



WILDLIFE DATA AS INDICATORS OF ECOSYSTEM HEALTH IN THE MEADOWLANDS

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New Jersey's Hackensack Meadowlands comprise a roughly 30-square-mile mosaic of diverse habitats and represent one of the largest remaining blocks of estuarine wetlands within the New York/New Jersey metropolitan area. The Meadowlands also lie within one of the most densely populated and heavily industrialized regions in the world. The Hackensack River, the region's primary drainage, flows approximately 45 miles from its headwaters in Rockland County, New York, to its mouth at Newark Bay in New Jersey. The Oradell Dam divides the river into a freshwater upper section and a tidally influenced lower section.

Historically, the Meadowlands encompassed more than 21,000 acres of freshwater marshes and cedar forests along the Hackensack River. However, over the past two centuries, landfills, industrial and residential development, transportation corridors, and utility infrastructure degraded and fragmented these habitats. Pollution, contamination, tidal restrictions, and invasive species have also impacted the approximately 8,000 acres of remaining open space and now-brackish marshes.

Since the adoption of the Clean Water Act, agencies and organizations have worked to protect and restore the Meadowlands' wetlands and other wildlife habitats. These efforts have restored and/or preserved more than 3,500 acres of tidal wetlands, properly capped and closed all landfills, and eliminated point sources of industrial contamination. The U.S. Fish and Wildlife Service and other resource agencies now recognize the Meadowlands as a regionally significant habitat complex.

Scientists at the New Jersey Sports and Exposition Authority's Meadowlands Research and Restoration Institute (MRRI) have monitored these habitats and the wildlife communities that depend on them to better understand population dynamics, biodiversity trends, and overall ecosystem health. More than 40 years of fish, avian, and diamondback terrapin monitoring, coupled with recent bioacoustic data, indicate that habitat protection and restoration have increased wildlife populations and biodiversity. These findings suggest that Meadowlands ecosystems are becoming more functional, stable, and resilient over time.

The following sections summarize several long-term MRRI monitoring programs and their preliminary results, illustrating continued improvements in the ecological health of the Meadowlands' wetlands and other habitats.

THE MEADOWLANDS FISH INVENTORY

MRRI has collected fisheries samples in the Meadowlands for nearly 40 years. The inaugural Meadowlands Fisheries Inventory took place in 1987–1988, followed by inventories in 2001–2003, 2013–2015, and most recently in 2023–2025. Each inventory consists of two years of seasonal sampling at standardized locations along the Hackensack River and its tributaries. Using multiple net types to sample the lower Hackensack River fish community, these surveys track long-term changes in species composition, abundance, and community structure.

The 1987–1988 inventory indicated that the river was largely dominated by the pollution- and disturbance-tolerant mummichog (*Fundulus heteroclitus*), with relatively few higher trophic-level fishes. This community composition suggested that the Meadowlands did not support a robust or functionally diverse fish community.

The second and third inventories documented increased species diversity and trophic complexity, characterized by reduced dominance of mummichog and greater abundance and diversity of higher trophic-level species, including striped bass (*Morone saxatilis*) and white perch (*Morone americana*). These changes likely resulted from improvements in water quality and wetland habitat relative to conditions during the first inventory. Water quality improved following the cessation of much of the heated discharge from three generating stations and the installation of landfill leachate collection and treatment systems, which prevented millions of gallons of contaminated leachate from entering the river. Habitat quality also improved following the restoration of more than 1,000 acres of wetlands throughout the district during this period.

The fourth inventory indicates that although the river remains dominated by species such as white perch, other species more commonly associated with coastal estuaries continue to increase in distribution and abundance. This trend presents a unique ecological shift, as the Meadowlands increasingly functions as a coastal estuary despite its location within the Piedmont physiographic region.

