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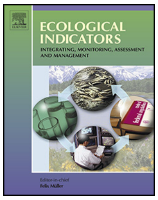

Waterbirds as indicators of ecosystem health in the coastal marine habitats of southern Florida: 1. Selection and justification for a suite of indicator species

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ABSTRACT

The coastal marine environment is currently under threat from many anthropogenic pressures that were identified by the MARES project. Indicators of ecosystem health are needed so that targets can be set to guide protection and restoration efforts. Species of birds that are dependent on coastal habitats are ubiquitous along the coasts of southern Florida. Generally referred to as waterbirds, these species, although not all taxonomically related, share a common dependency on the marine environment for food, nesting habitat, or both. A suite of waterbirds was selected based on their perceived sensitivity to pressures in multiple coastal habitat types. The list of species was refined on the basis of a review of life history for characteristics that might make the species particularly vulnerable. Each selected species was then evaluated for sensitivity to the identified pressures using a hierarchical assessment that took into account the sensitivity, severity, and the temporal and spatial scales of the indicator to the given pressures. The selected suite of indicators was collectively sensitive to all the pressures except one.

1. Introduction

For centuries, humans have used the coastal marine ecosystems of southern Florida for sustenance, recreation, and economic gain. Like many coastal ecosystems around the world, however, burgeoning human populations, overuse of natural resources, and development have had significant impacts on the southern Florida landscape, causing the loss of much of the habitat and living resources that make this region a special and valued place. The National Oceanic and Atmospheric Administration has made a concerted effort to restore and maintain these habitats for the future. Part of that effort was to establish the MARES (MARine and Estuarine goal Setting) project to facilitate ecosystem-based management of southern Florida's coastal marine ecosystems (Fig. 1; http://www.sofla-mares.org). The overall project goal was to reach a scientifically based consensus on the defining characteristics and fundamental regulating processes of southern Florida's coastal resources that are both sustainable and capable of providing the diverse ecosystem services upon which our society depends.

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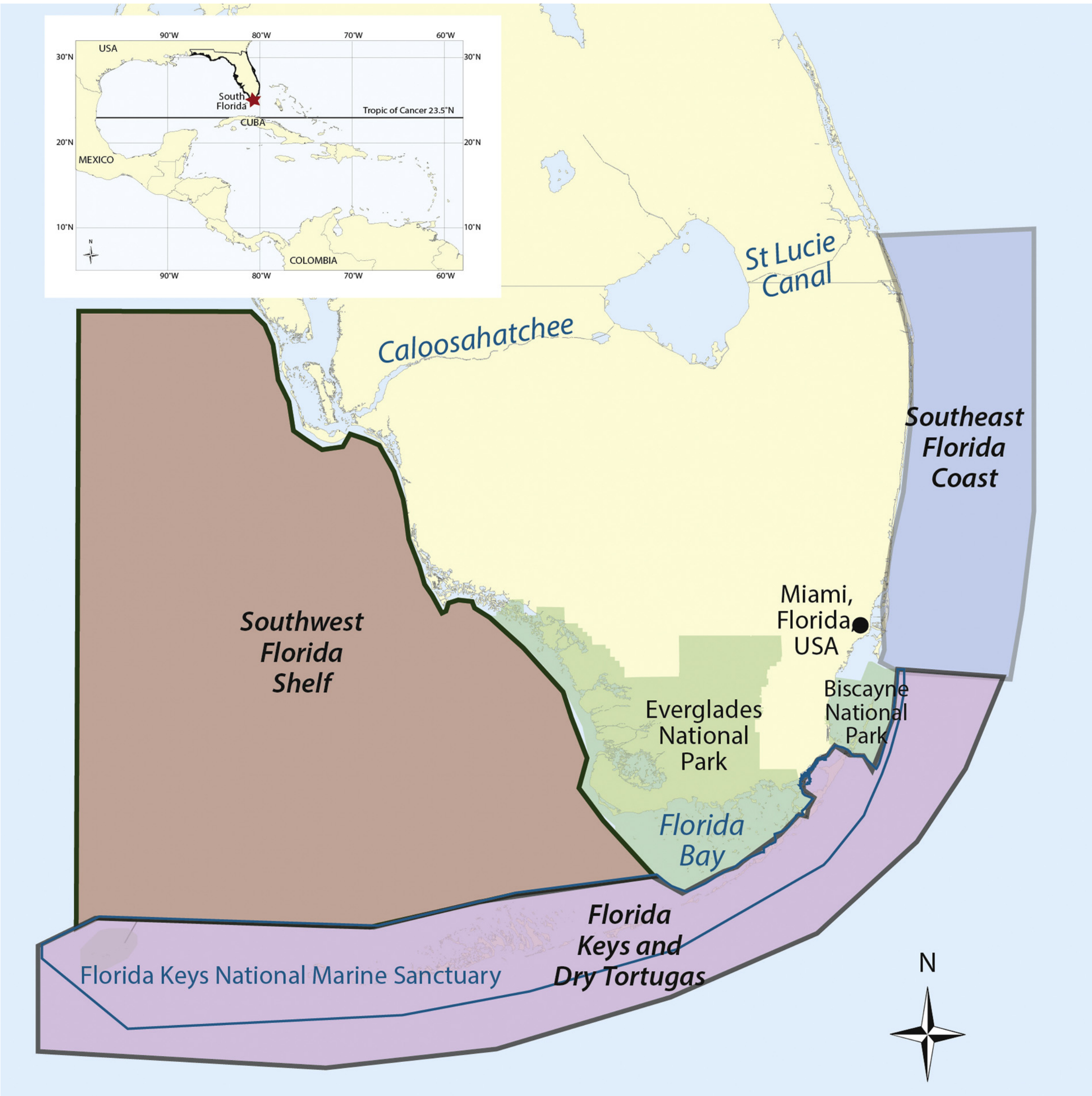

Fig. 1. The MARES domain includes three zones: the Southwest Florida Shelf, Florida Keys and Dry Tortugas, and Southeast Florida Coast.

MARES convened 124 relevant experts (both natural system and human dimensions scientists), stakeholders, and agency representatives in a series of workshops to reach consensus on our understanding of the natural process that make the coastal environments so valuable. The final step in the MARES process was to identify indices of ecosystem health that document trajectories toward (or away from) a sustainable and satisfactory condition.

One of the earliest products from MARES was the identification of drivers and pressures that affect coastal marine habitats in southern Florida (Tables 1 and 2). Drivers are human activities that are the underlying cause of change in the coastal marine ecosystem and reflect human needs. Drivers can be any combination of human and institutional actions or processes. Pressures are the particular manifestations of drivers within the ecosystem and are the physical, chemical, and biological mechanisms that directly cause change in the ecosystem. There is an inherent hierarchical scale consisting of drivers, which are the ultimate expression of human needs and desires, and pressures, which are the proximate factors affecting the ecosystem. For example, human population growth leads to increased energy requirements that are met through the burning of fossil fuels. Burning fossil fuels (Driver) leads to the emission of carbon dioxide (CO_2) into the atmosphere, which is transferred to the ocean, producing ocean acidification that directly affects the ecosystem (Pressure).

Birds have been frequent choices as biological indicators (Caro and O'Doherty, 1999) because they are often high in trophic webs, are important energetic components of ecosystems, show remarkable movement abilities in response to both adversity and opportunity, and are conspicuous and relatively easy to quantify in space and time. However, early efforts to use birds as indicators have met with varying success, and not a little criticism (e.g., Morrison, 1986; Temple and Wiens, 1989; Niemi et al., 1997). While this is partly because of poor definition of terms and goals, and insufficient data linking avian parameters to ecological attributes of interest, there are always important pitfalls in collecting and interpreting data about bird populations. First, it is crucial to distinguish between monitoring birds to understand avian populations, and using birds as indicators of some other attribute

Table 1
Far-field drivers and pressures of greatest importance to the Florida Keys/Dry Tortugas. Drivers are in bold.

