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YOUNG VOICES AND VISIONS FOR THE UN DECADE OF RESTORATION

REVIEW ARTICLE

The past, present, and potential future of phosphorus management in the Florida Everglades

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The Florida Everglades, the largest subtropical wetland in North America, is in the midst of one of the most comprehensive and expensive environmental restoration efforts in history. Over the past 150 years, the Everglades has suffered substantial degradation due to massive drainage projects, polluting agricultural practices, and urban population growth. Decades of scientific investigation have shown that phosphorus (P) pollution is a primary driver of this environmental decline. This paper reviews how and why specific P-management goals and strategies have been adopted in support of Everglades restoration, focusing on the often-contentious process for converting science into restoration policies and standards. We synthesize current P-management successes, failures, and tradeoffs, including the challenge of balancing multiple hydrologic and water quality restoration goals with the priorities and values of a diverse group of stakeholders. We then highlight promising future directions for Everglades P policy and propose questions to help guide the discussion of future restoration priorities and research needs in this and other complex social–ecological systems. The overall goals of this review are thus twofold: (1) to support an in-depth understanding of the past, present, and potential future of P management approaches in this globally unique social–ecological system; and (2) to provide a broader framework for understanding how the coevolution of science and policy can support or undermine large-scale ecosystem restoration.

Key words: Everglades, phosphorus, policy, restoration, water quality, wetlands

Implications for Practice

(1) Developing the ecological knowledge needed to make good policy decisions is a long and iterative endeavor that can be at odds with the information requirements of policymakers.
(2) Policy development and decision-making can be complicated or hamstrung when scientists or science-producing organizations arrive at contrasting conclusions.
(3) A policy focus on one geographical location (at the expense of other regions) can lead to inequitable and unintended environmental outcomes.
(4) The notion that all stakeholders in a complex social–ecological system can "win" is likely more idealistic than realistic; some or all parties will have to make concessions to meet system-level goals.

Introduction

The United Nations deemed 2021–2030 the "Decade on Ecosystem Restoration" (Cooke et al. 2019), yet societies across the globe still struggle to balance economic and population growth while maintaining the healthy and functioning natural ecosystems upon which they depend (Goudie 2018). As an iconic example of this challenge, the growth of South Florida over the past century threatens the Florida Everglades, which is crucial to Florida's economic and environmental wellbeing (Milon et al. 1999). Deemed a "Wetland of International Significance" by the Ramsar Convention and a World Heritage Site by the United Nations Educational, Scientific and Cultural Organization, the Everglades has long been at the center of public discourse about environmental management and restoration at state, national and international levels (Maltby 1994). Tensions between preservation and development in the Greater Everglades region (Fig. 1) have existed since at least the 1880s, when comprehensive efforts began to drain the ecosystem to "reclaim" land for agriculture and development (Guest 2000). Despite the

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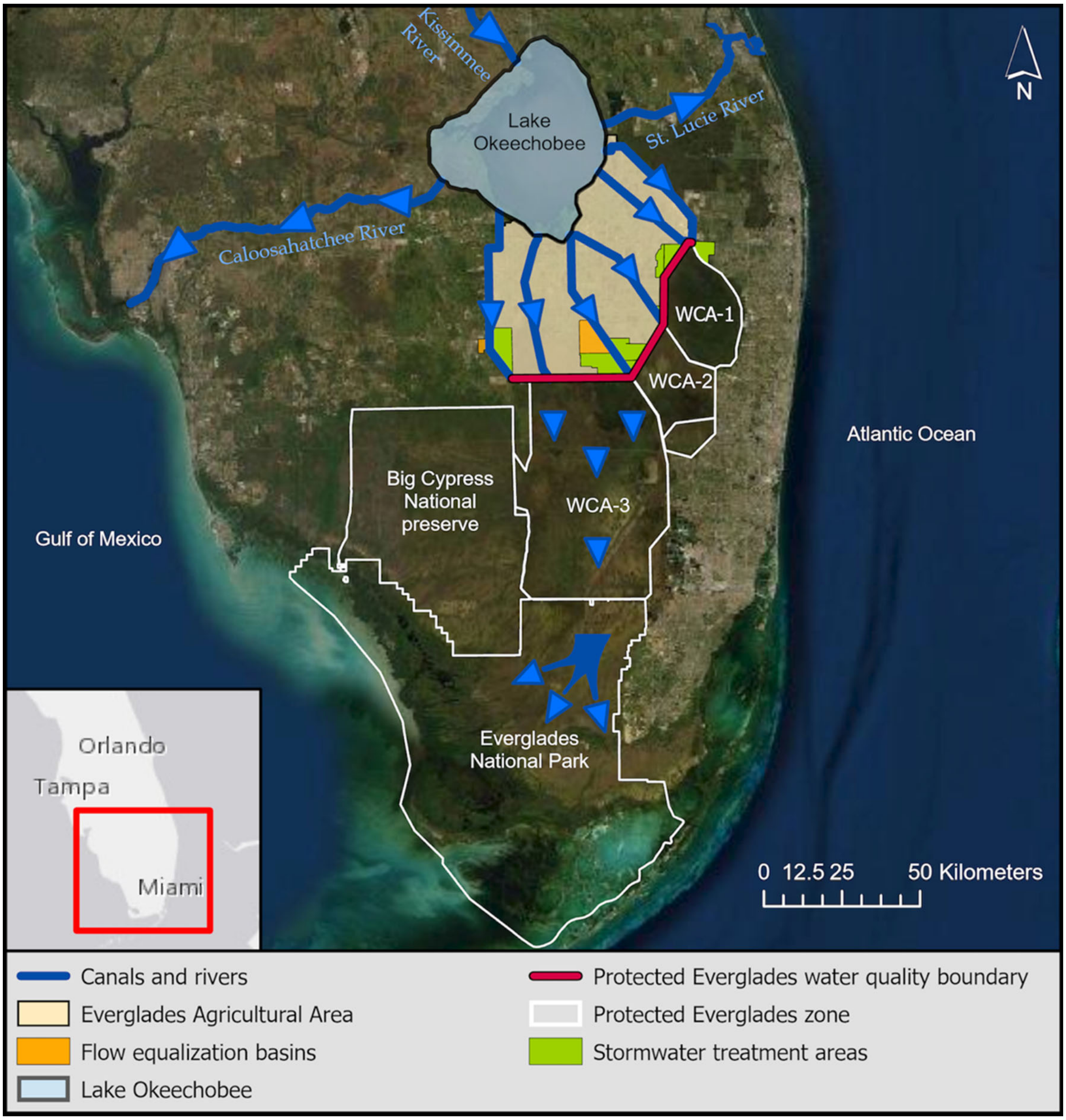

