FEATURE

Habitat management and restoration as missing pieces in flats ecosystems conservation and the fishes and fisheries that they support

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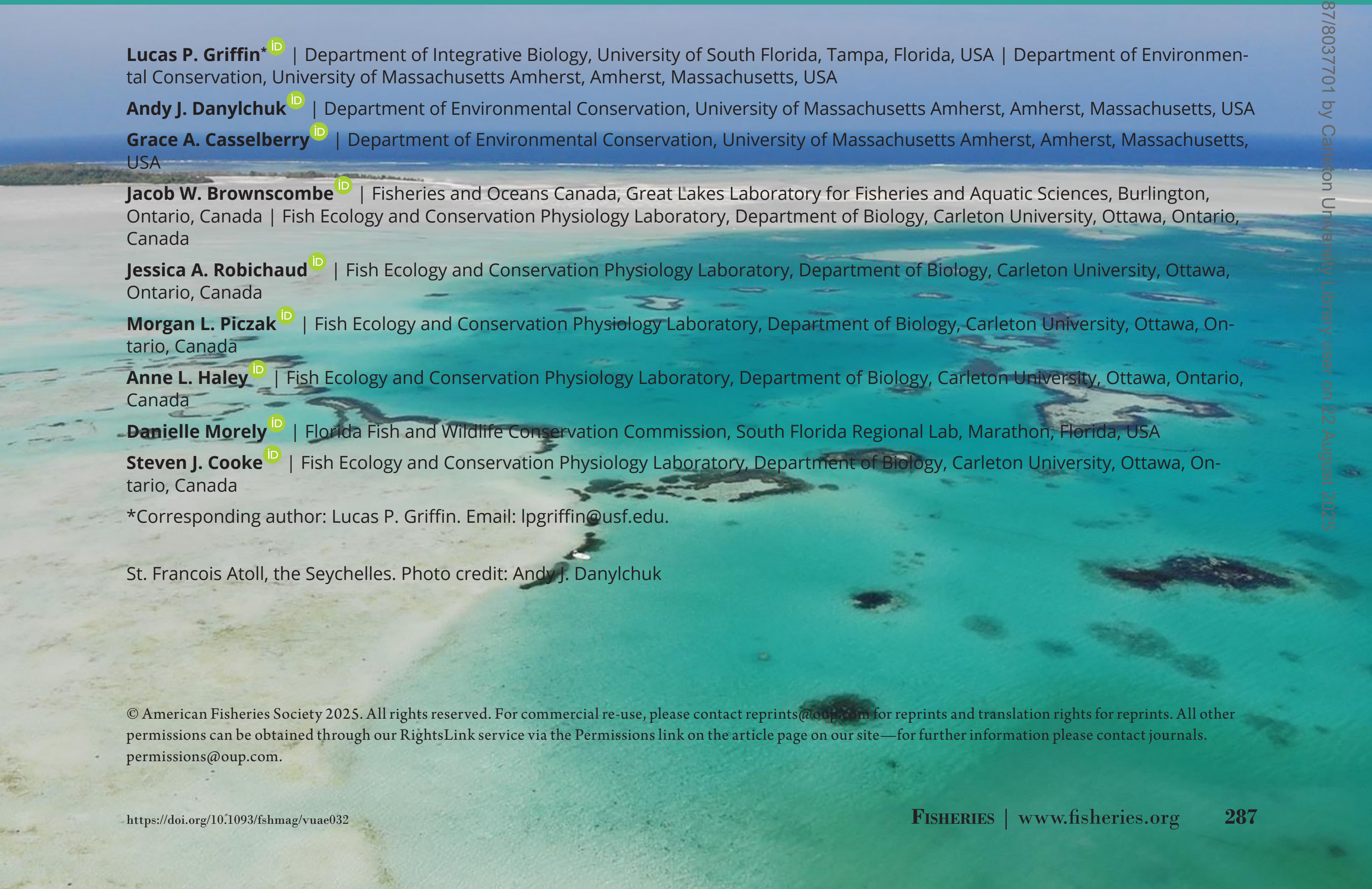

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ABSTRACT

Flats ecosystems are dynamic, shallow, nearshore marine environments that are interconnected and provide immense ecological and socio-economic benefits. These habitats support a diversity of fish populations and various fisheries, yet they are increasingly threatened by anthropogenic stressors, including overfishing, habitat degradation, coastal development, and the cascading effects of climate change. Effective habitat management and restoration are essential but are often missing for flats ecosystems. Despite navigating a landscape of imperfect knowledge for these systems, decisive action and implementation of habitat protection and restoration is currently needed through policy and practice. We present a comprehensive set of 10 strategic guiding principles necessary for integrating habitat management and restoration for the conservation of interconnected flat ecosystems. These principles include calls for comprehensive ecosystem-based management, integrating adaptive strategies that leverage diverse partnerships, scientific research, legislative initiatives, and local and traditional ecological knowledge. Drawing on successes in other environmental management realms, we emphasize the importance of evidence-informed approaches to address the complexities and uncertainties of flats ecosystems. These guiding principles aim to advance flats habitat management and restoration, promoting ecological integrity and strengthening the socio-economic resilience of these important marine environments.