Climate change	**All pressures that arise from increasing CO_2**
Ocean acidification Sea-level rise Increasing water and air temperature Altered regional rainfall and evaporation patterns Changes in tropical storm intensity, duration, and/or frequency	
Water-based activities	**Recreation, fishing, tourism, commerce/shipping**
Fishing	Commercial, recreational, and subsistence
Marine Debris	Ghost traps, fishing line, waste
Contaminant releases	Marine spills, pathogen shedding, disease transport
Land-based activities	**Tourism, agriculture, shelter, water management, waste management, and human population**
Changes in freshwater inflow	Quality (nutrient loading, contaminants), quantity, timing, or distribution
Contaminant releases	Septic tanks, fertilizers, industrial waste, construction debris, manufacturing and industrial pollutants (e.g., Mercury from coal plants)

of the ecosystem. The former is laudable but unless linked to specific ecosystem attributes, cannot be used as an indicator of the environment (Temple and Wiens, 1989; Stolen et al., 2005). Second, the linkages of the indicator species must be specifically defined – claims that population change reflects *ecosystem health* or species *are barometers of change* are simply too broad, and mechanistic linkages between avian response (e.g., population size, reproductive success, movement behavior) and ecological parameters must be well developed. Third, mechanistic links need to be validated at the appropriate biological level. Many species of birds may have demonstrated links between food and reproductive success, for example – but the population as a whole may be limited by some other process like disease, hunting or episodic weather events (e.g., Cezilly flamingos). Similarly, there may be important time lags for bird responses, especially at the population level (Newton, 1998; Nagelkerke et al., 2002), and cause and effect therefore have to be linked at the appropriate temporal grain. For many long-lived birds, population response may be inappropriately matched to annual environmental changes, but reproductive or behavioral parameters may be (Montevecchi, 1993; Erwin and Custer, 2000). Finally, a link between an avian species response and an environmental variable may not be of great import if there are no other species similarly affected. Therefore, the ability to infer broader effects from the response of a single species depends strongly on how the ecological parameter of interest relates to other species.

Table 2
Near-field drivers and pressures of greatest importance to the Florida Keys/Dry Tortugas. Drivers are in bold.

Water-based activities	**Recreation, fishing, tourism, commerce/shipping**
Fishing	Commercial, recreational, and subsistence
Groundings	Benthic habitat/community destruction, propeller scars, anchor damage
Dredging	Damage to bottom benthic habitat/community destruction, sedimentation, and altered circulation
Marine debris	Ghost traps, fishing gear, waste
Noise	Boating, military, oil exploration, and drilling
Invasive/nuisance species	For example, lionfish, raccoons, rats, pythons, crows
Contaminant releases	Marine spills, pathogen shedding, disease transport
Land-based activities	**Tourism, agriculture, shelter, water management, waste management**
Alteration of shorelines	Shoreline hardening, increased impermeable surface area, loss of wetlands, dredging
Changes in freshwater inflow	Quality (nutrient loading, contaminants), quantity, timing, or distribution
Contaminant releases	Septic tanks, fertilizers, industrial waste, construction debris, manufacturing and industrial pollutants (e.g., mercury from coal plants)

Clearly, there are good reasons the use of waterbirds as environmental indicators must be approached with caution. However, there are also numerous examples where links between avian status and environmental variation has been effectively demonstrated and applied (Noss, 1990). Waterbirds have been frequently used to monitor the accumulation of contaminants (Erwin and Custer, 2000) and many contaminants have been shown to affect populations of a suite of aquatic species (e.g., DDT, Carson, 1962; PCBs and organochlorines, Fox, 2001). Populations of herons, egrets, ibises, and storks have been shown to respond reproductively to specific hydrological patterns in the Everglades (Ogden, 1994), primarily through availability of prey (Frederick and Spalding, 1994; Gawlik, 2002; Herring et al., 2010). Fish and macroinvertebrates in the Everglades have in turn been shown independently to react to specific hydropatterns with population and community level responses (Trexler et al., 2005; Dorn et al., 2006) thus forming a continuous link at the landscape scale between water management and functional response by avian populations (Frederick et al., 2009). Similarly, reproductive parameters of some seabirds are known to be strongly sensitive to changes in local availability of fish stocks (Wanless et al., 2007) and can become a useful tool in monitoring fisheries (Montevecchi, 1993; Frederiksen et al., 2007; Einoder, 2009).

Birds that are dependent on coastal habitats are ubiquitous along the coasts of southern Florida. Generally referred to as waterbirds, these species derive from several taxonomic groups, and share a dependency on the marine environment for food, nesting habitat, or both. Some generic representatives are Pelecaniformes (wading birds, pelicans, cormorants, and frigate birds), Charadriiformes (shorebirds, gulls, and terns), Anseriformes (waterfowl), and some Falconiformes (osprey and eagles). Waterbirds occur throughout marine habitats of southern Florida, are sensitive to anthropogenic perturbations, and are representative indicators for most habitats encompassed by the MARES program. Because they have highly specialized feeding and nesting behaviors, waterbirds are highly affected by southern Florida's land and water management practices but are also threatened throughout the region by human disturbance to nesting and foraging sites, predation or displacement by introduced species, and marine debris. Furthermore, because of their high trophic position within multi-tiered aquatic food webs, waterbirds are very susceptible to contaminants that bioaccumulate (Bernanke and Köhler, 2009). In addition, aquatic birds must traverse the water surface in order to feed and are, therefore, susceptible to oiling and other effects from land-based run-off and from spills in the marine environment (Kajigaya and Oka, 1999).

Waterbirds are also susceptible to environmental pressures from outside the region of southern Florida. These pressures include the effects of global climate change in the form of loss of nesting and foraging sites due to sea level rise, destruction of nesting habitat by increased tropical storm systems, and by altered rainfall patterns. Atmospheric deposition of contaminants from far-afield such as mercury may affect waterbirds more than other vertebrate species due to the unique role of wetlands in methylating mercury (Wolfe et al., 1998). In addition to serving as excellent indicators of ecosystem health, waterbirds have long been appreciated esthetically and culturally, as evidenced by the fact that people continually advocate and promote actions that protect birds and lead to the enjoyment of birds, as well as having established myriad laws protecting these species.

MARES enlisted the first author (JCO) to develop the waterbird ecosystem indices. In cooperation with the senior author (JJL), species were identified that were representative of as many of the MARES habitat types as possible. The birds selected to represent the various habitats were specialized in their foraging and nesting needs; however, these needs may have been met in multiple MARES habitats. For example, a species may require a certain submerged aquatic vegetation (SAV) type for food, but that SAV may occur in both seagrass beds and interior wetlands. On the other hand, some species are so specialized in their use of habitat that they may stand alone as the indicator for that habitat type. Our goal was to justify the selection of the suite of indicators (this manuscript) and use a companion manuscript to develop Conceptual Ecological Models that demonstrate the overall effect on various habitats. Well into this process, the lead author was diagnosed with and succumbed to a rapidly developing form of cancer. The senior author then enlisted the help of the remaining authors to complete the original task. Collectively, these authors have more than 300 years of scientific experience studying waterbirds and/or conducting ecosystem studies in southern Florida. Our consensus was that the species selected well represented the identified habitats. The species selected are considered to be (1) good indicators of the representative pressures on waterbirds in southern Florida estuaries and marine habitats and (2) representative of the major coastal habitat types in this same region, i.e., these species represent the waterbirds within each habitat type that are most affected by the pressures. Although one indicator, wintering shorebirds, represents a group of species, we use the term *species* for all indicators for simplicity.

The objectives of this paper were to: (1) identify potential indicator species for the coastal habitats of southern Florida and provide the background to justify their use and (2) evaluate the impact of environmental pressures on these indicators using a hierarchical numerical assessment as proposed by Altman et al. (2011). The description of ecosystem responses to the pressures that affect these species as well as an assessment of the usefulness of the species is presented in a companion manuscript.

2. Aspects of species life histories that justify their use as indicators

2.1. Reddish egret (*Egretta rufescens*)

The reddish egret is a non-migratory resident of coastal Florida that breeds in winter and spring (dry season), and reportedly disperses widely during the summer and fall (Lowther and Paul, 2002), however, satellite tracking of individuals in the lower keys indicated that at least this group was largely sedentary (KDM, unpublished data). The state of Florida classified the reddish egret a “threatened species” because of the species’ small population size, restricted range, limited habitat, and declining population trends in portions of its range (Butler et al., 2000; Florida Fish and Wildlife Conservation Commission, 2011a). Reddish egrets forage visually for small fish such as sheepshead minnow (*Cyprinodon variegatus*), longnose killifish (*Fundulus similis*) and several other species of killifish, mullet (*Mugil curema*, *M. cephalus*), pinfish (*Lagodon rhomboides*), tidewater silverside (*Menidia peninsulae*), and sailfin molly (*Poecilia latipinna*) that school in shallow water over intertidal flats in estuaries, gulf beaches, or saline ponds (Paul, 1991; Lowther and Paul, 2002). They generally nest in mangroves on islands isolated from terrestrial predators, preferring dense thickets of larger trees over water (Lowther and Paul, 2002). The flight distance between the nesting colony and foraging sites ranges from nearby the nest to ± 25 km (Paul, 1991; Lowther and Paul, 2002; Hodgson et al., 2006; Hodgson and Paul, 2010, 2011).

