Addressing climate change and development pressures in an urban estuary through habitat restoration planning

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## Abstract

Native habitats in Florida face dual pressures at the land-sea interface from urban development and sea-level rise associated with climate change. To address these pressures, restoration practitioners require robust tools that identify reasonable goals given historical land use trends, current status of the habitat mosaic, and anticipated future impacts from coastal stressors. A target-setting approach for native habitats was created for the Tampa Bay watershed that identifies current restoration opportunities and establishes short (2030) and long-term (2050) goals. The approach was informed through a three-decade habitat change analysis and over forty years of habitat restoration experience in the region. Restoration goals were defined based on what is possible today and the projected needs for the future, rather than attempting to replicate past ecological conditions. The new paradigm also accounts for the expected impacts of sea-level rise, climate change, and watershed development - stressors which are pervasive in Florida. The resulting habitat goals are spatially explicit with maps that identify remaining restoration and conservation opportunities, while also providing an approach for the entire watershed that targets subtidal, intertidal, and coastal uplands. This approach represents a general framework to support coastal planning decisions that need to address competing interests and could be applied in other coastal settings where sustainable urbanization practices need to co-exist with natural environments. Methods for repeatable analyses are also available using an open source workflow to update progress over time and for adoption by others.

## Introduction

The health of estuarine systems, coastal habitats, and associated fauna and flora are inextricably linked to land uses and management throughout the watershed (Yoskowitz and Russell, 2015) These habitats provide multiple ecosystem services, including wildlife shelter and migratory corridors (Yoskowitz and Russell, 2015), fisheries production (Houde and Rutherford, 1993), water quality improvement (Kushlan, 1990; Sprandel et al., 2000; Ávila-García et al., 2020), erosion and flood attenuation (Calil et al., 2015; Menéndez et al., 2018), carbon sequestration (Dontis et al., 2020) and recreation (Chung et al., 2018). The Tampa Bay Estuary Program (TBEP) is one of 28 programs administered by the US Environmental Protection Agency (USEPA) under the National Estuary Program (NEP). In recognition of threats to habitats from development and climate change stressors, the TBEP and partners recently created the third iteration of a plan to establish targets and goals for habitat restoration within the Tampa Bay watershed. As an NEP, the program has guided regional environmental restoration initiatives for the estuary since 1991. The methodologies used in the creation of a 2020 Habitat Master Plan Update for Tampa Bay (Robison et al., 2020) are highly transferable to both coastal and non-coastal systems.

## Development, climate change, and coastal squeeze

Development causes multiple perturbations within any watershed. The accumulated impacts of construction and associated infrastructure remove or substantially modify existing habitats, and can alter hydrology of nearby streams and rivers (Theobald et al., 1997; Sim and Mesev, 2014). Given the degree to which the Tampa Bay watershed has been urbanized, the synergistic effects of continued coastal development and future climate change are primary concerns for maintenance of estuarine and coastal habitat health. Observed and potential adverse effects of climate change and sea level rise on marine and estuarine ecosystems are well-documented (Scavia et al., 2002; Spalding and Hester, 2007; Titus et al., 2009). With regard to estuarine habitats, the primary concerns are that sea level rise is now occurring at such a rapid rate that the landward migration of tidal wetlands in response cannot keep pace; or that the upland slope has already been lost to urban development and hardening, leaving no place for tidal wetland migration (Titus et al., 2009). Geological, physical and chemical changes could include alterations in sediment deposition and erosion patterns, micro-topography, and water quality (Whitehead et al., 2009; Arnell et al., 2015).

Related changes in habitats in response to climate change (sea level rise and warming) include landward migration of mangroves into salt marshes, upstream migration of salt marshes within tidal tributaries, and upland forest migration (Brinson et al., 1995; Vogelmann et al., 2012; Cavanaugh et al., 2019). Species dependent upon these habitats will be forced to change use patterns or adapt to the new conditions (Iwamura et al., 2013). For example, while black needle rush (*Juncus roemerianus*) can tolerate a wide salinity range (Eleuterius and Eleuterius, 1979; Stout, 1984), the largest remaining *J. roemerianus* marshes in Tampa Bay are located in the lower-salinity reaches of tidal rivers and creeks. The greatest extents of those marshes occur in river systems where their upstream extent is constrained by impoundments for public water supplies. Spatial restriction in these hydrologically truncated rivers may make these marshes particularly vulnerable to “pinching out”, as upstream migration in response to sea level rise will be cut off by anthropogenic barriers. Similarly, landward migration of salt barrens (high marsh areas in Tampa Bay) in response to sea level rise will be restricted by the filling and hardening of coastal uplands associated with existing or future urban development.

## Need for a paradigm shift

The synergistic effects of development and climate change diminish the available space for future restoration in urbanizing estuaries, thereby impacting the variety of ecosystem services provided by these habitats and the wildlife they support (Enwright et al., 2015). Given projected habitat losses without intervention efforts and the limited resources (including time, land, funding, and labor force) available, it is important to appropriately and realistically site restoration projects to increase the likelihood of success. To achieve this objective, a new restoration approach on a broad watershed scale will be implemented.

Previously, a “retrospective” approach to setting habitat protection and restoration targets in Tampa Bay was employed (Lewis and Robison, 1996; Robison, 2010; Cicchetti and Greening, 2011; Russell and Greening, 2015). Under this paradigm, priority was given to restoration activities focused on habitat types, important for a suite of ten estuarine faunal guilds, that were disproportionately lost or degraded compared to a benchmark period. Primary criticisms of this approach included a lack of consideration for future sea level rise and other climate change factors (Yoskowitz and Russell, 2015), use of expanded and different habitats outside the Tampa Bay watershed by the faunal guilds (Robison, 2010), lack of attention to upland or freshwater wetland habitats, and little recognition of other stressors such as land development trends or actual available space for restoration efforts.

Past approaches for guiding restoration planning have been successfully used in other contexts, but they do not fully balance competing needs. For example, an integrated watershed approach (Environmental Protection Agency, 1996) has been utilized since the early 1990s to diagnose and manage water quantity and quality problems that have contributed to seagrass restoration in the system. Additionally, the habitat mosaic approach (Henningsen, 2005) of including multiple habitat types within restoration projects is recognized as necessary in Tampa Bay (Hughes et al., 2011) and elsewhere to allow for ecosystem state changes in response to different environmental pressures (Duarte et al., 2009; Palmer, 2009).

Adaptive management (Holling, 1978; Gregory et al., 2006) components have been increasingly used to address challenges of sea level rise, climate change, and development stressors, including monitoring to identify critical restoration decision points and needed intervention with contingency plans. Rising sea levels and temperatures and altered rainfall patterns are causing observable changes to habitats on a global scale (Cavanaugh et al., 2014; Garner et al., 2015; Yoskowitz and Russell, 2015), including within Tampa Bay (Price et al., 2017), and those changes are expected to become more pronounced over the next several decades (Sheehan et al., 2016; Nerem et al., 2018).

## Updating the approach

The new approach integrates the whole watershed, addresses historical changes, focuses on trajectories that have occurred during more contemporary time periods, and considers both current and future stressors – particularly land development and sea level rise. There is relatively consistent extent and distribution data for most Tampa Bay habitats of interest (1988 to 2018), representing a time period when federal, state and local regulations were in effect and regional impacts from climate change are documented (Raabe et al., 2012; Cavanaugh et al., 2014). This approach establishes a broader framework that guides both watershed-level habitat master planning and site-level restoration design activities and incorporates applicable elements of the other habitat restoration paradigms discussed above (Palmer, 2009). Our broader framework for guiding restoration activities includes 1) designation of habitat types by strata relative to the aquatic-terrestrial gradient, 2) quantification of historical trends by habitat types to identify appropriate future targets in acreage, and 3) identification of opportunity areas that could be used by practitioners to achieve restoration goals based on habitat type and past trajectories.