Figure 1. Map of the greater South Florida watershed and surface water network, including estuaries, rivers, lakes, reservoirs, canals, protected lands, stormwater treatment areas (STAs), water conservation areas (WCAs), and flow equalization basins (FEBs); water flows illustrated in blue arrows (base map sourced from National Agricultural Imagery Program).

ecological significance of the Everglades, drainage and pollution over the past century have devastated the ecosystem (Douglas 1947), and the Everglades is currently half of its original size (Galloway et al. 1991). This large-scale environmental degradation mirrors changes in other global ecosystems ranging from the drainage of the Aral Sea to widespread seasonal hypoxia in the Gulf of Mexico (Rabalais et al. 2002; Glantz 2007) and Chesapeake Bay (Powledge 2005).

Unique among global ecosystem restoration projects is the scale of science development, public funding, and policy debate that has surrounded Everglades restoration. By the 1980s, sufficient public concern had developed for the U.S. Congress to address the degraded Everglades with a series of environmental restoration projects (Rizzardi 2001). In 2000, the restoration movement culminated in the legislative authorization of the Comprehensive Everglades Restoration Plan (CERP), which included over 68 distinct projects (Carter & Sheikh 2003) estimated at the time to cost $8 billion and span 40 years. With a restoration framework in place, the U.S. federal government, Florida state government, and citizens of South Florida seemed ready to tackle the challenges of safeguarding the Everglades and the greater south Florida watershed. In the past two decades, two stretches of Tamiami Trail, a U.S. highway connecting Miami and Tampa, have been raised to allow for more natural water flow (Sarker et al. 2020), along with other flow augmentation projects (NASEM 2020). The Kissimmee River, a channelized river flowing into Lake Okeechobee (Fig. 1), has been restored with natural bends and floodplain connections to improve hydrologic function and nutrient cycling (Koebel & Bousquin 2014). And six stormwater treatment areas (STAs), designed to remove phosphorous from water flowing into the Everglades, have been completed and currently in use (Fig. 2). Despite numerous projects completed or underway, however, the vision outlined in CERP remains far from complete (Amorino 2020), with a current estimated cost of $23.2 billion (NASEM 2020) and a timeline extending up to 65 years (Congressional Research Service 2017).

Eutrophication from phosphorus (P) pollution remains among the most serious challenges of Everglades restoration (Schade-Poole & Möller 2016). Naturally low levels of nutrients in the Everglades form a unique, oligotrophic ecosystem of specific flora and fauna (Brix et al. 2010). Even small increases

