM). Although highly variable (both in quantity and quality, as discussed later), surface waters of much of the KLOE watershed are naturally highly colored with organic matter (Parker et al. 1955; for review of DOMs role in the mercury (Hg) cycle, see Chap. 4, Volume II).

The Everglades has a generally subtropical climate (for review, see Chap. 1, this volume) with only occasional freezes associated with winter cold fronts (for review, see Duever et al. 1994). Tall convective thunderstorms (12–16 km) that extend into the upper troposphere are the major source of rainfall (for the influence these storms have on Hg atmospheric deposition, see Chap. 3, this volume) along with hurricanes and infrequent rain associated with winter frontal systems (average yearly rainfall ranges from 119 cm to 157 cm; Duever et al. 1994; the reader is referred to Chaps. 3 and 4, this volume for in-depth discussion of wet and dry Hg deposition). The wet season extends from May to October (75% of the rainfall) while the dry season occurs from November to April (25% of the rainfall). However, there is great spatial and temporal variability in rainfall with very wet years interspersed with droughts (Duever et al. 1994).

The Everglades is topographically flat with elevations generally less than 6 m (NGVD). The ground surface gently slopes from north to south with an average gradient of 2.8 cm/km (Parker et al. 1955). Consequently, the frequent intense, but short, rainfall events characteristic of the region result in extended periods of flooding that was augmented by drainage from Lake Okeechobee. When it filled from direct rainfall and inflow from the large watershed to the north, Lake Okeechobee historically overflowed along much of the southern rim into the Everglades because it had no well-defined outlets (Jones 1948). These waters would then sheet flow slowly southward to Florida Bay.

Davis (1943) produced the first comprehensive map of vegetation patterns (Chap. 1, this volume, Fig. 1.5) and reported that most of the original Everglades marsh was covered by sawgrass and other grasses (the reader is referred to Chap. 1, Volume II for in-depth discussion on susceptibility of marshes for Hg methylation). Gunderson (1994) describes the evolution of species endemic to the region and the floral assemblages of the Everglades. The unique vegetation communities are thought to have been selected because they flourished within an oligotrophic environment characteristic of extremely low levels of nutrients (Davis 1994). Historically, atmospheric precipitation had been the primary source of nitrogen (N) and phosphorus (P) to the Everglades (SFWMD 1992; Davis 1994). As discussed later, such ombrotrophic peatlands produced from plants grown under these conditions are generally nutrient poor (for review, see Koch and Reddy 1992 and references therein).

2.2 Anthropogenic Modifications to the System

The first major effort to drain the Everglades began in 1881 with a contract between Hamilton Disston and the Trustees of the Internal Improvement Fund (Jones 1948; for review, see Chap. 1, this volume). While Disston began connecting a series of lakes in the upper Kissimmee basin and dug a canal connecting the Caloosahatchee River and Lake Okeechobee, it was the creation of the Everglades Drainage District (EDD) in 1907 that produced major changes to the KLOE watershed (for review, see Chap. 1, this volume). By 1917, the EDD had completed construction of four major canals from Lake Okeechobee through the Everglades to Atlantic Ocean: the Miami, North New River, Hillsboro, and West Palm Beach Canals (Light and Dineen 1994; Chap. 1, this volume). By 1931, 440 miles of canals had been dug, 47 miles of constructed levees and 16 lock and dams built (Jones 1948). However, a dry spell between 1931 and 1945 revealed that this system engineered to drain the Everglades worked *too* well (Finkl and Makowski 2017; for ranks of droughts in Miami, Kissimmee and Florida as a whole, see Parker et al. 1955). The 1938–39 drought allowed saltwater intrusion into a Miami municipal well field, which prompted intensive investigations of water resources in southeastern Florida (Jones 1948). Water consumption for communities along the east coast, from West Palm Beach to Key West, was already at 50 million gallons per day (mgd) at that time (Parker et al. 1955; for a review of how the population went from 50,000 in 1845, when Florida gained statehood, to what it is today, 21 million, see Solecki et al. 1999). This over-drainage also resulted in frequent peat fires which prompted the creation of the Everglades Fire Control District in 1939. While the initial focus had been on draining the Everglades, Resource managers began to realize that "conservation and control of water was important for preserving the organic soils, irrigation of the farm crops, and for replenishment of subsurface storage from which the municipal supplies are pumped" (Jones 1948). For anyone that remained unconvinced that further water management was necessary, the great flood of 1947 demonstrated that besides over draining the system during dry periods, the system could not accommodate excessive rainfall (Finkl and Makowski 2017). Consequently, in 1948 and 1949 both the federal and state governments, respectively, took further steps to manage water. This led to creation of the Central and Southern Flood Control District (later to become the South Florida Water Management District) by the state to serve as the local sponsor to work with the US. Army Corps of Engineers. They immediately established the Central and Southern Florida Project for Flood Control and other Purposes (CSF Project) which began construction of perimeter levees and flood control structures that would define both the Water Conservation Areas (WCAs, encompassing approximately a million acres or 3500 km^2) and the Everglades Agricultural Area (EAA, which today encompasses approximately 2872 km^2; Redfield et al. 1999).