With regard to habitat restoration projects, the design approach must envision not only what is possible today, but also what the coastal landscape will look like in 50 years and beyond. Design features should continue to use the historical “habitat mosaic” approach, but should also include coastal upland features that accommodate tidal inundation and the landward advance of emergent tidal wetlands (Enwright et al., 2016).

## Methods

### Study area

Tampa Bay is a large open water estuary (open water area approximately 983 km2) on the west-central coast of Florida (Fig 1). Its watershed encompasses another 5,872 km2, for a total combined area of approximately 6,855 km2. It is subtropical, and within the current (2020) ecotone for mangrove and salt marsh habitats. The upstream watershed includes multiple habitats, including pine flatwoods, forested freshwater wetlands and non-forested vegetated wetlands. The watershed is heavily developed with an estimated (2019) population of 3.3 million people in the four counties that comprise most of the watershed (Rayer and Wang, 2020)*.* Numerous anthropogenic changes have been made to the natural systems within and surrounding Tampa Bay, including direct removal of habitat (including dredge and fill of bay bottom), alteration of hydrology, and destruction and fragmentation of habitat from development.

### Habitats of Tampa Bay

Addressing the full suite of habitats in a watershed is now recognized as critical for large-scale restoration planning efforts (Palmer, 2009; Lamb, 2018)**.** The major habitat types of Tampa Bay can be described and organized relative to tidal influence and location in the watershed. Subtidal habitats include those that are submerged all or most of the time; emergent tidal wetlands include those that are submerged during high tides but exposed during low tides; and supratidal habitats include those that occur above the high tide line.

Habitats generally described as ‘subtidal’ include hard bottom (Jaap and Hallock, 1990; Ash and Runnels, 2005), artificial reefs (Dupont, 2008), tidal flats (Moore et al., 1968; Eisma, 1998)*,* seagrasses (Heck et al., 2003; Sherwood et al., 2017), and oyster reefs (Coen et al., 2007; Ermgassen et al., 2013). Mangroves (Odum and McIvor, 1990), salt marshes (Comeaux et al., 2012; Raabe et al., 2012), salt barrens (Bertness, 1985; Hsieh, 2004)*,* tidal tributaries (Sherwood, 2008; Janicki Environmental, Inc. and Mote Marine Laboratory, 2016, 2020; Wessel et al., 2022), and living shorelines (National Oceanic and Atmospheric Administration, 2015; Restore America’s Estuaries, 2015; Smith et al., 2018) are classified as emergent tidal wetlands. For the purposes of this planning effort, supratidal habitats included non-developed uplands (Meyers and Ewel, 1990), freshwater forested wetlands (Conner et al., 2007), and freshwater non-forested wetlands (Kushlan, 1990)*.* As discussed below, uplands are sub-divided into coastal and non-coastal uplands, based on location relative to the 5-foot contour.

### Approach

Recommended targets were created stepwise with geospatial analyses: 1) quantifying habitat status and historical trends; 2) synthesizing historic habitat restoration efforts; and 3) identifying and defining remaining ‘opportunities’ for restoration that integrated results from the first two analyses. Final development of restoration targets and goals integrated strata and opportunity area information with an analysis of past restoration implementation to use previous completed projects as a guide to a feasible amount of restoration that could be conducted by partners. This approach will ensure that the estuarine-dependent species and faunal guilds throughout the watershed, as defined in the original approach, will continue to be supported.

### Habitat status and trends

For the majority of subtidal, intertidal and supratidal habitats, primary data derived from two routine spatial assessment programs conducted by the Southwest Florida Water Management District (SWFWMD) were utilized. However, to address data gaps for some habitats, results from special studies were integrated with the primary data sources. These included hard bottom (Kaufman, 2017; CSA Ocean Sciences, 2019), dredged holes (Griffen and Greening, 2005; Raulerson et al., 2019) and oyster habitat (O’Keife et al., 2006)*.*

The source data used to estimate the most current coverage of seagrasses, tidal flats, and oysters was the *Seagrass in 2018* geospatial database (Southwest Florida Water Management District, 2019). The bi-annual seagrass monitoring program was initiated in 1988 under SWFWMD’s Surface Water Improvement and Management program (Sherwood et al., 2017; Tomasko et al., 2020)*.* SWFWMD has estimated oyster bed coverage as part of this program since 2014.

The source data used to estimate and map trends in development, emergent tidal wetlands, freshwater wetlands, and native upland habitats was the SWFWMD Land Use Land Cover (LULC) series geospatial database (Southwest Florida Water Management District, 2018). This comprehensive database classifies the land use and cover types (natural and developed) pursuant to the Florida Land Use Cover and Forms Classification System (Florida Department of Transportation, 1999; Southwest Florida Water Management District, 2014)*.* Mangroves, salt barrens, and salt marshes were reported individually. While the photointerpretation of specific freshwater wetland types is often very difficult, it is possible to accurately distinguish forested wetlands from non-forested wetlands. Therefore, for this analysis, all applicable FLUCCS codes representing the suite of natural freshwater wetlands were combined within those two classifications. Similarly, within the target- and goal-setting exercise, uplands were combined in one classification. These classifications were reported for each mapping exercise conducted every 2-3 years from the start of the program 1990 through 2017, the most recent year with available data.

To quantify the extent of tidal creeks, GIS data (Janicki Environmental, Inc. and Mote Marine Laboratory, 2016, 2020) was clipped to the Florida Department of Environmental Protection stream segments that were classified as estuarine.

### Restoration database

We quantified past restoration efforts in each of the major habitat types to guide decisions on future targets and goals. Information regarding habitat restoration and enhancement activities in the Tampa Bay area over the past 40 years were compiled, reviewed, and consolidated into a single, consistent geospatial database. Data were gathered from the SWFWMD Surface Water Improvement and Management Program, Federal Government Performance and Results Act (GPRA) reporting, the Tampa Bay Water Atlas (<https://www.tampabay.wateratlas.usf.edu/>), Tampa Bay Watch, and the Technical Advisory Committee of the TBEP. Primary data collected included project name, year, description, lead partner, size (area or length), and latitude and longitude. Data gaps were supplemented by archival research, site visits, contacting the responsible entities, and documenting the knowledge of local professionals. Living shoreline projects, including seawall enhancements and oyster reef modules, were inventoried separately.

### Creating and combining opportunity layers

[Figure 1](#fig-gisworkflow)

Three strata, distinct geographic breakpoints in the watershed where different habitat management and restoration activities could take place, were created to establish the process for target and goal-setting within this framework. The first is the coastal stratum, which extends from the local Mean Lower Low Water elevation to elevation 5 feet above Mean Sea Level and is likely to be affected by frequent tidal flooding or inundation by 2070. The coastal stratum is the zone where emergent tidal wetland restoration would be conducted and includes low lying coastal uplands which serve as important tidal wetland buffers that will be critically important in the future as lands reserved to accommodate ideal wetland migration in response to sea level rise. The river floodplain stratum includes all hydrologically contiguous forested and non-forested wetlands within the river and stream corridors of the Tampa Bay watershed. Floodplain corridors provide vital watershed functions including fish and wildlife habitat and migratory pathways, floodwater attenuation and storage, erosion control, and delivery of complex organic matter to the estuarine food web. Finally, the upland stratum encompasses those areas outside of the coastal and river floodplain strata, including native upland habitats as well as hydrologically isolated wetlands. These habitats provide important aquifer recharge and wildlife habitat functions.

Opportunity areas, defined here as locations where habitat protection and restoration activities are possible, and where they should best be focused to attain defined targets, were also analyzed. The definition and mapping of opportunity areas is necessary to quantify the “restoration potential” for a particular habitat type, which is a measure of what is actually possible under current and future projected conditions. The most appropriate opportunity areas are generally not developed and located on existing public lands or areas identified for acquisition.

