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The Hackensack Meadowlands: History, Ecology, and Restoration of a Degraded Urban Wetland

The Hackensack Meadowlands (also called the Hackensack Meadows or New Jersey Meadowlands), broadly defined, comprise a large area of tidal and nontidal wetlands, wetland fill, and small natural uplands associated with the estuary of the Hackensack River from the Oradell Dam south to Newark Bay. Three centuries ago, the Meadowlands were predominantly a mosaic of Atlantic white cedar swamps, salt marshes, and other wetland and upland habitats. Today they are a system of fragmented and contaminated urban wetlands dotted with dumps, crisscrossed by highways, railroads, pipelines, and dikes, and closely surrounded by dense industrial, commercial, and residential development a few miles from Manhattan. Yet these degraded ecosystems are a magnet for migrant and breeding marsh, water, and shore birds and are inhabited by a moderate diversity of fish and other animals. They are also home to rare plants and have a moderate to high rate of marsh-plant productivity. Moreover, people are increasingly using the Meadowlands for recreation, nature tourism and study, and scientific research.

This issue of *Urban Habitats* presents seven studies of the Meadowlands and one study of the neighboring Passaic River. These studies range from an examination of the heavy metal molecules contaminating Meadowland marsh sediments to a characterization of the entire Meadowlands region using remote sensing technology. The papers are drawn from recent research presented at the Meadowlands Symposium, a conference held in October 2003 in Lyndhurst, New Jersey. Hosted by the New Jersey Meadowlands Commission and the Meadowlands Research Institute, and cosponsored by the U.S. Fish and Wildlife Service, Hudsonia Ltd., and the U.S. Army Corps of Engineers, this conference was attended by more than 200 researchers, natural resource managers, policy specialists, and graduate students—most of them actively involved in the study or management of the Meadowlands.

The diverse nature of this collection of papers tells us much about the complexity of studying, conserving, and managing the Meadowlands. The data herein, along with other current research, will help us to improve landscape preservation, biological conservation, wetland restoration, and water management in the Meadowlands, as well as in other urban wetlands. Many studies done in the Meadowlands recently and in years past have of necessity focused on one or two sites, a few sampling stations, or small sets of samples (e.g., plots, gill-net collections, bird counts, cores for pollen analysis). But each individual site or sampling station in nature is different, and often dramatically so where both intensive human activity and changing tides and salinity add more variables to already complex landscapes. Studying one or two sites in the Meadowlands is often a good start, but it does not necessarily generate data that are representative of the entire system—or of nearby urban reed-marsh complexes such as the Arthur Kill drainage, Jamaica Bay, or Delaware Bay. Spatial and temporal replication of these studies will help determine which results can be generally applied, and how plants, animals and ecological processes vary with the seasons, sea-level rise, contamination, salinity, and other environmental factors. Similarly, many studies in the Meadowlands have focused on just a few groups of organisms, not the entire range of species from bacteria to vertebrates, and studies of one group do not necessarily predict the species list and ecological functions of another. Further research spanning a broader spectrum of taxonomic groups is needed.

Several challenges of development and environmental management loom over the Meadowlands: converting inactive landfills to golf courses while maintaining habitat for a broad spectrum of native plants and animals; managing floodwaters to reduce damage to property and infrastructure; controlling mosquitoes to reduce nuisance and the risk of disease; designing, implementing, and maintaining wetland mitigation projects that demonstrably replace wetland functions and values lost to development; and managing and restoring plants, animals, and ecological functions in open-space preserves. The research presented in this issue, as well as other research being conducted in the Meadowlands and in urban wetlands elsewhere, will help us meet some of these challenges and formulate other questions as decisions are made.

Many human societies have evolved and flourished, and some have perished, in wetland regions of the world. Wetlands provide ecosystem services, food, travel routes, refuges, fertile soils, raw materials, and other resources to humans, but they also present risks of flooding, land subsidence, and disease. Wetlands that are misunderstood and mismanaged during the process of development and urbanization may become more hazardous than provident. The Hackensack Meadowlands and other urban wetlands around the world hold the knowledge we need to live in balance with wetland systems, if ever we are able to do so.

Erik Kiviat
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The Meadowlands Before the Commission: Three Centuries of Human Use and Alteration of the Newark and Hackensack Meadows*

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Abstract

Human use and alteration have caused dramatic changes in the Newark and Hackensack meadows during the three centuries following European settlement of northeastern New Jersey. Human activities have historically fallen into four major categories: extraction of natural resources; alteration of water flow; reclamation, land making, and development; and pollution by sewage, refuse, and hazardous waste. By the time of the creation of the Hackensack Meadowlands Development Commission in 1969, the original 42-plus square miles of tidal and freshwater wetlands had been radically transformed. Tidal flow of saltwater extended much farther into the estuary's waterways, transforming previous freshwater portions of the wetlands into brackish and saltwater habitats. The southern third of the Meadowlands had been entirely developed, and the remainder was a patchwork of developed upland and undeveloped wetlands. Total wetland acreage had been reduced to about 13 square miles, much of it polluted by sewage and solid waste.

Key Words: estuary; garbage; Meadowlands; Hackensack River; land making; landfills; municipal water supply; Passaic River; pollution; reclamation; tidal wetlands.

Introduction

This paper provides an overview of the major types of human use and alteration of the Newark and Hackensack meadows, from the time of the first European settlements in the mid-1600s to the creation of the Hackensack Meadowlands Development Commission in the late 1960s.

Before European settlement the Newark and Hackensack meadows (also known as the Meadowlands, the Jersey Meadows, and the Newark and Hackensack Tidal Marsh) made up a large complex of tidal, brackish, and freshwater wetlands located in northeastern New Jersey. They surrounded most of the lower Hackensack River, bordered part of the lower Passaic River, and formed the western edge of Newark Bay.

The Newark Meadows and much of the Hackensack Meadows no longer exist. The official boundary of the present-day Hackensack Meadowlands, as defined in the 1968 Hackensack Meadowlands Development Act, encompasses approximately 32 square miles. It includes all or parts of 14 municipalities in Bergen and Hudson counties (Figure 1). Almost half the area of the officially defined Meadowlands has been transformed into dry upland, leaving slightly more than 13 square miles as wetlands (Figure 2). A large number of former open

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dumps and sanitary landfills are located in the Meadowlands (New Jersey Meadowlands Commission, 2002; New Jersey Meadowlands Commission, n.d.).

The present-day Meadowlands cover a much smaller area than in the past. An 1896 survey by the state geologist calculated the total acreage of the Newark and Hackensack meadows as slightly less than 43 square miles. The Meadowlands then extended north to Hackensack and south to Elizabeth (Figure 3). The southern portion of the Meadowlands, located on the west side of Newark Bay, was known as the Newark Meadows and has been entirely developed. These former wetlands are now covered by Port Newark/Elizabeth, Newark Liberty International Airport, the New Jersey Turnpike, and other urban infrastructure.

The Meadowlands are relatively well known, since they are within three miles of Manhattan and are bordered and crossed by several major transportation routes (Figure 4). Railroad facilities bordering or crossing the Meadowlands are used by New Jersey Transit and the Port Authority Trans-Hudson Line, as well as Conrail and other private railroad companies. Major highways include the New Jersey Turnpike, Interstate Highways 80 and 280, and New Jersey Highways (Routes) 3, 17, 46, and 120. Sports enthusiasts know of the Meadowlands Sports Complex, home of the New York Jets, New Jersey Nets, New Jersey Devils, New York Giants, and other teams. Additional public awareness has resulted from scenes of the Meadowlands in films such as *Being John Malkovich* (1999) and *Broadway Danny Rose* (1984), as well as in the opening credits of the television series *The Sopranos* (1999–). The Meadowlands have also been a favorite subject for artists, including George Inness and Martin Johnson Heade in the 19th century and, more recently, Herman Hartwich, Gary Godbee, and Tim Daly.

The creation of the Hackensack Meadowlands Development Commission (HMDC) in 1969 marked the start of a new era in the history of the Meadowlands, characterized by extensive government regulation. The enabling legislation gave the commission five goals, of which two were considered primary: facilitation of coordinated planning and development of the remaining wetlands, and regulation of garbage disposal. It was originally assigned only limited conservation goals. Within several years after its creation, however, the HMDC shifted its focus to the preservation of the remaining wetlands and the remediation of polluted or destroyed acreage (Ginman, 1968; Boldt, 1972; Goldman, 1975; Goldshore, 1976). The agency's revised mission was recently symbolized by the enactment of legislation in 2001 that changed its name to the New Jersey Meadowlands Commission.

Several excellent books describe the work of the HDMC and the recent history of the Meadowlands (Sullivan, 1998; Quinn, 1997). This paper focuses on the history of the Meadowlands during the 300 years before the creation of the HMDC. A study of this period reveals long-term trends that might be relevant to understanding the history of other present (and former) wetlands in the New York–New Jersey metropolitan region, such as Flushing Bay, Jamaica Bay, Newtown Creek, and Gowanus Canal (Figure 5).

Three Aspects of Environmental History

The primary aim of this paper is to describe the pattern of major human uses and alterations of the Newark and Hackensack meadows. A description of human impact on the environment, however, is not the only possible focus of environmental history. There are at least two other aspects of environmental history worth noting. Environmental historians Donald Worster and William Cronon have proposed using “three levels of analysis in environmental history.” These include not only how human activities have modified the natural environment but also the political economy that caused these changes, as well as the prevailing beliefs and idea systems though which decisions and changes were interpreted (Cronon, 1990).

This section of the paper briefly addresses the two latter aspects of historical analysis. A study of the underlying political economy that encouraged (or prevented) various types of activities affecting wetlands shows a pattern of government involvement divided into two periods. The first period lasted from the 1660s to the early 1900s. During this time there was minimal use of government power regarding the wetlands. The government’s role was primarily to 1) distribute title to the wetlands (and all other land in New Jersey) from the government to private individuals, and 2) set up a legal system whereby the owners could develop the land in any way they desired. Legal historian Willard Hurst described this process as “the release of energy” associated with early American capitalism. There were minimal restraints upon disposition of land: It could be easily purchased and easily sold. Society relied upon the market system for the optimal disposition of all land (including wetlands), which was simply treated as another form of private property (Hurst, 1956).

The second period began in the 20th century and was characterized by a more active government role. Public agencies, as well as private firms and individuals, acquired and developed portions of the Meadowlands. The Newark Meadows were developed almost entirely by government entities. The city of Newark initiated the construction of Port Newark in 1914 and Newark Airport in 1927. Two decades later, these projects were taken over and expanded by the Port of New York Authority (now called the Port Authority of New York and New Jersey) (Doig, 2000). In the late 1960s, the New Jersey Legislature created the HMDC (and the New Jersey Sports and Exposition Authority) to hasten development of the northern portion of the Meadowlands.

Analysis of the second major aspect of environmental history noted by Cronon and Worster—the set of prevailing public attitudes regarding the environment—shows an unbroken trend throughout the 300 years following the first European settlement. During this entire period, attitudes toward wetlands were uniformly negative, a position almost completely reversed today (Viliesis, 1997; Prince, 1997).

For three centuries, wetlands in general, and the Newark and Hackensack meadows in particular, were unanimously regarded as “wastelands.” They were viewed as unpleasant, unhealthy, unproductive places that ought to be “improved” out of existence as rapidly as possible. A journalist describing the Meadowlands in 1867 began his article with this description: “Swamp-lands are blurs upon the fair face of Nature; they are fever-breeding places; scourges of humanity; which, instead of yielding the fruits of the earth and adding wealth to the general community, only supply the neighboring places poisonous exhalations and torturing mosquitos. They are, for all practical purposes, worthless; and the imperative necessity for their reclamation is obvious to all, and is universally conceded.” (“The New System of Reclaiming Lands,” 1867).

Identical sentiments were voiced half a century later by Colonel Joseph O. Wright, a federal engineer who surveyed the Newark and Hackensack meadows in 1907. He declared, “The marsh in its present condition is not only worthless, but is a detriment to public health and a nuisance to the residents of the adjacent upland.” It was “a prolific place for mosquitoes,” containing sewer filth “both obnoxious and unwholesome.” Wright added that even apart from “the question of sanitation,” the meadows should be reclaimed. Their geographical position, “within eight miles of the city of New York and traversed by three great trunk-line railways,” made the meadows “too valuable to longer remain idle.” (“Expert Advice on Ship Canal,” 1908; “Wright Shows How Meadows Can Be Easily Reclaimed,” 1908).

As late as 1969, the wetlands naturalists John and Mildred Teal could still declare, “Marshes are generally considered useless land that must be made useful as quickly as possible. ‘Useful,’ of course, means destruction of the marsh in most cases and conversion of the area to ground on which people can stand, and water on which they can float boats.” (Teal & Teal, 1969).

During the final third of the 20th century, however, public attitudes toward wetlands began to change. Rather than unpleasant and unhealthy places that ought to be “improved” (i.e., made into developed upland), wetlands came to be viewed as unique and valuable components of the environment. The change in public feeling about tidal wetlands was exhibited in the publication of books emphasizing the importance of this special “edge of the sea” (Carson, 1955; Teal & Teal, 1969).

Extraction of Natural Resources

The earliest human use of the Newark and Hackensack meadows was the extraction of natural resources. The European settlers, like the Native Americans who preceded them, used the Meadowlands (and other wetlands) as a source of fish, oysters, fowl, and small mammals for food, furs, and sport (McCay, 1998; MacKenzie, 1992). This activity continued through the 1870s and into the 1880s, when a combination of diminishing water flow and increasing pollution made consumption of such food dangerous (Iannuzzi, 2002; Olsen, 1999; Crawford, Bonnevie, Gillis & Wennig, 1994).

The European settlers also began extracting another natural resource: salt hay for feeding and bedding livestock. The founders of Newark introduced the practice of dividing the Meadowlands into long, narrow lots, which were allocated to the male heads of households. Owners were required to excavate small ditches (six feet wide and two feet deep) to identify property boundaries (Shaw, 1884).

The settlers and their descendants engaged in the large-scale harvesting of salt hay for more than two centuries, from the 1660s through the 1920s. The cutting and piling of salt hay usually occurred in mid-autumn, but the hay was not removed until winter, when horses could be brought into the frozen wetlands (Seybold, 1992; Stilgoe, 1999). An 1884 newspaper reported “hundreds of men” harvesting salt hay, using “old style scythes, long-handled rakes, and two-tined pitchforks of the olden time,” since it was “impossible to use mowing machines, horse rakes, or other improved machinery on the soft marshes.” (“Mowing on the Marsh,” 1884).