Although native Americans had been farming in south Florida for thousands of years, farming by white pioneers began only in the early 1900s along the shores of Lake Okeechobee on what is sometimes called Torry muck (also known as

Okeechobee muck, i.e., one of three general categories of highly organic mucks found in the region that are differentiated by mineral content; Snyder and Davidson 1994). Later, farming expanded further south into areas of sawgrass muck (i.e., Loxahatchee peat) but encountered difficulties (Snyder and Davidson 1994). Many of these difficulties had been predicted in a 1915 report by the U.S. Department of Agriculture that questioned the value of the soils (Jones 1948). Later it was shown that to grow anything other than sawgrass on the sawgrass muck would require "heavy application of phosphate and potash, and light application of certain elements such as copper, manganese, and zinc, usually in the sulfate form" (Jones 1948, pg 72; for a review, see McCally 1999). Reports of experiments at the Everglades Agricultural Experimental Station in the late 1920s, for example, showed that the addition of 50–100 pounds of manganese sulfate added to the commercial fertilizer (per acre) would make farming more profitable (Allison 1928 as cited by McCally 1999; also see Jones 1948). Farmers are reported to have quickly embraced these recommendations for truck crops and sugarcane (Jones 1948; McCally 1999). Later, it was recommended that agricultural sulfur (comprised of 98% elemental sulfur) be added as a soil amendment to reduce soil pH and enhance uptake of phosphorus and solubilize micronutrients (at a rate of 500 lbs to 2 tons per acre; Bottcher and Izuno 1994; for review of current sugarcane fertilizer recommendations, see Morgan et al. 2015; for review of sulfur sources and relation to the Hg cycle, see Chaps. 2 and 3, Volume II). Large acreage farms of sugarcane began appearing in the 1920s (125-acre farm in 1920, Snyder and Davidson 1994). Although plagued with numerous obstacles, including quota limitations for sugarcane production and the 1928 hurricane, agricultural production in the region advanced during the 1930s and 1940s. While sugarcane production reached 37,800 harvested acres in 1949–1950, vegetable farming was the most active segment during that time (Snyder and Davidson 1994). With more flood control in the 1960s and 1970s, sugarcane production increased to 300,000 acres by 1975 (Clarke 1977 as cited by Light and Dineen 1994).

Although a substantial portion of the structural changes for flood control (e.g., perimeter levees and flood control structures) were completed by 1963, subsequently (1965–73) changes had to be made to improve conveyance and meet the environmental water demands of Everglades National Park (ENP; Chimney and Goforth 2001; for review, see Light and Dineen 1994). Construction of the levees had eliminated overland sheet flow southward through the formerly contiguous wetland to ENP.

Initially, Lake Okeechobee was used as a balancing reservoir, as it is today, but also "as a disposal reservoir for natural and artificial drainage of excess storm water from the agricultural lands to the south and east" (Parker et al. 1955). Water from the northern one-third of EAA was routinely back-pumped into Lake Okeechobee (Dickson et al. 1978; Belanger et al. 1989). However, due to mounting concerns regarding the poor quality of this water (stemming from a 1969 USGS report; for review, see Dickson et al. 1978), this practice was stopped in 1979. Instead, all agricultural drainage was directed into the WCAs (Belanger et al. 1989).

The hydrology of the system had thus been fundamentally altered with the initial objective to drain land for human activities (agriculture and urban development).