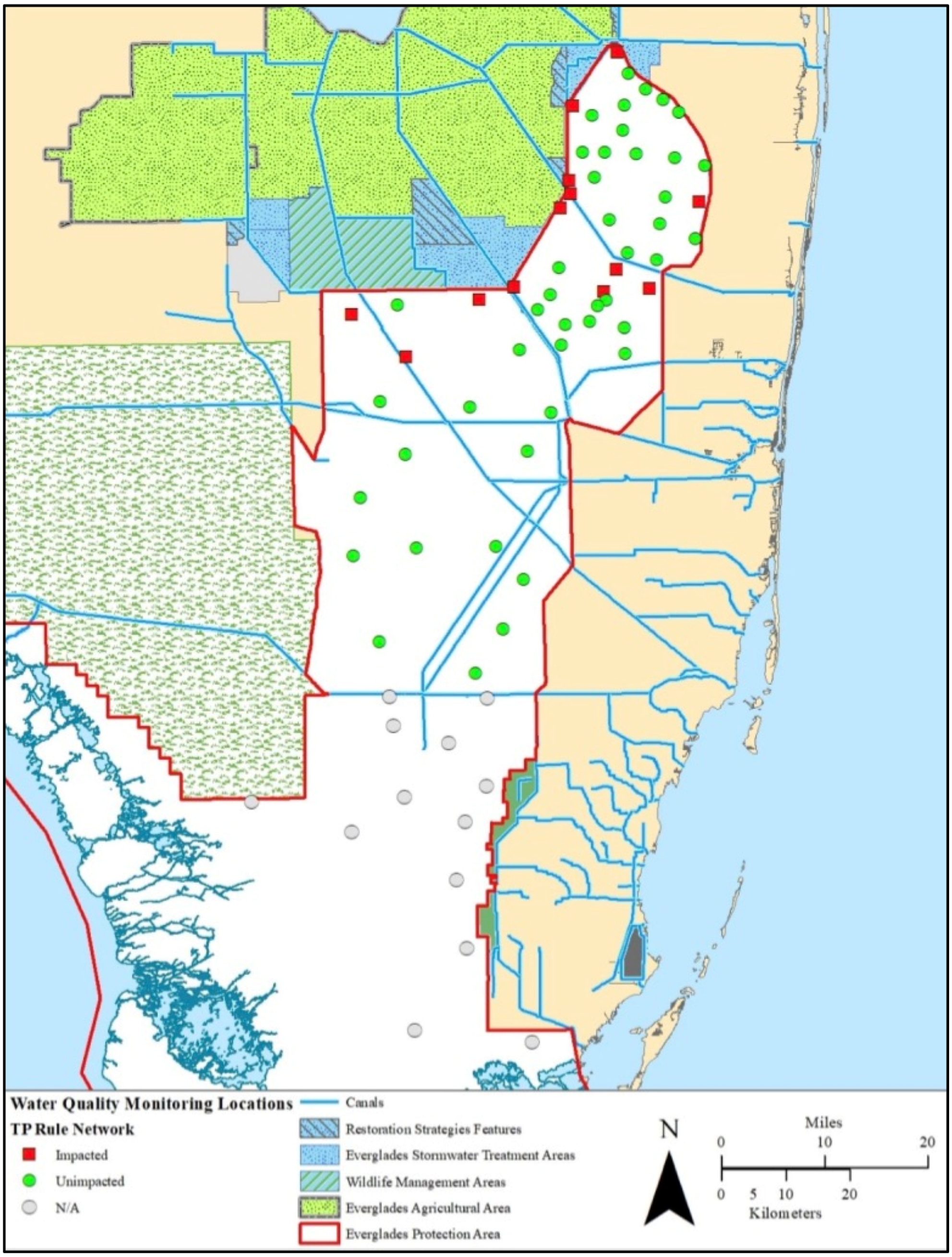

Figure 2. Water quality monitoring stations across the water conservation areas and Everglades National Parks, indicating whether they met the 10 ppb TP standard between 2015–2019. Green dots, red squares and gray squares represent stations that either complied, failed, or were not included in the SFWMD's assessment (source: Appendix 3A-6: South Florida environmental report – Volume 1).

in P quickly disturb the natural vegetation community, and this transformation negatively impacts habitat quality for endangered and endemic species (Malinoski 2004). In the 1990s, the South Florida Water Management District (SFWMD) concluded that P concentrations had increased from below 10 parts per billion (ppb) in precolonial times to as high as 173 ppb in the 1980s (McCormick et al. 2000). It also became clear that human-sourced P far exceeded natural levels and threatened ecosystem integrity. As the scope of water quality problems became apparent, policy makers and environmental managers responded with legislation and civil works projects, while environmental advocates filed lawsuits claiming these actions were insufficient. Several decades have passed since the initial water quality-based legislation, and P concentrations have declined in many locations, with 90% of Everglades water quality monitoring stations meeting the 10 ppb TP standard in 2018 (SFWMD 2018). Despite these successes, management interventions have yet to consistently achieve all adopted regulatory standards (Julian & Gilhooly 2020).

Given this long and often contentious scientific and management effort—and the history of resulting successes and failures—the overarching goal of this review is to synthesize the available literature on P-management science and policy in the Florida Everglades. In doing so, we aimed to answer four primary questions: (1) what were the major scientific and policy interactions that led to the existing P regulation regime (*the past*); (2) how successful have P-management strategies been in achieving ecosystem restoration—and what tradeoffs have been required (*the present*); (3) where should Everglades P management go from here (*the future*); and (4) can the lessons of science-policy coevolution in the Everglades provide useful insights for other large-scale ecosystem restoration projects worldwide? Our review spanned the scientific literature, agency reports, case law, and resources from the popular press; quantitative results from this bibliometric survey are presented in Supplement S1.

Developing Everglades Phosphorus Thresholds and Standards (*The Past*)

Connecting Nutrients and Everglades Ecology

The freshwater Everglades is oligotrophic and characterized by extremely low phosphorus levels; high levels of phosphorus cause a cascade of deleterious ecological transformations (Richardson et al. 2007). The most rapid ecological response is seen in periphyton, an assemblage of algae, bacteria, and decomposing organic matter, which plays a pivotal role in the creation of marsh sediments (Richardson et al. 2007). Even small increases in P (above 10 ppb total phosphorus [TP]) can lead to rapid disappearance of periphyton algal mats, followed by changes in the composition of macroinvertebrates and aquatic plants. Specifically, P pollution is associated with a shift in the dominant species of marsh vegetation from sawgrass (*Caldium jamaicense*) to cattail (*Typha domingensis*) (Richardson et al. 2007); this process has been characterized as an invasion due to its rapid succession and impact on the natural "ridge and slough" landscape (Noe et al. 2001). Notably, these indicators of an unbalanced ecosystem also violate specific legislative directives mandating that "there should be no changes in the Everglades' natural flora and fauna" in the Everglades Forever Act (1994).

The intricacies of phosphorus-driven eutrophication in the Everglades have been elucidated over 70 years of scientific pursuit (i.e., since Odum 1953). One of the first motivations to understand the role of P in this ecosystem arose in the 1970s when the federal government required minimum water deliveries of "good quality" to Everglades National Park (Rosendahl & Rose 1979). Scientists and policymakers were tasked with defining what constituted good water quality, and over the next decade, researchers began investigating the presence and role of P in the Everglades ecosystem (Bayley & Odum 1976). Major early findings included the fact that sawgrass plant tissue was adapted to naturally low levels of P, leading to the conclusion that low-P soil and water concentrations helped maintain the dominance of sawgrass within the ecosystem (Steward & Ornes 1975). Throughout the 1980s, experimental and mesocosm studies found that even slight perturbations in P concentrations could have harmful effects on the Everglades, such as sawgrass replacement by cattail (Jamieson 1988).