The most recent survey also documented more young-of-year individuals than all previous inventories combined, including Atlantic menhaden (*Brevoortia tyrannus*), Atlantic croaker (*Micropogonias undulatus*), spot (*Leiostomus xanthurus*), and oyster toadfish (*Opsanus tau*). In addition, the survey recorded the first observations of black sea bass (*Centropristis striata*), silver perch (*Bairdiella chrysoura*), and frilled anemone (*Metridium senile*), as well as substantially greater numbers of blue crab (*Callinectes sapidus*) and eastern oyster (*Crassostrea virginica*) than in previous inventories.

The inventory data further indicate that species representing multiple trophic levels and ecological niches have established populations throughout the Meadowlands. Surveys have documented larval, young-of-year, juvenile, and adult life stages, demonstrating that many species use the Meadowlands' waters and wetlands throughout their life cycle. Collectively, these findings indicate that the Meadowlands now provides the habitat quality and ecological function necessary to support a diverse and self-sustaining aquatic community.

THE MEADOWLANDS BIRD BANDING STATION

Birds serve as valuable indicators of habitat quality because they occupy a wide range of ecological niches and respond rapidly to changes in environmental conditions (Burnett et al., 2005; Rodewald and

Brittingham, 2007; Nur et al., 2008). To evaluate avian diversity, habitat use, and ecosystem function in the Meadowlands, MRRI initiated a bird banding program in 2008. Banding continued through 2014, resumed in 2019, and expanded in 2020 to include the Monitoring Avian Productivity and Survivorship (MAPS) Program. The study operates at Harrier Meadow and Erie Landfill, two adjacent sites within the Sawmill Creek Basin that encompass a variety of restored marsh, shrubland, grassland, and upland habitats.

Birds are captured using standardized mist-netting protocols during spring and fall migration and, since 2020, throughout the breeding season as part of the MAPS program. Banding data provide information on species diversity, abundance, habitat use, site fidelity, survivorship, and reproductive activity.

From 2008–2014, MRRI banded 33,520 individuals representing 135 species. Nearly two-thirds of all captures consisted of five species: American goldfinch (*Spinus tristis*), yellow-rumped warbler (*Setophaga coronata*), Savannah sparrow (*Passerculus sandwichensis*), song sparrow (*Melospiza melodia*), and swamp sparrow (*Melospiza georgiana*). During this period, researchers documented more than 3,100 recaptures, demonstrating that many migratory birds remained in the Meadowlands long enough to replenish energy reserves before continuing migration. Birds recaptured more than three days after their initial capture showed significant increases in body mass, suggesting that the Meadowlands provides abundant food resources during stopover.

The long-term recapture data also demonstrate strong site fidelity. Fifty-nine individuals returned in subsequent years, including 26 that revisited the Meadowlands at least two years after their original banding. One indigo bunting (*Passerina cyanea*) returned six years after its initial capture, while a blackpoll warbler (*Setophaga striata*) was recaptured during the following fall migration. Such records, particularly for long-distance Neotropical migrants, indicate that birds repeatedly select the Meadowlands as a reliable migration stopover. Likewise, the repeated return of breeding and wintering species suggests that Meadowlands habitats function as high-quality habitat rather than an ecological trap. A study by Haas in 1998 demonstrated that birds experiencing successful nesting are significantly more likely to return to the same breeding sites than individuals experiencing nest failure, supporting the conclusion that repeated returns reflect habitat quality rather than simply site fidelity (Haas, 1998).

The banding program also documented numerous species of conservation concern, including northern harrier (*Circus hudsonius*), vesper sparrow (*Pooecetes gramineus*), bobolink (*Dolichonyx oryzivorus*), American kestrel (*Falco sparverius*), grasshopper sparrow (*Ammodramus savannarum*), Savannah sparrow, and black-billed cuckoo (*Coccyzus erythrophthalmus*). Savannah sparrow was the most abundant state-listed species, with 4,589 individuals banded.

Since banding resumed in 2019, MRRI has encountered more than 15,000 birds representing 113 species despite substantially lower sampling efforts than the original study conducted from 2008-2014. The most abundant species now include yellow-rumped warbler, gray catbird (*Dumetella carolinensis*), common yellowthroat (*Geothlypis trichas*), song sparrow, and yellow warbler (*Setophaga petechia*). These shifts likely reflect changes in habitat conditions and, to a lesser extent, differences in net placement.