INTRODUCTION

Flats are shallow intertidal areas of the marine environment predominantly located nearshore, spanning from the shoreline to open coastal waters, and are also around isolated atolls (Alongi, 2002; Barbier et al., 2011; Danylchuk et al., 2023). These ecotones form a complex mosaic of habitats (Adams, 2017), featuring diverse array of substrates such as sand, mud, and coral rubble, along with biological structures, such as seagrass meadows, oyster reefs, adjacent coral reefs, and mangroves. They are prone to natural extremes, such as tidal regime, temperature, salinity, and nutrient and sediment loading from interconnected shorelines and watersheds (Amos et al., 2013; Gao, 2019; R. R. Carlson et al., 2021; Teneva et al., 2016; Waycott et al., 2011). These conditions result in dynamic physiochemical environments conducive to the establishment of a mosaic of benthic habitats, which collectively shape the structure and function of flats ecosystems. These habitats, in turn, serve as nursey grounds for a diverse range of sessile and motile fauna (Lefcheck et al., 2019), from reef fish (Nagelkerken et al., 2000) to sharks and rays (Leurs et al., 2023). Within nearshore flats ecosystems, they often comprise of a diversity of fishes across a range of life history stages, as well as shorebirds (Cai et al., 2024), and, whether daily and/or seasonally, their movements to and from nearshore flats can represent important connections with other ecosystems (Adams et al., 2023). Given their proximity and interconnectedness to shore, as well as the diversity of habitats and species they support, flats provide immense economic and societal benefits (Barbier et al., 2011), including through commercial fisheries, tourism, and recreational activities like flats fishing, which is popular in coastal communities worldwide (M. Smith et al., 2022; Perez et al., 2020; Wood et al., 2013). Although covering less than half a percent of the ocean surface, flats and associated habitats, such as seagrasses, salt marshes, macroalgae, and mangroves, are responsible for 50% of carbon burial in marine sediments (Duarte et al., 2005), thereby providing an important regulating ecosystem service. These areas also provide coastal protection (Duarte et al., 2013; Elliff & Silva, 2017; Reed et al., 2018; Zhang et al., 2024) that is essential for growing coastal populations (Neumann et al., 2015).

Coastal flats and their associated fisheries face increasing threats from climate change (Danylchuk et al., 2023; Waycott et al., 2011) and are further compounded through localized human-induced stressors, such as overfishing, which can alter both food web dynamics and disrupt habitat bioengineering processes through the removal of herbivorous fish and megafauna (Jackson et al., 2001). Additional cumulative pressures include coastal development and poor water quality and management practices that lead to large scale regime shifts in seagrasses and seascape structure (Danylchuk et al., 2023; Hall et al., 2016; Santos et al., 2020). Recent estimates (2014–2016) indicate that 68% of tidal flats experience moderate to very high levels of human pressure, ranging from infilling and coastal hardening, vegetation loss, reduced sediment flow, and increased nutrient loads (Hill et al., 2021). This increase in anthropogenic stressors has significantly contributed to the widespread loss of flats habitats (Miththapala, 2013). Moreover, over the past few decades, tidal flats in North America, East Asia, and the Middle East have experienced a substantial decline, with approximately 16% of these critical habitats disappearing between 1984 and 2016 (Murray et al., 2019). These losses pose severe ecological and economic consequences, particularly in regions heavily reliant on flats ecosystems. As demonstrated in a recent climate vulnerability assessment focused on Caribbean flats, these systems are becoming increasingly vulnerable to climate change, including rising sea surface temperatures, sea level rise, coastal erosion, ocean acidification, and intensified storm events (Carroll et al., 2023). These changes are expected to have far-reaching consequences for economically important flats-dependent fisheries throughout the region, such as bonefish *Albula* spp., permit *Trachinotus* spp., and Atlantic Tarpon *Megalops atlanticus* (Adams et al., 2023; Carroll et al., 2023; Danylchuk et al., 2023).

With only limited information available on their demographics and population statuses, effective management of flats-dependent species is difficult due to often being categorized as data poor. Specific to fisheries, information on population trends has largely been collected through local ecological knowledge, e.g., bonefish (Kroloff et al., 2019; Larkin et al., 2010; Rehage et al., 2019; Santos et al., 2019), permit (Piczak et al., 2023a), Atlantic Tarpon (Griffin et al., 2023c). When examining trends in the bonefish fishery in the flats habitats of the Florida Keys, Boucek et al. (2023) used a combination of tournament data, angler logbooks, and local ecological knowledge surveys to highlight a two-fold increase in bonefish catch rates since 2015; therefore, reflecting a potential increase in populations. Although empirical evidence is needed, this catch increase coincided with an archipelago-wide initiative