Later the extensively engineered system of canals, levees, and dikes was regulated with two objectives: (1) minimizing flood risk during the hurricane season and (2) maximizing water storage during the dry season (Light and Dineen 1994).

2.3 Changes in Water Quality

Changes in water quality were first reported in the major canals as early as 1955 by Parker et al. (1955). They found highly mineralized water in the Hillsboro and North New River canals as compared to inflows to Lake Okeechobee. They also found elevated nutrient concentrations in these canals ranging up to 2.4 mg nitrate/L (Parker et al. 1955). They offered several possible explanations for the high concentrations of dissolved minerals in the canals. First, they had found highly mineralized groundwater (i.e., connate seawater) underneath large areas of the Everglades (Parker et al. 1955). They speculated that under low water conditions, i.e., base flow, that a large proportion of water in the canals might originate from this shallow mineralized groundwater (Parker et al. 1955). They also suggested that the quality of water pumped from the agricultural area was another factor possibly responsible for the high dissolved solids in the canals. Alternatively, based on low concentrations observed in Lake Okeechobee and the Everglades, they concluded that flow from these sources were not the source but instead would dilute the canal water (Parker et al. 1955).

The concern was that water in the canals, contaminated with minerals and nutrients, might intrude into the marsh altering its ecology. The difference in water levels between the canal and marsh had been assumed to be the dominant factor controlling canal water intrusion (Surratt et al. 2008). More recently, however, the extent of canal water intrusion into the marsh has been shown to be a bit more complex and a function of the relative inflow and outflow rates for the canal, the duration of the canal inflows as well as sediment elevations and micro-topographic barriers in the marsh (Surratt et al. 2008). Equally important, while the incursion and penetration of chemical constituents carried by surface runoff was a function of the extent of this overland flow, it also depended on the rate of retention of the chemical constituents within the marsh (for review, see Davis 1994). Controversy continues to surround the relative importance of this connate seawater in groundwater versus agricultural drainage as a source of mineralized water to the marshes (for review, see Chap. 2, Volume II). Clearly, connate seawater will have a greater effect on the quality of water in the canals during base flow. Yet, we must also consider how much of this canal water will infiltrate the marshes (and how far it will penetrate) during these low water periods as compared to high water periods where a greater proportion of the canal water will be from stormwater and agricultural drainage.

Follow-up water quality surveys to the canal study were not completed in the marshes until the 1970s (for review, see SFWMD 1992). One of the first surveys was done by McPherson (1976) who sampled 21 sites within WCA 2A and 3A and reported high levels of dissolved solids, trace metals (including copper and zinc), nutrients and pesticides with highest concentrations in the north and lowest in the south. Results of this and other studies indicated "waters draining the agricultural lands to the north of the WCAs was of poor quality…impacting the north and northeast portions of the WCAs" (SFWMD 1992, pg 152). Flora and Rosendahl (1982) reported a 140% increase in conductivity and a 300–400% increase in sodium and chloride concentrations in the waters entering the ENP beginning in the early 1960s.

While the exact timing of nutrient enrichment within the marshes of the WCAs remains uncertain due to the delay in following up the survey by Parker et al. (1955), results from sediment cores would suggest it occurred in the early 1960s upon completion of construction of the water control structures and levels (Craft and Richardson 1993; Bartow et al. 1996). In addition to nutrients, trace metals including copper and zinc were also found to be accumulating in sediments from about this time (Bartow et al. 1996). The authors speculated that the metals probably originated from the EAA since they were known to be applied as micronutrients (Bartow et al. 1996). The timing of sulfur increases in sediment cores from WCA-2A have been found to also correlate with accumulations of phosphorus and probably originated from the EAA (Bates et al. 1998; Chap. 2, Volume II).