The harvesting of salt hay declined during the early 1900s because of changing regional agricultural patterns and local transportation habits. Most of the region's farms began to specialize in truck gardening and nursery work as dairy-farming operations migrated to upstate New York and the Great Lakes area. At the same time, horses were being replaced by tractors for farmwork and by automobiles and trucks for transportation. Decreased numbers of cows and horses meant less demand for salt hay, and eventually the end of salt hay harvesting (Barron, 1997; Danbom, 1979; Schmidt, 1973; Cunningham, 1955; Mighell & Black, 1951).

Alteration of Water Flow

From the 1820s through the 20th century, various engineering projects altered the area's hydrology by decreasing the flow of freshwater and increasing the flow of saltwater into and through the Meadowlands. Prior to the late 1820s, water flowing at the mouths of the Passaic and Hackensack rivers into Newark Bay was fresh enough for cattle to drink ("The Newark Meadows," 1826). The sea level along the Atlantic coast has been slowly rising for approximately 20,000 years, gradually making estuarine waters more saline (Stoffer & Messina, n.d.; Pugh, 2004; Pirazzoli, 1996). However, the acceleration of human-engineered alterations of water flow in the Hackensack Meadows in the early 1900s rapidly and drastically altered the salinity of its waters.

Construction of dams to create millponds along the Passaic and Hackensack rivers and their tributaries began diminishing the rivers' flow during the late 1600s and 1700s. In the 1830s, construction of the Morris Canal, the eastern half of which drew water from the tributaries of the Passaic River, further decreased the flow along the lower Passaic River (Kalata, 1983). Newark and Jersey City, the two largest cities in New Jersey, started pumping water from the Passaic River in the mid-1800s for their municipal water supplies. During the late 1800s, new and larger dams were constructed on the tributaries of the upper Passaic River to create large reservoirs for municipal use (Iannuzzi, Ludwig, Kinnell, Wallin, Desvousges & Dunford, 2002; Galishoff, 1988; Brydon, 1974; Winfield, 1874; Shaw, 1874; Miri, 1971).

The flow of freshwater in the Hackensack River was also reduced by diversion into municipal water systems during the mid-1800s. The Hackensack Water Company was created in the late 1860s to supply the cities of Hoboken, Weehawken, and Hackensack. It initially used a system of wells, pumping stations, and holding pools along the Hackensack River to obtain water, but the region's growing population soon required larger volumes and a more extensive infrastructure. Starting in 1901, the water company began constructing dams and reservoirs throughout the Hackensack River watershed, initially at Woodcliffe and later at Oradell and Clarkstown (Clayton, 1882; Van Valen, 1900; Van Winkle, 1924; Leiby, 1969).

Extensive dredging of the Passaic and Hackensack rivers from the late 1800s onward further altered the waters of the Hackensack Meadowlands. Initially both rivers had shallow beds: In 1845 the U.S. Coast Survey measured depths of 5 to 7 feet inside the mouth of the Passaic River and depths of 10 to 18 feet at the mouth of the Hackensack River (U.S. Coast Survey, 1845) (Figure 6). The dredging allowed larger amounts of seawater to flow north from Newark Bay into the rivers' deepened channels.

During the late 1800s the U.S. Army Corps of Engineers began dredging Newark Bay, and then the Passaic and Hackensack rivers (Klawonn, 1997; Iannuzzi et al., 2002; Livermore, 1905). During the

1880s, the corps dredged a 200-foot-wide channel 10 feet deep along the lower Passaic River bordering Newark. Later dredging deepened and extended the Passaic River channel, which is now 30 feet deep for the first 2 1/2 miles and 20 feet deep for the next 4 1/2 miles (U.S. Army Corps of Engineers, 2004).

Dredging of the Hackensack River began in the 1900s, when the corps dug a 12-foot-deep channel. The current Hackensack River channel is 32 feet deep for the first 3 miles, 25 feet deep for the next 1/4 mile, and 15 feet deep for an additional 1/2 mile. The channel varies between 800 and 200 feet in width.

The decrease in the volume of freshwater flowing in the Passaic and Hackensack rivers and the dredging of the riverbeds to three to four times their original depths allowed the saltwater in Newark Bay to flow farther and farther north into the Hackensack Meadows. The freshwater wetlands at the northern part of the Hackensack Meadows began turning brackish, and the brackish wetlands in the middle and southern part of the Hackensack Meadows were transformed into saltwater habitats. *Phragmites* and other plants associated with brackish and freshwater wetlands were displaced by *Spartina* and other species associated with saltwater wetlands (Ehrenfeld, 2000; Ravit, 2002).

Extensive forests of cedar trees covered parts of the Meadowlands as late as the early 1800s, but they can no longer grow there because of the salinity of the surface and ground water ("Meadows Were Once Newark Forests," 1936; Heusser, 1949; Sipple, 1971; Harshberger & Burns, 1919; Wright, 1988). The only forested area now located within the boundaries of the Meadowlands is a small grove of deciduous trees at Schmidt's Park in an upland section of Secaucus.

Reclamation, Land Making, and Development

The third type of human alteration of the Meadowlands was the structural transformation of portions of wetlands into dry upland. The initial efforts, during the 19th century, were land-reclamation projects involving dikes and drains that left the reclaimed acreage below the high-tide level. Later, in the 20th century, land-making projects resulted in new upland above the high-tide level. Both types of projects were aimed at "improving" wetlands by transforming them into dry upland suitable for agricultural, commercial, and industrial uses.

Distinctions between the different types of structural transformation (and the appropriate terminology) were commendably noted in a recent comprehensive study of Boston's former wetlands (Seasholes, 2003):

> The Quincy Market area, the Bullfinch Triangle, and the airport...were also once under water. Like many areas of Boston, they are "made land," created by filling in the tidal flats and marshes that once surrounded the city—a process that can be termed *land making*. Many call this process *land filling* or *land reclamation*. But neither term is correct. *Landfill* not only evokes images of garbage dumps but can also mean fill added on top of existing land. And since in Boston it was water that was filled, not land, *landfilling* is actually an oxymoron. *Land reclamation* is not an accurate term either, for land in Boston was actually made by filling, not by diking, pumping, and draining to reclaim it from the sea. So *land making*, a term coined by archaeologists, has been chosen as the appropriate term for this study, because it describes what really occurred in Boston—making land by filing in areas of water.

The Newark and Hackensack meadows experienced a pattern of development different from that of the Boston wetlands because the initial wetlands development projects were land-reclamation efforts. The largest pre–Civil War projects were undertaken by the New York City–based Swartwout family, from the 1820s through the 1840s. Robert Swartwout and his brothers organized a variety of companies to construct a system of earthen dikes and tidal gates to reclaim several square miles of land located between the lower Hackensack and Passaic rivers and develop them as farmland. Their companies, however, were all economic failures (Sullivan, 1998; Brooks, 1957).

The next major reclamation project occurred after the end of the Civil War. An engineer, Spencer B. Driggs, teamed up with New York City real estate developer Samuel Pike to reclaim the same portion of the Meadowlands as the Swartwouts had. Driggs and Pike also used a system of dikes and tidal gates, supplemented by water pumps (Iron Dike and Land Reclamation Company, 1867; "The New System of Reclaiming Lands," 1867). They also introduced the practice of building the earthen dikes around large overlapping iron plates, designed to prevent muskrats and other animals from burrowing through and weakening the dikes. The death of Pike in 1872 and the onset of the financial depression of 1873 led to the abandonment of the project (Figures 7 and 8).

During the latter half of the 19th century, government officials joined private businessmen in advocating development of the Meadowlands. Several influential Newark businessmen (and two U.S. senators, John Kean of Elizabeth and James Smith Jr. of Newark) proposed various projects to reclaim all or part of the Newark Meadows. ("Draining the Meadows," 1884). The Geological Survey of New Jersey made several visits to inspect reclamation projects in Holland and in the Fens region of England. State geologists issued reports recommending the reclamation of the Meadowlands, which they characteristically described as "a blot upon an otherwise fair landscape," using a combination of dikes and dredged navigation channels (Vermeule, 1897, 1898). These state reports were supplemented by studies conducted by engineers retained by the city of Newark (Greene & Adams, 1909; Owen, Hand & Goodrich, 1909).

Until the early 1900s, all development proposals for the Meadowlands were based on reclamation technologies using dikes and drains similar to those used in the Netherlands (albeit without windmills). According to these plans, the reclaimed land would lie below the high-tide level and would be devoted to farming. Although cities and industries were located behind dikes in the Netherlands and behind Mississippi River levees in Louisiana, none of the 19th-century Meadowlands reclamation projects proposed using the reclaimed lands for any purpose except farming.

In the 20th century, however, the major Meadowlands reclamation proposals advocated the more expensive land-making technologies of dredging and filling in. Instead of creating reclaimed land lying below the level of high tide, the developers proposed using massive amounts of fill to permanently elevate the reclaimed land several feet above high tide. Some of the fill would be obtained by dredging navigation channels in nearby rivers and bays. Other sources of fill were municipal garbage and excavation debris from the construction of tunnels, skyscraper foundations, and subways.

This new reclamation method was much more expensive, but proponents argued that the resulting permanent upland could be used for a larger number of activities. The higher initial investment would be offset by higher rents and larger profits realized from developing the new upland, assured by the increasing demand for real estate arising from the growing metropolis.

The burgeoning urban population in the late 1800s created a growing demand for land in the vicinity of New York City. Between 1870 and 1900, the city's population increased from 1.5 million to 3.4 million. In New Jersey, Newark grew from 115,000 to 287,000 (Mitchell, 1993). In 1870, the combined population of Essex, Union, Hudson, and Bergen counties was only 345,000 persons; by 1900, the combined population of the four counties had nearly tripled, to 924,000 (N.J. Department of State, Census Bureau, 1906; New Jersey State Data Center, 1991).

Starting in the early 1900s, the New Jersey Terminal Dock and Land Improvement Company began attempting to transform five square miles of land between the Hackensack and Passaic rivers (the same site as the Swartwouts' and the Driggs-Pike projects). The company's organizers were associated with a firm engaged in dredging Ambrose Channel in New York Harbor and other dredging projects in Newark Bay and the Passaic River. In addition to the dredge spoils from its projects, the company also used excavation debris from the construction of the trans-Hudson tunnels and garbage transported in barges from New York City.

The expanding urban population, combined with increasing prosperity, resulted in a rapidly growing amount of garbage (Strasser, 1999). Garbage collected by private scavengers or municipal agencies was mixed with clean fill (chemically inert solid materials, such as rocks, gravel, cinders, bricks, and concrete) and used for the new land-making projects. In 1909 a Newark newspaper reported (admiringly) that "New York rubbish is being turned into Jersey soil by scow after scow from Manhattan." ("Sees Need of Rushing Canal," 1909).

The city of Newark started constructing Port Newark in 1914, dredging a ship channel one mile long from Newark Bay into the Meadowlands. The city mixed the dredged fill with garbage and ashes and dumped it on the wetlands on the north side of the channel. Eventually, the land was elevated several feet above sea level, and docks and warehouses were constructed on it (Hallock, 1914).

Additional portions of the Newark Meadows were similarly reclaimed during the 1920s for the expansion of Port Newark and the construction of the original Newark Airport. These land-making projects elevated the wetlands by using a combination of fill: dredge spoils from Newark Bay, Newark garbage, and excavated fill from the construction of Newark's skyscrapers and subway system. Between 1914 and 1974, the Newark Meadows portion of the Meadowlands was totally filled in and covered by the Port Newark/Elizabeth marine terminal, Newark Liberty International Airport, and the New Jersey Turnpike (Hallock, 1914; Folson, Fitzpatrick & Conklin, 1925; Cunningham, 2002).

The Hackensack Meadows were not developed until much later than the Newark Meadows. The Hackensack Meadows were divided among many more municipalities, and none of these local governments had the resources to finance a major land-making project. Although construction of Teterboro Airport started during World War I, most of the development of the Hackensack Meadows came several decades later, and in much smaller increments than the giant construction projects of

Port Newark and Newark Airport. However, from the 1920s through the 1960s, more than half the acreage of the Meadowlands lying north of Newark Bay was filled in to make new upland (Meadows Reclamation Commission, 1930; Mattson, 1970; Baldi, 1981; Sellnow, 1930).

Large-scale proposals to develop the remaining Meadowlands arose in the 1950s, after the construction of the New Jersey Turnpike along its eastern edge. Placement of a turnpike interchange at Route 3 in Secaucus began the transformation of a small village known primarily for its pig farms into a substantial city known for shopping malls and factory outlets. The Meadowlands Regional Development Agency was created by the state legislature in the late 1950s to facilitate Meadowlands development, but it was mainly a fact-finding body and had little impact (Sullivan, 1998; Rockland & Gillespie, 1993; Meadowlands Regional Development Agency, 1960).

Further incentive for developing the remaining portions of the Meadowlands came during the late 1960s, when the New Jersey Turnpike Authority decided to widen the existing turnpike and construct a western spur through the very center of the wetlands to connect with Route 3 in East Rutherford, near the Hackensack River. The administration of Governor Richard Hughes predicted that this interchange would become the center of a major new city on the reclaimed wetlands, with housing, industry, commercial centers, and recreation facilities rivaling those of Manhattan. Governor Hughes persuaded the legislature to enact the Hackensack Meadowlands Development Act in 1968, to facilitate the development of the remaining Meadowlands. His successor, William Cahill, persuaded the legislature to enact the New Jersey Sports Authority Act in 1969, with the more focused mission of developing a major sports center at the intersection of the turnpike and Route 3 (Ginman, 1968; Goldman, 1975).

A dramatic change in public attitudes regarding the value of wetlands, along with new federal legislation in the early 1970s mandating stricter criteria for water pollution and wetlands reclamation, slowed efforts to develop wetlands. The 1972 election of Governor Brendan Byrne, who supported stricter state environmental laws and appointed more environmentally concerned commissioners to the HMDC, also slowed and then halted most efforts to develop the remaining Hackensack Meadowlands (Goldman, 1975; Goldshore, 1976).

Pollution

The fourth major type of human impact was pollution—the import and deposit of refuse, sewage, and hazardous wastes in the Meadowlands. This activity often involved making extensive structural changes to certain portions of the meadows, such as enlarging the old boundary ditches and digging wider and deeper sewage channels (Whigham, Simpson & Lee, 1980). The structure of the Meadowlands was also altered by the creation of large open dumps and sanitary landfills, although even the largest landfill in the Meadowlands is still only a fraction of the size of New York City's Fresh Kills Landfill on Staten Island (Rathje & Murphy, 1992).