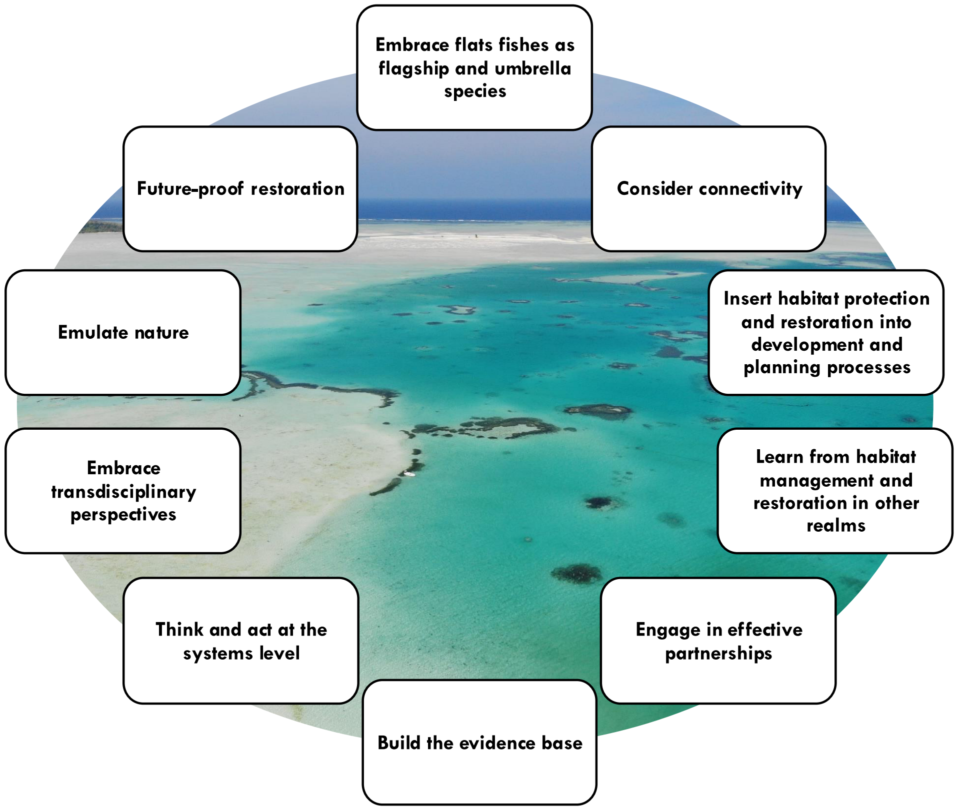

Figure 1. Ten guiding principles to integrate habitat management and restoration for the conservation of flats ecosystems.

to transition from septic systems to central sewer systems, potentially improving water quality and, thus, supporting the recruitment and survival of juvenile bonefish (Boucek et al., 2023). While the causal link between the bonefish recovery following its collapse (Brownscombe et al., 2019b) remains unknown and could also be tied to recruitment or fishing effort, prioritizing habitat improvements and protection offers a precautionary approach to safeguard these fragile nearshore ecosystems (Boucek et al., 2024).

Restoration efforts can vary widely. They often involve converting degraded habitats, such as reestablishing mangroves, restoring seagrass beds where they have been lost due to sedimentation, poor water quality, or prop scars, or rehabilitating areas impacted by coastal development to reestablish ecological function. Importantly, understanding the connections between flats habitats and the ecosystem services they provide is important for directing management and restoration initiatives. Given the absence of initiatives for formal stock assessments on recreational flats species, it is imperative to restore and maintain the diverse mosaic of flats habitats, which should help to support habitat function, connectivity, and integrity (Adams & Cooke, 2015). Furthermore, integrating habitat restoration into broader fisheries management aligns with global initiatives aimed at transitioning toward comprehensive ecosystem-based management approaches (Arkema et al., 2006). The overarching objective of this paper is to identify a comprehensive set of guiding principles (Figure 1) necessary to incorporate habitat management and restoration into the conservation of flats ecosystems and the fishes and fisheries they support.

TEN GUIDING PRINCIPLES

Embrace flats fishes as flagship and umbrella species

Effective conservation initiatives can strategically incorporate management surrogates, often designated as flagship and/or umbrella species (Hunter et al., 2016; Lindenmayer & Westgate, 2020). These surrogates play two roles: flagship species possess the potential to engage and mobilize public support for conservation efforts (Verissimo et al., 2011), while protecting umbrella species extends these benefits to an array of co-occurring species (Caro, 2010; Roberge & Angelstam, 2004). Wilson et al. (2023) advocated for the Common Snook *Centropomus undecimalis* as a flagship species due to its socio-economic importance and the attention it receives from anglers regarding its conservation and management. Further, the Common Snook can also be regarded as an umbrella species because protecting their nursery habitats, including mangrove creeks and wetlands, not only benefits snook but also supports the conservation of 55 other co-occurring species (Wilson et al., 2023). Like Common Snook, recreational flats species should be recognized as flagship species. The catch-and-release fishery for bonefish, Atlantic Tarpon, and permit alone contributed US$474 million annually to the Florida Keys economy in 2012 (M. Smith et al., 2022). Moreover, recreational fishers involved in these Florida Keys flats fisheries frequently participate in conservation and management efforts through individual and collective action (Gervasi et al., 2022a, 2022b; Humston et al., 2008; Larkin et al., 2010).