The reddish egret is one of the few herons found characteristically in open marine habitats and coastal marine lagoons (Butler et al., 2000) and occurs only rarely in freshwater habitats (Lowther and Paul, 2002), mainly as immature birds dispersed after the breeding season. They forage on broad “bank” systems and tidally exposed sand or mud “flats” that are generally barren or sparsely covered with submerged aquatic vegetation, often found inside or surrounding mangrove islands. Feeding occurs in hypersaline pools, salterns, and lagoons and in shallow tidal streams, cuts, and pools that have hard, unvegetated bottoms (particularly in the Florida Keys; Butler et al., 2000; Lowther and Paul, 2002). Water depth over the intertidal flats is a controlling factor as egrets pursue small fish in shallow water less than 15 cm deep (Lowther and Paul, 2002). Selection for such distinctive, narrowly distributed foraging habitat may constrain the small, resident population in Florida Bay and the Florida Keys, where intraspecific aggression on foraging sites appears to be relatively high (KDM, unpublished data). Since much of the historic habitat has been lost to dredge-and-fill urban development (Strong and Bancroft, 1994) a return to historic numbers seems unlikely.

Reddish egrets were extirpated from Florida by hunting for the millinery trade in the late 1800s and early 1900s. The Florida population experienced a very slow increase since a single nest was located in Florida Bay in 1937, but has attained only about 10% (about 250–300 breeding pairs) of the state’s pre-1880s estimated population (Desmond, 1939; Green, 2006; Florida Fish and Wildlife Conservation Commission, 2011a; Hodgson and Paul, 2011; Kushlan, 2012). Fragmented regional population estimates, mostly for Florida Bay and the upper Florida Keys, exist, and our current estimate of nesting effort within the MARES domain is approximately 75–100 nesting pairs (10–15 along the southeast coast, 50–60 in the Florida Keys/Dry Tortugas, and 15–25 along the southwestern shelf).

2.2. Roseate spoonbill (*Platalea ajaja*)

The state of Florida has classified the roseate spoonbill as a “threatened species” because of the bird’s small population and restricted range (Florida Fish and Wildlife Conservation Commission, 2011b). Roseate spoonbills feed on small fish, e.g., sheepshead minnow, mosquitofish (*Gambusia holbrooki*), sailfin mollies, and killifish (Fundulids), and on prawns (Palaemonetes) (Dumas, 2000). Spoonbills are tactile foragers, and are most successful at capturing prey when prey densities are comparatively high, as occurs with dropping tides or drying wetlands that concentrate prey into the deeper remaining ponds and creeks (Dumas, 2000; Lorenz, 2013a). Compared to reddish egrets, which often nest in similar locations and habitats, spoonbills often forage at greater distances from nesting colonies, and do more foraging at inland wetland sites (e.g., spoonbills nesting in Florida Bay often feed well inland in the drying Everglades). The average flight distance between nesting colony and feeding sites was 12 km in a Florida Bay study, with a maximum distance of 65 km (Powell and Bjork, 1989). Spoonbills breed in winter and spring in Florida (dry season) and can disperse widely during the summer and fall (JJL, unpublished banding and tracking data).

The roseate spoonbill occurs primarily in mangrove-dominated wetlands fringing the southern and central Florida mainland (Dumas, 2000). Almost all spoonbill nesting colonies are on islands, usually dominated by mangroves. Spoonbills forage in shallow marine, estuarine, or freshwater sites, including tidal pools, estuarine and freshwater sloughs, mudflats, mangrove-fringed creeks, and along the estuarine-freshwater ecotone of the southern Everglades (Powell et al., 1989; Lorenz, 2000).

The roseate spoonbill was almost extirpated in Florida during the early decades of the 20th century. By 1935, the only known nesting colony anywhere in the state was about 15 pairs on Bottle Key in Florida Bay (Allen, 1942). The population slowly increased from that low point to about 100 pairs by the late 1940s and reached a peak in Florida Bay of 1250 pairs in 18 nesting colonies in the late 1970s (Powell et al., 1989). Beginning in the 1980s, the number nesting in Florida Bay substantially declined from the peak, to less than 100 nests in 2010 (Lorenz et al., 2002; Lorenz and Dyer, 2011). This decline has been attributed to water management practices that lowered the overall productivity of the spoonbill's primary foraging grounds (Lorenz, 1999, 2000, 2013b; Lorenz et al., 2002; Lorenz and Serafy, 2006).

2.3. Great white heron (*Ardea herodias occidentalis*)

The great white heron is a subspecies of the great blue heron (*Ardea herodias*) and is not currently protected as an imperiled species at the state or federal level, despite its small and declining population size, and its being a unique evolutionary element within the species. Hunter et al. (2006) identified the great white heron as the highest priority wading bird for management attention in the Southeast. In fact, it qualified for "Critical Recovery", the highest action level in the Southeast United States Regional Waterbird Conservation Plan (Hunter et al., 2006) at both the regional and continental levels, due to its small population size and highly localized occurrence. The great white heron has a very small global distribution limited to extreme southern Florida, coastal areas of southwestern Cuba, Puerto Rico, and the Yucatan Peninsula, and coastal islands of Venezuela (Robertson and Woolfenden, 1992; Stevenson and Anderson, 1994; Powell, 1996). Within its U.S. range, great white herons breed primarily within Florida Bay and the Florida Keys, although some nests have been noted on the west-central Florida coast. The Florida population may constitute the largest portion of the breeding birds of this species in the world. Long thought to be a color morph of the great blue heron, it is now recognized that both white and blue morphs within Florida Bay and the Keys are genetically distinct from great blue herons elsewhere on the Florida peninsula and in the USA (McGuire, 2001). Though some great white herons may move seasonally into peninsular Florida, mainland-resident individuals are thought to occur only in the coastal embayments south of Tampa and Merritt Island on the Gulf and Atlantic coasts, respectively.

Unlike the nominate race of *A. herodias*, the great white heron seems to be an obligate coastal and estuarine specialist. It occurs only rarely in freshwater habitats, and freshwater seems to be used primarily by juvenile or dispersing birds (Powell and Bjork, 1990). Juveniles in freshwater habitat had low foraging success and very poor survival. Breeding occurs on mangrove-dominated islands in coastal areas primarily within Florida Bay and the lower Keys. Multiple nests may be on a single island, but large distances between nests (>50 m) are typical, and solitary nesting is common. Foraging is in shallow, expansive seagrass and marl flats in marine or estuarine salinities, with small (c. 52 ha) feeding areas used repeatedly and often defended from other herons. Their main prey are fish, particularly toadfish (Batrachoididae), red porgy (*Pagrus* spp.), pipefish (Syngnathidae), and needlefish (*Strongylura* spp.) (Stevenson and Anderson, 1994), which they hunt using slow walking or sit-and-wait tactics in shallow, clear water. They have a clear preference for expansive grass flats (92% of observations) relative to availability of this habitat (Meyer and Kent, 2011). Patchy, discontinuous stands of seagrass do not attract herons, suggesting that large size and continuous cover are the characteristics of grass flats that support heron feeding. Feeding during breeding season is in shallow areas of seagrass and mud flats, usually within several kilometers of nests (Meyer and Kent, 2011).

During the early 1960s, the breeding population in Florida Bay was estimated at 800–900 breeding pairs or 1600–1800 breeding individuals (Powell et al., 1989, Robertson and Woolfenden, 1992). Intermittent surveys between 1959 and 1984 indicated that the population remained fairly constant at about 2000–2300 individuals (Powell et al., 1989). Hurricanes (e.g., Donna in 1960 and Betsy in 1965) resulted in large-scale mortality in this species, but the population was resilient and recovered quickly (Powell et al., 1989). However, a three-year study of great white herons in the early 1980s indicated that nest production was much lower than similar records collected in 1923 (Powell and Powell, 1987). Powell and Powell (1987) also found that birds that received supplemental food from humans had similar production rates to those of 1923 while those that were not supplemented had much lower production. They concluded that foraging habitat quality had been reduced. Complete nest counts have not been performed since 1984, however, monitoring within Florida Bay and the Everglades suggests that in the mid-1990s numbers of great white herons fell below 2000 individuals and, since then, they have continued to decline (Cook and Call, 2006). No annual count has exceeded 500 since 2000.

2.4. Brown pelican (*Pelecanus occidentalis*)

The brown pelican is an important indicator of the health of near-shore fish populations, and any decrease in populations or nesting activity may be an indication of an imbalance in that ecosystem (Florida Fish and Wildlife Conservation Commission, 2011c). Brown pelicans eat only fish, which they capture by diving headfirst into the water – with bill and pouch extended (the only pelican to have this foraging technique; Schreiber, 1978; Fogarty et al., 1981; Shields, 2002). Common prey in Florida are menhaden (*Brevoortia* spp.), threadfin and other herring (*Opisthonema* spp.), mullet, drum (Sciaenidae) and pinfish.

The brown pelican is the only exclusively estuarine/marine species of pelican in the world (Shields, 2002) and is ubiquitous along the coast of southern Florida. The species forages at the surface, primarily in waters that are less than 150 m in total depth along coasts usually within 20 km from shore (Shields, 2002). Pelicans most often nest on small to medium-sized mangrove islands or spoil islands that are separated by open water from adjacent land and roost on similar islands and on sand or mud embankments (often exposed only at low tides).