In the 19th century, the southern portion of the Meadowlands began experiencing substantial pollution from the sewage and industrial wastes poured into the Passaic River. The effect of wastes from the growing cities and industries was aggravated by the fact that water-supply pumping stations, and later dams and reservoirs, were steadily decreasing the amount of freshwater flowing through the river (Iannuzzi & Ludwig, 2004; Iannuzzi et al., 2002; Galishoff, 1988; Brydon, 1974).

In the early 1900s, Newark, Paterson, and other cities along the Passaic River collaborated to construct a major trunk sewer line to pump sewage into Newark Bay, and later New York Harbor. This decreased pollution of the river to some extent, but Newark Bay remained extremely contaminated (Feng, Jaslanek, Stern, Jones & Onwueme, 2003; Modica, 2001; Crawford et al., 1994; Suszkowski, 1978; Gallishoff, 1970; Potts, Vermeule & Sherrerd, 1920).

The portion of the Meadowlands surrounding the Hackensack River initially experienced less pollution than the Passaic River section, largely because no large cities bordered that river. But the mean range of tides in Newark Bay was 5.1 feet, and tides entering the Hackensack extended as far north as New Milford, a distance of more than 21 miles (Figure 9). Twice each day, the waters (and waterborne pollutants) of Newark Bay would flow north into the Hackensack with a tidal current reaching 1.1 knots (Suszkowski, 1978; U.S. Department of Commerce, Coast and Geodetic Survey, 1946.)

Dredging of the Hackensack, which began in the early 1900s, facilitated the entry of larger volumes of these increasingly polluted tidal waters. At the same time, however, land making and construction of infrastructure upon the mud flats bordering both banks of the lower Hackensack in Harrison and Jersey City narrowed the river and acted to restrict the flow of fresh and tidal waters (Artigas & Yang, 2004).

In much the same way that garbage from Newark had been used in the land-making projects that destroyed the Newark Meadows, starting in 1906, New York City garbage was used to build up the five-square-mile portion of the Meadowlands between the mouths of the Passaic and Hackensack rivers.

Before then, New York City's garbage had either been dumped at sea or mixed with clean fill and used for land making at the tidal wetlands bordering lower Manhattan and the eastern shore of Brooklyn. During the mid-1800s, city garbage was also used for land making in the extensive tidal flats along the edge of Hudson County lying east of Bergen Hill (Miller, 2000; Walsh & LaFleur, 1995; Walsh, 1989; "Where Street Refuse Goes," 1869). Indeed, the precedent for using rubbish to create upland was such that "the present contours of virtually every portion of New York City and the neighboring parts of New Jersey and Long Island have all been shaped by fill, much of it garbage." (Rathje & Murphy, 1992.)

By the mid-20th century, even garbage not being used for land-making projects was brought to the Meadowlands. It was simply deposited in open dumps, and later, in sanitary landfills. The disposal of garbage in a manner that simply polluted and did nothing to make new land resulted from several factors. The most important factor was the growing population of New York City and adjacent municipalities, which generated ever-increasing amounts of garbage. In addition, the automobile revolution of the 1920s also provided relatively inexpensive trucks to transport garbage out of the city to the Meadowlands on the growing network of paved streets and highways (Miller, 2000; Melosi, 2000, 1981; Strasser, 1999; Colten & Skinner, 1995; Tarr, 1996; Hird, 1994; Goddard, 1975; Bower, 1968; Fee & Corey, 1994).

In 1957, New York City stopped providing municipal garbage removal for commercial firms, which required companies to hire private garbage collectors. Some of these private haulers were associated with organized crime and chose to eliminate the expense of garbage dump "tipping fees" by simply depositing refuse at any available unwatched location. Its highway access to the city, as well as its low population density and corresponding difficulty of identifying illegal dumpers, made the northern portion of the Meadowlands attractive for unregulated garbage dumps.

The explosive growth of the local garbage-collection industry after 1957—and corresponding increase in the frequency and quantity of illegal dumping in the Meadowlands—created a situation that might be called the Tony Soprano version of "the tragedy of the commons." When there are only two or three "midnight dumpers" operating intermittently on a small scale, their illegal operations might go unnoticed and undisturbed for a long time. But when dozens of dumpers begin making a continuous round of trips to an ever-increasing number of illegal sites, they arouse the attention of local residents, newspaper reporters, law-enforcement officials, and eventually the local and state governments.

As a consequence, when the New Jersey Legislature enacted the Hackensack Meadowlands Development Act in 1968, one of the resulting commission's primary goals was the elimination of illegal dumping and the enforcement of regulations concerning legal dumping at the Meadowlands. Changes in public attitudes regarding wetlands eventually led the commission to abandon its other original goal of actively promoting development and to strengthen its efforts to regulate garbage disposal (New Jersey Meadowlands Commission, 2002, 2003).

Over the past several decades, shifts in people's attitudes about wetlands and the recognition that much of the remaining portions of the Newark and Hackensack meadows have suffered extensive environmental damage have led to studies regarding the extent of the damage and possible means to remediate it. As a result, the commission (and the affiliated Meadowlands Environmental Research Institute) has become a major sponsor of wetlands environmental research (Meadowlands Environmental Research Institute, 2004).

Conclusion

During the 300 years before the creation of the Hackensack Meadowlands Development Commission, the Newark and Hackensack meadows experienced several important changes as the result of human use and alteration. The first 150 years of relatively benign extraction of natural resources was superseded by more drastic changes starting in the early 1800s. The steady decrease of fresh river water flowing into the Meadowlands and the later dredging of the river bottoms combined with a rising sea level to increase the salinity of the Meadowlands' waters. Initial land-reclamation efforts with dikes and drains, and later land-making efforts using dredging and filling, transformed more than two-thirds of the Meadowlands' 42-square miles into elevated upland.

In their seminal book *Life and Death of the Salt Marsh*, John and Mildred Teal noted, "The closer the marsh lay to New York City, the more likely it was that it was destroyed by the spreading urban complex." (Teal & Teal, 1969). The development of the Newark and Hackensack meadows was a minor variation on this theme: They were close to New York City, but even closer to Newark. The southern portion of the Meadowlands, comprising the former Newark Meadows and the five-square-mile portion of the Hackensack Meadows lying between Newark Bay and the PATH rapid-transit train lines, was completely developed and excluded from the jurisdiction of the Hackensack Meadowlands Development Act. The pattern of extraction, alteration, development, and pollution of the Newark and Hackensack meadows might also be useful for understanding the history of other degraded wetlands in the New York City area, as well as ones near Boston, San Francisco, and other urban centers.

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Wright shows how meadows can be easily reclaimed. (1908, February 1) *Newark Morning Star*, p. 2.

Figure 1

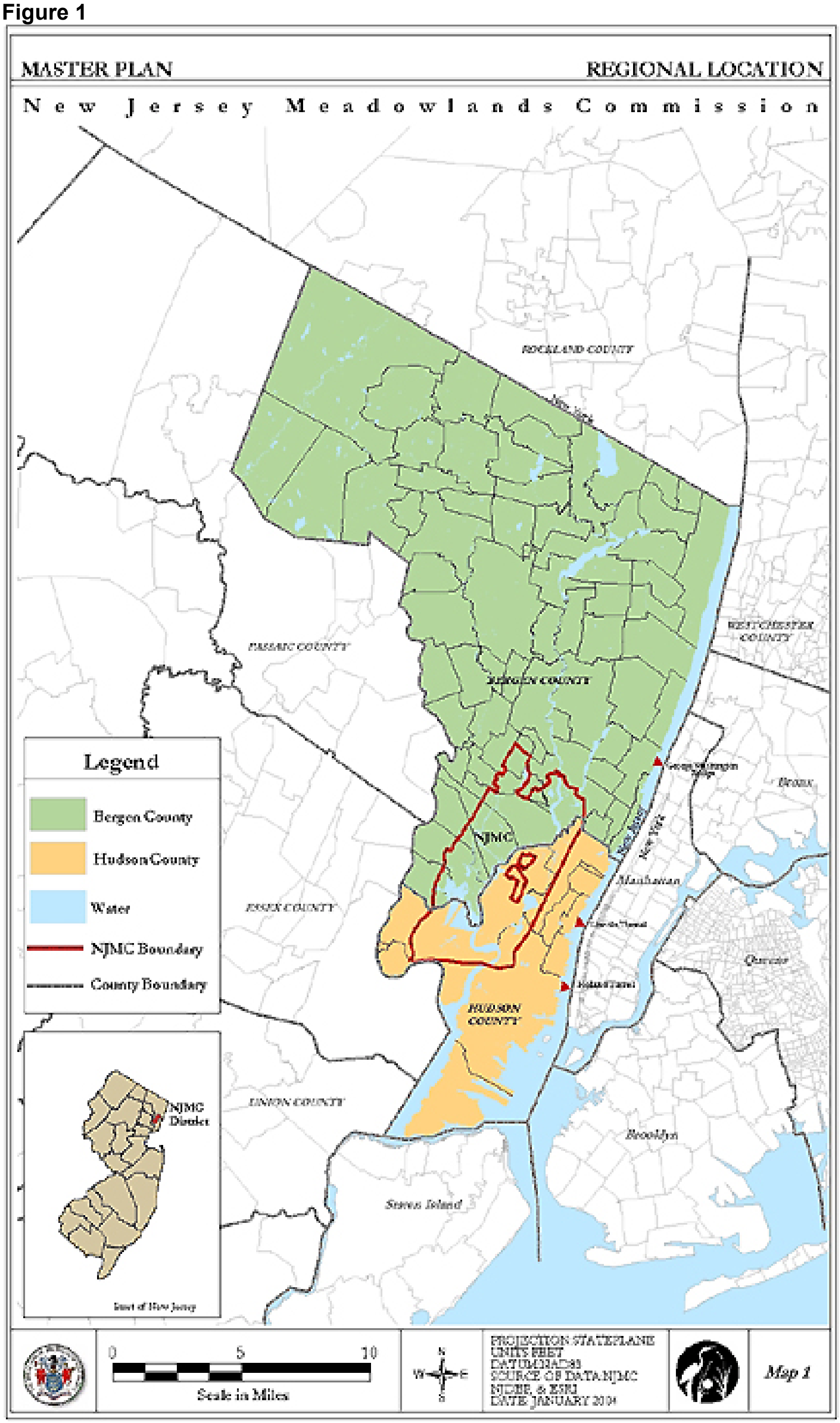

Figure 1: New Jersey Meadowlands Commission Regional Location Map
Photo Credit: New Jersey Meadowlands Commission

Figure 2

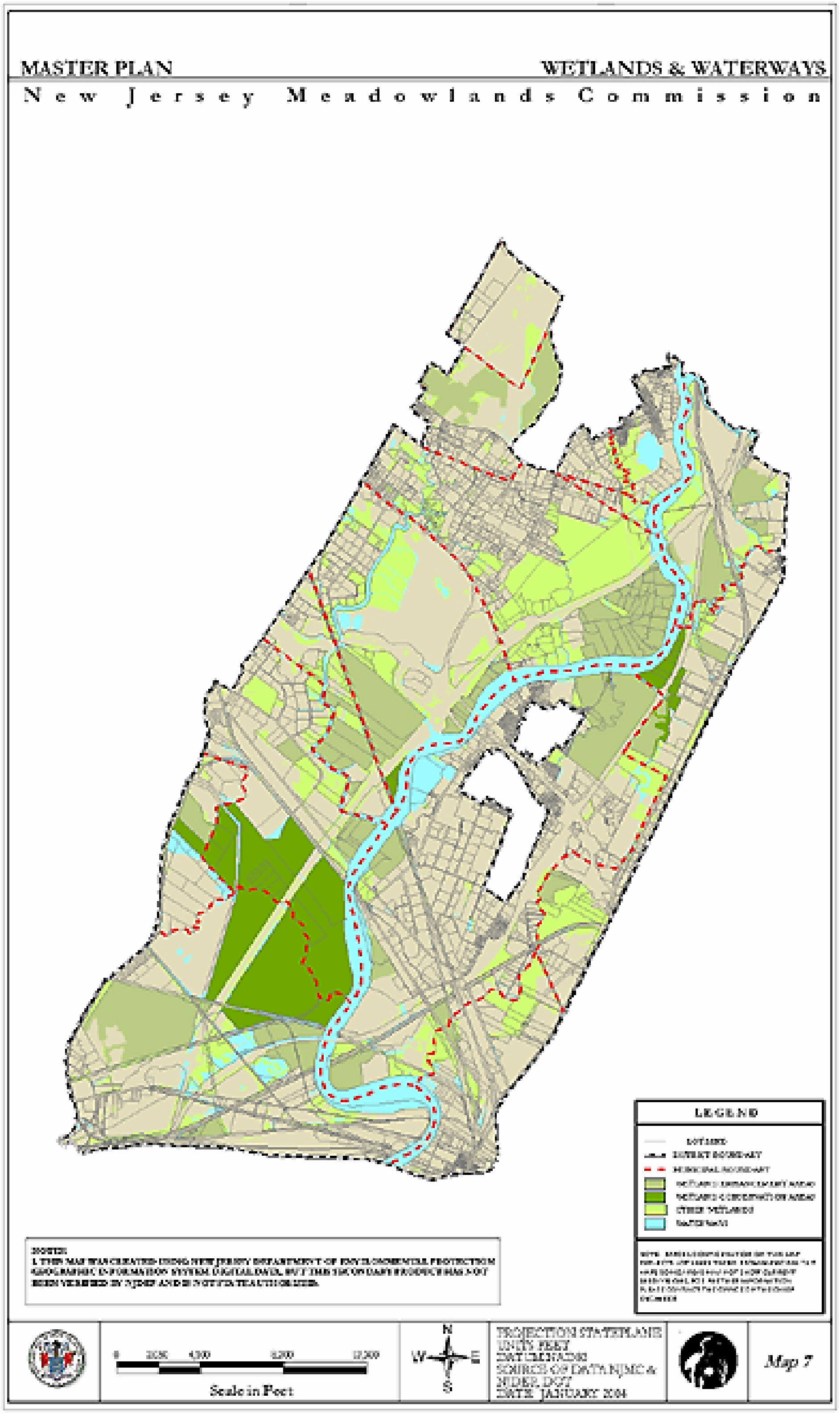

Figure 2: New Jersey Meadowlands Commission Wetlands Map
Photo Credit: New Jersey Meadowlands Commission