Protecting the habitats of flats species, such as seagrass beds, coral reefs, and mangroves, extends protection as an umbrella to a broad spectrum of marine life that relies on these environments. Using permit in the Florida Keys as an example, Brownscombe et al. (2022b), using stable isotope analysis and acoustic telemetry, highlighted the reliance of the permit on seagrass ecosystems for feeding, with a median of 70% of their prey coming from seagrass assemblages despite their frequent movements between the Florida reef tract and seagrass flats. Thus, focusing on the protection of mangrove and seagrass habitats for permit, would, in turn, support the habitats that serve as nurseries for both artisanal and commercial fisheries, further underlining the interconnectedness of marine ecosystems (B. S. Thompson & Rog, 2019; Bertelli & Unsworth, 2014; Saenger et al., 2013). Similarly, because of their dependence on interconnected habitats throughout their life cycle, bonefish and Atlantic Tarpon have been previously suggested as umbrella species candidates (Boucek et al., 2019; Perez et al., 2020). Embracing these surrogate designations for flats species would help further conservation and restoration efforts for these nearshore ecosystems.

Consider connectivity

Flats fishes serve as vectors connecting the flats with other disparate habitats across their varied life history strategies and movement patterns (Adams et al., 2023). For instance, adult Atlantic Tarpon undertake extensive seasonal migrations, sometimes thousands of kilometers, exposing them to a variety of habitat and fisheries-related stressors (Griffin et al., 2023a; Luo et al., 2020). Comparatively, adult permit in the Florida Keys primarily reside within this region but move between flats foraging habitats and nearshore reefs to form spawning aggregations (Brownscombe et al., 2019d, 2022b). Bonefish exhibit the highest site fidelity (Griffin et al., 2023b) but undergo extensive offshore spawning migrations (Adams et al., 2019; Danylchuk et al., 2011; Larkin et al., 2008). The spawning locations and timing of these flats fishes, in relation to oceanic current patterns and downstream recruitment habitats, are also important for understanding habitat connectivity (Lombardo et al., 2022; X. Zeng et al., 2019).

Seascape connectivity, the linkages between multiple habitat patches (Grober-Dunsmore et al., 2009; Sheaves, 2009), is another aspect to recognize as this connectivity fluences the function of flats ecosystems, as well as the mechanisms for effective restoration. If connections across habitats are lost, the role and effectiveness of singular habitats alone may be disrupted (P. L. Thompson et al., 2017; Ries et al., 2004). For instance, Olson et al. (2019), found that Common Eelgrass *Zostera marina* nursery sites adjacent to Bullwhip Kelp *Nereocystis luetkeana* forests led to higher quality foraging opportunities for young-of-the-year rockfish *Sebastes* spp., leading to better body conditions relative to sites adjacent to sand. Similarly, Meijer et al. (2021) demonstrated how mangrove connectivity, extent, and configuration drove the microbenthic communities of nearby intertidal mudflats. By recognizing connectivity throughout restoration efforts, flats species can effectively interact across habitat mosaics, from intertidal to subtidal regions (McAfee et al., 2022). Adopting the land-to-sea continuum or ridge-to-reef approach, restoration efforts can expand beyond focal habitats and extend to watershed hydrology that support nearshore environments (J. K. Carlson et al., 2019). These strategies will be important in addressing anthropogenetic stressors from a more comprehensive ecosystem-based management approach.

Insert habitat protection and restoration into development and planning processes

Flats ecosystems, often near population centers, face risks of habitat alterations, ranging from removal to sinking of habitats, reduced sediment load, and increased erosion (Murray et al., 2019). If the functional loss of these habitats occurs, it can lead to widespread ecological shifts, particularly for species that rely on them for food and shelter across multiple life stages (Danylchuk et al., 2023). Considering the high costs of marine habitat restoration to return their functional roles (Bayraktarov et al., 2016), proactive protection of these ecosystems is essential to mitigate impacts from human activity and population growth (Y. Zeng et al., 2022). Marine spatial planning (MSP) is central in offering a balanced approach to environmental protection and human development (Trouillet & Jay, 2021) in that it can strategically designate areas for both important ecological functions and human activities, aligning conservation with socio-economic objectives (Katona et al., 2017). However, with only 55% of MSP claiming to address land–sea integration in their plans (Ehler, 2021), MSP often lacks the integration of terrestrial, freshwater, and marine ecosystems' connectivity. Despite efforts towards directed frameworks, such as integrated coastal zone management, the scale and integration of administrative and institutional frameworks remains challenging (H. D. Smith et al., 2011; Kerr et al., 2014).

Particularly for flats ecosystems, it is important to incorporate the protection and/or restoration of ecological connections between marine, terrestrial, and freshwater regions in MSP initiatives (Lagabrielle et al., 2011). Indeed, in a global analysis of where mangrove, seagrass, and reef communities co-occurred, R. R. Carlson et al. (2021) estimated only 18% of these interaction zones were covered by protected areas. In another example, restoring natural freshwater flows regionally from the Florida Everglades could re-establish historic salinity levels and reduce pollutant effluents (Guardo & Tomasello, 1995; Sklar et al., 2005), thereby improving habitat quality for species like bonefish in South Florida (Brownscombe et al., 2019b). Additionally, in the Florida Keys National Marine Sanctuary, integrating spatial data on human activity, e.g., fishing effort (Black et al., 2015) and recreational boating (Anderson, 2022; Boucek et al., 2024), has been and will continue to be important for revising spatial management strategies. These approaches to integrating protection and restoration into development and planning processes would help to ensure the sustainability and health of flats ecosystems, addressing both ecological and human needs.