Challenges Converting Science to Policy

As a result of these scientific findings, the Miccosukee Tribe filed a lawsuit against the SFWMD and the federal government for allowing water with elevated P levels to pass onto tribal lands (Rizzardi 2001). The federal government argued that the SFWMD was at fault, contending that Everglades water quality should be protected under the Clean Water Act. The federal government and Miccosukee Tribe joined forces against the SFWMD in 1988, eventually yielding a consent decree in 1992 (Rizzardi 2001). As a result, a TP water quality standard and compliance criteria were set at 10 ppb (Payne et al. 2003). Two years later, the Florida Legislature passed the Florida Forever Act, which provided a legal framework for maintaining the historic composition of flora and fauna while managing P. Despite this legislative clarity, the scientific community recognized the need to further refine the science supporting the 10 ppb TP concentration regulation from the 1992 consent decree so that it could be definitively written into Florida Administrative Code.

By 2003, the Florida Department of Environmental Protection (FDEP) was under intense pressure to promulgate specific administrative rules addressing TP. In response, FDEP created an Environmental Regulation Commission (ERC), tasked with reviewing the existing science and setting a clear numeric P standard by the end of 2003 (Malinoski 2004). However, the body of research available at that time presented conflicting results, slowing policy decisions and implementation (Malinoski 2004). Analysis of natural P inputs (primarily atmospheric deposition) suggested background TP concentrations <10 ppb (Davis 1994), which was supported by contemporary observations in the least impacted, "interior" Everglades (McCormick et al. 2000). While these studies quantified TP concentrations from natural sources, they did not identify relationships between higher P concentrations and ecological degradation. Correlating water quality data with areas of ecological change showed that areas with elevated TP were more likely to be invaded by cattail, while areas with TP <10 ppb remained in their unaltered state (McCormick et al. 2000). In contrast, Richardson et al. (2000) correlated ecological indicators like macrophytes and periphyton to TP and found that most ecological transformations occurred at substantially higher concentrations (17–22 ppb). After review, the ERC concluded that the Richardson et al. (2000) study suggesting slightly elevated P levels were not harmful was scientifically valid but decided that a 10 ppb TP standard should be implemented because it was a conservative and "round" number (Payne et al. 2003). After this drawn-out process, most stakeholders accepted the 10 ppb TP standard as finalized law (Water Quality Standards 2005), though vigorous scientific debate on the specific number continued (Gaiser et al. 2004, 2005, 2006; Richardson et al. 2007, 2008, 2014).

Where Should the Water Quality Standard Apply?

The Everglades P standard was scientifically and politically contested for three decades, and scientists and policymakers both understood that setting specific criteria for compliance would be complex (Payne et al. 2003). Critically, while the 10-ppb standard was considered protective of ecological function within the Everglades, achieving this standard required setting P limits in other locations (e.g., exiting the Everglades Agricultural Area [EAA] and within STAs, both described in more detail below). The FDEP thus created two separate sets of policies: the first regulated P within the interior Everglades, and the second focused on outflows from the STAs. In other words, STA outflows needed to be regulated so that the 10-ppb standard was achieved within the Everglades. This became known as the Water Quality-Based Effluent Limit (WQBEL) and was set higher than 10 ppb, with the expectation that concentrations would be within compliance before reaching the interior Everglades (SFWMD 2012) (Table 1).

To set the WQBEL, scientists at the SFWMD correlated flow-weighted P concentrations in STA discharge to P concentrations in the interior of the Everglades (Payne et al. 2010), yielding a WQBEL from 17.2 to 19.1 ppb. A modeling study using the dynamic model for STAs predicted a WQBEL between 14.3 and 16.7 ppb (Walker 2005). Combining results from their statistical analysis and model results from Walker (2005), Payne et al. (2010) concluded that the WQBEL should range from 15.1 and 19.2 ppb, with an annual average TP <18 ppb. These derived values became the scientific basis for the current WQBEL (Table 1), and a "Restoration Strategies Regional Water Quality Plan" was introduced in 2012 to resolve disagreements about the WQBEL and put forward implementation timelines (SFWMD 2012; USACE & SFWMD 2014). In 2013, Florida and the USEPA agreed that STA effluent should meet WQBEL requirements by 2025. As with the 10-ppb criterion, however, researchers and conservation advocates continued a contentious debate over the WQBEL, arguing that "current measures implemented to reduce P are not sufficient to reach the [10 ppb] ecological threshold" (Zapata-Rios et al. 2012). Overall, the relationship between WQBELs, the mandated 10 ppb TP standard, and the completion of STA infrastructure has been controversial, and communication on the topic has been unclear, even among leading scholars.

Phosphorus Management Successes, Failures, and Tradeoffs (*The Present*)

Achieving Phosphorus Reduction

In response to the 1994 Everglades Forever Act, the FDEP developed several total maximum daily load (TMDL) programs for the region specifying the load of nutrients permitted to enter waterbodies. The TMDL framework had already been well developed and widely implemented in many impaired waterbodies such as the Chesapeake Bay and Lake Champlain since its inclusion in the Clean Water Act of 1972 (Powledge 2005; Smeltzer 2015). The Lake Okeechobee TMDL has been central to setting water quality restoration goals in the Everglades because of its upstream position (Fig. 1). The TMDL was promulgated in 2001, specifying a maximum TP load of 140 tons (t)/year and requiring that TP concentrations remain below 40 ppb to prevent in-lake and downstream eutrophication (Havens & Walker 2002). The Lake Okeechobee Watershed Act was amended in 2005, mandating the TMDL be reached by 2015. Despite these actions, P loading to Lake Okeechobee has instead increased to a current average of 500–600 t/yr, and

Table 1. Comparison of Everglades total phosphorus (TP) and Water Quality-Based Effluent Limits (WQBEL) regulatory standards. F.A.C, Florida Administrative Code; WCA, water conservation areas; ENP, Everglades National Park; STA, Stormwater treatment areas. The TP criteria includes specifications both for individual stations and stations within measurement networks (WCA-1, WCA-2, WCA-3, and ENP), though ENP is not currently assessed for compliance.