Figure 3

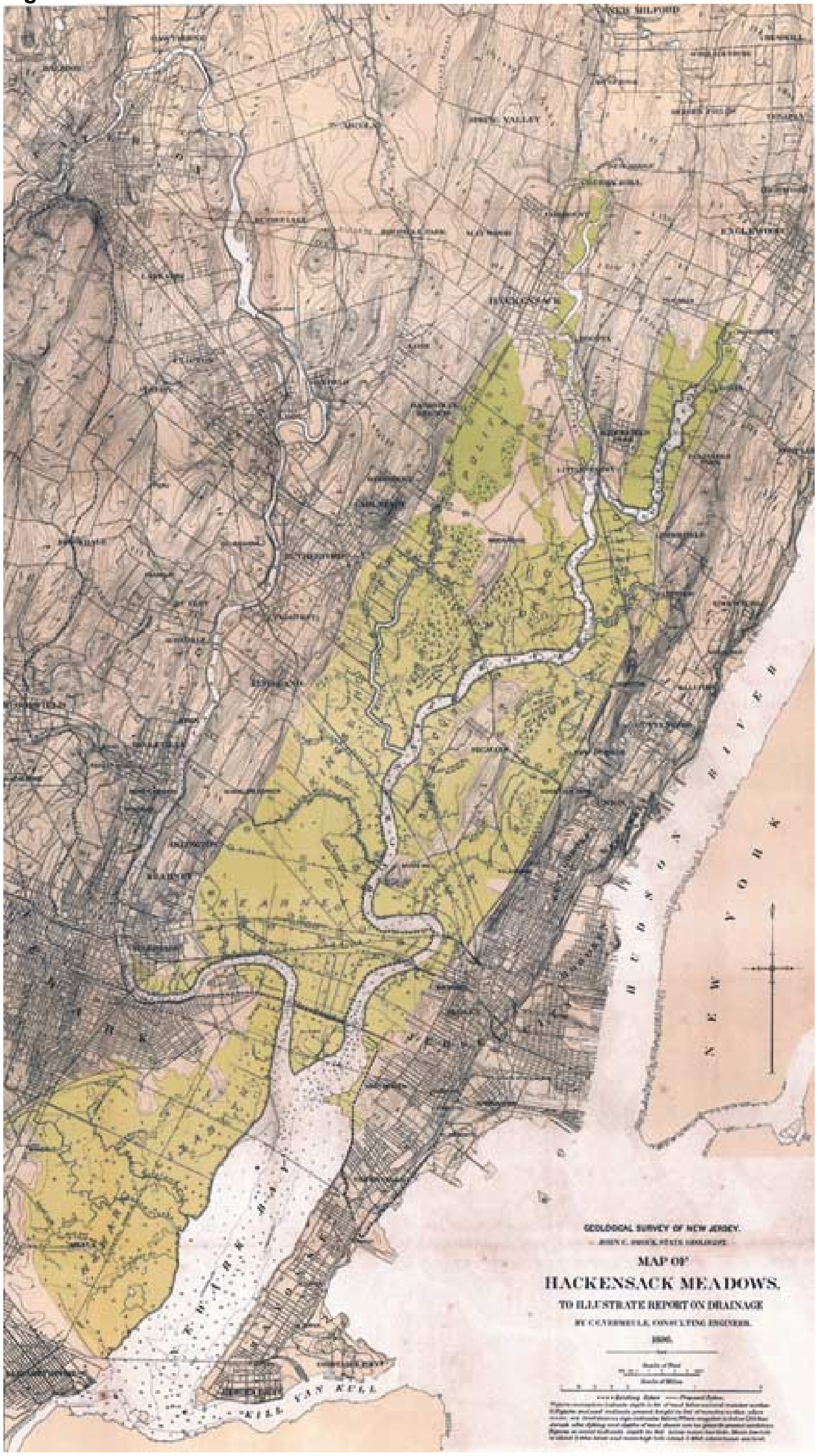

Figure 3: 1896 Map of Hackensack Meadows
Photo Credit: U.S. Fish and Wildlife Service

Figure 4

Figure 4: Satellite Image of the Meadowlands
Photo Credit: NASA

Figure 5

Figure 5: RPA Map: Nature's Estuary, the Historic Tidelands of the New York New Jersey Harbor Estuary
Photo Credit: Regional Plan Association, New York

Figure 6

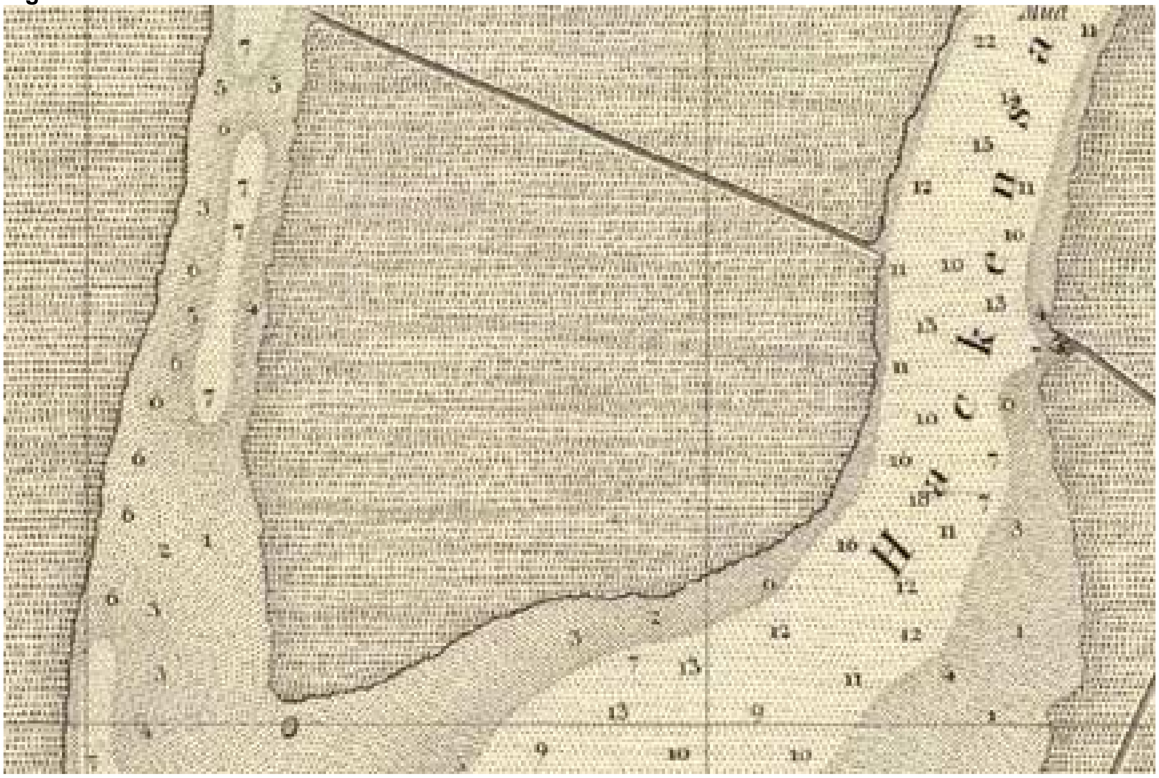

Figure 6: 1845 U.S. Coast Survey Map Depicting Depth Readings of Passaic and Hackensack Rivers
Photo Credit: David Rumsey Map Collection

Figure 7

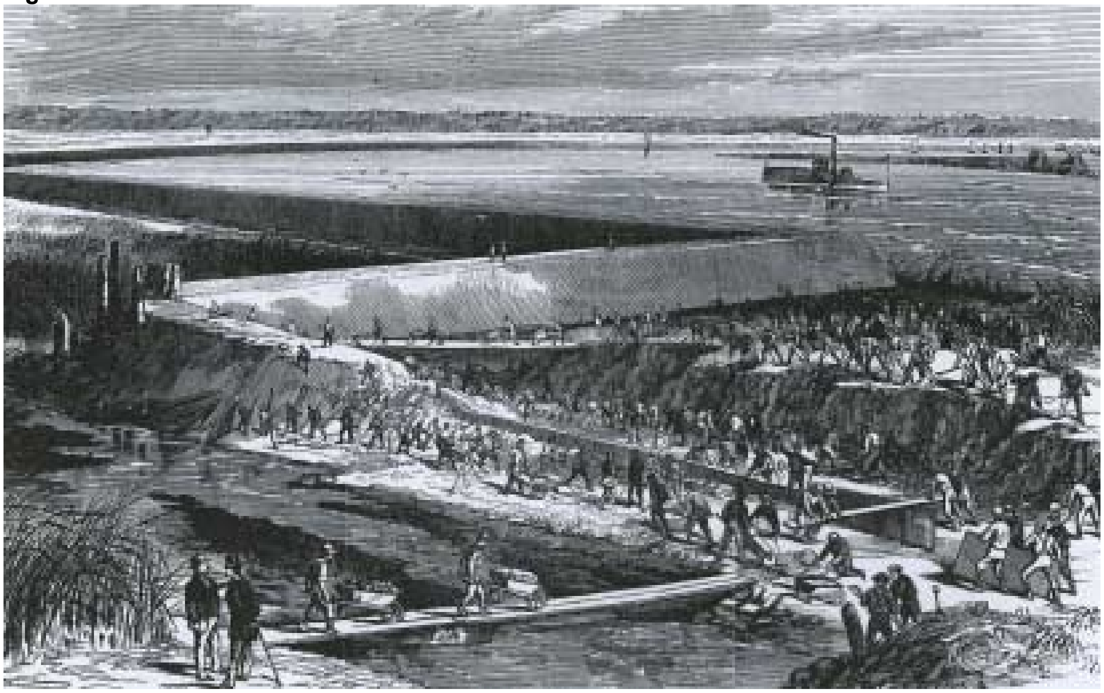

Figure 7: Reclamation of Lower Hackensack Meadows (1), 1867
Photo Credit: ***Frank Leslie's Illustrated Newspaper*****, November 16, 1867.**

Figure 8

Figure 8: Reclamation of Lower Hackensack Meadows (2), 1867
Photo Credit: ***Frank Leslie's Illustrated Newspaper*****, November 16, 1867.**

Figure 9

Figure 9: Tidal Current Chart, New York Harbor, 1946
Photo Credit: U.S. Department of Commerce, Coast and Geodetic Survey

Biodiversity Patterns and Conservation in the Hackensack Meadowlands, New Jersey*

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Abstract

The 8,300 hectares (roughly 20,500 acres) of wetlands, uplands, and developed areas of the Hackensack Meadowlands in northeastern New Jersey are a major urban biodiversity reservoir in the New York metropolitan region. Species documented so far include 260-plus birds (33 of which are state-listed as endangered, threatened, or declining), 22 mammals, 51-plus fishes, 51 bees, and 420 plants. Wetlands make up 3,200 hectares (roughly 7,800 acres) of the Meadowlands, and they include brackish and freshwater marshes dominated by the common reed (*Phragmites australis*) as well as cordgrass (*Spartina*) marshes and hardwood swamps. Upland habitats are found on bedrock hills and wetland fill. The mix of wetlands and uplands gives rise to a diversity of plant and animal life. The marshes and swamps of the Meadowlands provide critical habitat for many species, and several species also rely on the upland habitat types. Relatively well-studied groups, such as birds and fishes, have received the most attention from local conservation planners. However, other, poorly studied organisms (invertebrates, for example) also contribute to the biodiversity value of the Meadowlands and should be taken into account. Conservation planners should also consider the constraints and opportunities imposed by the urban context of the Meadowlands, especially with regard to the management of habitats dominated by *Phragmites*. Factors associated with urbanization, such as sediment contamination, as well as the presence of many common and rare species in reed marshes, indicate that alteration rather than eradication of reed stands should be considered. In addition to a continued focus on wetlands, successful maintenance and enhancement of biodiversity in the Meadowlands will require attention to upland habitats, including some that are artificial. Principles of biodiversity conservation in the Meadowlands are broadly applicable to large urban wetlands elsewhere.

Keywords: Biodiversity; degraded wetlands; habitat management; Hackensack Meadowlands, New Jersey; *Phragmites*; urban wildlife; wetland restoration

Introduction

With nearly all the 50 largest metropolitan areas in the United States located on coasts or major waterways, urban expansion has unavoidably influenced, and been influenced by, wetlands. Because urban wetlands are intensely altered by human activities, they have often been accorded

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lower priority for protection by regulators and environmentalists. However, growing recognition of the important functions of urban wetlands in densely settled regions, including water filtration, flood control, and green space, has begun to reverse this attitude. Recent research has demonstrated that urban wetlands have unique ecological and social values precisely *because* they are located within an urban context (Ehrenfeld, 2000).

Other research has demonstrated that species diversity in urban habitats is low compared with more rural or pristine habitats due to the dominance of a few hardy generalist or invasive species and a loss of sensitive, specialist species (Adams, 1994). Because diversity of species is an important measure of the value of wetlands, this has often led to the destruction of natural wetlands in urban areas. We argue that, to the contrary, some urban wetlands support a high richness and abundance of fauna and flora, and that this diversity of species is influenced by the urban context in both positive and negative ways. Furthermore, species richness depends on the taxa studied and the adequacy of survey techniques in detecting rare species. The importance of common species increases in urban areas, where many species common in rural or wildland areas do not survive, and where wildlife is available for viewing by large numbers of people. We believe a different framework is needed for evaluating biodiversity in urban wetlands. We therefore present a case study of the Hackensack Meadowlands, which contain 3,200 hectares (7,907 acres) of wetlands just five kilometers[*] from midtown Manhattan.

Many important decisions are being made about landscape preservation, habitat management and restoration, remediation of contamination, and development in the Meadowlands. For example, there are plans to preserve as a wildlife refuge and environmental park a total of more than 3,000 hectares (7,413 acres) of wetlands, and approximately 1,400 hectares (3,460 acres) have already been preserved (Kiviat & MacDonald, submitted for publication). There is an ongoing project to cap and develop 531 hectares (1,312 acres) of inactive solid waste landfills for golf courses and associated facilities ("Landfills to Open Space," 2003). The largest remaining privately owned wetland in the Meadowlands, the 236-hectare Empire Tract, is about to be preserved, and decisions on how to manage this site will need to be made. A comprehensive restoration plan for the Meadowlands is being prepared. Although considerable funds have been expended on biological studies, most taxa, biodiversity patterns, and ecological processes have been considered barely or not at all in the planning of land use and restoration.