Learn from habitat management and restoration in other realms

Terrestrial ecosystems have long been at the forefront of conservation and restoration efforts, with freshwater systems also gaining increasing attention more recently (Piczak et al., 2023b). Marine environments, however, have been comparatively overlooked due to a more recent history of focused conservation efforts and an "out of sight, out of mind" mentality (Fairweather, 2004; Saunders et al., 2020). Yet, lessons from terrestrial and freshwater conservation successes offer valuable insights. For example, the focus on the interconnected protection and restoration of habitats within waterfowl management (Anatidae family) has led to the rebound of struggling populations (Bolen, 2000). Leading these efforts, Ducks Unlimited, a habitat-dependent outdoor recreation and conservation organization (Raynal et al., 2020), effectively engaged resource users to support waterfowl and wetland conservation, as well as catalyzing grassroots advocacy for management changes (Melinchuk, 1995; Tori et al., 2002). Their efforts, supported by 684,000 members in 2023, have contributed to the conservation of over 16 million acres of waterfowl habitat since the organization's inception in 1937 (Ducks Unlimited, 2023). Going beyond traditional fishery management techniques, engaging flats anglers through habitat-dependent outdoor recreation and conservation organizations could similarly drive positive policy changes for flats habitat management and restoration.

Moreover, habitat management in systems beyond the marine environment has continued to evolve, with adaptive management playing an important role, whereby new information is iteratively incorporated into decision making and management to reduce uncertainty (Williams & Brown, 2014). For example, within the Columbia River estuary, a combined 77 restoration projects were iteratively implemented to improve juvenile salmonid habitats resulting in 7,000 acres of floodplain habitat restored (Littles et al., 2022). With the understanding that the loss of floodplain habitat was the most important limitation for juvenile salmonids, these projects leveraged multiple pilot initiatives, such as exploring habitat creation using dredged materials, invasive vegetation removal, and hydrological reconnections (Littles et al., 2022). To do this within the context of flats systems will require rigorous evidence-informed monitoring (Elliott et al., 2007; Holl & Cairns, 2002). This is especially true when carrying out management strategies such as habitat restoration (Block et al., 2001) and the incorporation of other types of fisheries knowledge, such as local/traditional ecological knowledge (Mamun, 2010) and Indigenous ways of knowing (Reid et al., 2021).

Engage in effective partnerships

Management for conservation in marine environments is a complex process that frequently involves numerous partnerships. Partnerships may include participants from municipal, state/provincial, and federal government agencies, habitat-dependent outdoor recreation and conservation organizations, local/traditional ecological and rights holders, and research scientists. Working directly with local partners and bridging academic knowledge production is essential for producing practical, actionable, and relevant conservation and restoration programs (Gonzalo-Turpin et al., 2008). Flats management have already benefited from partnerships with fishing guides and anglers who have strong local ecological knowledge of a given area or species (Gervasi et al., 2022a, 2023). Engaging these partners within the context of flats fisheries can promote knowledge coproduction and enhance monitoring and conservation strategies (Griffin et al., 2021). Meant to promote effective conservation action, knowledge coproduction incorporates diverse perspectives from varying partnerships into management planning in an engaging and transparent manner (Cooke et al., 2021). Engaging partners through knowledge coproduction also empowers those involved by allowing their voices to be heard and helps to improve the overall planning process (Abas et al., 2023). In addition to two-way knowledge sharing, such partnerships can support cultural education and preservation, as seen in a seagrass restoration project in Gathaagudu (Shark Bay), Australia, between non-Indigenous and Aboriginal Traditional Custodians (Sinclair et al., 2024).

Partnership engagement is most effective when partners are included through each step of the process (i.e., management design, implementation, and evaluation; G. Smith, 2018). Therefore, partners should be brought in early on when projects are being considered. Engaging partners and resource users can also help make research actionable (see Shephard et al., 2022), where the science is applied to conservation efforts. In an example in the Florida Keys, Brownscombe et al. (2019a) highlighted how resource users' involvement and local ecological knowledge led to a rapid policy change surrounding harvest closures for permit at spawning sites. Highlighting this engagement within a restoration context, DeAngelis et al. (2020) outlined three case studies from the USA, including oyster restoration in Chesapeake Bay, Maryland and Virginia; tidal marsh restoration in San Francisco Bay, California; and seagrass restoration in Tampa Bay, Florida. Each case study documented how public outcry in response to well-documented ecosystem declines led to political intervention and actionable restoration efforts. Challenges of knowledge coproduction surrounding restoration efforts may include consistency in participation, limitations in time commitments, and funding constraints; however, these can be mitigated by developing strong relationships with partners that maximize inclusively, and clearly outline responsibilities and long-term goals (Piczak et al., 2022).