Water Quality Rule	*Where it Applies*	*Station Annual Geo. Mean*	*Station 5-year Geo. Mean*	*Network Annual Geo. Mean*	*Network 5-year Geo. Mean of TP*
TP criteria (62–302.540, F.A.C)	Everglades protection area (WCAs and ENP)	≤15 μg/L	≤10 μg/L	≤11 μg/L	≤10 μg/L
		Annual flow-weighted mean	5-year flow-weighted mean		
WQBEL (62–650.200, F.A.C)	STA outflows	≤19 μg/L	Shall not exceed ≤13 μg/L in more than 3 of 5 water years on a rolling basis		

TP concentrations currently average near 100 ppb (Khare et al. 2019). One major challenge of achieving the Lake Okeechobee TMDL is that agricultural and other land uses continue to release P. In addition, P loads from previous decades have become incorporated in Lake Okeechobee's sediments and surrounding agricultural soils (Khare et al. 2021). This legacy phosphorus can be resuspended in the water column or leach out of soils, hindering water quality improvement even if current management practices are improved. Indeed, one study found that Lake Okeechobee's bottom sediments could release 500 t/yr of TP for the next 20–50 years (Reddy et al. 2011).

While excessive P loading continues to affect Lake Okeechobee, restoration and regulatory efforts have yielded better results elsewhere. Agricultural best management practices (BMPs) have proven to be effective measures for limiting P run-off from farming activities in the EAA (Rice et al. 2013). In 1991, the Everglades Restoration Act implemented a BMP program with the requirement of reducing the annual P load run-off by at least 25% compared to historic loads by 1995 (Wan et al. 2001). Growers also needed to pay an annual EAA privilege tax to support restoration and water quality monitoring. The 1994 Everglades Forever Act combined the BMP program with STA projects, forming a comprehensive water quality plan (Wan et al. 2001). The University of Florida's Extension centers played a central role in developing farming practices that were economically feasible such as leveling fields, adding sediment sumps, allowing vegetation growth in canals, growing cover crops, applying slow-release fertilizers, and testing soils/plant tissues for optimizing P application (Rice et al. 2013; Faridmarandi & Naja 2014). Overall, the BMP program has been successful in reducing TP in EAA run-off by >50% (Rice et al. 2013) and further P load reduction is likely possible by optimizing BMP strategies (Faridmarandi & Naja 2014). The potential for this kind of reduction in P load from agriculture has also been found in Vermont, where 90% of P reduction to Lake Champlain since 2016 has been attributed to BMPs (Smeltzer 2015).

Another successful component of Everglades nutrient management has been the implementation of STAs, large, human-constructed wetlands that reduce nutrients through plant and microbial uptake and sorption into soils. Though treatment wetlands are now commonly constructed, the Everglades restoration effort was one of the first initiatives to implement this practice at such a large scale (Mitsch et al. 2015). In 1994, the Everglades Forever Act financed the construction of six STAs (totaling 10,000 ha) at a cost of $1.35 billion (Entry & Gottlieb 2014). Currently, these projects cover over 23,000 ha (Fig. 1) (Chimney 2020). From 1995 to 2020, STAs have filtered over 25 billion m^3 of water and retained approximately 2,800 t of P (Chimney 2020). As of 2019, overall STA TP removal efficiency was around 80%, and the best-performing cells consistently removed 85% of incoming P (Chimney 2020). Differences in performance have been attributed to hydraulic loading rate, dissolved and particulate organic P fraction, wetland age, and water temperature (Jerauld 2010). Overall, the STAs have performed well in nutrient reduction and provided additional benefits for recreation and habitat for endemic flora and fauna (Chimney 2020), however, it is evident that additional infrastructure is necessary to meet mandated water quality goals. In particular, STAs require relatively steady flow for optimal P reduction, but Everglades hydrology is strongly seasonal. To compensate for this, two large water storage basins called flow equalization basins (FEBs) (Fig. 1) were built in 2017; together, they hold up to 130 million m^3 of water in wet periods and release it in the dry season (Chimney et al. 2017).

As an outcome of these interventions, P levels have significantly improved in the interior and exterior Everglades in most locations (Fig. 2). Specifically, average TP concentration of inflows to WCA-1, WCA-2, and WCA-3 decreased by 83, 84, and 65%, respectively, between the periods of 1978–1990 and 2016–2020 (SFWMD 2021). Inflow concentrations to ENP were also reduced by 40 to 50% in the same timeframe (SFWMD 2021). Reflecting these water quality inflow improvements, approximately 90% of monitoring stations within the protected Everglades are now in compliance with the 10 ppb TP standard (SFWMD 2018) (Fig. 2). Notably, ecosystem responses to improved water quality have been observed, including the stabilization of cattail encroachment throughout the WCAs and Taylor Slough (Zhang et al. 2017; Xue 2018; August & Osborne 2019). While these results are promising, satisfying water quality goals in all locations and at all times remains elusive, especially considering the challenge of legacy P (Reddy et al. 2011; Sarker et al. 2020). This mixed outcome has also been seen in the restoration of Chesapeake Bay watersheds, where P loads from some tributaries have been reduced while others have increased (Kleinman et al. 2019).

Water Quality-Water Quantity Tradeoffs

Despite this progress, questions about the P-management process and its outcomes remain, including whether the standards are working sufficiently—and at what cost? A critical question is whether other aspects of ecosystem management have been neglected in favor of P management. In particular, water quality and quantity are inextricably connected elements of Everglades ecology (NASEM 2012). In practice, stringent TP standards mean that less water is available to hydrate the Everglades if it does not meet regulatory requirements (Mitsch et al. 2019). However, many endemic species and natural physical features in the Everglades have evolved with strongly seasonal water level variation; when this pulsing hydrology is not maintained, substantial ecological shifts can occur even if water quality is protected (Watts et al. 2010). Moreover, at the watershed scale, the diversion of high-P water away from the Everglades to coastal estuaries has been associated with massive freshwater and marine algal blooms (Mitsch 2016; Medina et al. 2020, 2022). In short, there are conflicts between water quality and ecosystem management objectives that have yet to be resolved, and water management and policy must consider both quality and quantity when seeking to "optimize" Everglades restoration.