Brown pelicans in southern Florida did not experience the severe population declines that were caused by pesticide contaminants in the north-central and western Gulf of Mexico during the 1950s and 1960s (Kushlan and Frohling, 1985). Florida breeding populations have been approximately stable since the 1960s (Florida Fish and Wildlife Conservation Commission, 2011c; Sauer et al., 2011). In contrast, the population in the MARES domain is declining. Complete surveys of the breeding population in Florida Bay from 1977 to 1982 declined from 849 nests to 447 (Kushlan and Frohling, 1985). In 1993 only 350 nests were found (Ogden, 1993) and in 2007 only about 150 were observed (LDO unpublished data) throughout the bay. Prior to the early 1980s, pelicans commonly nested in northeastern Florida Bay (Ogden, 1993; J. Ogden, personal observation), however, in surveys of nesting colonies in this region from 1995 to 2009, pelicans only nested in 5 years with less than 50 nests in each of the years (LDO, unpublished data). Furthermore, nesting throughout Florida Bay has become rare, with multi-year gaps between nesting activity, and nesting activity through 2012 was almost completely isolated to the western portion of the bay (JJL, personal observation; LDO, unpublished data). Kushlan and Frohling (1985) hypothesized that the reason for an observed decline in nesting in Florida Bay from 1977 to 1982 was a reduction in prey availability. Although the pelican prey base was not investigated, changes in fish community structure as a result of water diversion may support their hypothesis (Lorenz, 2013b). More recently, in the lower Florida Keys, the number of pelican nesting colonies has declined from three traditional sites to one and the remaining colony dropped from 110 nests in 1991 to 13 in 2010 (Tom Wilmers, U.S. Fish and Wildlife Service, personal communication). In addition, boater disturbance at nesting sites may be significant. Another major mortality and injury factor for pelicans is encounters with fishing gear (Schreiber, 1978; Schreiber and Mock, 1988; Shields, 2002; Forrester and Spaulding, 2003). Because pelicans are visual predators, they often focus on injured or outlying members of a school of fish, which commonly leads to mistaking fishermen's' baited hooks or artificial lures as prey. Additionally, pelicans attempting to eat fileted skeletal carcasses of bigger fish discarded by fishermen suffer from choking, tearing of the gular pouch, or intestinal puncture resulting in peritonitis. Habituation to people feeding them also increases the likelihood that birds will forage near fishermen (Sachs et al., 2013).

2.5. *Osprey (Pandion haliaetus) and Bald Eagle (Haliaeetus leucocephalus)*

The osprey and bald eagle are two of the most recognized and well-studied top avian predators associated with aquatic environments. Populations of both species have been used as 'sentinel' bio-indicators of ecosystem health, due to the expanse of life history information available, coupled with known reproductive responses to a variety of natural and anthropogenic pressures (Bowerman et al., 2002; Grove et al., 2009; Henny et al., 2010). Operating at high trophic levels, these raptors share many ecological similarities and frequently overlap in distribution in southern coastal Florida.

Ospreys feed almost entirely on fish, which they capture by steep, swift dives into the water, with talons extended. Common prey are benthic species feeding in shallow water. In coastal southern Florida, these include at least sea catfish (*Arius felis*), mullet, drums (*Pogonias cromis* and *Sciaenops ocellatus*), jack crevalle (*Caranx hippos*), and spotted sea trout (*Cynoscion nebulosus*) (Ogden, 1977; Poole et al., 2002). Bald eagles are opportunistic predators and scavengers that prefer live fish, given a choice. Diets are typically composed of fish (56%), birds (28%), mammals (14%), and other (2%) across their range (Buehler, 2000). In Florida Bay, nesting eagles had a diet of fish (77%) and birds (21%), with few mammalian or reptilian prey (JDB, unpublished data). They forage on the same fish species as ospreys, and eagles will routinely kleptoparasitize osprey (Ogden, 1975; Buehler, 2000).

In southern coastal Florida, both ospreys and eagles are winter breeders, laying eggs primarily between November and early January, which is earlier than elsewhere in Florida (Ogden, 1977; Baldwin et al., 2012). Osprey nesting in coastal regions from approximately southern Collier County and southern Biscayne Bay, south through Florida Bay and the Florida Keys, are non-migratory (Poole et al., 2002; Lott, 2006; Florida Fish and Wildlife Conservation Commission, 2013). North of this region, ospreys appear to participate in the regular, seasonal migrations characteristic of all other North American osprey (Ogden, 1977; Martell et al., 2004; Florida Fish and Wildlife Conservation Commission, 2011d). Telemetry studies indicate that juvenile bald eagles of central Florida also make regular seasonal migrations (Mojica et al., 2008); however, those hatched in Florida Bay may be non-migratory (B.K. Mealey, Institute of Wildlife Sciences, personal communication).

Ospreys are commonly associated with coastlines and lake shores. Three key requirements for good osprey nesting habitat are (1) an adequate supply of fish no greater than 10–20 km from the nest sites, (2) extensive areas of shallow water, 0.5–2.0 m deep, and (3) open structured nest sites free of mammalian predators (Poole et al., 2002). In southern Florida, ospreys often nest in tall mangroves on the mainland, but also in low, scrubby mangrove associated trees on islands, as well as on any elevated, artificial platform that meets the above requirements (e.g., utility poles, channel markers, etc.). Osprey in the Florida Keys may have become dependent on artificial platforms as nesting structures (Florida Fish and Wildlife Conservation Commission, 2013); they often use cell towers or tall light structures associated with urban development. In the southern coastal areas of Florida, bald eagle nest sites are located principally on the coast or near shore keys within 50 m of open water, almost exclusively (96.9%) in black (*Avicennia germinans*) and red (*Rhizophora mangle*) mangroves (Curnutt and Robertson, 1994; U.S. Fish and Wildlife Service, 2007). While ospreys will frequently nest using man made structures, bald eagles in general do not in the MARES domain. Within the region of Everglades National Park, ospreys and bald eagles nest primarily on islands adjacent to the mainland coast that are characterized by close proximity to shallow mud banks and seagrass flats, which offer the best foraging opportunities and have relatively low occurrences of mammalian predators (Fleming et al., 1989; OLB, personal observation). Because they have strong nest site fidelity and their nesting status is readily observable and easily detected by aerial/ground/boat surveys, the osprey and bald eagle are valuable and efficient sentinels of ecosystem integrity.

Although ospreys across the U.S. showed great sensitivity to pesticide contaminants during the 1950s–1960s (Poole et al., 2002; Henny et al., 2010), only low exposure rates were detected among ospreys in southern Florida during this period (Ogden, 1977). The statewide nesting population was estimated at 2500–3000 pairs in 1994 (Poole et al., 2002), and it has likely increased to 3500–4000 pairs (Florida Fish and Wildlife Conservation Commission, 2013). In contrast, surveys of ospreys nesting in Florida Bay showed about 200 pairs during the late 1960s/early 1970s (Ogden, 1977), and a 58% decline by the early 1980s (Kushlan and Bass, 1983). Florida Bay presently has only about 60 pairs of nesting ospreys (OLB, unpublished data). A more recent decline in nesting ospreys along the Florida Keys also appears to be occurring (OLB, personal observation). A similar trend is seen with bald eagles, as breeding pairs have increased by >300% statewide in the past 25 yrs, approaching 1500 (Florida Fish and Wildlife Conservation Commission, 2012a,b, 2008). In contrast, the number of nesting pairs of bald eagles in extreme southern Florida coastal areas, although stable from the 1960s to the early 1990s, declined more recently, with breeding territory occupancy decreasing by 43% in Florida Bay (Baldwin et al., 2012). The decline in both osprey and bald eagle populations in southern coastal Florida is consistent with a pattern of declines by other top-of-the-food-chain, fish-eating birds throughout this region and believed to be caused by an overall lack of biological productivity (Lorenz, 2013b).

2.6. *Least tern (Sternula antillarum)*

Migrant least terns occur in Florida between April and July and have localized distributions on coastal beaches on both the Gulf and Atlantic coastlines in Florida (Thompson et al., 1997; Hodgson et al., 2006; Hodgson and Paul, 2010; Florida Fish and Wildlife Conservation Commission, 2011e). Least terns nest on the ground in colonies with typically 10–150 nests. Historically, most nesting colonies were located on sparsely vegetated (<20% vegetation cover) sand or shell beaches, dried mudflats, on dredged-material spits and islands, or on gravel rooftops (Thompson et al., 1997) located close to foraging locations. Birds readily relocate colony sites between years in response to disturbance or loss of habitat, such as vegetation succession or alteration, but sites in longer use tend to have higher levels of nesting success (Thompson et al., 1997).

Least terns feed almost entirely on small surface-schooling fish (a high percentage is sardines, etc., or *Gambusia holbrooki* in fresh water), which they capture by diving from an aerial hover into the shallow water surface (Thompson et al., 1997). Most foraging occurs in bays, lagoons, estuaries, river mouths, and tidal marshes near nesting colonies.