Recapture data collected since 2019 further demonstrate the long-term value of Meadowlands habitats. Researchers recorded 796 recaptures of 493 individuals representing 32 species, including 188 individuals recaptured in different calendar years. Several individuals returned over three, four, and even five years, while 25 birds were recaptured more than 1,000 days after their original capture. The longest interval,

1,799 days, occurred for a red-winged blackbird (*Agelaius phoeniceus*). These observations confirm that many birds not only survive migration but repeatedly return to the Meadowlands over multiple years.

The MAPS program has also demonstrated that the Meadowlands supports a productive breeding bird community. From 2020–2025, researchers encountered 64 species during the breeding season, with gray catbird, American robin (*Turdus migratorius*), song sparrow, common yellowthroat, red-winged blackbird, and Traill's flycatcher (*Empidonax alnorum/trailii*) among the most abundant. Thirty-two species exhibited physiological evidence of breeding, while hatch-year or locally fledged individuals of 29 species confirmed successful reproduction within or immediately adjacent to the study area.

Collectively, more than 15 years of banding and MAPS data demonstrate that the Meadowlands functions as an important migratory stopover, breeding area, and year-round habitat for a diverse avian community. Long-term trends in species diversity, body condition, site fidelity, and breeding activity indicate that habitat restoration and management have produced resilient, high-quality habitat capable of supporting birds throughout multiple stages of their annual life cycle. These findings also align with previous studies documenting increased avian abundance and diversity following wetland restoration (Seewagen and Newhouse, 2018) and the Meadowlands' support of diverse year-round bird communities (Kiviat and MacDonald, 2004).

THE MEADOWLANDS LONG-TERM DIAMONDBACK TERRAPIN MARK-RECAPTURE STUDY

Diamondback terrapin (*Malaclemys terrapin*), a species endemic to brackish and mangrove marshes along the Atlantic and Gulf coasts of the United States, was not documented in the Meadowlands until the 1970s. Although the timing and mechanism of its arrival remain unclear, the first scientific records date to 1988, when terrapins were collected as bycatch during MRRI's inaugural fisheries survey (Bragin et al. 2005).

Diamondback terrapins remained a game species in New Jersey until 2016, when state legislation granted them non-game status. The species is currently listed as Special Concern because of threats including road mortality, commercial and recreational crabbing, and illegal harvest for food and the pet trade (DiLeo 2016; Seigel and Gibbons 1995). Their long lifespan also increases their potential to accumulate environmental contaminants where those contaminants occur (Vargas 2021).

Although listed as a species of Special Concern in New Jersey, diamondback terrapins show evidence of population expansion within the Meadowlands, a region that historically provided limited suitable habitat. Once largely restricted to the more saline marshes of the southern Meadowlands, terrapins now occur throughout much of the District and continue expanding into historically less saline upriver marshes.

To evaluate these changing conditions as well as population dynamics, survivorship, longevity, and distribution, MRRI has been conducting a long-term mark-recapture study of diamondback terrapins since 2009. The study began in Sawmill Creek Marsh, expanded to Mill Creek and Western Brackish Marshes between 2014 and 2022, and refocused on Sawmill Creek Marsh in 2023. Standardized trapping and Passive Integrated Transponder (PIT) tagging allow researchers to monitor individuals through time and quantify long-term survival, site fidelity, and population trends.

Recapture data provide valuable information on longevity and survival by documenting the interval between initial capture and subsequent recaptures. Combining these data with age estimates based on shell morphology allows researchers to estimate minimum age and years at large for individual terrapins. The first five years of data (2009–2013) provided an initial population estimate for Sawmill Creek Marsh, and a second population analysis will evaluate changes after completion of the current five-year sampling period.