The Land Use Land Cover 2017 geospatial database (Table 1) was used as the baseline for cataloguing existing and opportunity areas for intertidal and supratidal habitats in the Tampa Bay watershed. All FLUCCS classification codes were placed into one of three categories. First, native habitats cover the full range of natural plant communities and other habitats that are endemic to the Tampa Bay watershed, and were further grouped into three major habitat types (tidal wetlands, freshwater wetlands, and uplands). Second, restorable habitats include existing altered but non-hardened and pervious FLUCCS codes that could potentially support native habitats through the restoration of more natural hydrology, soils strata, and/or topography. Third, existing development includes developed land FLUCCS codes that are hardened and impervious (e.g., structures and pavement) and not suitable for habitat restoration activities.

Layers for existing public lands and parcels targeted for acquisition were compiled by combining data from the Florida Natural Areas Inventory (Table 1), consulting staff from various federal, state and local entities, and inventorying conservation and drainage easements data.

Compared to vegetation communities, soil characteristics typically change slowly (e.g., decades to centuries) in response to hydrologic impacts, unless physically disturbed (Osland et al., 2012; Stockmann et al., 2014). Therefore, soils distributions can be used to generally represent historical habitat distribution, and can be used to provide generalized restoration guidelines (e.g., tidal wetlands, freshwater wetlands, and native uplands). Ries and Scheda (2014) created a soils suitability analysis for wetland mitigation and restoration sing data from the USDA Web Soil Survey (Table 1) and classified all soils in the Tampa Bay soils into one of three categories (xeric, mesic, and hydric). The mesic and hydric categories were combined to represent wetland restoration potential, while the xeric category was used to represent upland restoration potential.

A distinction was made between tidal and freshwater wetland restoration potential by intersecting the combined mesic and hydric soils polygons with the coastal stratum. Mesic or hydric soils that occur below the 5-foot contour were classified as having tidal wetland restoration potential, while mesic or hydric soils occurring above the 5-foot contour were classified as having freshwater wetland restoration potential.

Within the Tampa Bay region, lands adjacent to waters with average salinity values greater than 18 psu are considered most appropriate for higher salinity mangrove/salt barren restoration, while lands adjacent to waters with average salinity values less than 18 psu are considered most appropriate for lower salinity salt marsh (*Juncus* spp.) restoration (Eleuterius and Eleuterius, 1979). To estimate the relative restoration potential of mangrove/salt barrens and salt marshes, a regional long-term water quality data set was used to create salinity isohalines, which was then binned into two salinity categories: greater and less than an annual mean of 18 psu (Table 1).

All acquired and created GIS layers (Table 1) were converted to 10m x 10m raster data sets and delimited using a previously established watershed boundary. The reservation, restorable, conservation, acquisition, soils, and salinity isohaline layers were then merged to create a comprehensive set of maps and matrices of all possible combinations of opportunity areas. Within an ArcGIS Pro 2.x GIS environment, the SWFWMD 2017 FLUCCS and 2018 submerged data was classified and extracted to the study area into described categories. The dataset was then spatially assigned to existing and proposed restoration areas, reservation areas, soil type, and salinity level.

## Results

### Habitat status and trends

#### Subtidal habitats

[Figure 2](#fig-subtchgdatalluv)

While no trend information is available, the best cumulative estimate of natural hard bottom extent in Tampa Bay is 171 ha (Table 2). Oyster bars covered 69 ha (Table 2) in 2018, and a 30% (6 ha) increase reflected since mapping began in 2014 (Table 3a) probably represents improved ground-truthing and photointerpretation of oyster bar signatures from aerial photography. Twelve artificial reefs in Tampa Bay are managed by Hillsborough, Manatee, and Pinellas Counties. Surface area estimates were not available for the Manatee and Pinellas County reefs, but assuming an average size of 4.2 ha, based on the Hillsborough County reefs, the total coverage of artificial reefs in Tampa Bay is estimated to be approximately 67 ha (Table 2).

Table 1

Total seagrass coverage has increased by 7,027 ha (75%) during the 30-year period of record (Table 3a), and the most current (2018) estimate of total seagrass meadow coverage in Tampa Bay is 16,452 ha. The 2018 coverage of tidal flats and sand other than beaches in Tampa Bay was 6,564 ha (Table 2). A decrease of 4,496 ha (55%) during the 30-year period of record (Table 3a) is associated with the expansion of seagrass to previously non-vegetated bottom area.

#### Intertidal habitats

[Figure 3](#fig-chgdatalluv)

Table 2

Between 1990 and 2017, the suite of emergent tidal wetlands (mangroves, salt barrens, and salt marshes) experienced a net gain of 725 ha (10%, Table 3b). The current estimate of the extent of mangrove forests in Tampa Bay is 6,192 ha. Mangrove forest coverage increased by 684 ha (12%). Salt marshes in Tampa Bay cover 1,844 ha, and coverage increased by 30 ha (2%). However, from 1990 to 2017, it is estimated that a net area of 219 ha of salt marshes converted from salt marsh to mangrove habitat (<https://tbep-tech.github.io/landuse/>). The 2017 estimate of the extent of salt barrens in Tampa Bay is 201 ha, and coverage has increased by 14 ha (7%) during the 27-year period of record (Table 3b). Based on GIS data from Janicki Environmental and Mote Marine Laboratory (Janicki Environmental, Inc. and Mote Marine Laboratory, 2016, 2020), the extent of tidal creek habitat in the Tampa Bay watershed is approximately 623 km (Table 2). No trend analysis is available.

#### Supratidal habitats

[Figure 3](#fig-chgdatalluv)

Table 2

As determined in the 2017 land use/land cover update, the most current estimate of the extent of non-coastal native upland habitats in the Tampa Bay watershed is 56,899 ha, and the extent of “coastal uplands” (defined as below the 5-foot contour) in the Tampa Bay watershed is 1,465 ha (Table 2). Over the 27-year period of record, the suite of native upland habitats has experienced a net loss of 37,051 ha (39%, Table 3b).

The 2017 extent of freshwater wetlands in the Tampa Bay watershed was 88,917 ha (Table 2). Of this total, forested freshwater wetlands comprised 61,565 ha (69%), while non-forested freshwater wetlands comprised 27,351 ha (31%). From 1990-2017, the suite of freshwater wetlands experienced a net gain of 2,444 ha (3%, Table 3b). There has been a 5,335 ha (24%) increase in vegetated non-forested freshwater wetlands since 1990, while forested freshwater wetlands have decreased by 2,891 ha (4%).

### Habitat restoration

A total of 460 projects were documented between 1971 and 2019 (Table 4), addressing the full range of habitat types, including Estuarine (n=228), Freshwater (n=53), Uplands (n=119), and Mixed (n=60). A total of 1,978 ha have been restored, and 12,930 ha and 42.8 km of linear projects were enhanced during the time period. Forty lead partners were documented as responsible for the projects, although some of these lead partners are departments within the same overall agency. Eighty-nine living shoreline projects, seawall enhancements, and oyster reef module installations along shorelines were inventoried, with a linear footprint of 18.2 km.

### Habitat restoration opportunities

[Figure 4](#fig-oppmap)

In 2017, 1,555 km2 of land (26.5%) in the Tampa Bay watershed above the MLLW line was classified as natural and 2,144 km2 (37%) was considered restorable. Developed areas in the Tampa Bay watershed encompassed 2,172 km2 (36.5%) of the 5,872 km2 watershed area. Between 2014 and 2017, the developed footprint increased by seven percent (7%, Fig 2).

The Tampa Bay watershed included a total of 1,260 km2 of existing conservation lands, either publicly owned or in conservation easements. However, excluding subtidal areas owned by the State of Florida results in a total of 816 km2 of conservation lands, about 13.9% of the watershed area occurring above the MLLW line. (Fig 3). Proposed conservation lands in the Tampa Bay watershed total 1,254 km2. The mapped proposed conservation lands generally link eastward and provide wildlife connectivity to the larger-scale Florida Wildlife Corridor (Fig 3).

Reservation lands, from the MLLW line landward to elevation 5-feet (NAVD 88), currently (2017) include 4,622 ha proposed for conservation in the Tampa Bay watershed, with 3,303 ha of native habitats and 1,319 ha of restorable habitats (Fig 1).