In this paper, we analyze biodiversity patterns, identify the significance of the Meadowlands for biological conservation, and discuss implications for land-use planning and habitat management. This discussion is intended to broaden the framework for decision making in the Meadowlands and other areas of the New York–New Jersey metropolitan region. As urbanization rapidly proceeds, areas like the Meadowlands are increasingly important for conservation and offer a glimpse of the environmental future of many now rural and wildland areas.

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[*] Except where noted, measurements throughout this paper are in metric notation; conversions to U.S. equivalents can be obtained at http://www.onlineconversion.com/length.htm.

Methods

Study Area

The Hackensack Meadowlands proper are about 16 kilometers long north to south and cover an area of about 8,300 hectares (roughly 20,500 acres) that was once almost entirely wetland (see Quinn, 1997; Day, Staples, Russell, Nieminen & Milliken, 1999). The Hackensack Meadowlands District consists of 7,889 hectares (19,494 acres) of residential, commercial, and industrial development; landfills; roads and railways; natural uplands; and wetlands (Figure 1). In this paper, we also consider adjoining wetlands and floodplains, including the narrow riparian area extending north from Teterboro along the upper Hackensack River estuary. The Meadowlands are shown on U.S. Geological Survey 7.5-minute topographic map quadrangles (Elizabeth N.J.–N.Y. 1995, Hackensack N.J. 1997, Jersey City N.J.–N.Y. 1967 [Photorevised 1981], Orange N.J. 1955 [Photorevised 1970], Weehawken N.J.–N.Y. 1967, Yonkers N.J.–N.Y. 1956).

Bedrock underlying the Meadowlands is shale, sandstone, and, locally, diabase and hornfels (Wolfe, 1977). The elevation of the wetlands is 0 to about 3 meters above sea level; bedrock hills and landfills rise to as much as 30 to 50 meters. Thirty-meter clay bluffs and 10-meter cliffs of shale and sandstone occur locally at the edges of the Meadowlands (Bosakowski, 1983; Kiviat, personal observation). Deep mineral and organic wetland soils are found in most of the Meadowlands, and in limited areas there are natural upland soils, most of which have been highly altered.

Meadowlands habitats include the deep tidal channel of the Hackensack River main stem; a variety of brackish tidal creeks, canals, and ditches; tidal marshes ranging from nearly fresh to very brackish; impounded brackish and nearly fresh marshes with little or no tidal flux; nontidal marshes and hardwood swamps; woodlands, shrublands, and meadows on low-lying wetland fill or elevated solid waste landfills; meadows, scrub, and woodland on clayey or sandy soils; road verges, dikes and berms, industrial areas, residential yards, urban parks, and other developed areas; storm-water ponds and clay pit lakes; and clay bluffs and bedrock outcrops that vary from quarried to nearly undisturbed (Figures 2 to 8; Kiviat & MacDonald, 2002). Only stumps remain from once extensive Atlantic white cedar (*Chamaecyparis thyoides*) swamps (Heusser, 1963; Harmon & Tedrow, 1969).

Salinity in the Hackensack River ranges from 0 to about 24 parts per thousand (ppt) (C. Woolcott, personal communication, 2004). Salinity is generally highest in late summer and fall and lowest in spring (Kraus & Bragin, 1988). Tidal circulation has been modified by the Oradell Dam at the upper end of the estuary and by ditches, dikes, tide gates, dams, road beds, fill, and subsequent breaching of a few water-control structures. These structures drained freshwater from many areas, impounded other areas, or prevented brackish water intrusion.

Until the late 1960s, most of the sewage discharged into the Hackensack River was untreated, according to a study by the Interstate Sanitation Commission (Crawford, Bonnevie, Gillis & Wenning, 1994). There are now 7 sewage treatment plants, 32 combined sewer overflows and 12 emergency overflows in the Meadowlands District (Day et al., 1999). The annual range of dissolved oxygen is 1.0 to 15.5 milligrams per liter (Day et al., 1999) in the Hackensack River. Lead, mercury, zinc, chromium, PCBs, PAHs, petroleum hydrocarbons, and DDT metabolites contaminate the soils, submerged sediments, water column, and aquatic life of the Meadowlands, in some places reaching levels considered hazardous under federal regulatory standards (Bonnevie, Wenning, Huntley & Bedbury, 1993; Crawford et al., 1994; Huntley, Bonnevie, Wenning & Bedbury, 1993; Huntley, Bonnevie & Wenning, 1995; Hackensack Meadowlands Development Commission [HDMC], 1997, 2002; Durell & Lizotte, 1998).

Data Sources

Much biological fieldwork has been conducted in the Meadowlands, but few results have been published in the formal literature. This paper is based on data from formal scientific literature, gray literature (e.g., agency reports and consulting reports), master's and Ph.D. theses, a few popular articles, unpublished data, and discussions with scientists and naturalists (see Kiviat & MacDonald, 2002). We also conducted reconnaissance fieldwork in a number of areas of the Meadowlands from 1999 to 2004. In most cases there has been no analysis of how the Meadowlands support biodiversity. We set the stage for more formal analyses by assessing the state of knowledge about species diversity and the underlying ecological processes that support it. We also discuss opportunities to maintain or enhance Meadowlands biodiversity.

Results

Plant and Animal Life

Despite decades of study in the Meadowlands, data on the distribution and abundance of organisms are mostly qualitative and narrow in taxonomic representation. Birds are moderately well studied at the site level, and the fishes and macrobenthos have been sampled in the larger waterways and a few smaller tributaries. Most other taxa have been studied little or not at all. Table 1 summarizes what is known about various types of organisms in the Meadowlands. Here we discuss selected taxa of conservation interest or other importance.

Mammals

Of about 45 mammal species occurring in northeastern New Jersey (Whitaker & Hamilton, 1998), 22 have been reported from the Meadowlands, including 4 introduced species (dog, cat, Norway rat, and house mouse). Only 2 of 6 possible species of shrews and moles, 1 of 7 bats, and 8 of 16 rodents have been reported, indicating that there should be further fieldwork on the smallest mammals. Most reported Meadowlands mammals are common, urban-tolerant species of wetland or upland habitats (Kiviat & MacDonald, 2002), with the possible exceptions of the masked shrew (*Sorex cinereus*), eastern mole (*Scalopus aquaticus*), and meadow jumping mouse (*Zapus hudsonicus*). Two mammals known to be sensitive to environmental contaminants, mink (*Mustela vison*) and harbor seal (*Phoca vitulina*), are very rare in the Meadowlands (Kiviat & MacDonald, 2002).

The eastern cottontail (*Sylvilagus floridanus*), white-footed mouse (*Peromyscus leucopus*), meadow vole (*Microtus pennsylvanicus*), common muskrat (*Ondatra zibethicus*), Norway rat (*Rattus norvegicus*), and house mouse (*Mus musculus*) are apparently common and presumably important prey of predatory mammals, birds, and snakes. The Norway rat and house mouse are believed to have declined greatly in recent years due to the closing of all but one of the many garbage landfills. The common muskrat may be considered a keystone species because its feeding and building activities have major effects on vegetation, soils, microtopography, and animal habitats (Kiviat, 1978; Connors, Kiviat, Groffman & Ostfeld, 2000). The muskrat has declined in Hudson River marshes in recent decades (Kiviat, unpublished) and should be monitored in the Meadowlands. The beaver (*Castor canadensis*) is unknown (A. Galli, personal communication, 2001), and the white-tailed deer (*Odocoileus virginianus*) is mostly limited to the forests of northern areas (R. Kane, personal communication, 2000). Regional trends suggest that both species are likely to increase, and this would have substantial influences on the Meadowlands environment.

Birds

More than 260 species of birds, 5 of them introduced species, have been reported in the Meadowlands (New Jersey Turnpike Authority [NJTA], 1986; Meadowlands Environment Center, n.d.; Kiviat, personal observation). This species diversity, which includes resident, migrant, breeding, and wintering birds, is supported by the large expanses of estuarine marshes interspersed with diverse freshwater and upland habitats. There are 33 state-listed endangered, threatened, declining, or rare birds in the Meadowlands: 12 hawks and owls, 7 songbirds, 4 herons, 4 Charadriiformes, 2 rallids, and 4 others (a grebe, a cormorant, a hummingbird, and a woodpecker). Twenty of the listed species are generally associated with waters or wetlands, nine with grasslands, and four with upland forests.

The Meadowlands are one of 11 critical migration corridors in New Jersey identified by Dunne, Kane, and Kerlinger (1989). At one site, daily counts of migrant sandpipers have exceeded 5,000 in most years (Day et al., 1999). The Meadowlands are used intensively by wintering, breeding, and migrating waterfowl and have been designated an area of special concern under the North American Waterfowl Management Plan (Day et al., 1999). Midwinter aerial survey counts of waterfowl in the Meadowlands average 2,000 birds per day (Day et al., 1999). In addition, the Meadowlands are an important foraging area for herons from nesting colonies in other areas of the New York–New Jersey Harbor estuary complex (Murray, 1990; Day et al., 1999).

The Meadowlands support some surprising breeding birds. The American woodcock breeds in quaking aspen (*Populus tremuloides*) patches and other vegetation on garbage landfills (Rawson, 1993; R. Kane, personal communication, 2000; Kiviat, personal observation). Nests of the least tern (*Sterna antillarum*), listed as endangered in New Jersey, have been found on dredged material deposits and the roof of a commercial building (Day et al., 1999; R. Kane, personal communication, 2001; K. Spendiff, personal communication, 2003). Regionally rare breeding populations of the ruddy duck (*Oxyura jamaicensis*), which nests solely in common reed (*Phragmites australis*) marshes in New Jersey (Kane, 2001a), occur at two brackish water impoundments. At least one pair of northern harrier (*Circus cyaneus*) breeds in the Meadowlands (NJTA, 1986; Kane & Githens, 1997; Day et al., 1999; N. Tsipoura, personal communication, 2003); the statewide breeding population of this species is listed as endangered. Roosting congregations of northern harrier and short-eared owl (*Asio flammeus*), principally in common reed stands, no longer exist, probably because the closure of most garbage landfills greatly reduced populations of small rodent prey (Bosakowski, 1983, 1986; T. Bosakowski, personal communication, 2004; H. Carola, personal communication, 2004). Upland meadows and patches of woody vegetation, principally on fill, as well as small remnant forests in the north, support large numbers of Neotropical migrant warblers, vireos, kinglets, and flycatchers during spring and fall migrations (Kane & Githens, 1997). Fleshy-fruited shrubs and vines make upland habitats highly attractive to fall migrants (Suthers, Bickal & Rodewald, 2000). Limited areas of swamp or upland forest restrict the potential breeding habitat for many species. The swamp forest at Teterboro Airport has poorly developed shrub and herb layers and low breeding-bird diversity (MacDonald, personal observation). There are few data on upland birds.

Reptiles and Amphibians

Of 15 species of snakes occurring in northeastern New Jersey (Conant & Collins, 1991), 8 have been reported in the Meadowlands. Documentation is scant for three of these, and some may have been extirpated. Contaminants and the limited extent of natural uplands and low-salinity habitats may limit snake diversity. The northern water snake (*Nerodia sipedon*) and other species may once have been common (Quinn, 1997).

Six of the eight turtle species occurring in northeastern New Jersey have been reported in the Meadowlands (excepting sea turtles; Conant & Collins, 1991; Kiviat & MacDonald, 2002). Documentation is scant for two of the six species. Snapping turtle (*Chelydra serpentina*) and diamondback terrapin (*Malaclemys terrapin*) are locally common. Female terrapins attempting to cross, or nest on, major highways such as the New Jersey Turnpike are often killed (Urffer, 2002), and such road mortality may limit turtle populations in general, because they are highly mobile.

Ten of the 26 species of amphibians (13 frogs and 13 salamanders; Conant & Collins, 1991) occurring in northeastern New Jersey have been reported in the Meadowlands. Documentation is scant for six of the ten. A NJTA study (1986) found only two species, green frog (*Rana clamitans*) and Fowler's toad (*Bufo fowleri*). No salamander has been reported. The scarcity of natural upland soils and high-quality, fresh surface waters probably accounts for the low species richness of amphibians. Many reptile and amphibian species are intolerant of urbanization (e.g., Schlauch, 1976). One Meadowlands reptile is an introduced species, the red-eared slider (*Trachemys scripta elegans*); all amphibians are native.

Fishes

The Meadowlands are considered important habitat for migratory fishes (Day et al., 1999), and many migratory species have been found there, but there is little information on spawning and nursery areas. Atlantic tomcod (*Microgadus tomcod*), formerly listed as threatened in New Jersey, uses the Hackensack River from near its mouth to Sawmill Creek as a nursery, refuge, and spawning area (Kraus & Bragin, 1988). However, the species was very rare during a 2001–2003 resurvey (C. Woolcott, personal communication, 2004). The lower Hackensack River system was declared essential fish habitat by the National Marine Fisheries Service for six species: red hake (*Urophycis chuss*), black sea bass (*Centropristis striata*), Atlantic butterfish (*Peprilus triacanthus*), and three flounders (Pleuronectidae and Bothidae), and designation was pending for bluefish (*Pomatomus saltatrix*) and Atlantic herring (*Clupea harengus*) (Day et al., 1999).

Low-salinity tidal marshes in the Hudson River support moderately rich fish communities (Mihocko et al., 2003). In the Meadowlands, Feltes (2003) sampled 13 species during four years in mitigated and nonmitigated portions of Harrier Meadow, whereas the U.S. Army Corps of Engineers (2000) reported only 4 species in small waterways on the Empire Tract. Lower species richness in the Corps of Engineers data may be due to habitat diversity and sampling effort, but also to low dissolved oxygen (DO) and other water quality problems, which reduce species diversity in marsh creeks, small ponds, and even the mainstem of the Hackensack River (e.g., Day et al., 1999). In the Mill Creek system of the Meadowlands, Raichel, Able, and Hartman (2003) found that mummichog (*Fundulus heteroclitus*), the most abundant Meadowlands fish, was less numerous as larvae in common reed habitat than in smooth cordgrass (*Spartina alterniflora*) habitat, although the abundance of adults was similar. They identified two potential explanatory factors: the tendency of common reed to fill in irregularities in the marsh surface that are used by fish larvae at lower tide stages, and lower abundance of small animals that constitute potential prey for mummichog larvae. The spotfin killifish (*Fundulus luciae*) has been reported just downriver of the Meadowlands (Yozzo & Ottman, 2003), suggesting that this species and other uncommon fishes may occur in the Meadowlands.