As of 2024, researchers recorded 1,979 terrapin encounters in Sawmill Creek Marsh, representing 1,621 unique individuals. Of these, 309 individuals were recaptured a total of 358 times, resulting in an overall recapture rate of 18 percent. Most recaptured terrapins (87 percent) were encountered only once after their initial capture, although several individuals were recaptured three, four, five, and even six times.

More important than the total number of recaptures is the time elapsed between captures. Of the 309 recaptured individuals, 219 were recaptured during a different calendar year than their original capture, while 34 were recaptured at least 10 years after their initial capture. The average interval between captures was 2.41 years, providing strong evidence of long-term annual survival.

In 2024, researchers recaptured a terrapin originally tagged in 2009, documenting 14.92 years at large. Because this individual was already an adult at its initial capture, its age is estimated to be at least 19 years old. Another terrapin originally tagged in 2010 was also recaptured, resulting in two individuals with more than 14 years at large. Although these exceptionally long-term recaptures are uncommon, they demonstrate that Meadowlands terrapins achieve life spans comparable to those reported elsewhere in the species' range, where individuals commonly live 20–40 years (Brennessel 2021).

Prior to the 2024 field season, the Meadowlands record for years at large was 13.88 years, shared by two terrapins. Both individuals were first captured on 30 July 2009 and recaptured on 12 June 2023. They were captured in adjacent traps during the initial survey and in the same trap upon recapture. These observations not only demonstrate exceptional longevity but also suggest remarkable long-term site fidelity to relatively small areas within the marsh.

Overall, the recapture data indicate that Meadowlands terrapins survive at high rates over extended periods. Continued analyses will provide more refined estimates of annual survivorship, but the existing data clearly demonstrate that Meadowlands marshes provide habitat capable of supporting long-term survival.

Population estimates currently include only the initial five years of data collection (2009–2013). Updated analyses will incorporate the current sampling effort after completion of the second five-year study period. Initial population modeling estimated more than 1,800 males and 1,600 females in Sawmill Creek Marsh, suggesting a large and potentially dense population. Although the model predicted a slightly male-biased superpopulation, field captures showed a slight female bias. Differences in trapping effort and environmental disturbances, including Hurricane Sandy, may explain this discrepancy. Low mortality associated with the absence of commercial crab pots and limited road access likely contributes to the observed population stability and continued growth.

Additional diamondback terrapin observations have occurred throughout the Meadowlands, including the Richard P. Kane Mitigation Bank, Harrier Meadow, Richard W. DeKorte Park, Riverbend Wetland Preserve, and Laurel Hill Park. Many of these upriver locations historically lacked terrapin records. Their

increasing occurrence at these sites suggests continued dispersal beyond previously documented habitat and further expansion of the local population.

Collectively, the mark-recapture data indicate that diamondback terrapins are not only persisting but thriving in the Meadowlands. Individuals routinely survive for more than a decade, exhibit strong long-term site fidelity, and achieve life spans comparable to those reported in other estuaries. The growing distribution of terrapins throughout the Meadowlands further suggests that habitat conditions continue to improve and support a stable, expanding population. While additional analyses from Mill Creek, Western Brackish Marsh, and future years of monitoring will further refine these conclusions, the available evidence demonstrates that the Meadowlands provides high-quality habitat capable of sustaining diamondback terrapins over multiple decades.

ACOUSTIC MONITORING IN THE MEADOWLANDS

To better quantify biodiversity, document cryptic species, measure habitat function, and track ecological change over time, MRRI has developed a large-scale ecoacoustic monitoring program over the past four years. Autonomous recording units (ARUs) provide continuous, standardized, non-invasive monitoring across habitat types and seasons, generating long-term datasets that complement traditional wildlife surveys and extend sampling beyond the practical limits of conventional field methods.

Many wildlife species inhabiting the Meadowlands are secretive, highly mobile, nocturnal, or more readily detected by vocalizations than by visual observation. Dense marsh vegetation, inaccessible terrain, brief migration windows, and peak wildlife activity during dawn, dusk, and nighttime hours further limit the effectiveness of traditional surveys. ARUs address these limitations by providing continuous, repeatable monitoring across multiple sites simultaneously while creating permanent acoustic archives that can be reanalyzed as automated detection technology continues to improve.