Xeric soils were roughly aggregated in an east-west band through the middle of the watershed (Fig 4). Approximately 2,107 km2 was classified as xeric, while 3,760 km2 was classified as mesic/hydric.

[Figure 5](#fig-restmap)

Integration of all of the opportunity layers provides a summary of the available restoration for the TBEP habitats of interest (Table 5). The “Native Habitats” columns show the total current extent as well as the portion of the current extent occurring on existing conservation lands and proposed conservation lands, respectively. The “Restorable Habitats” columns show the total restoration opportunity as well as the portion of the total restoration opportunity on existing and proposed conservation lands. The majority of restoration opportunities on existing conservation lands are for native uplands and freshwater wetlands (Table 5). However, there are approximately 627 ha of emergent tidal wetland restoration opportunities on existing conservation lands, including 530 ha applicable to higher salinity mangrove forests and salt barrens, and 16 ha applicable to lower salinity salt marsh (e.g., *Juncus roemerianus*) restoration and creation.

The best estimates of total restoration opportunities for urban shorelines and tidal tributaries are provided by the Tampa Bay Living Shoreline Suitability Model (LSSM) prepared by the Florida Fish and Wildlife Conservation Commission (Boland and O’Keife, 2018). There is 2,566 km of shoreline in Tampa Bay, and approximately 33% is recommended for living shoreline enhancement.

### Establishment of goals and targets

Recommended targets were based on habitat status and trends, habitat restoration data, identified restoration opportunities, and current and anticipated trends in development, available funding, and regulations (Hilderbrand et al., 2005; Hobbs, 2007).

The targets and goals (Table 6) identify where the 2017 CCMP Bay Habitat goals and strategies and the 2021-2025 Strategic Plan (Burke and Amaral, 2020) thriving habitats and abundant wildlife programmatic priorities can be implemented. However, it also recognizes that the identified habitat protection and restoration areas will change over time, and will be revisited on a 10-year recurring cycle. A 30-year planning horizon (2050) is also identified based upon sea level rise projections developed specifically for Tampa Bay (Burke et al., 2019). The coastal stratum (from the existing mean low water line to the approximate 5-foot contour) is projected to directly experience the effects of sea level rise by 2050, and is the primary focus area for coastal habitat protection and restoration activities. Land acquisition or protection (through conservation easements or other mechanisms) will be needed to ensure completion of targets and goals for both salt marsh and upland habitats (Fig 3).

Targets that maintain current coverage (“hold-the line strategies”) were identified for habitats that appear to currently be sustained at acceptable levels. Evolving information such as an Oyster Habitat Suitability Index (Boswell et al., 2012) and ongoing mapping exercises will be used to identify optimal locations to conduct restoration activities that help achieve targets and goals. Coordination with the establishment of state-mandated minimum flows (Munson et al., 2007) will be necessary for restoration and maintenance of low-salinity salt marsh habitats that will experience higher salinities and rapid transition to mangroves under existing sea level rise scenarios (Sherwood and Greening, 2014; Geselbracht et al., 2015).

## Discussion

Because of multiple stressors such as encroaching development and climate change, habitat protection and restoration priorities should be tempered and “reality tested” by what is actually possible today, and what is possible in the future. Many native and potentially restorable habitats are limited, and there will always be restrictions on the financial resources that can be dedicated to public conservation land acquisition and habitat restoration activities.

This replicable method for setting restoration targets and goals provides a systematic attempt to identify habitat protection and restoration targets that are based on what is actually achievable within those limitations. It focuses on existing opportunities for all habitat types, and what is realistically possible in the future, rather than attempting to mimic previous ecological conditions.

### Habitat trends

When viewed as a whole, the most significant and meaningful trends in the TBEP habitats of interest over the periods of record examined include: 1) the 75 percent gain in seagrasses since 1988; 2) the slight gains in emergent tidal wetlands (10%) and freshwater wetlands (2%) since 1990; and 3) the 39% loss in native upland habitats since 1990.

The intertidal zone in Tampa Bay is currently experiencing dynamic change, driven by sea level rise and climate change, whereby mangrove forests are outcompeting salt marshes and salt barrens for the available niche space. Without increasing the total area of the intertidal zone, restoring a greater coverage of mangroves would reduce the niche space available for salt marshes and salt barrens. This phenomenon has been observed throughout the Gulf of Mexico, and has been attributed to both climate change (e.g., fewer freeze events) and sea level rise (Comeaux et al., 2012).

The observed gains in wetlands (Table 3b) are likely a reflection of: 1) the effectiveness of state and federal wetland regulatory programs; and 2) the cumulative gains resulting from, primarily, publicly-funded habitat restoration projects (Table 4). Minor gains in some emergent tidal wetlands (e.g., salt barrens) may also be a reflection of the landward expansion of the complex suite of these habitats associated with climate change and sea level rise. Gains in vegetated non-forested freshwater wetlands are related to the clearing of forested wetlands followed by the creation of herbaceous mitigation areas and stormwater systems.

The decrease in native uplands (Table 3b) is the result of continued development in the Tampa Bay watershed, combined with the lack of regulatory protection of native uplands. Attaining the target and goal will require concerted restoration of native upland habitats on existing conservation lands, as well as new conservation lands to offset the continued loss of these habitats to development, and amendments to existing planning, zoning and land development policies or regulations. While federal and state regulations related to listed species management impart some protection to certain rare habitats, such as scrub jay (*Aphelocoma coerulescens*) habitat, common and historically abundant native habitats, such as pine flatwoods, are left largely unprotected. Unless local governments in the Tampa Bay watershed improve local protections for native uplands, such as strengthening language within comprehensive plans and development ordinances, this trend will likely continue.

### Habitat restoration

Increases observed in tidal and freshwater wetlands are primarily due to publicly-funded habitat restoration projects, state and federal wetland regulatory programs, and to a lesser extent, regulatory mitigation. While restoration activities date to 1971, few projects were completed prior to 1990, and from 1990-2010, an annual mean of 68 ha of habitat was restored. Over the past decade (2010-2019), this rate of restoration project completion has increased to over 81 ha/yr. Assuming that funding levels remain in the same range as the past decade, this annual mean can be used to set reasonable limits on restoration potential and targets.

While existing development areas are not considered feasible for major habitat restoration activities at this time, there are many opportunities to enhance and restore habitat functions and improve coastal resilience in urbanized locations. Examples include the construction of living shorelines, placement of submerged habitat modules along developed urban shorelines and seawalls, and creation of backyard habitats. Tidal tributary restoration could also entail improvements including removal of salinity barriers and filling of dredged channel sections with low dissolved oxygen.

Four major types of disturbed sites around the Tampa Bay coastline have been identified as priority estuarine habitat restoration sites by TBEP stakeholders over the past two decades, including dredged holes, filled and spoil disposal areas, abandoned aquaculture ponds; and coastal borrow pits and stormwater ponds. Substantial opportunities also exist for upland restoration on reclaimed mined lands within the watershed.

There is a general consensus among restoration practitioners and natural resource managers that habitat restoration and management is most cost-effective on publicly-owned conservation lands and provides long-term benefits. Furthermore, given current development trends in the Tampa Bay watershed, public acquisition of remaining critical lands (e.g., coastal uplands, river floodplain wetlands) is a high priority, and some restoration targets (e.g., salt marshes) will not be feasible without additional public acquisition or public-private partnerships (Holl and Howarth, 2001; Benson et al., 2018). Therefore, varied approaches to leverage resources, including traditional grants, partner funding, and use of volunteers for habitat restoration are recommended to maximize the potential for successful target and goal achievement.