In addition to the interplay between water quality and quantity, the timing and spatial distribution of water are also central to ecosystem health. Precipitation is generally low in the winter and spring and plentiful in the summer (Duever et al. 1994). Surface water hydrology is correspondingly very seasonal, with water levels in the ridge and slough landscape varying from below-ground in the dry season to 50–100 cm in the wet season (Kaplan et al. 2012). Native flora and fauna have adapted to these seasonal variations. For example, the endangered Florida snail kite (*Rostrhamus sociabilis*) will forgo nesting if water levels are either too high or too low during nesting season (Beissinger & Snyder 2002). These seasonal hydrologic changes have become muted in many areas due to impoundment, with some regions becoming overly dry and others overly wet (Watts et al. 2010). Restoring natural flow patterns to these areas ("getting the water right") was one of the primary goals of CERP (Carter & Sheikh 2003), however, water quality has dominated much of the discussion, often to the exclusion of other ecosystem attributes (NASEM 2012). Similar water quantity–quality tradeoffs challenge other large-scale ecosystem restoration efforts, such as coastal wetland restoration in Louisiana, where high suspended sediment loads are needed to mitigate wetland subsidence, but high nutrient loads could cause unintended ecological damage (Day et al. 2019).

The optimization of water quality, quantity, and ecological health in the Everglades is made even more challenging when considering the greater South Florida ecosystem since environmental benefits in one region often come at the expense of environmental degradation elsewhere. Lake Okeechobee is the headwaters of not only the Everglades, but also the St. Lucie River and Caloosahatchee River (Fig. 1). When water levels rise in Lake Okeechobee, managers must decide between releasing flow south into the Everglades or east/west into these coastal rivers where excess nutrients can aggravate algal blooms (Paerl et al. 2008). These outflows might be considered the "worst of both worlds," with a dehydrated Everglades and eutrophic coastal waterways. While still a notable management challenge, substantial progress has been made in controlling the Lake Okeechobee water budget, reducing water releases to the rivers, and increasing low-P flows to the WCAs when seasonally appropriate (USACE & SFWMD 2014) (Fig. 3). These flows still fall short of historic Everglades flows (RECOVER 2020), but they are expected to drastically improve WCA hydration during the dry season and alleviate pressure to release water from Lake Okeechobee into the northern estuaries. Building on these improvements, the USACE has finalized a new water budget overhaul, the Lake Okeechobee System Operation, which is planned to replace the current Lake Okeechobee Regulation Schedule in April 2023.

Satisfying all Stakeholders?

Identifying all stakeholders affected by Everglades restoration is challenging because of the vast size and complexity of the system. In 2002, a congressional research report listed the following stakeholders: U.S. Congress, State of Florida, the South Florida Ecosystem Restoration Task Force, U.S. Department of the Interior, U.S. Department of Transportation, U.S. Environmental Protection Agency, U.S. Department of Agriculture, U.S. Army Corp of Engineers, National Oceanic and Atmospheric Administration, Office of the Governor of Florida, SFWMD, FDEP, Seminole Tribe, Miccosukee Tribe, and two Florida cities (Sheikh 2002). While these organizations actively participated in developing or implementing Everglades restoration policy, many nongovernmental organizations and private citizens are also affected by water management and restoration policy decisions; CERP itself identified dozens of additional groups that participated in restoration planning (USGAO 2000). Exhaustively cataloging each stakeholder's values and role is beyond the scope of this review, but stakeholder participation is known to be key when considering multi-criteria environmental decision analysis (e.g., Kiker et al. 2005).

At CERP's inception, it appeared that all parties believed they could be "winners" while restoring the ecosystem (USGAO 2000; USGAO 2002). Conversation in the Florida Legislature includes statements like: "successful implementation is dependent upon a maintaining a win–win approach" (Implementing the Comprehensive Everglades Restoration Plan 2002). However, as restoration efforts progressed, it became apparent that conflicting interests were unavoidable (USACE &

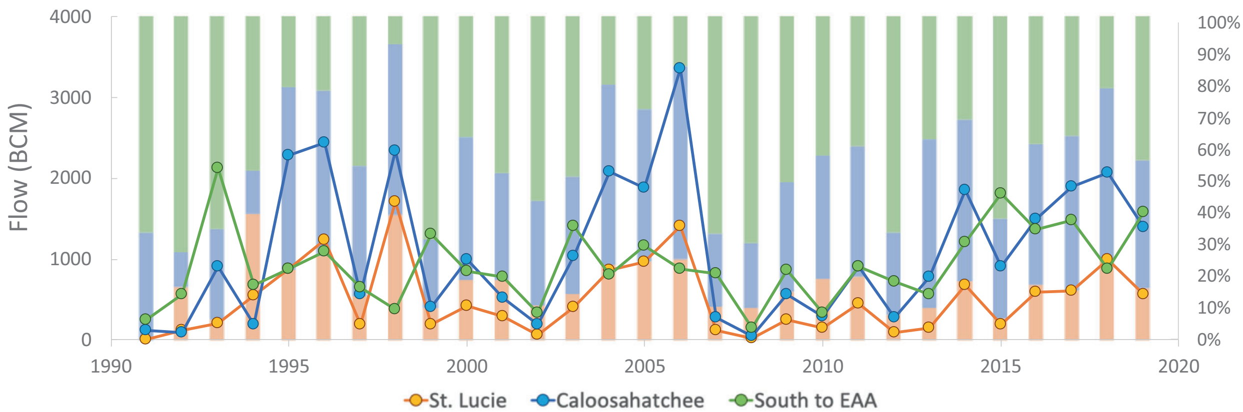

Figure 3. Water discharges in billions of cubic meters per year (BCM) from Lake Okeechobee to the St. Lucie and Caloosahatchee estuaries and south to the Everglades Agricultural Area (EAA) from 1991–2019. Proportion of flow to each region shown on second (right) *y*-axis. Data extracted from SFWMD (2020*a*, 2020*b*).