Build the evidence base

Developing and executing ecological restoration plans and projects that that are effective (i.e., achieve desired objectives) is challenging (Aronson & Vallejo, 2006). It is even more challenging if one does not have an evidence base to draw upon to guide them. Some forms of ecological restoration are very well studied to the point where there have been bespoke guidelines developed to assist practitioners in their work (e.g., the restoration of cold water streams to benefit fish; Roni et al., 2002). Such guidance would not be possible without a strong evidence base spanning multiple types of restoration, site characteristics, regions, fish communities, and so on. Indeed, there are hundreds of studies on stream restoration with endpoints of fish biomass and abundance that have been conducted enabling meta-analysis (Foote et al., 2020; Whiteway et al., 2010). Without such an evidence base, those designing and implementing restoration projects are forced to guess and make decisions in the face of uncertainties, which can lead to misuse of valuable resources and could cause more harm than good. A standardized marine restoration monitoring framework is necessary to ensure that detailed reporting contributes to the evidence base (Eger et al., 2022). However, reporting bias toward successful outcomes is pervasive, driven by scientific journal interests, human factors, or the need to meet funding goals (Catalano et al., 2019; Eger et al., 2022). Without proper monitoring and, ultimately, understanding, restoration efforts may be unneeded, misguided, or ineffective, especially if there is no clear picture of what a healthy system looks like or if the root cause of the problem remains unaddressed (Cooke et al., 2019).

Evidence-informed restoration has been touted as a logical approach for increasing the likelihood that restoration will deliver on its promise (Cooke et al., 2018). Unfortunately, for flats that are home to flats fishes, such empirical evidence on restoration effectiveness is scant. Techniques, such as electronic tagging (Brownscombe et al., 2022a; Gahagan & Bailey, 2020; Lapointe et al., 2013; Piczak et al., 2024) and the integration of ecological knowledge (Mamun, 2010; Uprety et al., 2012), have shown promising success and could offer valuable insights if broadly applied to the flats ecosystems. Additionally, stable isotope analysis (Loch & Cook, 2023; Wozniak et al., 2006) and environmental DNA studies (Capurso et al., 2023; Wee et al., 2023) are emerging as powerful tools for establishing ecological connections, monitoring biodiversity, and establishing habitat linkages. There is a need for more experimental approaches to flats and coastal restoration, incorporating appropriate reference sites, replication, and long-term monitoring (Cooke et al., 2019). Importantly, much of the current restoration work occurs outside formal research, highlighting the importance of capturing the experiences of practitioners.

While experimental marine restoration has primarily focused on corals (Bayraktarov et al., 2020), flats restoration efforts have largely focused on seagrasses (Rezek et al., 2019; S. S. Bell et al., 2014) and mangroves (Ellison et al., 2020). Emerging research in other flats habitats, such as re-establishing sponge communities in Florida Bay, is beginning to provide valuable insights into flats ecosystem dynamics. Sponges, often overlooked in restoration (J. J. Bell, 2008), have a fundamental role in structuring water columns and regulating sedimentation, contributing to the recovery of degraded hard-bottom areas (Butler et al., 2021). Expanding restoration research to include a wider variety of habitat types, such as sponges and others, will be key to building upon existing evidence. As flats and coastal restoration initiatives increase in the coming years, there will need to be recognition that every project represents a learning opportunity and that by synthesizing evolving evidence base, it will be possible to generate guidance for future projects.

Think and act at the systems level

Throughout all stages of the restoration process from planning to evaluating outcomes, it is important to consider implications across all trophic levels. Predator density and movements will vary across the seascape, influencing natural mortality as well as the potential for fishery induced mortality for recreationally targeted flats species (Griffin et al., 2022). In terrestrial systems, this has, at times, resulted in predator control programs to support target species recovery in restored habitats (Hale et al., 2020). This approach is not feasible when conflicts arise with protected predators; for example, marine mammal and some shark species in marine systems (R. R. Carlson et al., 2019). Indeed, this conflict between flats species and protected predators is especially true for Atlantic Tarpon, which are regularly depredated by Great Hammerhead *Sphyrna mokarran*—a protected species in Florida state waters—in the Florida Keys recreational fishery (Casselberry et al., 2024). Because of this, it is important to consider behavior of restoration target species, their prey, and their predators throughout restoration efforts (Hale et al., 2020).

Of all species targeted in flats fisheries, fine-scale habitat use and fishery-induced predation may be most thoroughly studied for bonefish. Bonefish habitats are host to numerous predators, particularly sharks and other predatory fish species. Post-release predation rates of bonefish after recreational angling events are highly variable (Cooke & Philipp, 2004; Danylchuk et al., 2007a, 2007b; Lennox et al., 2017; Moxham et al., 2019) and in some instances, may be more influenced by existing predator burden in the angling habitat than angler handling practices (Lennox et al., 2017), like air exposure (Cooke & Philipp, 2004; Lennox et al., 2017). Bonefish have been observed using deeper water post-release (Danylchuk et al., 2007b), which may be a strategy to avoid visual predators like Great Barracuda *Sphyraena barracuda* that occupy the flats (Brownscombe et al., 2019c). Thus, incorporating access to deeper water into flats restoration design may increase survival rates for economically important catch-and-release fisheries like bonefish by reducing post-release predation.