North American least tern populations were greatly reduced during the early 20th century by hunting for the millinery trade, but statewide populations increased after laws were enacted to end the hunting of birds (Thompson et al., 1997; Florida Fish and Wildlife Conservation Commission, 2011e). Dowling (1973) and Fisk (1978a,b) included southeast Florida in their surveys but their lists of colonies were not comprehensive. In the Atlantic zone (Indian River County through Dade County) an estimate of ≥1437 breeding pairs was recorded in 29 active colonies, of which 93% were located on roofs (Zambrano et al., 1997). On the Dry Tortugas, least terns have nested since at least the 1850s, peaking in the early 1900s at perhaps 1000 birds (Dutcher, 1908). Nesting ceased in the 1940s, beginning again in 1973 (Kushlan and White, 1985), but has been depauperate recently. Surveys of Florida Bay, alone, reported that about 600 least tern young were produced in the early 1940s (National Audubon Society, unpublished data). The nesting population appeared to increase in the Florida Keys in the 1960s–1970s as a result of new nesting habitat being created in the form of gravel rooftops and land fills. Kushlan and White (1985) estimated 1400 adults in a 1976 census throughout the Keys. In 1987, 37 colonies containing ≥689 breeding pairs were located from Key Largo to Key West (Hovis and Robson, 1989). In the southwest zone, historic information is not available, but recent data (this decade) suggests local colonies have been generally stable (FWC Florida Shorebird Database, 2013).

There are around 95 historic rooftop nesting colonies in the MARES region (southeast zone 41, Keys zone 32, and southwest zone 22; Florid Fish and Wildlife Conservation Commission, 2012b). Rooftops are currently estimated to support over 80% of the statewide breeding population, estimated at about 12,500 pairs from 1998–2000 (Gore et al., 2007). The concentration of tern nesting colonies on rooftops represents a significant shift from the late 1970s when it was estimated that only 21% of the state's least terns nested on rooftops (Fisk, 1978a,b; Zambrano and Warraich, 2012). As gravel rooftops are being replaced by a new technology of rubberized roof materials and human use of beaches increases, least tern nesting options are being reduced throughout their range in Florida. Declines in southern Florida's least tern population are due to low reproductive success, decrease in available nesting sites, increased predation, and vulnerability to stochastic events. Florida's population has a high probability of extinction within the next 100 years (Florida Fish and Wildlife Conservation Commission, 2011e). Resultantly, the state of Florida has classified the least tern as a "threatened species" (Florida Fish and Wildlife Conservation Commission, 2011e).

2.7. American oystercatcher (*Haematopus palliatus*)

The American oystercatcher is a large shorebird that is classified by the state of Florida as a "threatened species" and has been proposed as a 'sentinel' bio-indicator of ecosystem integrity because of the depth of life history information available, its specialized dependence on oysters and associated marine invertebrates, and known reproductive responses to a variety of natural and anthropogenic pressures (Nol and Humphrey, 1994; Rodgers et al., 1996; Brown et al., 2005; Florida Fish and Wildlife Conservation Commission, 2003, 2011f). Florida has a resident breeding population of the east coast and Gulf of Mexico subspecies (*H. p. palliatus*), and a large wintering population (Hodgson et al., 2008a; Schulte et al., 2010). As a brightly colored, iconic shorebird, it is easily identifiable by the public and is broadly distributed on coastal beaches in certain Florida areas (BirdLife International, 2009).

Oystercatchers feed almost entirely on marine bivalves (oysters, clams, mussels and some similar marine invertebrates), which they capture on oyster bars, mud flats and in salt marshes. They reside only in coastal areas that support intertidal shellfish beds. Occupied habitats include undeveloped barrier beaches, sandbars, sand spits at inlets, shell rakes, salt marsh islands, dredged spoil material islands, and oyster reefs. Nest sites are located principally on the coast or nearshore islands within 5 m of open water, almost exclusively on rock or sand beaches (Schulte et al., 2010); however, they occasionally nest on rooftops (Forys, 2010; Zambrano and Warraich, 2012). American oystercatchers breed along the east coast of Florida south to Palm Beach County and on much of the Gulf Coast south to Lee County (Douglass and Clayton, 2004; Burney, 2009; Schulte et al., 2010; Zambrano and Warraich, 2012). Within the MARES domain, they are winter migrants, only, from Collier County south to the Ten Thousand Islands around Cape Romano and uncommonly south to Biscayne Bay (National Audubon Society, 2010, S. Schulte, Manomet Center for Conservation Sciences, personal communication, 3 April 2013).

Because of their narrow niche, oystercatcher populations are believed to have declined in concert with widespread coastal development and increasing coastal disturbance. Cox et al. (1994) assessed as insufficient the habitat base required for long-term stability of American oystercatchers in Florida. The statewide nesting population was estimated at 213 (nesting confirmed) to 391 (total pairs observed) pairs in 2001 (Douglass and Clayton, 2004). The estimate was reduced to 170 breeding pairs statewide in 2010, a 56% loss in 9 years (Brush, 2010). Currently, within the MARES regions, there are fewer than 15 confirmed nesting pairs and 150–200 wintering individuals, mostly along the southwestern coast (Lee County). This species is included as an ecological indicator because of its close affinity with oysters and because the southwest coast is a refuge for wintering oystercatchers. It may have been much more abundant in the Ten Thousand Islands prior to oyster and clam depletion through historic unchecked harvesting from about 1910 to 1947 (McIver, 1989).

2.8. Lesser scaup (*Aythya affinis*) and American coot (*Fulica americana*)

The lesser scaup is a common migratory diving duck (Anseriformes) that nests in the boreal forests of Canada and Alaska and is a common winter resident in Florida. The American coot is a migratory rail (Gruiformes) that is a common to abundant winter resident in Florida and an uncommon to rare breeder during spring and summer. Florida is critical wintering habitat for both species (Chamberlain, 1960; Bellrose, 1980; Turnbull et al., 1986; Austin et al., 1998; Brisbin and Mowbray, 2002; Herring and Collazo, 2005). Scaup and coots winter in large open bodies of water such as fresh to brackish coastal bays and estuaries of the Atlantic and Gulf coasts where they often form rafts of many thousands of individuals. They are important indicator species of these habitats as they are among the most abundant and visible of the wintering waterfowl species (Rodgers, 1974; Johnson and Montalbano, 1989) and are highly mobile and respond rapidly to changes in ecological conditions. Both species are included here because of their contrasting food habits. The lesser scaup feeds primarily on aquatic invertebrates (Stephenson, 1994; Austin et al., 1998) by diving to depths <3 m. Coots are almost exclusively herbivorous, feeding on the leaves, roots and seeds of aquatic plants (e.g., *Ruppia*, *Chara*, *Nitella*) (Brisbin and Mowbray, 2002), by pecking, dabbling, or diving. Coot abundance can be positively correlated with non-native *Hydrilla* (Esler, 1990). In coastal regions, freshwater inflows are critical as scaup tend to use the fresher water areas for foraging and the open estuarine regions for resting (Herring and Collazo, 2004).

The lesser scaup is one of the most abundant and widely distributed of North American ducks (U.S. Fish and Wildlife Service, 1998). The breeding population declined steadily from the 1970s to a record low in 2005 (Austin et al., 2000, 2006), but exhibited a moderate recovery from 2006 to 2012 (Flyways.us, 2012). Population declines are thought to be due to lower reproductive output in the northern breeding areas as a consequence of reduced female survival and changes in food resources in winter, migration, or breeding habitats (Austin et al., 2006). The American coot is the most abundant and widely distributed rail in North America (Brisbin and Mowbray, 2002).

Population declines of scaup and coots in the southern Everglades have been relatively more severe in comparison to their entire ranges, and these declines began decades earlier than the declines elsewhere in Florida. Historically, the southern Everglades were an important winter feeding area for ducks and coots. Audubon warden patrols during the 1930s and 1940s consistently reported scaup, coots, and other species of waterfowl wintering throughout the lakes and bays of the coastal region, often in exceptionally high abundances. For example, 10,000 scaup and 75,000 coots were noted in Coot Bay in 1943, and 10,000 scaup were counted off Flamingo in 1940. However, long-term annual surveys of Coot Bay from 1949 to 2008 show that scaup abundance dropped precipitously in the mid-1950s (Madden et al., 2009). Average numbers changed from about 8800 birds per count during the years 1950–1960, to 42 birds per count, 2001–2010 (National Audubon Society, 2010). Between 1966 and 2010, summer counts of American coots in Florida showed only a 7% decline (Sauer et al., 2011), however, in Southwest Everglades National Park, average numbers from the Coot Bay Christmas Bird Count (CBC) changed from about 8500 birds per count during 1950–1960, to 875 birds per count during 2001–2010 (National Audubon Society, 2010). These declines are likely due to local changes in aquatic community structure and reduced food production as a result of altered hydrologic and salinity regimes (e.g., Frankovich et al., 2011), although broader trends affecting wintering waterfowl, such as climate change and the construction of impoundments in the southeastern USA causing birds to "stop-short" north of the Everglades, might also be important. Nevertheless, a considerable proportion of the North American wintering waterfowl population now overwinter in constructed wetlands in the northern Everglades, including about 8% of wintering American coot (Beck et al., 2013), suggesting that waterfowl populations can recover in the southern Everglades given sufficient food resources.