SFWMD 2014). For example, if the Miccosukee Tribe's demand for better water quality in the Everglades were met, less water could be sent south from Lake Okeechobee, dehydrating portions of the Everglades and exacerbating the risk of eutrophication for coastal communities. These conflicts exemplify the interactions between Everglades science and politics (Graf 2013) that lead to a specific set of policies and projects (with associated funding).

In 2014, CEPP addressed watershed-wide conflicts of interests when stakeholders and water managers discussed balancing stakeholder interests with the realities of the water budget (USACE & SFWMD 2014). This discussion generated a series of alternative water budgets and restoration timeline alternatives exploring the tradeoffs of different management strategies. One concrete outcome of this process was the eventual resolution for the construction of the EAA reservoir to increase storage and flows into the Everglades (USACE & SFWMD 2014). In 2017, Senate Bill 10 (SB10) was introduced in the Florida Senate to initiate the project (Krimsky 2017), but the bill received pushback from agricultural interests due to the perceived possibility of seizing farmland via imminent domain (Doris 2017). A public tug-of-war ensued between environmental advocates, who supported development of a large reservoir through the purchase of agricultural lands, and agricultural interests that did not want to cede any productive area (Doris 2017). Eventually, revisions to SB10 were made to preclude any taking of private lands by eminent domain and ensure the reservoir would be built only on public land, reducing the reservoir area from 24,000 to 6,000 ha (Krimsky 2017). While this scenario would not totally restore Everglades flow, nor prevent all future estuarine releases, participants found a compromise, consensus solution (Klas 2017). In this sense, CEPP served as an inflection point where stakeholders realized that in order to advance Everglades restorations, all sides must "…make concessions to economic and political interests in order to achieve cooperation among stakeholders" (Neary 2016). Once the need for a multi-criteria approach became more widely recognized (Fitz et al. 2011), stakeholders gained a better appreciation for fully quantifying these tradeoffs and including them in decision-making (USACE & SFWMD 2014). The notion of a "win–win" restoration effort had been (at least partially) replaced with the reality of tradeoff and compromise.

The Future of Everglades Phosphorus Management

Further Reducing Everglades Phosphorus Levels?

Ideas for continued improvement of P management in the Everglades watershed range from highly technical water quality treatment methods to simple adoption of alternative land use and management practices. To catalyze the development of new and innovative P-control technology, the Everglades Foundation created the George Barley Prize with an award of $10 million. The competition attracted 104 teams from around the world, with four finalists selected to move to the "Grand Stage" (Naja et al. 2020). However, the competition has not yet proceeded further, as none of the teams were able to successfully reduce P concentrations sufficiently to achieve the competition's 10 ppb TP flow-weighted mean criterion and meet additional requirements specified by the Everglades Foundation (Naja et al. 2020). While technological approaches continue to develop, large-scale restoration projects including STAs and FEBs have been the backbone of the system for meeting Everglades P standards. A series of recent scientific studies and years of operational experience have proven their exceptional ability to reduce P (e.g., Chen et al. 2015; Zamorano et al. 2018; Villapando & King 2019). Ongoing STA research (Supplement S1) is providing guidance on optimizing the makeup of submerged/floating aquatic vegetation, retention times, and water staging heights (Zamorano et al. 2018). Other recent publications suggest that STAs may have the capacity to bring effluent TP concentrations below 10 ppb (Marois & Mitsch 2016), however, this would require an additional 17,000–40,000 ha of STAs (Mitsch 2016; Mitsch et al. 2018). Doubling or tripling the current areas of STAs raises economic, social, and political challenges; land would need to be purchased and converted from agriculture when many growers and other stakeholders in the EAA do not want to see any further reduction in agriculture (Treadway 2018).

One possible solution to this conflict that has been advanced is rice paddy cultivation, by itself or in rotation with sugarcane. If cultivated correctly, rice paddies in the Everglades require little to no P-based fertilizer and can even filter P out of irrigation waters (Tootoonchi et al. 2018). For example, Duersch et al. (2020) found that rice production can reduce P by 14.7 kg/ha with each harvest, potentially representing an effective BMP for combating legacy P. Rice cultivation also has several other advantages including preventing soil subsidence, improving soil conditions for sugarcane, being able to grow a full yield between the sugarcane harvesting and planting seasons (Alvarez et al. 1979), and serving as habitat for wading birds and other wildlife (Pearlstine et al. 2005; Townsend et al. 2006). At the same time, rice production has several potential environmental downsides, including methane (CH_4) and nitrous oxide (N_2O) emissions, as well as nitrogen and pesticide run-off (Prasad et al. 2017). Rice cultivation in the EAA is still a developing practice, but several actions could improve its potential economic and environmental viability, including targeted breeding, subsidies (as with sugar), and a payment for ecosystem services program to compensate growers for extracting P from soils and water. Implementing a nutrient-trading program would allow nutrient contributors to sell nutrient credits when meeting TMDLs, and payments could be subsidized by restoration funding. There are already pilot nutrient trading programs in Florida and other parts of the United States. In the Chesapeake Bay region, nutrient trading is projected to reduce the cost of reducing P inputs by 60% (Jones et al. 2010).