### Rolling easements, mitigation, and restoration consortium

As discussed, land acquisition for coastal habitat restoration must prioritize adjacent low-lying coastal uplands to serve as buffers to accommodate future landward migration of tidal wetlands in response to sea level rise. Where public acquisition is not possible, other conservation mechanisms need to be explored. Coastal setbacks, buffers, or public easements are traditionally used to restrict development within a given distance from the shoreline. A rolling easement is a dynamic mechanism that “rolls” landward as sea levels rise and cause tidal encroachments onto low-lying coastal uplands (Titus et al., 2009). The application of rolling easements in Tampa Bay could disincentivize more intense urban development (e.g., discourage up-zoning) of low-lying coastal uplands that may be currently in less intense agricultural or recreational (e.g., golf courses) land uses. Under a rolling easement, landowners would be able to maintain current economic uses, while “reserving” such lands to accommodate tidal wetland migration with advancing sea level rise.

Wetland impacts and associated compensatory mitigation projects authorized under wetland regulatory programs have historically been conducted independent of watershed-level planning and monitoring processes. This disconnect has contributed to fragmented implementation and inconsistent compliance monitoring of mitigation projects, as well as historically poor documentation of wetland losses and gains in the Tampa Bay watershed. However, if properly focused and comprehensively coordinated, compensatory mitigation activities could significantly contribute to the attainment of wetland habitat restoration goals and targets for the Tampa Bay estuarine system and its contributing watershed.

TBEP will form a public-private partnership to provide the framework for the development of a coordinated approach linking regulatory (compensatory mitigation) and resource management (publicly funded habitat enhancement, restoration, and establishment) programs in the watershed. The creation of the Habitat Management Consortium is expected to provide benefits such as optimizing and improving the cost-effectiveness of habitat protection, restoration and mitigation activities in the watershed.

### Conclusion

The establishment of targets and goals considering climate change, development, land availability, and past achievements, expands the restoration palette to a more comprehensive list of habitats within the system. If successfully implemented, the 2050 goals would total over 4,000 ha of habitat restoration throughout the Tampa Bay watershed. Land acquisition will be an important component of successful completion of different targets and goals, including the salt marsh restoration target for the first ten years. Land acquisition will also provide new opportunities for outdoor access, given that these projects often have a public recreation component.

Our new approach will continue to engage multiple partner agencies, non-governmental organizations, and private citizens in the successful implementation of the restoration plan. Emphases will include recognition of land types particularly vulnerable to climate change or development stressors and these needs will be communicated to restoration partners. Consistent education, targeted funding opportunities, and reporting will also ensure that these newly established targets and goals lead to successful restoration projects, land acquisition, and enhanced ecosystem services.

## Figures

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| Figure 1: Spatial analysis workflow used to identify opportunity areas and restoration potential in the Tampa Bay watershed. Workflows are divided into binning of land use/land cover categories into relevant habitat types and spatial overlay of datasets to identify the opportunity areas. |

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| Figure 2: Change analysis of habitat categories in the subtidal strata of the Tampa Bay watershed. The left column shows relative areas in 1988 and the right column shows relative areas in 2018 for each habitat category. The grey lines show the proportional change of each habitat category between the years. |

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| Figure 3: Change analysis of habitat categories in the intertidal and supratidal strata of the Tampa Bay watershed. The left column shows relative areas in 1990 and the right column shows relative areas in 2017 for each habitat category. The grey lines show the proportional change of each habitat category between the years. |

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| Figure 4: Opportunity areas for habitat conservation and reservation in the Tampa Bay watershed. Green indicates existing conservation, blue indicates proposed conservation, and pink indicates reservations opportunities. Each category is also grouped into native and restorable habitats. |

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| Figure 5: Habitat restoration potential in the Tampa Bay watershed. Areas are identified as those where habitat restoration could target the four identified categories as coastal uplands, freshwater wetlands, native uplands, or tidal wetlands. Categories are based on the opportunity areas and soil types. |

## Tables

**Table**:Change over time in hectares for subtidal habitats in Tampa Bay. Columns show years with available data and the final two columns show the change and percent change from 1988 to 2018. Oyster bars were not meaningfully quantified prior to 2014.

| Habitat Type | 1988 | 1990 | 1992 | 1994 | 1996 | 1999 | 2001 | 2004 | 2006 | 2008 | 2010 | 2012 | 2014 | 2016 | 2018 | 1988 to 2018 | % change |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Seagrasses | 9,307 | 10,086 | 10,299 | 10,609 | 10,758 | 9,920 | 10,417 | 10,795 | 11,309 | 11,862 | 13,171 | 13,874 | 16,153 | 16,701 | 16,293 | 6,986 | 75 |
| Tidal Flats | 8,700 | 8,207 | 8,272 | 8,117 | 8,199 | 10,878 | 10,300 | 11,601 | 11,387 | 10,878 | 9,617 | 8,714 | 5,976 | 5,557 | 6,569 | -2,130 | -24 |
| Oyster Bars | - | - | - | - | - | - | - | - | - | - | - | - | 52 | 65 | 67 | - | - |

**Table**:Change over time in hectares for intertidal and supratidal habitats in Tampa Bay. Columns show years with available data and the final two columns show the change and percent change from 1990 to 2017.

| Stratum | Habitat Type | 1990 | 1995 | 1999 | 2004 | 2007 | 2011 | 2014 | 2017 | 1990 to 2017 | % change |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Intertidal |  |  |  |  |  |  |  |  |  |  |  |
|  | Mangrove Forests | 5,472 | 5,808 | 5,793 | 6,318 | 6,300 | 6,299 | 6,266 | 6,276 | 804 | 15 |
|  | Salt Barrens | 189 | 194 | 199 | 197 | 185 | 203 | 199 | 203 | 14 | 7 |
|  | Salt Marshes | 1,814 | 1,795 | 1,798 | 1,877 | 1,874 | 1,863 | 1,939 | 1,861 | 47 | 3 |
| Supratidal |  |  |  |  |  |  |  |  |  |  |  |
|  | Coastal Uplands | 2,055 | 2,122 | 2,014 | 1,672 | 1,515 | 1,498 | 1,999 | 1,446 | -609 | -30 |
|  | Developed | 150,724 | 159,180 | 171,066 | 193,986 | 203,438 | 209,081 | 214,710 | 217,047 | 66,324 | 44 |
|  | Forested Freshwater Wetlands | 64,573 | 63,766 | 62,726 | 63,109 | 62,258 | 62,081 | 63,562 | 61,667 | -2,906 | -5 |
|  | Native Uplands | 93,076 | 83,850 | 75,313 | 64,482 | 61,277 | 60,319 | 62,794 | 57,836 | -35,239 | -38 |
|  | Non-Forested Freshwater Wetlands | 22,037 | 20,831 | 20,710 | 23,662 | 26,363 | 27,893 | 27,972 | 27,358 | 5,320 | 24 |
|  | Open Water | 15,523 | 17,397 | 19,000 | 19,394 | 22,405 | 22,422 | 23,485 | 23,955 | 8,432 | 54 |
|  | Restorable | 231,288 | 232,195 | 228,531 | 212,549 | 201,609 | 195,529 | 184,342 | 189,512 | -41,777 | -18 |

**Table**:Summary of habitat restoration opportunities in the Tampa Bay watershed. Summaries are based on 2017 land use data, 2018 subtidal data, best estimates for habitat types not in existing GIS layers (e.g., living shoreline), and current extent of existing and proposed conservation lands.