2.9. Wintering shorebirds

The importance of the habitats that support extremely large numbers of wintering shorebirds in mixed species flocks along the southern Florida coastline is generally not well recognized. Past and future trends of abundance in these species may be an important indicator of overall habitat conditions. At least 26 shorebird species are common users of coastal habitat within the MARES region during winter including: black-bellied plover (*Pluvialis squatarola*), snowy plover (*Charadrius nivosus*), Wilson's plover (*Charadrius wilsonia*), semipalmated plover (*Charadrius semipalmatus*), piping plover (*Charadrius melodus*), killdeer (*Charadrius vociferus*), black-necked stilt (*Himantopus mexicanus*), American avocet (*Recurvirostra americana*), spotted sandpiper (*Actitis macularius*), solitary sandpiper (*Tringa solitaria*), greater yellowlegs (*Tringa melanoleuca*), willet (*Tringa semipalmata*), lesser yellowlegs (*Tringa flavipes*), whimbrel (*Numenius phaeopus*), long-billed curlew (*Numenius americanus*), marbled godwit (*Limosa fedoa*), ruddy turnstone (*Arenaria interpres*), red knot (*Calidris canutus*), sanderling (*Calidris alba*), semipalmated sandpiper (*Calidris pusilla*), western sandpiper (*Calidris mauri*), least sandpiper (*Calidris minutilla*), dunlin (*Calidris alpina*), stilt sandpiper (*Calidris himantopus*), short-billed dowitcher (*Limnodromus griseus*), and Wilson's snipe (*Gallinago delicata*).

These species probe and peck for mollusks, crustaceans, marine worms and aquatic insects in a variety of coastal habitats ranging from dry saltpans and prairies, where their diet may include terrestrial invertebrates and small vertebrates, to mudflats where they probe into the sediment and wade in waters up to 16 cm deep, depending on foraging style, and the length of the species' legs and bill. For example, least sandpiper may feed in water up to 4 cm deep, dunlin in water up to 5 cm deep, while long-billed curlew can use water up to 16 cm deep (Warnock and Gill, 1996; Dugger and Dugger, 2002; Nebel and Cooper, 2008). In general, these birds actively feed during ebbing and low tides and rest during high tides, when shorelines are inundated and foraging habitat is unavailable.

Flocks of mixed shorebird species occur primarily on broad, tidally flooded mud/marl flats along the coast, around the edges of shallow estuarine pools with sparse vegetation, and less often along sandy beaches. Habitat preferences and the composition of mixed flocks differ from zone to zone throughout the MARES region. Shorebirds are dependent on natural cyclical fluctuations in water levels and select feeding locations based on the availability of water depths in the appropriate range for their feeding. Thus, in southern Florida they respond to semi-diurnal, bi-weekly, and annual cycles of water level variation. Variation in water level among locations at points in time enables shorebirds to maintain their energy balance by moving from one location to another. Therefore, many locations are required to maintain shorebird populations wintering in southern Florida.

Tens of thousands of shorebirds winter in coastal southern Florida, however, regional population numbers and trends generally are unavailable. The CBC data acquired variously from 1938 to 2012 are the most comprehensive record of wintering shorebirds throughout coastal areas of southern Florida (National Audubon Society, 2010). Population trends over 25 recent CBC counts, from CBC 88 (winter of 1987–88) through CBC 112 (winter of 2011–12), were analyzed for 15 shorebird species (plovers, sandpipers, and their allies in the Charadriidae and Scolopacidae families) using data from 15 count circles. Six of these species are included in the United States WatchList (American Bird Conservancy, 2010; National Audubon Society, 2012), a project that identifies species of greatest conservation concern. Wilson's plover, red knot, sanderling, semipalmated and western sandpipers are in the Yellow List – species in decline. The piping plover is federally endangered and included in the Red List – species of highest national concern. Although some species have increased in some regions, most of the trends in these species are downward with only one species, least sandpiper, showing increases in all three MARES regions (Table 3). Further analyses of the CBC data for shorebirds were provided as Electronic Supplementary Material.

3. Evaluation of species using a modified Altman hierarchy

Altman et al. (2011) devised a scoring method for evaluating the effect of a pressure on an ecosystem based on the spatial and temporal scale of the impact, the impact's severity, and the resilience of the ecosystem in response to it. To justify the selection of the bird species, we have adapted their zero-to five scaling method (Fig. 2) to evaluate the relationship between pressures and individual bird species (Table 4). Each selected species is an indicator of multiple

Table 3
Trends for wintering shorebirds in south Florida zones from the 1987/88–2011/12 CBCs.

	Atlantic zone	Florida Bay/Keys zone	Southwest zone
Black-bellied plover	−28%	−25%	−25%
Wilson's plover	−58%	−50%	−100%
Semipalmated plover	−39%	−9%	−17%
Piping plover	−42%	−89%	−53%
Snowy plover	X	−100%	−59%
Spotted sandpiper	−22%	+53%	−11%
Willet	−50%	+2300%	+25%
Ruddy turnstone	−37%	−68%	−27%
Red knot	−60%	+260%	−100%
Sanderling	−0.2%	−78%	−34%
Semipalmated sandpiper	X	−65%	X
Western sandpiper	−81%	+16%	+94% (25 CBCs) −100% (10 CBSs[a])
Least sandpiper	+9%	+1350%	+300%
Dunlin	−34%	+3900%	+5000% (25 CBCs) −26% (10 CBCs[a])
Short-billed dowitcher	−98%	−20%	+364% (25 CBCs) −16% (15 CBCs[a])

[a] Most recent Christmas Bird Counts.

driver-pressure pairings that may be affecting a given habitat type, thereby making the species an indicator of that driver-pressure. The effect of a given driver-pressure pair varies among species.

3.1. Ocean acidification

Changes in carbonate chemistry of surface waters related to ocean acidification can alter calcification rates of marine organisms such as crustaceans and mollusks (Doney et al., 2009). This will likely affect marine ecosystems drastically by altering the planktonic base of the food web. Waterbirds will probably be affected at a similar global scale by reducing production of their direct prey or eroding away the base of their food webs. Acidification can also reduce bird habitats directly, such as coral and oyster reefs (Gutierrez et al., 2003). Nearshore water chemistry, however, can counter the effect of acidification (Borges and Gypens, 2010). Nearshore and inshore habitats in southern Florida could be buffered from acidification as a result of south Florida's calcareous limestone bedrock, which is largely exposed. Even if nearshore waters are less affected, it is also possible that changes in community composition of animals and plants in the oceans will affect coastal waterbirds and their prey directly and indirectly. These changes could include both positive and negative interactions of predators, prey and parasites. The net prediction is therefore far from clear. With the exception of oystercatchers, we considered that all the indicators would be mostly resilient to this pressure

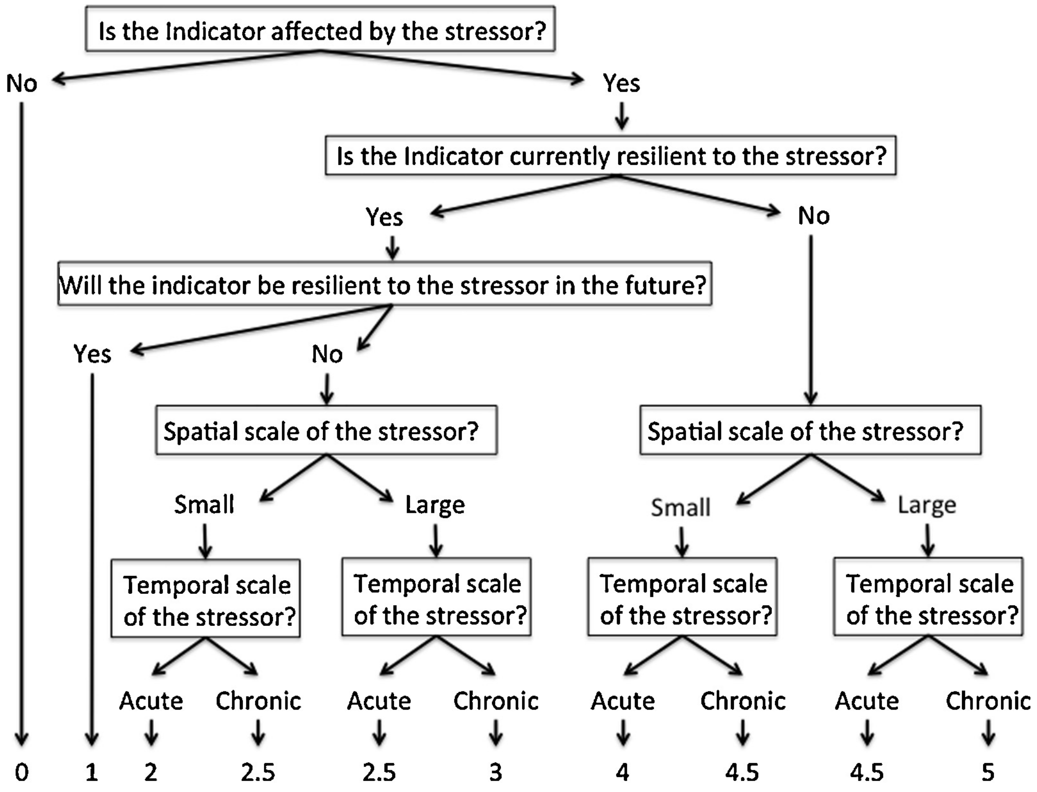

Fig. 2. Decision tree used to quantify the impact of pressures on indicator species.