2.4 Altered Hydrology and Water Quality Led to Other Changes

Altered hydrology has had many harmful effects on south Florida's environment, some of which were noted as early as 1938 (Beard 1938; Kolipinski and Higer 1969; for review, see Davis and Ogden 1994). Beard (1938), for example, noted alligator holes were drying up, a huge ibis colony site had been abandoned, and snail kites were no longer observed in the area under consideration for establishing ENP. Kolipinski and Higer (1969) later reported more quantifiable impacts such as a decrease in the acreage of wet prairie communities in ENP as a result of shorter periods of inundation. They also reported increased soil oxidation and loss and increased frequency of fires (Kolipinski and Higer 1969; for a review of the implications of a shorter hydroperiod, sediment oxidation and fires on the Hg cycle, see Chap. 1, Volume II). Stieglitz (1962 as cited in SFWMD 1992) reported the first account of cattail (*Typha sp.*) infestations along the Hillsboro canal within WCA-1. Cattails were also replacing sawgrass in WCA-2A with dramatic increases in cattail cover from 1973 through 1990s (Bartow et al. 1996; for review, see Newman et al. 1998).

Agricultural drainage and inputs of phosphorus into this historically oligotrophic system have been considered the primary factor influencing cattail infestations (Koch and Reddy 1992; Newman et al. 1998). Yet, Davis et al. (1994) and Newman et al. (1998) identify a number of variables that influence cattail expansion and the general vegetation patterns found within the Everglades, including climate, sea level, topography, hydroperiod, fire, alligator activity and anthropogenic nutrient inputs. As pointed out by Gunderson (1994), it is important to recognize that the processes affecting these patterns operate at distinct spatial scales (from meters to hundreds of kilometers) and distinct temporal rates (from days to centuries).

The impacts from altered water quantity and quality did not stop with changes in coverage and distribution of emergent vegetation. Because sawgrass detritus was more recalcitrant than cattail detritus, the biological "turnover" or degradation rate was found to be much greater for cattail (Belanger et al. 1989; Davis 1991). This in turn affected oxygen budgets with areas of sawgrass cover generally remaining aerobic while the nutrient–enriched, cattail areas frequently became anaerobic (Belanger et al. 1989). These results have been confirmed in subsequent studies that again show that vegetation regulated aquatic metabolism and dissolved oxygen dynamics, with dense emergent macrophytes limiting dissolved oxygen availability (Hagerthey et al. 2010). This resulted in reduced sediment redox and altered phosphorus biogeochemistry (for review, see Noe et al. 2001; for implications of hypoxia and reducing conditions in pore waters on the Hg cycle the reader is referred to Chaps. 1, 2 and 5, Volume II). Periphyton algae and microbial communities were also exhibiting changes in the Everglades (Reeder and Davis 1983; Swift and Nicholas 1987). Swift and Nicholas (1987), for example, report lower diversity and a shift in species of periphyton at nutrient and mineral enriched sites. Nutrient enrichment was found to shift microbial communities that were responsible for decomposition of leaf litter (Reeder and Davis 1983; for review, see SFWMD 1992). Furthermore, nutrient enrichment, changes in vegetation (as a source of detrital material), altered hydrology (particularly frequency of drying) and sulfate inputs have all likely affected the quantity and quality of DOM in the Everglades (Aiken et al. 2011; for implications on the Hg cycle, see Chap. 4, Volume II). As one example, currently, Everglades DOM is found to be appreciably enriched in sulfur compared to DOM from two other similar large subtropical freshwater wetlands (Chap. 4, Volume II and references therein).

2.5 Summary

As will become evident upon reading the subsequent chapters of this book, the natural Everglades, with its high rainfall and frequent tall convective thunderstorms, its expanse of marshes with shallow, slowly moving water, general lack of freeze-thaw cycles and high average annual temperatures, would have been susceptible to inorganic Hg deposition and its conversion to methylmercury (MeHg). However, the anthropogenic modifications to the Everglades, including altered hydrology, nutrient and sulfate inputs, altered vegetation and microbial communities, changes in DOM quantity and quality (which may have led to changes in photochemistry), lower sediment redox and shifts in biogeochemistry have formed a "perfect storm" making the system extraordinarily efficient at converting inorganic Hg to MeHg. Clearly, the number of biotic and abiotic variables (both internal and external to system, i.e., atmospheric deposition rate) and the spatial scales and temporal rates in which they operate increase the complexity of the Hg problem in the Everglades. This complexity exceeds that which Davis (1994), Gunderson (1994) and others have had to deal with in terms of the spread of cattails. The key to addressing the Hg problem in the Everglades will be to determine what the most influential factors are in leading to high MeHg concentrations in upper trophic level fish and wildlife and to determine which of these factors is most amenable to local control.

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