The Meadowlands is particularly well suited for ecoacoustic monitoring because of its complex and dynamic landscape. Habitat patches are highly fragmented, heterogeneous, and often separated by roads, rail lines, waterways, or development, making simultaneous, standardized sampling especially valuable. Wildlife communities can change dramatically over short distances as habitats transition among tidal marsh, freshwater wetland, grassland, shrubland, and forest edge. Many of the region's rare and state-listed species are highly vocal yet difficult to observe directly, making passive acoustic monitoring one of the most effective tools for documenting their occurrence. Ecoacoustics also provides a quantitative means of evaluating wildlife responses to habitat restoration and management while capturing broader soundscape characteristics, including anthropogenic noise. As the Meadowlands continues to respond to restoration, urbanization, vegetation change, and sea-level rise, long-term acoustic datasets will provide an increasingly valuable means of detecting ecological change and measuring ecosystem resilience.

Since 2023, NJSEA has deployed ARUs throughout the Meadowlands to assess the distribution and seasonal activity of birds, bats, amphibians, and other vocal wildlife. The monitoring network has expanded each year, substantially improving our understanding of habitat use, biodiversity, and ecosystem function across the region. Results to date include the following:

Saltmarsh sparrow (*Ammodramus caudacuta*) has been detected at five tidal marsh monitoring stations. Positive detections occurred only at sites dominated by *Spartina* high marsh. Neither *Spartina*-dominated

low marsh nor *Phragmites*-dominated high marsh produced detections. Notably, the Marsh Resources Meadowlands Mitigation Bank II, a marsh restored in 2001, yielded the greatest number of detections.

Seaside sparrow (*Ammodramus maritima*) has been detected at four tidal marsh monitoring stations. Positive detections occurred only at sites located along the main stem of the Hackensack River within *Spartina*-dominated marshes, including both high and low marsh habitats.

Bat monitoring has documented at least six species using Meadowlands habitats throughout the active season, including the federally proposed endangered tricolored bat (*Perimyotis subflavus*). The most frequently detected species was the big brown bat (*Eptesicus fuscus*), followed by eastern red bat (*Lasiurus borealis*), hoary bat (*Lasiurus cinereus*), silver-haired bat (*Lasionycteris noctivagans*), evening bat (*Nycticeius humeralis*), and tricolored bat. These findings demonstrate that the Meadowlands provides important foraging and commuting habitat for regional bat communities.

Although tricolored bats are typically associated with mature forests, their occurrence is not strongly limited by habitat fragmentation or urbanization alone (McChoshum et al. 2023). MRRI surveys collected expert-verified detections within small woodland patches, capped landfills, and upland parks, demonstrating its use of a variety of urban habitats (MacKenzie Hall, pers. comm.).

Atlantic Coast leopard frog (*Lithobates kauffeldi*) has been detected at three Meadowlands sites since 2023. Repeated detections provide insight into site occupancy, breeding phenology, and relative reproductive activity. Because amphibians are highly sensitive to changes in hydrology and water quality, long-term trends in calling activity may also serve as an early indicator of changing wetland condition.

Collectively, the ecoacoustic monitoring program has expanded MRRI's ability to document biodiversity, detect rare and cryptic species, and evaluate habitat quality across the Meadowlands. As this long-term dataset continues to grow across different sites and new target species, it will provide an increasingly valuable tool for measuring ecosystem health, evaluating restoration success, and guiding future conservation and management efforts.

MONITORING THE MEADOWLANDS INTO THE FUTURE

Over the past four decades, MRRI's long-term monitoring programs have documented a measurable recovery of the Meadowlands ecosystem. Independent datasets from fisheries surveys, bird banding, diamondback terrapin mark-recapture, and ecoacoustic monitoring each provide a different perspective on ecosystem condition, yet all point toward the same conclusion: wildlife populations have increased, biodiversity has expanded, and habitats now support more complex and resilient ecological communities than they did several decades ago.