Modified from Altman et al. (2011).

Table 4
Scoring of the degree of impact each pressure has on each indicator species based on the decision tree (Fig. 2) where 0 is no impact and 5 is the most impacted.

Drivers and pressures	Reddish egret	Roseate spoonbill	Great white heron	Brown pelican	Osprey	Bald eagle	Least tern	Oyster catcher	Lesser scaup	American coot	Wintering shorebirds	Mean	Maximum
Climate change													
Ocean acidification	1	1	1	1	1	1	1	3	1	1	1	1.18	3
Sea-level rise	2.5	2.5	2.5	0	0	0	5	5	2.5	2.5	5	2.50	5
Altered water and air temperature	4.5	4.5	4.5	4.5	2.5	2.5	2.5	2.5	0	0	0	2.55	4.5
Altered regional rainfall and evaporation patterns	3	3	3	1	1	1	1	1	1	1	1	1.55	3
Changes in tropical storm intensity, duration, frequency	3	3	3	3	3	3	3	3	3	3	3	3.00	3
Water-based activities													
Fishing	1	1	1	5	5	5	5	5	0	0	0	2.55	5
Marine debris	1	1	1	5	1	1	1	1	1	1	1	1.36	5
Contaminant releases	5	5	5	5	5	5	5	5	5	5	5	5.00	5
Groundings	0	0	0	0	0	0	0	0	0	0	0	0.00	0
Dredging	1	1	1	1	1	1	4.5	4.5	1	1	1	1.64	4.5
Human disturbance (noise etc.)	4	4	4	4	4	4	4	4	4	4	4	4.00	4
Invasive species	4	4	4	4	2	2	5	5	2.5	2.5	2.5	3.41	5
Land-based activities													
Changes in freshwater inflow	5	5	5	5	5	5	5	5	5	5	5	5.00	5
Alteration or loss of shorelines	4.5	1	4.5	1	1	1	5	5	1	1	4	2.64	5
Mean	2.82	2.57	2.82	2.82	2.25	2.25	3.36	3.50	1.93	1.93	2.32		
Maximum	5	5	5	5	5	5	5	5	5	5	5		

within the MARES domain in the near future due to near shore buffering (Score = 1; note that all scores are summarized in Table 4). In contrast, we determined that oyster reefs are likely to be susceptible to acidification because they lie in more open water and tidally flushed environments, therefore, oystercatchers will be vulnerable (Score = 5), as we believe that oyster reefs will not be resilient to acidification in the future and that the effect will be large scale and chronic.

3.2. Sea-level rise

Global sea level rise is expected to be as much as 0.59 m over the next 75–85 years (IPCC, 2007). This will mean that many of the shallow water habitats that these indicators use will be permanently altered. For example, as sea level rises, mangrove habitat will likely become mud flats (Wanless et al., 1994). Concurrently, however, some acreage of inshore freshwater habitat will become more saline and convert to mangrove habitat. It is unclear what the balance between created and lost habitat will be so it is unclear what the effect will be on most of the indicators. In part of the MARES domain, human development along the coast will not allow landward migration of habitat. From Naples to Homestead, however, the natural habitat landward of the mangrove zone remains largely intact, thereby allowing habitat to migrate upland, thusly maintaining the mosaic of coastal habitats that currently exist. Based on this scenario, the nesting or foraging habitats of eagles, osprey, and pelicans will not be affected by this pressure (Score = 0). Loss of foraging habitat for scaup, coot, and the wading bird species will occur along the developed coastlines, but substantial habitat may remain within what is now the protected area of the Everglades. We consider the spatial scale to be small within the MARES domain and the temporal scale to be chronic (Score = 2.5). Beach nesting and foraging birds will be deeply affected by this pressure since most habitat behind most beaches is heavily urbanized, and beaches are therefore, not likely to be replicated inland as the water rises. The effect on least terns, wintering shorebirds, and oystercatchers will be spatially large and temporally chronic (Score = 5).

3.3. Altered air and water temperatures

The predicted increase in mean temperatures seems unlikely to have any direct effect on the indicators. However, climate models also predict more variable weather patterns for southern Florida (IPCC, 2007, Wang et al., 2010). This suggests an increase in the number and severity of continental cold fronts moving through the MARES domain (Wang et al., 2010), which should have little direct impact on non-nesting migratory species (scaup, coot, and shorebirds; Score = 0). In contrast, severe cold fronts can result in nesting failure. This effect will be spatially large, and the consequences will be acute. Because their winter nesting range extends into cooler climates, we consider least terns, eagles, osprey, and oystercatchers to be fairly resilient (Score = 2.5), while pelicans and the wading birds will be less resilient (Score = 4.5).

3.4. Altered regional rainfall and evaporation patterns

Southern Florida ecosystems are somewhat resilient to this pressure in that these processes are already highly variable (Duever et al., 1994); therefore, most of the indicators will be minimally affected (Score = 1). Wading birds, however, are susceptible to altered rainfall patterns. Under current water management scenarios, wading bird nesting success is vulnerable to rainfall-induced reversals in drying patterns (Lorenz, 2013a) that disperse prey and radically lower foraging efficiency (Gawlik, 2002). If out-of-season rainfall events increase in number or intensity, these indicators will not be resilient over the MARES spatial scale, and the impact will be chronic (Score = 3). Freshwater discharge from the Everglades to the estuaries is highly dependent upon variation in rainfall; thus, reduced rainfall could severely limit estuarine habitat for all species that depend on intermediate salinities, particularly during the dry season. For example, lack of runoff might detrimentally affect habitat of American coots, lesser scaup, oystercatchers, and winter shorebirds. If rainfall extremes become more frequent, more species might be affected more than expected at present.

3.5. Changes in tropical storm patterns

If the heat content of seas in tropical zones increases, more numerous and severe tropical storms and hurricanes are predicted (IPCC, 2007), which could increase the mortality of year-round resident species and damage or eliminate habitat of all species. On the other hand, increased tropical storm activity might create habitat (Wanless et al., 1994; Wanless and Vlaswinkel, 2005). All of the indicators were rated moderately (Score = 3) since this future threat can impact the entire MARES landscape, and alteration of habitats can be considered chronic.

3.6. Fishing

Scaup, coot, and wintering shorebirds are unlikely to be affected by fishing pressures as they are not dependent on commercial and recreational fishery species for food (Score = 0). The remainder of the indicators are piscivorous or depend on fishery species, so they are likely to be impacted at some level by fish harvests (Borboen et al., 2013). The three wading bird species consume smaller fish in shallow water habitat that are unlikely to be harvested by humans, so they may be resilient to this pressure (Score = 1). Pelicans, eagle, osprey, least tern and oystercatcher all depend on species that are currently fishery species or could be fishery species in the future (Borboen et al., 2013). Overfishing has become a major problem around the globe, and this has had direct, measurable impacts on fish-eating birds (Tasker et al., 2000). With an ever-burgeoning human population in southern Florida, it is possible harvesting may become more intense as there will be greater demand for fish products and more people fishing for recreation. Increased demand could directly or indirectly result in depleted fishery stocks for these five species (Score = 5).

3.7. Marine debris

Although marine debris can cause mortality by entangling or through accidental ingestion, this pressure is, and probably will continue to be, a minuscule problem for all indicators (Score = 1) except pelicans. Damage from fishing gear is the leading cause of injury for pelicans that arrive at wild animal rehabilitation centers. Schreiber (1978) estimated that 80 percent of the living pelicans that he examined showed indications of injuries caused by fishing hooks or monofilament lines. These rescues are likely just a small fraction of the pelicans that encounter marine debris, with the majority going unnoticed and resulting in mortality. Schreiber (1978) estimated that 500 pelicans were killed annually in Florida by fishing tackle. With the increase in fishing activity since 1978 (Ault et al., 2008), this problem has likely become even more prevalent than as reported (Schreiber, 1978; Nesbitt, 1996; Shields, 2002) and will likely worsen in the future (Score = 5).