Invertebrates

There have been few surveys of aquatic and terrestrial invertebrates in the Meadowlands. The NJTA (1986), from an area that included the Meadowlands and extended well to the south, reported the following 50 estuarine and freshwater benthic macroinvertebrates: 3 Oligochaeta, 8 Polychaeta, 1 Hirudinea (leech), 7 Gastropoda (snails), 4 Bivalvia, 15 Crustacea, 1 Tunicata (tunicate), 1 Tentaculata (ctenophore), 1 Nematoda (roundworm), 4 Insecta, 1 Anthozoa, 1 Bryozoa (moss-animal), 1 Cnidaria, 1 Hydrozoa, and 1 Rynchocoela. The same study reported approximately 42 species from the Hackensack River and its major tributaries (Kiviat & MacDonald, 2002). Organisms tolerant of pollution and low DO were dominant (NJTA, 1986). Kraus and Bragin (1988) found 53 species in the Hackensack River and tributaries. Strayer and Smith (2001) reported 218 species from the freshwater-tidal Hudson River, of which 146 were associated with soft sediment. The larger number of species reported from the Hudson compared with the Hackensack may be due to the larger size of the system, more study, and identification to lower taxonomic levels as well as to better environmental quality (however, the Hackensack studies spanned a broader salinity gradient).

The clam shrimp *Caenestheriella gynecia* was abundant in permanent rain puddles on the dirt surface of a gas pipeline road in the Empire Tract (Kiviat & MacDonald, 2002). This species occurs only at about ten known localities range-wide in the eastern U.S. (R.E. Schmidt, personal communication, 2003).

Butterflies require specific larval food plants, and adults of most species require nectar sources. Many butterflies have narrow habitat affinities, and nonmigratory species may require specific overwintering habitats. Many species, some now rare in New Jersey, were reported a century ago from "Newark" (Gochfeld & Burger, 1997), which probably included the Hackensack Meadowlands as well as the now-filled Newark Meadows. Certain high-quality nectar plants are common in the Meadowlands (e.g., purple loosestrife, *Lythrum* *salicaria*, an introduced invasive species that is visited by many species). Although larvae of the broad-winged skipper (*Poanes viator*) specializes on common reed and is probably very abundant in the Meadowlands, the larvae of many species of skippers and other butterflies feed on wetland grasses and sedges other than common reed and cordgrasses. The Meadowlands lack extensive stands of most other grasslike plants, which may limit butterfly diversity.

There is a general concern about the decline of native pollinators, especially bees, in North America (Shepherd, Buchmann, Vaughan & Black, 2003). A diverse community of mostly native bees was studied at an inactive garbage landfill in the Meadowlands, where there were various nectar plants and nest habitats in eroding soil and hollow plant stems, including those of common reed (Yurlina, 1998; G.R. Robinson, personal communication, 2003). Other types of wetland fill containing nectar plants such as goldenrods (*Solidago*), the introduced invasive Japanese knotweed (*Fallopia japonica*), and purple loosestrife are also potentially attractive to bees, butterflies, and other flower visitors.

An area of the Meadowlands was surveyed for lady beetles (Coccinellidae) and their most important prey, aphids (Aphididae) (Angalet, Tropp & Eggert, 1979). The mealy plum aphid (*Hyalopterus pruni*), which alternates between common reed and woody plants of the genus *Prunus*, and several aphids found on mugwort (*Artemisia vulgaris*), an introduced species, were very abundant and the principal prey of lady beetles in the Meadowlands (Angalet et al., 1979). A native and an introduced lady beetle overwintered in association with the tussock-forming redtop grass (*Agrostis gigantea*), common mullein (*Verbascum thapsus*), and planted pines (*Pinus sylvestris, P. resinosa*), all introduced species (Angalet et al., 1979). The 15 species of aphid host plants reported were mostly introduced, weedy species of ruderal habitats or upland meadows.

Human-biting ticks are scarce in the Meadowlands, probably due to the limited occurrence of woodlands and white-tailed deer. Wood tick (*Dermacentor variabilis*) and black-legged (deer) tick (*Ixodes scapularis*) occur locally (Kiviat, personal observation).

Vascular Plants

The Meadowlands have a moderately diverse flora (Sipple, 1972). A list from Brooklyn Botanic Garden’s New York Metropolitan Flora Project, included in Kiviat and MacDonald (2002), contained 416 species. The Torrey Botanical Society reported 115 and the NJMC reported 145 species from Laurel Hill (Quinn, 1997), a highly altered igneous upland and wetland fill area.

New York City supports a number of rare plant species (e.g., Venezia & Cook, 1991), yet few species considered rare statewide have been reported from the Meadowlands. In Kingsland Creek and upper Penhorn Creek there are large stands of floating marsh-pennywort (*Hydrocotyle ranunculoides*) (Kiviat, personal observation), which are ranked S1 (the “S” rank, from the New Jersey Natural Heritage Program ranking system, refers to the number of localities where the species has been found in recent years in the state, with S1 the rarest and S5 the most common). A single plant of wafer-ash (*Ptelea trifoliate*), also ranked S1, was found on Laurel Hill; it is unclear whether this is a natural occurrence (Labriola, 2000).

Several other native plants occurring in the Meadowlands may be rare in northeastern New Jersey. These include five-angled field dodder

(*Cuscuta pentagona*), beardtongue (*Penstemon digitalis*), starry campion (*Silene stellata*), Virginia mountain mint (*Pycnanthemum virginianum*), pale corydalis (*Corydalis sempervirens*), and post oak (*Quercus stellata*) (Labriola, 2000; Kiviat, personal observations). Many fen and bog species were once found in the Meadowlands (Sipple, 1972), and some may survive in swamps of the northern Meadowlands, for example, at Teterboro Airport. The Metropolitan Flora list for the Meadowlands includes only four *Carex* species (sedges). This may reflect degradation of much of the Meadowlands, although additional survey work in the fresh swamps and wet clay meadows of the northern Meadowlands would surely find many additional *Carex*.

Mosses, Lichens, Terrestrial Algae, and Fungi

Although there has been no survey of Meadowlands "cryptogams" exclusively, diversity appears to be low. Mosses and lichens are rare, local, and mostly limited to small patches. Mosses and lichens do not generally thrive in urban areas due to pollution, low humidity, and acidification of bark due to air pollution (Gill & Bonnett, 1973), and the scarcity of large living and dead tree trunks, natural rock surfaces, natural soils, and other preferred substrates. This may inhibit macrofungi as well (Gill & Bonnett, 1973). There are some large tree trunks, mostly dead wood of Atlantic white cedar, but the majority of them are subject to flooding by brackish water, which presumably limits the diversity of fungi. Because they are sensitive to air pollution and therefore are rare in cities generally, we were surprised to find any lichens in the Meadowlands. The varied mineral composition of the igneous uplands (van Houten, 1969; Facciolla, 1981) is potentially capable of supporting a diverse community of mosses with different tolerances and requirements; however, surveys have yet to be conducted to determine if such a community exists in the Meadowlands. Sperling and Morgan (2003) reported 77 species of bryophytes from specimens collected in the 1970s and 1980s in the 578 hectares (1,428 acres) of two parks in Queens, New York, and Feuerer, Hertel and Deuter (2003) reported 226 species of epiphytic lichens from Munich, Germany, although 102 had not been found in a century. Only 28 species of lichens were reported in nearby Westchester County, New York (Prince, 1978). No taxonomic data are available on microfungi or other soil microorganisms in the Meadowlands.

Discussion

The patterns of biodiversity in the Meadowlands are a result of natural and artificial conditions acting at various spatial scales. In this section we outline some major factors affecting biodiversity and briefly discuss some of the taxa most affected.

Pollutants

Low dissolved oxygen, high turbidity, and high temperatures may lower diversity of fishes and benthic macroinvertebrates. Levels of metals in marsh plants (Kraus, 1988) are potentially toxic to herbivores such as muskrats, and Kraus (1989) showed that metals moved from sediments via chironomid midges to tree swallows in the Meadowlands. Despite at least locally high levels in Meadowlands sediments, studies have found comparatively low levels of metals and PCBs in fishes, turtles, and birds (Galluzzi, 1981; Albers, Sileo & Mulhern, 1986; Santoro & Koepp, 1986; Weis, Weis & Bogden, 1986; C. McIntyre, unpublished data cited in Kiviat & MacDonald, 2002).

It is remarkable that a region as contaminated as the Meadowlands can support the biodiversity observed and that documented contaminant levels are fairly low in fish-eating animals. Possible explanations are 1. fish-and crustacean-feeding birds such as pied-billed grebe, herons, bitterns, gulls, and terns are consuming mummichogs, fiddler crabs, or other prey that do not accumulate large amounts of contaminants (see Galluzzi, 1981); 2. studies have missed the sites, prey species, predator species, population classes, or tissues in which contamination is high; or 3. common reed and other plants are sequestering metals, or reduced conditions (lack of oxygen) in the sediments are immobilizing metals, making them unavailable to organisms higher in the food chain. Yet potential adverse effects of modest levels of mercury on health of fishes (Uryu, Malm, Thornton, Payne & Cleary, 2001) and waterbirds (Odom, 1975) may be relevant to the Meadowlands: Weis, Smith, Zhou, Santiago-Bass, and Weis (2001) reported that mercury-contaminated mummichogs from 15 kilometers south of the Meadowlands were slower to capture prey and escape predators, had more detritus in their diet, and had reduced growth and longevity compared with the same species in cleaner areas. Further study of contaminants in animal tissues is needed to confirm the low levels reported in the Meadowlands, and research is needed on health effects in animals. State Health Advisories (New Jersey Department of Environmental Protection, 2004) concerning PCBs and dioxin warn against any consumption of blue crab or striped bass from the Hackensack River estuary, and recommend American eel (*Anguilla rostrata*), white catfish (*Ameiurus catus*), and white perch (*Morone americana*) be eaten only once per year by the general population and not at all by high-risk individuals.

Sulfur oxides, nitrogen compounds, ozone, metals, fluoride, and other air pollutants have a wide variety of impacts on organisms (Barker & Tingey, 1992). The low diversity of lichens and mosses in the Meadowlands is presumably at least partly due to air pollution.

Invasive Plants

The proliferation of invasive nonnative or native organisms alters the composition of plant and animal communities and may cause changes in soils, hydrology, fire regime, nutrient cycling, or other habitat characteristics, thus affecting the abundance of many other species (e.g., Cox, 1999). Pollution and alteration of habitats commonly favor invasive over noninvasive plants. Invasive plants are an important concern in the Meadowlands, where common reed and mugwort dominate thousands of hectares, and tree-of-heaven (*Ailanthus altissima*), princess tree (*Paulownia tomentosa*), white mulberry (*Morus alba*), black locust (*Robinia pseudoacacia*), Himalayan blackberry (*Rubus discolor*), Japanese knotweed, purple loosestrife, and other exotics are abundant. Although hard data are lacking, some native plants are probably absent from the Meadowlands due to the proliferation of invasives.

Common reed is believed to build up tidal marsh surfaces and fill in headwater tidal creeks that fish, crabs, and grass shrimp use to move between marshes and open estuary (Weinstein & Balletto, 1999; Windham & Lathrop, 1999; Able & Hagan, 2000; Rooth & Stevenson, 2000). Large-scale wetland-restoration projects in the Meadowlands have aimed to remove or reduce reed stands and increase tidal flushing to improve access to the marshes for estuarine fishes and nektonic invertebrates, as well as to increase mudflat or pond habitat (Kiviat & MacDonald, 2002). Nonetheless, there are few data demonstrating the reed's effects on soils, hydrology, and plant and animal life specifically in the Meadowlands where wetlands are more degraded than in reed study areas elsewhere (see Kiviat & MacDonald, 2002). Common reed has been shown to have both negative and positive effects on habitats and biodiversity in the Meadowlands and elsewhere in the northeastern states (Kiviat & MacDonald, 2002). Monitoring data show that reed removal has reduced the number of birds that breed in reed marshes and that those birds have been partly replaced by the foraging and migrant birds of the new (intertidal cordgrass marsh, pool, or mudflat) habitats (A. Seigel, personal communication, 2004).

The Built Environment

Some native species benefit from the built environment. The chimney swift (*Chaetura pelagica*) is associated with increased building densities in other regions (Savard & Falls, 2001). The peregrine falcon (*Falco peregrinus*) benefits from increased abundance of prey in urban habitats, such as rock pigeons (*Columba livia*) and European starlings (*Sturnus vulgaris*) (Jenkins & Avery, 1999). In or near the Meadowlands, native species that have been observed using the built environment include woodchuck (*Marmota monax*), denning in berms and landfill cover; least tern, nesting on a roof; peregrine falcon, nesting on bridges and buildings; barn swallow (*Hirundo rustica*), nesting in observation blinds and under bridges; diamondback terrapin, nesting on highway shoulders), and native bees, nesting and foraging at inactive landfills. Trash and dumps support many native species, including American woodcock (*Scolopax minor*), brown snake (*Storeria dekayi*), milk snake (*Lampropeltis triangulum*), and the land snail *Zonitoides nitidus*.

The built environment also has negative influences on wildlife populations and their distribution in the Meadowlands. It has been estimated that buildings and windows account for as many as 980 million bird deaths, power lines up to 174 million bird deaths, and communication towers as many as 50 million deaths annually in the U.S. (Klem, 1990; Erickson et al., 2001). Tall, illuminated structures such as buildings and communication towers are a significant cause of death for nocturnally migrating songbirds (Taylor & Anderson, 1973; Taylor & Kershner, 1986; Crawford & Engstrom, 2001) and nonpasserine birds including green herons, rails, and coots (Taylor & Anderson, 1973; Seets & Bohlen, 1977). The impact of the many communications towers in the Meadowlands is being studied (N. Tsipoura, personal communication, 2004).

The effect of roads on mortality, reproduction, and species distribution in the Meadowlands has not been studied. Elsewhere, birds, mammals, reptiles, and amphibians suffer high levels of mortality from collisions with vehicles (Ashley & Robinson, 1996; Haxton, 2000; Mumme, Schoech & Woolfenden, 2000; Carr & Fahrig, 2001; Erickson et al., 2001; Gibbs & Shriver, 2002; Taylor, 2002). Forman, Reineking and Hersperger (2002) found that in areas of heavy traffic (more than 30,000 vehicles per day) the presence and breeding of grassland bird species was reduced as far as 1,200 meters from the roadway. That level of traffic is approached on several highways in the Meadowlands. Barrier fences have been erected at four locations to guide terrapins beneath the New Jersey Turnpike using existing waterways (Urffer, 2002).