Furthermore, restoring mangrove and seagrass ecosystems offer another important strategy for reducing natural and fishery-induced predation risk. For instance, mangroves provide critical refuge through their dense, complex root structures, allowing juveniles to shelter from predators (Kanno et al., 2023; Lewis & Gilmore, 2007). Such characteristics are important when implementing restoration. For example, in Queensland, Australia, Duncan et al. (2019) reported that predation rates were highest when restored oyster reefs were surrounded by non-vegetated seafloor far from seagrass and mangrove habitats. By considering the habitat needs of flats species at a systems level, including natural predators and angling, more effective restoration efforts should aim for supporting seascape complexity.

Embrace transdisciplinary perspectives

Nature is complex and when we think about habitat it inherently connects abiotic and biotic elements. For that reason, it is not probable that an individual with training or expertise in a single knowledge domain will be able to effectively deliver the restoration of coastal and flats habitats. Indeed, the dynamic nature of flats and coastal ecosystems, e.g., tides, thermal and oxygen variation, predator–prey abundance (Adams et al., 2023; Murray et al., 2019) and the complex ways those environmental and systems-level interactions occur demand perspectives of many different knowledge domains. For example, when interested in planting mangrove *Rhizophora* spp. propagules, one needs to understand the hydraulic conditions, water chemistry, and patterns of human use to ensure that such efforts are not futile. Indeed, in aquatic systems the nascent discipline of ecohydrology emerged in recognition of the complexity and inherent interconnectedness of the physical and biotic aspects of organismal performance (Wassen & Grootjans, 1996). Those designing restoration projects are often from engineering backgrounds (Masarei et al., 2021; Mitsch & Jørgensen, 2004), which may lack sufficient biological expertise emphasizing opportunity for co-learning. Of course, that assumes public support, which is not always the case emphasizing the role of human dimensions researchers (Egan et al., 2012). Ecological restoration has been critiqued for failing to embrace different knowledge systems (see Nilsson et al., 2005) emphasizing why such approaches are sorely needed. Restoration activities fail too often (Suding, 2011) such that there is much need to improve effectiveness. With restoration efforts often failing because the cause of habitat loss is not addressed, drawing upon diverse knowledge domains is a key starting spot. Building diverse teams that can objectively propose and explore different alternatives to restoration that are suited to the specific context is essential and that cannot be done without stepping outside one's comfort zone and across disciplinary boundaries.

Emulate nature

To maintain diversity and mitigate future losses, flats ecosystems require dynamic restoration actions that emulate natural processes. A range of multidisciplinary, nature-based strategies have been successfully implemented to restore these habitats, particularly in seagrass meadows and tidal flats. For example, in seagrass meadows, placing bird stakes over prop scars accelerates recovery by enhancing nutrient fluxes from wild bird feces (Kenworthy et al., 2018). One key process in restoring topography is sediment transport. Restoration designs should emulate natural flats by encouraging silt accumulation where the wave energy is low, slope is gentle, and hydrological connectivity is maintained (Ganju, 2019; Lee et al., 1998; Li et al., 2021). In this context, eco-engineering solutions have been particularly effective in restoring ecosystems by recreating hydrodynamic conditions, reestablishing tidal regimes, and controlling flow and sediment movement. Examples include the use of artificial and biogenic reefs, such as oyster beds, which help stabilize tidal flats by attenuating wave energy and trapping sediment (Bakker & Piersma, 2006; de Paiva et al., 2018). Living shorelines also provide a natural alternative to hard structures, such as storm walls and breakwaters, using environmental features to mitigate sea level and erosion while maintaining ecological function (Bilkovic et al., 2016; Leo et al., 2019). Even more innovative and emerging eco-engineering approaches, such as "SmartGates," have been proposed to recreate tidal regimes in coastal areas (Sadat-Noori et al., 2021). Collectively, these strategies are increasingly recognized for their ability to restore natural processes and maintain ecological function, offering promising pathway for long-term sustainability of flats ecosystems. While these eco-engineering interventions can yield positive outcomes, it is important to consider potential unintended consequences. Structural interventions, like SmartGates, though beneficial for tidal regimes, can inadvertently create barriers that disrupt the movement of fish and marine megafauna. These types of interventions may create ecological traps, where species are attracted to "restored" areas that appear favorable but ultimately reduce their fitness (Battin, 2004; Swearer et al., 2021). A key example is artificial reefs, which are often constructed to increase fish production but can function as fish attractants, making species more susceptible to harvest and failing to promote long-term population growth (Bohnsack, 1998). These unintended consequences highlight the need for careful design, monitoring, and adaptive management of restoration efforts. Moreover, preventing and mitigating existing stressors should be prioritized before and during restoration, as this is often the most effective way to facilitate natural recovery (Elliott et al., 2007).