|  | | Native Habitats | | | Restorable Habitats | | |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Stratum | Habitat Type | Current Extent | Existing Conservation Lands | Proposed Conservation Lands\* | Total Restoration Opportunity\*\* | Existing Conservation Lands Restoration Opportunity | Proposed Conservation Lands Restoration Opportunity\* |
| Subtidal | | | | | | | |
|  | Hard Bottom | 171 ha | 171 ha | N/A | N/A | N/A | N/A |
|  | Artificial Reefs | 88 ha | 88 ha | N/A | N/A | N/A | N/A |
|  | Tidal Flats | 6,569 ha | 6,569 ha | N/A | I/D | I/D | N/A |
|  | Seagrasses | 16,293 ha | 16,293 ha | N/A | 5,719 ha | 5,719 ha | N/A |
|  | Oyster Bars | 67 ha | 67 ha | N/A | I/D | I/D | N/A |
| Intertidal | | | | | | | |
|  | Living Shorelines | 18 km | LSSM | N/A | LSSM | N/A | N/A |
|  | Mangrove Forests | 6,276 ha | 4,516 ha | 1,604 ha | 1,044 ha | 521 ha | 522 ha |
|  | Salt Barrens | 203 ha | 177 ha | 25 ha |
|  | Salt Marshes | 1,861 ha | 881 ha | 917 ha | 527 ha (JU) | 102 ha (JU) | 424 ha (JU) |
|  | Tidal Tributaries | 622 km | N/A | N/A | LSSM | N/A | N/A |
| Supratidal | | | | | | | |
|  | Coastal Uplands | 1,446 ha | 722 ha | 664 ha | 513 ha | 128 ha | 385 ha |
|  | Non-Forested Freshwater Wetlands | 27,358 ha | 4,761 ha | 10,353 ha | 63,705 ha | 11,034 ha | 52,671 ha |
|  | Forested Freshwater Wetlands | 61,667 ha | 24,052 ha | 22,399 ha |
|  | Native Uplands | 57,836 ha | 27,083 ha | 21,256 ha | 17,637 ha | 5,419 ha | 12,217 ha |
| N/A - Not Applicable; I/D - Insufficient Data; LSSM - Living Shoreline Suitability Model; JU - Potential*Juncus* Marsh Opportunity | | | | | | | |
| \*All lands identified for acquisition by partners, does not represent a 2030 target or 2050 goal | | | | | | | |
| \*\*Does not account for lands neither currently protected nor currently under consideration for acquisition | | | | | | | |

Table 4: Targets

## References

Arnell, N. W., Halliday, S. J., Battarbee, R. W., Skeffington, R. A., and Wade, A. J. (2015). The implications of climate change for the water environment in England. *Progress in Physical Geography* 39, 93–120. Available at: <https://doi.org/10.1177/0309133314560369>.

Ash, T., and Runnels, R. (2005). Hard bottom habitats an overview of mapping and monitoring needs on epibenthic communities in Tampa Bay, Florida. in *Proceedings of the tampa bay area scientific information symposium (BASIS 4)*, ed. S. F. Treat (St. Petersburg, Florida: Tampa Bay Estuary Program), 179–182.

Ávila-García, D., Morató, J., Pérez-Maussán, A. I., Santillán-Carvantes, P., Alvarado, J., and FA., C. (2020). Impacts of alternative land-use policies on water ecosystem services in the rio grande de comitan-lagos de montebello watershed, mexico. *Ecosystem Services* 45. Available at: <https://doi.org/10.1016/j.ecoser.2020.101179>.

Benson, C. E., Carberry, B., and Langen, T. A. (2018). Public-private partnership wetland restoration programs benefit species of greatest conservation need and other wetland-associated wildlife. *Wetlands Ecology and Management* 26, 195–211. Available at: <https://doi.org/10.1007/s11273-017-9565-8>.

Bertness, M. D. (1985). Fiddler crab regulation of *spartina alterniflora* production on a New England salt marsh. *Ecology* 66, 1042–1055.

Boland, C. D., and O’Keife, K. (2018). Living shoreline suitability model for Tampa Bay: A GIS approach. Gulf of Mexico Alliance, Habitat Resources Priority Issue Team.

Boswell, J. G., Ott, J. A., Birch, A., and Cobb, D. (2012). *Oyster habitat restoration plan*. Punta Gorda, Florida: Charlotte Harbor National Estuary Program.

Brinson, M. M., Christian, R. R., and Blum, L. K. (1995). Multiple states in the sea-level induced transition from terrestrial forest to estuary. *Estuaries* 18, 648–659.

Burke, M. C., and Amaral, M. (2020). Tampa Bay Estuary Program: Strategic plan 2021-2025. Tampa Bay Estuary Program, St. Petersburg, Florida Available at: <https://drive.google.com/file/d/11xohuoaHDxNHRqgXoOHdI37FpWvac_rn/view?usp=sharing>.

Burke, M., Carnahan, L., Hammer-Levy, K., and Mitchum, G. (2019). Recommended projections of sea level rise for the Tampa Bay region (update). Tampa Bay Estuary Program, St. Petersburg, Florida Available at: <https://drive.google.com/file/d/1c_KTSJ4TgVX9IugnyDadr2Hc0gjAuQg2/view?usp=drivesdk>.

Calil, J., Beck, M. W., Gleason, M., Merrifield, M., Klausmeyer, K., and Newkirk, S. (2015). Aligning natural resource conservation and flood hazard mitigation in california. *PLoS One* 10, e0132651. Available at: <https://doi.org/10.1371/journal.pone.0132651>.

Cavanaugh, K. C., Dangremond, E. M., Doughty, C. L., Williams, A. P., Parker, J. D., Hayes, M. A., et al. (2019). Climate-driven regime shifts in a mangrove-salt marsh ecotone over the past 250 years. *Proceedings of the National Academy of Sciences* 116, 21602–21608. Available at: <https://doi.org/10.1073/pnas.1902181116>.

Cavanaugh, K. C., Kellner, J. R., Forde, A. J., Gruner, D. S., Parker, J. D., Rodriguez, W., et al. (2014). Poleward expansion of mangroves is a threshold response to decreased frequency of extreme cold events. *Proceedings of the National Academy of Sciences* 111, 723–727. Available at: <https://doi.org/10.1073/pnas.1315800111>.

Chung, M. G., Dietz, T., and Liu, J. (2018). Global relationships between biodiversity and nature-based tourism in protected areas. *Ecosystem Services* 218, 11–23. Available at: <https://doi.org/10.1016/j.ecoser.2018.09.004>.

Cicchetti, G., and Greening, H. (2011). Estuarine biotope mosaics and habitat management goals: An application in Tampa Bay, FL, USA. *Estuaries and Coasts* 34, 1278–1292.

Coen, L. D., Brumbaugh, R. D., Bushek, D., Grizzle, R., Luckenbach, M. W., Posey, M. H., et al. (2007). Ecosystem services related to oyster restoration. *Marine Ecology Progress Series* 341, 303–307.

Comeaux, R. S., Allison, M. A., and Bianchi, T. S. (2012). Mangrove expansion in the Gulf of Mexico with climate change: Implications for wetland health and resistance to rising sea levels. *Estuarine, Coastal and Shelf Science* 96, 81–95. Available at: <https://doi.org/10.1016/j.ecss.2011.10.003>.

Conner, W. H., Doyle, T. W., and Krauss, K. W. (2007). *Ecology of tidal freshwater forested wetlands of the southeastern United States*. Dordrecht, Netherlands: Springer Available at: <https://doi.org/10.1007/978-1-4020-5095-4>.

CSA Ocean Sciences (2019). Tampa Bay hard bottom mapping project. Tampa Bay Estuary Program, St. Petersburg, Florida.

Dontis, E. E., Radabaugh, K. R., Chappel, A. R., Russo, C. E., and Moyer, R. P. (2020). Carbon storage increases with site age as created salt marshes transition to mangrove forests in tampa bay, florida (USA). *Estuaries and Coasts* 43, 1470–1488. Available at: <https://doi.org/10.1007/s12237-020-00733-0>.

Duarte, C. M., Conley, D. J., Carstensen, J., and Sánchez-Camacho, M. (2009). Return to Neverland: Shifting baselines affect eutrophication restoration targets. *Estuaries and Coasts* 32, 29–36. Available at: <https://doi.org/10.1007/s12237-008-9111-2>.

Dupont, J. M. (2008). Artificial reefs as restoration tools: A case study on the West Florida shelf. *Coastal Management* 36, 495–507. Available at: <https://doi.org/10.1080/08920750802395558>.

Eisma, D. (1998). *Intertidal deposits: River mouths, tidal flats, and coastal lagoons*. London: CRC Press Available at: <https://doi.org/10.1201/9780138750308>.

Eleuterius, L. N., and Eleuterius, C. K. (1979). Tide levels and salt marsh zonation. *Bulletin of Marine Science* 29, 394–400.