Landscape Perspective

Urbanization causes habitat fragmentation, increases the diversity of habitat types in the landscape (Gilbert, 1989), and may also result in the preservation of large blocks of undevelopable habitat. The ability of species, populations, and communities to respond to natural and uniquely urban conditions is largely moderated by the spatial configuration of habitats within the larger landscape, and by the scale at which individual organisms perceive the landscape.

The large expanses of wetlands in the Meadowlands, and the variety of types of wetlands and waterways, are the best explanations for the dense congregations and high diversity of marsh and water birds found there. The common reed marshes alone display great variety due to differences in tidal influence; depth and duration of standing water; stand size, density, and stature; stand shape and edge configuration; interspersion of reed with patches of other vegetation and pools of open water; mixture of other plants within and at the edges of the reed patches; lodging or falling over of reeds in storms; muskrat activities; fire effects; all-terrain-vehicle trails; and the surrounding landscape (Kiviat & MacDonald, 2002; Kiviat, personal observation). Extensive stands of reed or other nonforest vegetation are necessary to support nesting of the northern harrier, a bird that requires large areas of contiguous habitat and is sensitive to human intrusion near its nest.

Although larger wetlands are better habitat for many organisms, small isolated wetlands or ponds are better for amphibian larvae, clam shrimp, and other animals that are sensitive to competition or predation, and these wetlands also act as "stepping stones," connecting other wetlands (Semlitsch & Bodie, 1998). This "gain" in habitat diversity is, of course, offset by the historic loss of large areas of salt meadow, Atlantic white cedar swamp, and natural upland habitat in the Meadowlands.

The need for habitat connectivity is species-specific and varies with the scale at which organisms are able to use a landscape (Hostetler, 2001). Wide-ranging animals such as red fox (*Vulpes vulpes*) and northern harrier in the Meadowlands require large areas in order to locate adequate prey. However, even species with small ranges typically require large or connected habitats for dispersal, immigration, emigration, exploitation of patchy resources, and, in the case of a tidal system such as the Meadowlands, daily migrations necessitated by rising and falling water levels. Shorebirds, waterfowl, and wading birds are highly mobile and use a spatially dispersed complex of habitats on tidal, daily, and seasonal cycles (Kiviat, 1989; Haig, Mehlman & Oring, 1998). Particular species may focus their activities in small areas of the Meadowlands or range across the entire New York–New Jersey Harbor estuary.

Maintenance of locally and regionally diverse wetland complexes may be an important factor in conserving waterbird diversity. Many Meadowlands animals require adjacent upland and wetland habitats. Some species use wetlands and waterways for foraging but nest in adjacent, dry uplands (for example, the diamondback terrapin). Many shorebird species move into adjacent shallow water and mudflat areas when water levels in impoundments or tidal marshes become too deep (Kane & Githens, 1997). More highly mobile species such as bats, canids, waterfowl, herons, and dragonflies should be able to exploit the fragmented Meadowlands landscape more effectively than small terrestrial mammals, reptiles, amphibians, and snails, whose ability to move among habitat patches is limited and whose risk of mortality during migration or dispersal is greater.

Management Implications

1. Species diversity in the Meadowlands requires maintaining a diversity of habitats.

The preservation of all the major wetlands in the Meadowlands district has been proposed, and there is interest in preservation along the upper Hackensack River estuary between the northern end of the district and Oradell Dam (T. Schvejda, personal communication, 2004). In addition to the better-known tidal, impounded, and nontidal wetlands, conservation planning should consider other habitats that support biodiversity in the Meadowlands. This biodiversity is not limited to large wetlands, tidal wetlands, cordgrass marshes, or restored sites: Thirteen of the 33 listed bird species are associated with upland habitats, and wetland wildlife needs upland buffer zones. Therefore, preserving the wetlands alone will not protect all the resources needed by the listed birds (and many other species). Very little is known about habitat combinations required by native animals for the avoidance of predators and during different life stages, seasons, and weather and food-availability conditions; upland-wetland complementary resource use is crucial for many species and needs to be considered during planning.

Habitats such as the oligohaline tidal marshes and dry sand scrub of the upper Hackensack River estuary and the puddles supporting clam shrimp should also be considered for conservation purposes, as should rocky upland habitats, which are important for terrestrial biodiversity. Which landfills should be maintained as green space and how they should be managed (e.g., for native pollinators and birds of prey) should be assessed; one possible model is the grassland bird habitat that has been successfully developed on the large, capped Croton Point Landfill in Westchester County, New York. It is also important to know which habitats in the Meadowlands support a diverse community of native pollinators and to protect these habitats or ensure that developed areas such as golf courses provide a functional replacement. New golf courses should be designed for low environmental impact (with integrated pest management, xeriscaping, low fertilizer input, and out-of-play areas designed to provide habitat for native pollinators, the American woodcock, and other native species of conservation concern).

In the Meadowlands, there are three areas that are as much as a kilometer from the nearest railroad or public road. This isolation from human disturbance is remarkable in the New York metropolitan area. In addition, examination of aerial photographs shows continuous major wetlands along the entire north-south length of the Meadowlands west of the Hackensack River. Proximity to roads and fragmentation of Meadowlands habitats by roads and railways undoubtedly restricts the presence or reproduction of many animals, some of them rarities (although it may also restrict the number of predators, white-tailed deer, or humans in marsh interiors, thus releasing certain other species from the pressures of predation, competition, or human intrusion). Some herons and the northern harrier, for example, are sensitive to human activities and predators near their nesting sites. For these reasons, larger and more isolated sites are important in conserving biodiversity. However, small habitat fragments provide locally important habitat for certain plants or invertebrates. For example, the native hackberry tree (*Celtis* *occidentalis*), which occurs in small local populations, potentially supports two uncommon *Asterocampa* butterfly species.

2. The costs and benefits of common reed need to be weighed objectively.

One of the most contentious and complex issues in the Meadowlands is the management of common reed stands (see Kiviat & MacDonald, 2002). Reed stands in the Meadowlands are highly varied, and their associated organisms are not well understood, although there is evidence that they support rare species as well as common species of amenity value (i.e., nonmaterial value, such as aesthetic). Reed management methods used in other regions, for example, in the British Isles (Hawke & José, 1996) and the Delta Marsh in Manitoba, Canada (Ward, 1942), and may prove useful in altering the characteristics of Meadowlands reed stands to accomplish specific goals of conserving biodiversity and ecosystem services. Based on what is known about how reed stands affect Meadowlands biodiversity, we believe the recent emphasis on controlling the reed with herbicide, lowering and recontouring substrates to enhance tidal flushing, creating ponds and islands, and planting smooth cordgrass (Scarlatelli, 1997; HMDC, 1999; Doss, 2000; Hartman, 2003) is too narrow an approach. For example, such controls favor estuarine benthos, estuarine fishes, and migrant waterbirds and shorebirds over terrestrial invertebrates, breeding birds, and mammals; they don't take into consideration the species of vascular plants and invertebrates associated with reed stands (Kane, 2001a, b); they ignore the potential impact of remobilizing sediment and toxic contaminants; and they don't account for the future maintenance costs associated with sea-level rise or reinvasion of common reed. The habitat functions and ecological services associated with existing stands of invasive plants must be assessed objectively and weighed against the potential costs of restoration, nontarget impacts, long-term management, and unknowns associated with attempts to trade, for example, common reed for cordgrass, cattail (*Typha* species), submergent aquatic plants, or mudflats. When the reed stands are used by numerous endangered, rare, declining, or vulnerable species, as is the case in the Meadowlands, the assessment and decision-making process should be nuanced, and science and values should not be confused. Whatever the mixture of introduced and native plants, it may be less expensive and environmentally risky to maintain an existing community that is providing habitat and amenity in an urban environment than to attempt to create or re-create a community of native species that once may have existed in the area or that now exists in a more rural or wild environment elsewhere (Gilbert, 1999).

3. Specific prescriptions for management.

The biodiversity value of the Meadowlands raises questions about how the area might be managed to maintain and improve habitat for species of concern. We discuss here a few important opportunities for improving habitat to enhance biodiversity.

There are old drainage ditches still drying out the swamp forest and wet meadows at Teterboro Airport (Berger Group, 2000), apparently compromising their ability to support biodiversity (MacDonald, personal observation). The ditches could be plugged and hydrology restored. Mowing (frequent for a few years, then less often, and avoiding the bird-nesting season) could improve grassland bird habitat in selected portions of the large areas of inactive landfill dominated by mugwort and upland common reed stands. Forest cover could be established (Robinson & Handel, 2000) or shrubs and quaking aspen planted for woodcock. Planting nectar plants in parks, medians, yards, and recreation areas could enhance the landscape for native bees, butterflies, and other flower-visiting insects. The water level in Kearny Marsh West apparently needs to be lowered to prevent further deterioration of some common reed stands, with the goal of achieving extensive areas of reed with numerous small and large shallow pools for water and marsh bird breeding and foraging habitat. Existing small stands of purple loosestrife that have developed on floating mats of peat and dead reed rhizomes support a diverse community including mosses and nectar-seeking butterflies. The loosestrife stands increase the biological diversity of the marsh and should be left unless they become very extensive or very dense and the associated biota becomes species-poor. Large wet meadows dominated by common reed, such as portions of the Empire Tract, would benefit from excavation of shallow pools about 50 to 100 meters in diameter for marsh and water birds as well as other wildlife. Mowing or prescribed livestock grazing of reed between the bluejoint (*Calamagrostis canadensis*) meadows on the west side of the Paterson Lateral gas pipeline might be used to maintain and expand these meadows. To avoid further damage to adjoining marshes, off-road vehicles need to be confined to the pipeline road, where they could be used to maintain the existing clam shrimp pools on the road surface.

Siting, height limits, and lighting of tall structures in the Meadowlands should be based upon the best available information for minimizing bird collisions. Unlit, un-guyed towers less than 60 meters tall pose the least threat to migrating birds (Manville & Evans, 2000). The Federal Aviation Administration requires aviation safety lighting on structures 60 meters or taller. On these structures, solid red or blinking incandescent aviation lighting appears to be more of a hazard than white flashing strobes (Manville & Evans, 2000). Siting of these tall structures has a major influence on bird mortality. According to Manville (2000), the worst-case scenario includes having tall structures next to a wetland, a major songbird migration corridor, and fog. The Meadowlands meet at least the first and second criteria, and probably the third. In addition, power lines adjacent to wetlands are a known hazard to waterbirds taking off and landing in these habitats, and they should also be considered a problem in the Meadowlands.

Certain species are missing from the Meadowlands. In some cases these are species with limited ability to disperse from source populations outside the Meadowlands. There may be species for which reintroduction would make sense; a large-scale turtle reintroduction experiment at Floyd Bennett Field in Brooklyn, New York, part of the Gateway National Recreation Area, may provide a model (Cook, 1996). It may also be helpful to create corridors or highway crossings designed for particular organisms.

4. The varied human uses of Meadowlands plants and animals should be considered.

Wildlife is the focus of much recreational and educational activity, notably observation of birds and to a lesser extent mammals, butterflies, dragonflies, and wildflowers. For example, sportfishing is common on the Hackensack River main stem and a few accessible tributaries. People also find practical uses for wild organisms, and we increasingly discover or develop ways to use them as foods, pharmaceuticals, specialty woods, fuels, industrial feedstocks, and pesticides. Among Meadowlands species that may prove useful in the future are the oyster mushroom (*Pleurotus sapidus*), for food; the princess tree, as a high-quality hardwood; common reed, for thatch, energy, and fiber; and Japanese knotweed, for medicine. Biodiversity managers must be aware of the potential for overexploitation of native species such as large fungi; management of invasive species through consumption; public exposure to contaminants or pathogens through the use of wild plants and animals; and ecological side effects of harvesting these organisms.

5. Research is needed to study the effects of contaminants and urban habitats on species survival and productivity.

Although the Meadowlands exhibit a high diversity of wildlife, decision makers would benefit from a more detailed assessment of how artificial and altered habitats, as well as fragments of seminatural habitats, meet the environmental tolerances and ecological needs of organisms. In particular, studies of whether such habitats may be hazardous or unhealthy for certain species (for example, the northern water snake, night herons, raptors, mink) are needed. Such information would allow for more effective conservation and ecological restoration.

6. Additional taxonomic survey work is needed.

Better data would enable restoration, management, and development planning to proceed with sensitivity to the Meadowlands' special biological values. Missing information and lack of survey coverage for many taxa and habitats inhibit the understanding of Meadowlands biodiversity. This is especially true for smaller animals and plants, and for organisms of habitats other than marshes. Among these less-studied habitats are the meadows, scrub, and swamp forests of the northern Meadowlands, including wet clay meadows and bluejoint meadows; small or temporary pools; storm-water ponds; artificial habitats such as mines, landfills, and other wetland fill; habitats associated with invasive plants such as tree-of-heaven, princess tree, mugwort, Japanese knotweed, and purple loosestrife, as well as common reed; and habitat fragments enclosed by built environments such as highway intersections, railroads, parking lots, and buildings. The relict native plants and plant communities in many areas need to be studied. We also need to understand larger-scale space use by mobile animals in relation to habitats and hazards (e.g., highways, antennas, contaminant hot spots). Where it is determined that mortality or morbidity associated with anthropogenic hazards is unacceptable for particular species, the built environment or other habitats can be modified to reduce the exposure of those species to risk.

Applicability to Other Urban Wetland Complexes

The Meadowlands contain a large area of degraded wetlands that support numerous species, many of which are rare or vulnerable. In this respect, the area is similar to other urban wetland complexes, such as Jamaica Bay Wildlife Refuge in New York City, a component of Gateway National Recreation Area (Tanacredi, 1995), Union Bay in Seattle (Higman & Larrison, 1951), Tinicum Marsh in Philadelphia (McCormick, Grant & Patrick, 1970), and the San Francisco Bay estuary complex (Josselyn, 1983). Because rich natural resources and natural transportation corridors have supported the development of many "wetland cities" around the world (Kiviat, 1991), we expect there are many biodiverse urban wetland complexes elsewhere. In general, although each locality has its own species and unique problems, they are all subject to fragmentation, contamination, poor water quality, and other hazards. Urban wetland complexes are inhospitable to many nonflying, area-sensitive animals (i.e., animals that need large areas of contiguous habitat); organisms sensitive to pollutants such as PCBs, heavy metals, or airborne sulfur; and organisms requiring habitats that are scarce in urbanized areas, such as natural upland soils, unaltered streams, or forest interiors. However, they should be favorable for migratory animals that move along riverine or coastal corridors; marsh and water birds requiring isolation from human intrusion; raptors preying on peridomestic small mammals or birds; and organisms that tolerate urban conditions and benefit from reduced grazing, predation, or competition.