Connecting Science and Values to Future Policy

Assigning a value to a particular ecological condition or service is inherently subjective, with opinions often varying widely among different groups of stakeholders (Borsuk et al. 2001). An obvious example is the contrast between environmental groups that want better water quality flowing out of the EAA and growers that believe they have sufficiently reduced their environmental impact and met regulatory requirements. In the Everglades, connections and feedbacks among water management, land use and development, climate change, and sea-level rise all come together to affect habitat for organisms (Ogden 2005), and there may never be a complete accounting of how specific management decisions affect each ecosystem component (Odum & Odum 2003). Critically, even relatively "simple" goals like meeting TP geometric means and WQBELs are not currently being achieved at all times and locations; it is difficult to imagine balancing all ecological services and tradeoffs when these mandatory environmental regulations are not being attained.

While environmental science and policy linkages are imperfect, refining knowledge of the ecosystem is fundamental for helping decision-makers better manage the ecosystem (Graf 2013). In the Everglades, this need was specifically addressed by the Progress Toward Restoring the Everglades Biennial Review (NASEM 2010), which spawned CEPP to better allocate ecosystem service tradeoffs and revitalize the restoration effort (USACE & SFWMD 2014). Several scientific initiatives have modeled and quantified these tradeoffs, including the multi-agency REstoration, COordination and VERification (RECOVER) science team and Synthesis of Everglades Research and Ecosystem Services Project. Reviews from several of these initiatives were released in 2020 (NASEM 2020; RECOVER 2020) and have served as the bedrock for sound restoration policy and implementation. Similar science-based guidance has been critical in guiding other large-scale restoration and adaptive management programs around the world (Boesch 2006; Cooke et al. 2019).

Broader Context

To summarize the current state of science and policy on phosphorus management in the Florida Everglades, we revisit the four questions posed by Rizzardi (2001): (1) How low does the P standard need to go? (2) How do we evaluate compliance? (3) Who pays? and (4) Who cares? The current regulatory answer to "how low?" is 10 ppb TP for the interior of the Everglades and a two-part test for STA outflows: an annual flow-weighted TP mean not to exceed 13 ppb in more than three out of five water years (on a rolling basis), nor exceed 19 ppb in any water year. Regarding compliance, the 10 ppb TP geometric mean requirements are being satisfied in most of the interior Everglades. WQBELs are not consistently being met, but this could change as new STAs are built and BMPs become more effective. Answering "who pays?", Florida and the Federal government have spent $1.8 billion and $1.2 billion, respectively over the past 20 years (Congressional Research Service 2017). In 2020, Florida's Governor allocated an additional $300 million for Everglades restoration, which was matched by a $250 million federal pledge (Space Coast Daily 2020). While the restoration effort is being funded, the overall $16 billion price tag and 65-year timeline remain daunting (Congressional Research Service 2017). Perhaps most important is the answer to "who cares" and why? Most stakeholders have now come to a consensus that the 10-ppb standard is important and appropriate, and most also understand the realities of managing P in the greater Everglades ecosystem: it is an expensive and difficult mission for public agencies to achieve, and it produces environmental and societal tradeoffs.

In 2004, Malinoski (2004) asked if the10 ppb TP standard might be a hollow promise. Subsequent years have revealed the answer: P-reduction policies have led to a 90% reduction of P loads into the Everglades (Xue 2018) and an apparent halt to the cattail invasion (RECOVER 2020). It is thus reasonable to say the standard was *not* a hollow promise. However, a new set of issues should be given priority as we evaluate Everglades P management in the future: (1) What is the point of diminishing returns as abatement costs rise and further P-removal becomes more difficult? (2) How can we optimize flows and water quality at the whole-watershed scale? (3) How will the increased flow of the new EAA reservoir be matched with treatment capacity? (4) Is there potential for combining additional treatment wetland area with flooded rice cultivation? We propose these questions to help guide future management decisions and research as the challenging job of Everglades restoration continues.

As we enter the second year of the United Nations Decade on Ecological Restoration, several large and prominent ecosystems affected by excessive nutrients continue to undergo extensive restoration efforts, including the Chesapeake Bay, Lake Champlain, and the Mississippi River Delta, providing an opportunity for cross-system understanding (Boesch 2006). While the Everglades is a unique ecosystem in a specific social, environmental, and political setting, this review highlights several of the challenges of science and policy integration surrounding large-scale nutrient abatement and ecosystem restoration projects worldwide. First, developing the fundamental ecological knowledge needed to make good policy decisions is a long (and often iterative) endeavor. This process can be at odds with the information requirements of policymakers, who need to make decisions quickly and generally recoil from the concept of uncertainty (Meah 2019). Next, policy development and decision-making can be especially complicated—or even hamstrung entirely—if scientists or science-producing organizations arrive at contrasting conclusions. Even after policies are developed, their implementation can bring new information, needs, or conflict to light. In the Everglades, implementation of a policy focused on water quality threatened ecological processes related to water quantity, timing, and distribution. Similarly, a policy focus on one geographical location at the expense of other regions can lead to inequitable and unintended environmental outcomes. Finally, the notion that all stakeholders in a complex social–ecological system can "win" is likely more idealistic than realistic; some or all parties will have to make concessions to meet system-level goals. In the Everglades, an "all of the above" approach that advances alternative cropping and nutrient-management systems, nutrient trading programs, and innovative treatment technologies, alongside the vast public infrastructure investment, is likely necessary to further the restoration of this globally important ecosystem.

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Supporting Information

The following information may be found in the online version of this article:

Supplement S1: Web of Science bibliometric survey results from 1985 to 2019 showing publication rates of “Everglades phosphorus” (black line) and other key phrases and article types (colored bars on right vertical axis).

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