Environmental Protection Agency (1996). Watershed approach framework. Office of Water (4501F).

Enwright, N. M., Griffith, K. T., and Osland, M. J. (2015). Incorporating future change into current conservation planning - evaluating tidal saline wetland migration along the U.S. Gulf of Mexico coast under alternative sea-level rise and urbanization scenarios. U.S. Geological Survey Available at: <https://dx.doi.org/10.3133/ds969>.

Enwright, N. M., Griffith, K. T., and Osland, M. J. (2016). Barriers to and opportunities for landward migration of coastal wetlands with sea-level rise. *Frontiers in Ecology and the Environment* 14, 307–316. Available at: <https://doi.org/10.1002/fee.1282>.

Ermgassen, P. S. E. zu, Spalding, M. D., and Grizzle, R. E. (2013). Quantifying the loss of a marine ecosystem service: Filtration by the eastern oyster in U.S. estuaries. *Estuaries and Coasts* 36, 36–43.

Florida Department of Transportation (1999). *Florida land use, cover and forms classification system*. Third. Tallahassee, Florida: FDOT Surveying; Mapping Office Geographic Mapping Section.

Garner, K. L., Chang, M. Y., Fulda, M. T., Berlin, J. A., Freed, R. E., Soo-Hoo, M. M., et al. (2015). Impacts of sea level rise and climate change on coastal plant species in the central California coast. *PeerJ* 3, e958. Available at: <https://doi.org/10.7717/peerj.958>.

Geselbracht, L. L., Freeman, K., Birch, A. P., Brenner, J., and Gordon, D. R. (2015). Modeled sea level rise impacts on coastal ecosystems at six major estuaries on Florida’s Gulf Coast: Implications for adaptation planning. *PLoS ONE* 10, e0132079. Available at: <https://doi.org/10.1371/journal.pone.0132079>.

Gregory, R., Ohlson, D., and Arvai, J. (2006). Deconstructing adaptive management criteria for applications to environmental management. *Ecological Applications* 16, 2411–2425.

Griffen, L., and Greening, H. (2005). Tampa Bay dredged hole habitat assessment project. Tampa Bay Estuary Program, St. Petersburg, Florida.

Heck, K., Hays, G., and Orth, R. (2003). Critical evaluation of the nursery role hypothesis for seagrass meadows. *Marine Ecology Progress Series* 253, 123–136.

Henningsen, B. (2005). The maturation and future of habitat restoration programs for the Tampa Bay estuarine ecosystem. in *Proceedings of the tampa bay area scientific information symposium (BASIS 4)*, ed. S. F. Treat (St. Petersburg, FL: Tampa Bay Estuary Program), 165–170.

Hilderbrand, R. M., Watts, A. C., and Randle, A. M. (2005). The myths of restoration ecology. *Ecology and Society* 10, 19.

Hobbs, R. J. (2007). Setting effective and realistic restoration goals: Key directions for research. *Restoration Ecology* 15, 354–357.

Holl, K. D., and Howarth, R. B. (2001). Paying for restoration. *Restoration Ecology* 8, 260–267. Available at: <https://doi.org/10.1046/j.1526-100x.2000.80037.x>.

Holling, C. S. (1978). *Adaptive environmental assessment and management*. Chichester, UK: John Wiley & Sons.

Houde, E. D., and Rutherford, E. S. (1993). Recent trends in estuarine fisheries: Predictions of fish production and yield. *Estuaries* 16, 161–176. Available at: <https://doi.org/10.2307/1352488>.

Hsieh, Y. P. (2004). “Dynamics of tidal salt barren formation and the record of present-day sea level change,” in *The ecogeomorphology of tidal marshes*, eds. S. Fagherazzi, M. Marani, and L. Blum (Washington: American Geophysical Union), 231–245.

Hughes, F. M. R., Stroh, P. A., Adams, W. M., Kirby, K. J., Mountford, J. O., and Warrington, S. (2011). Monitoring and evaluating large-scale, ’open-ended’ habitat creation projects: A journey rather than a destination. *Journal for Nature Conservation* 19, 245–253. Available at: <https://doi.org/10.1016/j.jnc.2011.02.003>.

Iwamura, T., Possingham, H. P., Chadés, I., Minton, C., Murray, N. J., Rogers, D. I., et al. (2013). Migratory connectivity magnifies the consequences of habitat loss from sea-level rise for shorebird populations. *Proceedings of the Royal Society B: Biological Sciences* 280. Available at: <https://doi.org/10.1098/rspb.2013.0325>.

Jaap, W. C., and Hallock, P. (1990). “Coral reefs,” in *Ecosystems of florida*, eds. R. L. Myers and J. J. Ewel (Orlando, Florida, USA: University of Central Florida Press), 574–618.

Janicki Environmental, Inc. and Mote Marine Laboratory (2016). Southwest florida tidal creeks nutrient study, final report submitted to the Sarasota Bay Estuary Program. Tampa Bay Estuary Program, St. Petersburg, Florida.

Janicki Environmental, Inc. and Mote Marine Laboratory (2020). Southwest Florida tidal creeks: Nutrient management framework and indicator development, final report submitted to the Sarasota Bay Estuary Program. Tampa Bay Estuary Program, St. Petersburg, Florida.

Kaufman, K. (2017). Tampa Bay Environmental Restoration Fund final report: Hard bottom mapping and characterization for restoration planning in Tampa Bay. Tampa Bay Estuary Program, St. Petersburg, Florida.

Kushlan, J. A. (1990). “Freshwater marshes,” in *Ecosystems of florida*, eds. R. L. Myers and J. J. Ewel (Orlando, Florida: University of Central Florida Press), 324–363.

Lamb, D. (2018). Undertaking large-scale forest restoration to generate ecosystem services. *Restoration Ecology* 26, 657–666.

Lewis, R. R., and Robison, D. E. (1996). Setting priorities for Tampa Bay habitat protection and restoration: Restoring the balance. Tampa Bay Estuary Program, St. Petersburg, Florida.

Menéndez, P., Losada, I. J., Beck, M. W., Torres-Ortega, S., Espejo, A., Narayan, S., et al. (2018). Valuing the protection services of mangroves at national scale: The philippines. *Ecosystem Services* 34(A), 24–36. Available at: <https://doi.org/10.1016/j.ecoser.2018.09.005>.

Meyers, R. L., and Ewel, J. J. (1990). *Ecosystems of florida*. Orlando, Florida: University of Central Florida Press.

Moore, H. B., Davies, L. T., Fraser, T. H., Gore, R. H., and López, N. R. (1968). Some biomass figures from a tidal flat in Biscayne Bay, Florida. *Bulletin of Marine Science* 18, 261–279.

Munson, A. B., Delfino, J. J., and Leeper, D. A. (2007). Determining minimum flows and levels: The Florida experience. *Journal of the American Water Resources Association* 41, 1–10. Available at: <https://doi.org/10.1111/j.1752-1688.2005.tb03712.x>.

National Oceanic and Atmospheric Administration (2015). *Guidance for considering the use of living shorelines, final guidance document prepared by the NOAA living shorelines workgroup*. Silver Spring, Maryland: National Oceanic; Atmospheric Administration.

Nerem, R. S., Beckley, B. D., Fasullo, J. T., Hamlington, B. D., Masters, D., and Mitchum, G. T. (2018). Climate-change driven accelerated sea-level rise. *Proceedings of the National Academy of Sciences* 115, 2022–2025. Available at: <https://doi.org/10.1073/pnas.1717312115>.

O’Keife, K. W., Arnold, D., and Reed, D. (2006). Tampa Bay oyster bar mapping and assessment: Final report to Tampa Bay Estuary Program. Tampa Bay Estuary Program, St. Petersburg, Florida.

Odum, W. E., and McIvor, C. C. (1990). “Mangroves,” in *Ecosystems of florida*, eds. R. L. Myers and J. J. Ewel (Orlando, Florida: University of Central Florida Press), 517–548.