3.8. Contaminant releases

Although the list of contaminants that could potentially damage populations of all of the indicators is extensive, large accidental releases of petroleum products alone elevated the score for all of the indicators (Score = 5). Water birds are highly susceptible to becoming coated with oil, which, without human intervention, invariably results in mortality – usually through thermal imbalance (Jenssen, 1994; Kajigaya and Oka, 1999). Even birds that are cleaned and rehabilitated likely suffer permanent physiological damage (Kajigaya and Oka, 1999) with low likelihood of survival after release (Briggs et al., 1997; Nariko, 1999). Petroleum products can permanently damage water bird habitats and destroy their prey base (Maccarone and Brzorad, 1995). If the Gulf of Mexico loop current had been unfavorable during the 2010 Deep Water Horizon incident, massive amounts of crude oil could have easily been deposited along the MARES coastline, thereby causing irreparable damage to all of the marine habitats (Jackson et al., 1989; Duke et al., 1997).

3.9. Boat groundings

Although grounding can massively damage all shallow water habitats, none of the indicators are susceptible to direct damage from such events (Score = 0).

3.10. Dredging

Dredging can destroy wetlands and alter shorelines, thereby making some localized habitats unsuitable, however, the beneficial use of dredged spoil material also can provide new habitat (Lewis and Lewis, 1978; U.S. Environmental Protection Agency, 2007; Hodgson et al., 2008b). Waterbirds are somewhat resilient to habitat loss in that they can move to a new location if suitable alternative habitat is available. Furthermore, much of the habitat within MARES is now protected against most dredging activities. All of the indicators were scored low (Score = 1), except beach-nesting birds (least tern and oystercatcher), because this pressure is spatially large but temporally acute (Score = 4.5).

3.11. Human disturbance

Noise can flush birds from roosts and nests and cause nest failure and abandonment (Rodgers and Smith, 1991; Carney and Sydeman, 1999; JJL, personal observation). Persistent noise or disturbance might cause non-nesting species to abandon a foraging ground, but they demonstrate resilience by moving to less disturbed sites. But, when human disturbance becomes temporally or spatially ubiquitous, birds may abandon those habitats permanently (York, 1994). With regard to current human population predictions, the MARES domain can be expected to be increasingly impacted by ever-growing recreational boat usage and fishing pressure (York, 1994). Repeated disturbance from increased boating activity on foraging, roosting, and nesting grounds might reduce foraging efficiency, raise stress levels, and bring about nesting failure, and possibly even increase adult mortality (York, 1994). An aerial survey of boater use in the marine waters of Everglades National Park indicated that boater use had increased 250% between the 1970s and 2007 (Ault et al., 2008). The spatial scale would be small and the temporal scale acute based on each individual disturbance for all indicators (Score = 4).

3.12. Exotic and nuisance species

This pressure includes human subsidized nuisance species such as black (*Rattus rattus*) or Norway rats (*Rattus norvegicus*), and raccoons (*Procyon lotor*). Species that nest in the MARES domain are more susceptible to this pressure than non-nesting species. Beach-nesting species (least tern and oystercatcher) are almost constantly under threat of nest disturbance and mortality from dogs, cats, rats, raccoons, and people (Hunter et al., 2002). This type of disturbance is ubiquitous and constant during the nesting season (Score = 5). Colonially nesting species (pelicans and the three wading bird species) tend to nest where they are likely to be isolated from terrestrial predators, however, a single raccoon can disrupt an entire nesting colony (Allen, 1942). This pressure acts on a localized scale and causes acute events (Score = 4). Bald eagles and osprey nest in the MARES domain, however, they nest territorially, so any disruption in nesting will not affect the entire population, therefore they are more resilient (Score = 2). Non-nesting species (scaup, coot and wintering shorebirds) are more resilient in that invasive species are likely to have only a localized impact, but this impact may also be chronic (Score = 2.5). Predation by exotic species is also a potential factor. For example, Burmese pythons (*Python bivittatus*) have been found with myriad avian species, along with eggs, in their guts, which indicates nesting disruption (Perez, 2012).

3.13. Changes in freshwater flow

Changes in freshwater flows to the coasts have been implicated in reducing the food base (Sprandel et al., 1997; Herring and Collazo, 2004; Seavey et al., 2011; Lorenz, 2013b). This affects all the indicator species over the entire MARES domain and has been a chronic problem (Score = 5). Freshwater flows can be changed by variation in rainfall, as well as by human water management and consumption.

3.14. Alteration or loss of shorelines

Beach-nesting birds (least tern, oystercatcher) have a persistent and ongoing problem of having reduced nesting habitat due to humans altering the shoreline and by a recent change to plasticized rubber roof construction materials that precludes roof nesting (Score = 5). Alteration or loss of shoreline has greatly reduced habitat for overwintering shorebirds (Senner and Howe, 1984) across the MARES landscape and may increase with the human population (Score = 4). The wading birds feed in shallow water habitats that have been severely affected by altered shorelines in the past (e.g., Lorenz et al., 2002) however, most of the remaining habitats are largely protected in conservation lands (parks, refuges and sanctuaries) and is unlikely to change going forward (Score = 1). All other species are fairly resilient to this pressure (Score = 1).

4. Discussion

Each indicator received a score for each pressure (Table 4). Only two species had a mean score above 3 but all species scored a 5 for at least one pressure. We proposed a suite of species as indicators of coastal marine habitats of southern Florida since no single species was sensitive to all pressures. Means and maxima for each pressure were, in most cases, less than 3, but at least one species scored a 3 or higher for all but one pressure (groundings). This demonstrates that the suite of indicators selected was representative of, and sensitive to, the pressures of the coastal marine system. Other waterbird species may be added but only if other pressures that begin to impact the system do not affect the current set of indicators.

Three pairs of indicators provided identical scoring for all of the pressures (scaup/coot, osprey/eagle and great white heron/reddish egret). This redundancy might lead falsely to the conclusion that one of each of the pairs should be removed from the suite of indicators to streamline the monitoring effort that is the basis for any adaptive management plan for the coastal marine ecosystems. These species pairs, however, are representative of different elements within the ecosystem or ecosystem functions, thereby requiring some redundancy within the selection and evaluation process. The companion manuscript to this one examines how these species react to the pressures within each ecosystem type by examining relationships that were scored higher than 3 in this manuscript. The justification for using a score of 3 as a threshold is that this was the lowest maximum score for all pressures (other than 0 for groundings). The companion manuscript uses conceptual ecological models to graphically demonstrate the interaction between the pressure on a given ecosystem and how the indicator would respond to positive or negative management decisions that affect the coastal marine environments.

John Ogden justified using waterbirds as ecosystem indicators thusly:

> "The most deeply-rooted link between birds and human values and priorities is the intrinsic appreciation that many people have for almost all birds. This appreciation is not limited to water birds, although large, charismatic water birds undoubtedly are primary beneficiaries of such attitudes. For those of us who grew up in environments where birds were our neighbors, the sight and sound of birds provides familiar and friendly surroundings. As a result, the conservation of birds has a strong advocacy that strengthens the rationale that people value birds highly and consider them important. The desire to promote the wellbeing of birds manifests itself in many ways: the abundance of osprey nesting platforms, the use of pelicans as a symbol of Florida tourism, the number of half-tame great white herons named "George", the popularity of bird rehabilitation centers, the protection of birds provided by the system of national and state parks and national wildlife refuges, the protective legislation for migratory and "plume" birds, the abundance of Audubon chapters and members, the number of bird books and bird feeding stations sold annually, and the promotion of a "Florida Birding Trail". There are many other examples. The Fish and Wildlife Service estimates that there are more than 50 million people in the United States who identify themselves as bird-watchers. These people spent 36 billion dollars on birding-related activities and products in the U.S. in 2006 (Carver, 2009). Questions of "value" for water birds are not so much applicable at the level of individual species (although there certainly are good examples of specific species that are valued) as they are of birds collectively. Collective appreciation far outweighs in overall importance the values placed on individual species. From this perspective, the primary objective of conservation actions should be to recover and sustain the diversity and abundance of the regional avifauna, including water birds. When someone drives the Overseas Highway through the Florida Keys, for example, they want to see abundant numbers of pelicans, egrets, spoonbills, osprey, and other water birds, as they would have historically, as one important indication that all is well in our world. The species of water birds selected as indicators of the southern Florida estuarine avifauna were primarily selected because their abundance and distribution reflects the ecological functionality of the major estuarine habitat of various types and, with it, the well-being of many other water birds in southern Florida estuaries".

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecolind.2014.03.007.

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