Future-proof restoration

Restoration efforts must consider environmental changes, including global climate change and resilience, to ensure long-term ecosystem benefits (Frietsch et al., 2023). In short, static restoration strategies will likely fall short of long-term restoration objectives (Harris et al., 2006). Adapting to contemporary disturbances regimes like altered precipitation and intensifying storms can enhance the resilience of habitats and their species ( ). Such efforts may also future-proof key ecosystem attributes, such as genetic variability that can help maintain diverse population structures capable of rebounding from increased disturbance regimes (Coleman et al., 2020; Harris et al., 2006). Given that contemporary restoration efforts are complex social-ecological endeavors, limited future-proofing may also erode trust in the process of restoration efforts and the potential goods and services they can provide to society (Frietsch et al., 2023).

To provide an example in flats ecosystems, a focus is often on restoring shoreline vegetation, particularly red mangroves *Rhizophora mangle*, which play an important ecosystem role but are frequently disturbed by shoreline development (Alongi, 2002). Once damaged or removed, red mangroves have a reduced capacity to combat erosion, facilitate nutrient transport to offshore waters, and provide structural complexity for flats fauna (Blanco-Libreros & Ramírez-Ruiz, 2021). However, mangrove restoration and subsequent survival, involving propagule planting, is influenced by physical conditions like water velocity and wave height (Fillyaw et al., 2021). Considering the vulnerability of shallow-water flats to climate change induced sea level rise (Martyr-Koller et al., 2021), it is important to future-proof mangrove restoration efforts. This includes considering sea level rise projections and extreme storm disturbance probabilities for guiding planting locations and employing additional tactics, such as breakwaters, to enhance survival and growth (Fillyaw et al., 2021). While mangrove restoration yields ecological and economic benefits (Su et al., 2021), its long-term success hinges on future-proofing and adapting to rapidly changing environmental conditions.

SYNTHESIS AND CONCLUSION

Despite navigating a landscape of imperfect knowledge, decisive action is needed through policy and practice to conserve flats ecosystems, their biodiversity, the fisheries they support and the ecosystem services they provide. This necessitates leveraging the best available scientific research, incorporating diverse sources of knowledge, and employing innovative strategies into habitat management and restoration. An important tool for habitat management, the protection of intact habitats through legislative measures is a well-established strategy for conserving biodiversity. However, habitat protection remains more commonly used in terrestrial ecosystems, where 16.6% of land and inland water ecosystems is protected but only 7.7% of oceans (Bingham et al., 2021). The establishment and governance of marine protected areas (MPAs) pose specific challenges (Agardy et al., 2011). Designating catch-and-release species as conservation surrogates can support conservation goals, particularly in alignment with no-take areas, provided that mortality, whether through depredation or post-release, remains low and bycatch is minimized (Cooke et al., 2006). When carefully designed and enforced, MPAs have shown great potential for substantial conservation outcomes when protections extend to habitats and not just fish (Gaines et al., 2010). Building upon these efforts, restoration can complement MPAs and other MSP initiatives and fit within them (e.g., Gianni et al., 2013).

Despite the recognition of marine ecosystem restoration as a priority, as evidenced by the United Nations declaring the years 2021 to 2030 as the "Decade on Ecosystem Restoration" (United Nations, 2019), progress has often been inhibited by existing policy frameworks, which are challenged by complex, uncoordinated legislative and permitting processes (Shumway et al., 2021). There is a need for policies that simplify and expedite processes and effectively incorporate conservation and restoration efforts into a unified legislative strategy. This approach is particularly difficult when working across the land-to-sea gradient where jurisdictional boundaries are blurry and where multi-scalar governance is common, but sectoral interplay is needed (Alexander & Haward, 2019). If habitat management and restoration can be implemented in flats ecosystems, it will not only help to respond to the immediate challenges those ecosystems face but also help to future-proof against future stressors and disturbance regimes.

The synthesis of our current knowledge and needs suggests that embracing an ecosystem-based management approach is essential. This transdisciplinary approach acknowledges the interconnectedness of species, habitats, and human activities. It requires managing ecosystems in their entirety and beyond (i.e., watersheds), considering the cumulative and future impacts of various stressors. This perspective is especially relevant for flats ecosystems, where the interplay of physical, biological, and human factors shapes the ecological dynamics. Engaging in effective partnerships and coproduction of knowledge is another key element where collaboration occurs across scientists, local communities, anglers, policymakers, and other interested parties. These partnerships foster a shared understanding and commitment to conservation goals, leveraging diverse knowledge systems and perspectives (Cooke et al., 2021). Collectively, these 10 guiding principles, while grounded in current understanding, also acknowledge the uncertainties and complexities inherent in ecosystem management. They advocate for a pragmatic approach that is flexible, evidence-informed, and open to learning and adaptation as new knowledge and threats emerge. Through science, policy, and practice, habitat management and restoration efforts will be pivotal for preserving flats ecosystems and the socio-ecological systems dependent on them.

DATA AVAILABILITY

No new data were generated or analysed in support of this research.

ETHICS STATEMENT

There were no ethical guidelines applicable to this study.

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CONFLICTS OF INTEREST

A.J.D. and S.J.C. are editors for *Fisheries* and, therefore, were not part of the reviewing of this manuscript.

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