Osland, M. J., Spivak, A. C., Nestlerode, J. A., Lessmann, J. M., Almario, A. E., Heitmuller, P. T., et al. (2012). Ecosystem development after mangrove wetland creation: Plant-soil change across a 20-year chronosequence. *Ecosystems* 15, 848–866. Available at: <https://doi.org/10.1007/s10021-012-9551-1>.

Palmer, M. A. (2009). Reforming watershed restoration: Science in need of application and applications in need of science. *Estuaries and Coasts* 32, 1–17. Available at: <https://doi.org/10.1007/s12237-008-9129-5>.

Price, R., Loy, D., and Robison, D. (2017). Critical coastal habitat assessment: Baseline monitoring report. Tampa Bay Estuary Program, St. Petersburg, Florida.

Raabe, E., Roy, L. C., and McIvor, C. (2012). Tampa Bay coastal wetlands: Nineteenth to twentieth century tidal marsh-to-mangrove conversion. *Estuaries and Coasts* 35, 1145–1162. Available at: <https://doi.org/10.1007/s12237-012-9503-1>.

Raulerson, G., Hershorin, A., Karlen, D., MacDonald, T., and Tyler-Jedlund, A. (2019). Tampa Bay dredged hole assessment and management recommendations: 2019 synthesis report, final report prepared for the Tampa Bay Environmental Restoration Fund. Tampa Bay Estuary Program, St. Petersburg, Florida.

Rayer, S., and Wang, Y. (2020). Projections of Florida population by county, 2020-2045, with estimates for 2019. *Florida Population Studies* 53, 186.

Restore America’s Estuaries (2015). *Living shorelines: From barriers to opportunities*. Arlington, Virginia: Restore America’s Estuaries.

Ries, T., and Scheda, S. (2014). Master plan for the protection and restoration of freshwater wetlands in the Tampa Bay watershed, Florida. Tampa Bay Estuary Program, St. Petersburg, Florida.

Robison, D. E. (2010). Tampa Bay Estuary Program Habitat Master Plan Update. Tampa Bay Estuary Program, Saint Petersburg, Florida.

Robison, D., Ries, T., Saarinen, J., Tomasko, D., and Sciarrino, C. (2020). Tampa bay estuary program: 2020 habitat master plan update. Tampa Bay Estuary Program, St. Petersburg, Florida Available at: <https://drive.google.com/file/d/1Hp0l_qtbxp1JxKJoGatdyuANSzQrpL0I/view?usp=drivesdk>.

Russell, M., and Greening, H. (2015). Estimating benefits in a recovering estuary: Tampa Bay, Florida. *Estuaries and Coasts* 38, 9–18. Available at: <https://doi.org/10.1007/s12237-013-9662-8>.

Scavia, D., Field, J. C., Boesch, D. F., Buddemeier, R. W., Burkett, V., Cayan, D. R., et al. (2002). Climate change impacts on U.S. Coastal and marine ecosystems. *Estuaries* 25, 149–164. Available at: <https://doi.org/10.1007/BF02691304>.

Sheehan, L., Crooks, D., Robison, D., and Tomasko, D. (2016). Tampa Bay blue carbon assessment: Summary of findings. Final report prepared for the Tampa Bay Environmental Restoration Fund (2014) for Restore America’s Estuaries. Tampa Bay Estuary Program, St. Petersburg, Florida.

Sherwood, E. (2008). Tampa bay tidal tributary habitat initiative: Integrated summary document, Tampa Bay Estuary Program tidal tributaries project team. Tampa Bay Estuary Program, St. Petersburg, Florida.

Sherwood, E. T., and Greening, H. S. (2014). Potential impacts and management implications of climate change on Tampa Bay estuary critical coastal habitats. *Environmental Management* 53, 401–415. Available at: <https://doi.org/10.1007/s00267-013-0179-5>.

Sherwood, E., Greening, H., Johansson, J. O. R., Kaufman, K., and Raulerson, G. (2017). Tampa Bay (Florida, USA): Documenting seagrass recovery since the 1980’s and reviewing the benefits. *Southeastern Geographer* 57, 294–319.

Sim, S., and Mesev, V. (2014). Measuring and modeling of urban growth and its impacts on vegetation and species habitats in greater orlando, florida. *International Journal of Geospatial and Environmental Research* 1, 1–5.

Smith, C. S., Puckett, B., Gittman, R. K., and Peterson, C. H. (2018). Living shorelines enhanced the resilience of saltmarshes to Hurricane Matthew (2016). *Ecological Applications* 28, 871–877. Available at: <https://doi.org/10.1002/eap.1722>.

Southwest Florida Water Management District (2014). Photo interpretation key for land use classification.

Southwest Florida Water Management District (2018). Land use land cover data. c1990-2017. Available at: <https://data-swfwmd.opendata.arcgis.com/>.

Southwest Florida Water Management District (2019). Seagrass in 2018. Available at: <https://data-swfwmd.opendata.arcgis.com/datasets/seagrass-in-2018>.

Spalding, E. A., and Hester, M. W. (2007). Interactive effects of hydrology and salinity on oligohaline plant species productivity: Implications of relative sea-level rise. *Estuaries and Coasts* 30, 214–225.

Sprandel, J. A., Gore, D., and Cobb, T. (2000). Distribution of wintering shorebirds in coastal florida. *Journal of Field Ornithology* 71, 708–720.

Stockmann, U., Minasny, B., and McBratney, A. B. (2014). How fast does soil grow? *Geoderma* 216, 48–61. Available at: <https://doi.org/10.1016/j.geoderma.2013.10.007>.

Stout, J. P. (1984). Ecology of irregularly flooded salt marshes of the northeastern Gulf of Mexico: A community profile. National Coastal Ecosystems Team, Division of Biological Services, Research; Development, Fish; Wildlife Service, U.S. Department of the Interior.

Theobald, D. M., Miller, J. R., and Hobbs, N. T. (1997). Estimating the cumulative effects of development on wildlife habitat. *Landscape and Urban Planning* 39, 25–36. Available at: <https://doi.org/10.1016/S0169-2046(97)00041-8>.

Titus, J. G., Hudgens, D. E., Trescott, D. L., Craghan, M., Nuckols, W. H., Hershner, C. H., et al. (2009). State and local governments plan for development of most land vulnerable to rising sea level along the US atlantic coast. *Environmental Research Letters* 4, 044008. Available at: <https://doi.org/10.1088/1748-9326/4/4/044008>.

Tomasko, D., Alderson, M., Burnes, R., Hecker, J., Iadevaia, N., Leverone, J., et al. (2020). The effects of Hurricane Irma on seagrass meadows in previously eutrophic estuaries in Southwest Florida (USA). *Marine Pollution Bulletin* 156, 111247. Available at: <https://doi.org/10.1016/j.marpolbul.2020.111247>.

Vogelmann, J. E., Xian, G., Homera, C., and Tolk, B. (2012). Monitoring gradual ecosystem change using Landsat time series analyses: Case studies in selected forest and rangeland ecosystems. *Remote Sensing of Environment* 122, 92–105. Available at: <https://doi.org/10.1016/j.rse.2011.06.027>.

Wessel, M. R., Leverone, J. R., Beck, M. W., Sherwood, E. T., Hecker, J., West, S., et al. (2022). Developing a water quality assessment framework for southwest Florida tidal creeks. *Estuaries and Coasts* 45, 17–37. Available at: <https://doi.org/10.1007/s12237-021-00974-7>.

Whitehead, P. G., Wilby, R. L., Battarbee, R. W., Kernan, M., and Wade, A. J. (2009). A review of the potential impacts of climate change on surface water quality. *Hydrological Sciences Journal* 54, 101–123. Available at: <https://doi.org/10.1623/hysj.54.1.101>.

Yoskowitz, D., and Russell, M. (2015). Human dimensions of our estuaries and coasts. *Estuaries and Coasts* 38(S1), 1–8. Available at: <https://doi.org/10.1007/s12237-014-9926-y>.