No single monitoring program can fully characterize ecosystem health. Fisheries inventories reveal changes in aquatic community structure and trophic function. Bird banding documents migratory stopover quality, breeding activity, survivorship, and long-term site fidelity. Diamondback terrapin monitoring provides insight into population growth, longevity, and habitat suitability within tidal marshes. Ecoacoustic monitoring complements these traditional approaches by expanding detection of vocal species while providing continuous, standardized observations across seasons and habitat types. Together, these programs produce a comprehensive understanding of the Meadowlands ecosystem that would not be possible through any individual method alone.

As ecological restoration and habitat stewardship continue throughout the Meadowlands, long-term monitoring will remain essential for evaluating biological response. Restoration success cannot be measured solely by changes in vegetation or hydrology; it must ultimately be reflected in the wildlife communities that occupy these habitats. Continued monitoring will allow MRRI to quantify changes in species distributions, population trends, breeding activity, community composition, and habitat use while identifying emerging conservation challenges.

The Meadowlands will continue to be vulnerable to climate-driven ecological change, making long-term monitoring essential. Traditional monitoring techniques coupled with acoustic datasets can help detect wildlife responses to sea-level rise and climate change, especially where increasing inundation alters nesting habitat or marsh vegetation. Salt intrusion into freshwater systems may shift community composition and reduce suitability for freshwater-dependent species. Heat stress may alter calling behavior, breeding timing, or occupancy patterns during increasingly warm summers. Following major storm events, monitoring can help assess disturbance impacts and subsequent recovery. Together, these wildlife indicators not only reveal how the Meadowlands has been transformed over the past 40 years but is also forward-facing, providing an early-warning system for climate-related transformation across the Meadowlands.

Future efforts will increasingly integrate these complementary datasets to evaluate ecosystem condition across multiple spatial and temporal scales. Monitoring will expand beyond individual species to assess ecological guilds, habitat-specific wildlife communities, and landscape-level biodiversity patterns. Combining traditional field surveys with advances in ecoacoustics and other emerging technologies will improve the ability to detect ecological change, evaluate restoration outcomes, and guide adaptive management throughout the Meadowlands.

Long-term ecological monitoring represents one of MRRI's most valuable conservation tools. The datasets developed over the past 40 years provide an irreplaceable record of environmental change and establish the baseline needed to evaluate future restoration efforts, climate-driven habitat shifts, and emerging threats. As these datasets continue to grow, they will not only guide management within the Meadowlands but also contribute to a broader understanding of ecological recovery in highly urbanized estuarine landscapes.

SUMMARY

Ultimately, the collective evidence presented by these monitoring programs demonstrates that the Meadowlands has undergone substantial ecological recovery. Continued investment in long-term, science-based monitoring will ensure that this recovery is documented, understood, and sustained, providing the information needed to protect and enhance one of the largest remaining estuarine wetland complexes in the New York–New Jersey metropolitan region.

The transformation of the New Jersey Hackensack Meadowlands serves as a national model for urban estuary revitalization. Few metropolitan landscapes combine such high biodiversity value, intense development pressure, habitat restoration activity, and long-term ecological need within a single region. By implementing rigorous monitoring, MRRI is demonstrating how modern biodiversity tools can be applied in urban environments to guide conservation and restoration. The Meadowlands can therefore serve not only as a monitored ecosystem, but as a leading example of how cities and wildlife can be studied and managed together through advanced ecological technology.

Most importantly, monitoring the urban wildlife using both traditional methods and advanced technological methods provides a means of evaluating ecological resilience. Habitats that maintain diverse and functional wildlife communities despite disturbance, climatic stress, or urban pressures may be demonstrating resilience, while declining diversity or reduced occupancy may signal emerging vulnerability. Over time, these records become one of the clearest measures of whether the Meadowlands ecosystem is stabilizing, improving, or entering new ecological states.

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