The creation and maintenance of large blocks of aquatic and terrestrial habitat interconnected by suitable corridors for many of the organisms that otherwise tolerate urban conditions are high priorities for landscape planning and management. Yet smaller habitat fragments are also important. Urban wetlands should be viewed as habitat both for rare species of general conservation significance and for common species that nonetheless may be an important amenity for urban humans.

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Glossary

Benthic: Organisms (e.g., protozoa, nematodes, insects) living on or in the bottom of water bodies.

Bivalvia: A class of mollusks with a shell in two parts, hinged together.

Canid: A member of Canidae, the family of carnivorous mammals that includes foxes, jackals, coyotes, wolves, and domestic dogs.

Charadriiformes: A large, diverse order of mostly aquatic or semiaquatic birds, including sandpipers, plovers, skimmers, terns, and gulls.

Cnidaria: A phylum of marine animals formerly called Coelenterata: the sea anemones, jellyfish, hydroids, sea pens, and corals.

Combined sewer overflows: Discharges into waterways during rainstorms of untreated sewage and other pollutants via combined sewers carrying both sanitary sewage and storm-water runoff from streets, parking lots, and rooftops. This occurs mainly in older sewage systems that do not have completely separated sewage and storm-water pipes. The term also refers to the physical structure of the pipes.

Emergency overflows: Discharges into waterways of untreated sewage and other pollutants during maintenance of sewage systems.

Estuarine: Of or relating to an estuary, a coastal body of water in which freshwater mixes with seawater and which has a free connection with the open sea and is often subject to tidal action.

Igneous: Rock that has crystallized from magma.

Keystone species: A species that has a major influence on the structure of an biological community. Its presence affects many other members of the community, and if its population dwindles or disappears, there can be far-reaching consequences for the community.

Macrobenthos: Organisms (e.g., protozoans, nematodes, insects) living on or in sea or lake bottoms whose shortest dimension is greater than or equal to 0.5 millimeters (0.019 inches).

Microfungi: Small fungi whose spore-producing structures can be observed only through a microscope.

Nektonic: Actively swimming.

Nonpasserine: Relating to or characteristic of birds other than the songbirds and flycatchers.

Oligochaeta: A class of annelid worms, including the earthworms and their aquatic relatives.

Oligohaline: Of or relating to a body of water with a salinity content of less than 5 parts per thousand (or 5 grams of salt per liter).

PAHs (polyaromatic hydrocarbons): A range of persistent, toxic organic compounds produced by the incomplete combustion of petroleum fuels and also originating from creosote, a wood preservative.

PCBs (polychlorinated biphenyls): A range of persistent, toxic organic compounds formerly used as liquid insulators in electrical transformers and capacitators, as well as in many consumer products.

They cause reproductive problems and other health problems in mammals, birds, and reptiles.

PCBs (polychlorinated biphenyls): A range of persistent, toxic organic compounds formerly used as liquid insulators in electrical transformers and capacitators, as well as in many consumer products. They cause reproductive problems and other health problems in mammals, birds, and reptiles.

Peridomestic: Around the home.

Qualitative: Based on individual, often subjective analysis.

Rallid: A marsh or water bird in the family Rallidae, including rails, gallinules (moorhens), and coots.

Riparian: Pertaining to a river or dwelling on the banks of a river.

Rhynchocoela: A phylum of bilaterally symmetrical, unsegmented, ribbonlike worms.

Ruderal species: Species characteristic of lands (such as road verges) that are highly disturbed but may be rich in water, nutrients, and other resources.

Taxon (pl. taxa): The organisms composing a particular unit of classification, such as phylum, class, family, genus, or species.

Tentaculata: A class of comb jellies with two feathery tentacles, which they can retract into specialized sheaths.

Tunicata: A grand division of the animal kingdom that is intermediate, in some respects, between the invertebrates and vertebrates (and grouped with the latter by some authorities). The body of a tunicate is usually covered with a firm external tunic with two openings, one for the entrance and the other for the exit of water.

Turbidity: Level of cloudiness due to suspended particles in water.

Figure 1

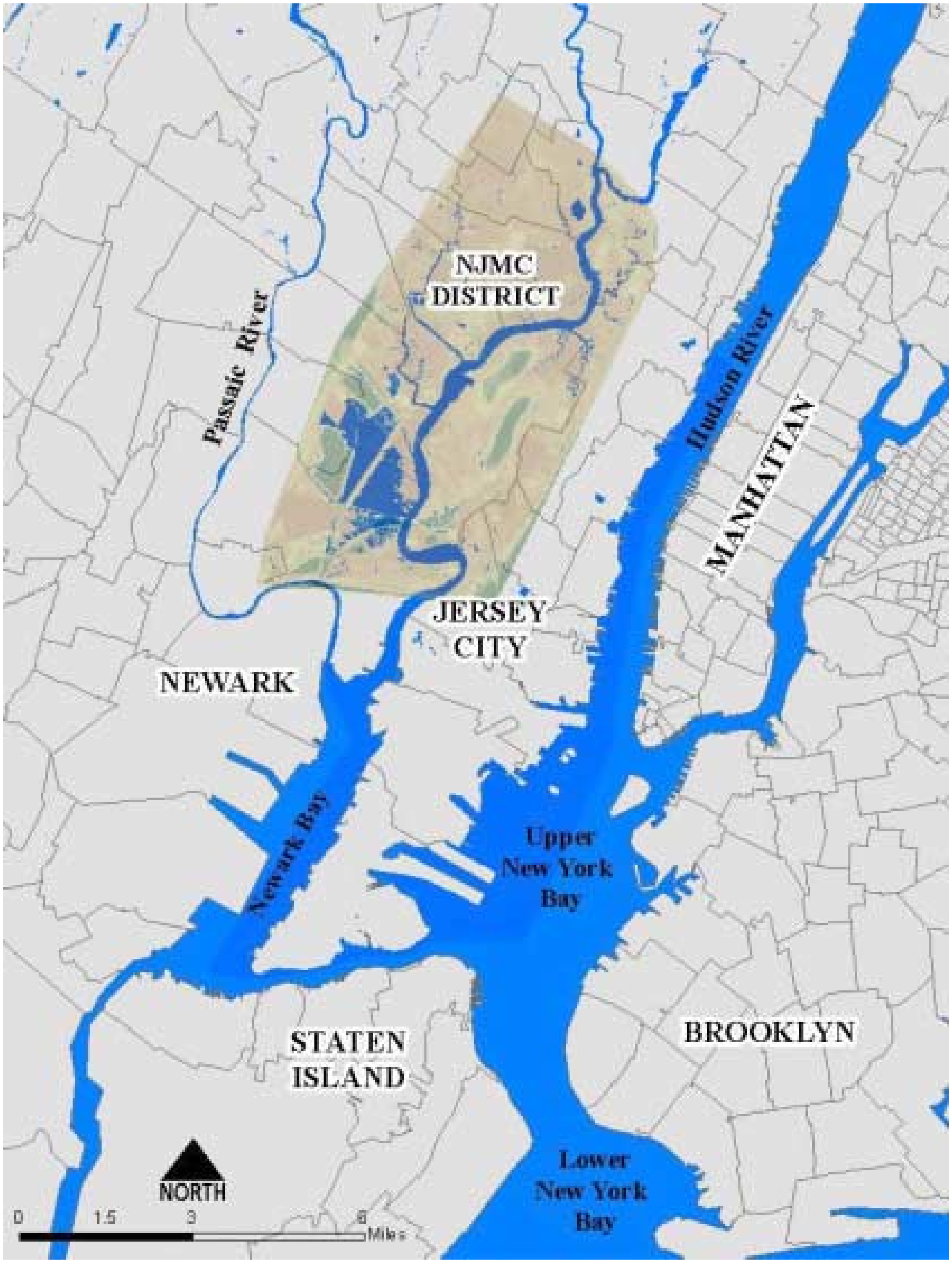

Figure 1. Map showing the location of the official Hackensack Meadowlands District (green) in the New York–New Jersey Harbor estuary region. Contiguous wetlands and riparian areas exist both north and south of the district and should be considered as part of the Meadowlands biodiversity landscape. (Map courtesy of New Jersey Meadowlands Commission.)

Figure 2.

Figure 2. Creek bordered by common reed (*Phragmites australis*), Empire Tract, Hackensack Meadowlands, New Jersey. Creeks like this are used by ducks in bad weather, muskrat, dragonflies, and several species of fishes. Photograph by Erik Kiviat.

Figure 3.

Figure 3. Bluejoint (*Calamagrostis canadensis*)—common reed (*Phragmites australis*) meadow, Empire Tract, Hackensack Meadowlands, New Jersey. Bluejoint (the shorter grass) dominates a remnant native plant community. Photograph by Erik Kiviat.

Figure 4.

Figure 4. Common reed (*Phragmites australis*)—tree-of-heaven (*Ailanthus altissima*) stand at Cromakill Creek, Hackensack Meadowlands, New Jersey. The eastern cottontail eats bark and the northern cardinal eats seeds of tree-of-heaven. Common reed supports a variety of mammals, birds, insects, and spiders. Photograph by Erik Kiviat.

Figure 5.

Figure 5. Wet clay meadow with white beardtongue (*Penstemon digitalis*) near Mehrhof Pond, Hackensack Meadowlands, New Jersey. This is a remnant native plant community. Photograph by Erik Kiviat.

Figure 6.

Figure 6. Purple loosestrife (*Lythrum salicaria*) stand where death of common reed (*Phragmites australis*) has caused a peat mass to float to the surface in Kearny Marsh West, Hackensack Meadowlands, New Jersey. This loosestrife was attended by several species of butterflies as well as other flower visitors. Photograph by Erik Kiviat.

Figure 7.

Figure 7. Chestnut oak (*Quercus montana*) woods on Laurel Hill, Hackensack Meadowlands, New Jersey. This is a remnant native plant community on an unmined area of the hill. Photograph by Erik Kiviat.

Figure 8.

Figure 8. Atlantic white cedar (*Chamaecyparis thyoides*) stump at the Mill Creek mitigation site, Hackensack Meadowlands, New Jersey. All that persists of once-extensive cedar swamps, such stumps could support interesting invertebrates that may be specialized to this microhabitat. Photograph by Erik Kiviat.

Table 1. Summary of Knowledge of Groups of Organisms in the Hackensack Meadowlands, New Jersey.

Group	**Knowledge**	**Species**	**Diversity patterns**	**References**
Mammals[1]	Few data	22	Moderate diversity	NJTA, 1986; Quinn, 1997; Berger Group, 2001
Birds of prey	Good (few data on nesting)	21	Low breeding, moderate nonbreeding diversity	NJTA, 1986; Bosakowski, 1982, 1983, 1986, Bosakowski et al., 1989; Wander & Wander, 1995; Kiviat & MacDonald, 2002
Marsh & waterbirds[2]	Good	53	Moderate to high diversity & abundance	NJTA, 1986; Wargo, 1989; Kane & Githens, 1997; also see Kiviat & MacDonald, 2002
Shorebirds, gulls, terns	Moderate	55	Diverse & abundant migrant fauna; few breeders	NJTA, 1986; Wargo, 1989; Kane & Githens, 1997; Day et al., 1999; Kiviat & MacDonald, 2002
Other birds	Moderate	130	Moderately diverse migrant fauna	Kiviat & MacDonald, 2002
Reptiles	Few data	10–16	Moderately low diversity & mostly low abundance	NJTA, 1986; Quinn, 1997; Kiviat & MacDonald, 2002; Kiviat, personal observations
Amphibians	Few data	3–10	Low diversity & abundance	NJTA, 1986; Quinn, 1997; Kiviat & MacDonald, 2002
Fishes of Hackensack River & larger tributaries	Moderate	ca. 60–70	Moderately diverse	NJTA, 1986; Kraus & Bragin, 1988; Kiviat & MacDonald, 2002; NJMC in preparation
Fishes of ponds, small creeks, marsh surfaces	Few data	14	Low to moderate	NJTA, 1986; USACOE, 2000; Feltes, 2003; Yozzo & Ottman, 2003; C. Woolcott, thesis in preparation
Estuarine macro-invertebrates[3]	Moderate, limited in scope	53	Moderate?	Kraus & Bragin, 1988;
Freshwater macro-invertebrates[3]	Few data, few habitats studied	?	?	NJTA, 1986; Grossmueller, 2001
Chironomid midges	Few data	?	Diversity unknown; high abundance	Utberg & Sutherland, 1982; Hartman & Smith, 1999; Grossmueller, 2001
Planktonic & benthic Protozoa	1 study	112	?	Jones & Isquith, 1981
Other aquatic micro-invertebrates	No data	?	?	
Land snails	Casual	4	Low diversity & abundance?	Kiviat, collections
Arachnids (spiders; ticks & other mites)	Few data	?	Identified only to higher taxa; moderate?	Grossmueller, 2001; Kiviat, observations & collections
Mosquitoes	Moderate?	22	Moderate	Headlee, 1945
Bees	1 study	51	High?	Yurlina, 1998
Butterflies	Few data	?	Low to moderate diversity	Kane & Githens, 1997; Quinn, 2000; Kiviat, observations
Dragonflies & damselflies (odonates)	1 study	8	Low?	Hartman & Smith, 1999
Lady beetles (Coccinellidae)	1 study	17	Moderate diversity & abundance?	Angalet et al., 1979
Aphids (Homoptera, in part)	1 study	26	Moderate?	Angalet et al., 1979
Other terrestrial invertebrates	Few data	?	Moderate?	Hartman & Smith, 1999; Grossmueller, 2001; Kiviat &

				MacDonald, observations
Vascular plants	Moderate (poor for rare species)	ca. 420	Moderate	Sipple, 1972; USACOE, 2000; Kiviat & MacDonald, 2002
Bryophytes (mosses, etc.)	Casual	ca. 10	Low	Kiviat & MacDonald, 2002; Kiviat, observations & collections
Phytoplankton	1 study	232	Moderate?	Foote, 1983
Attached aquatic algae	Casual	?	?	Utberg & Southerland, 1982
Terrestrial algae	No data	≥ 1	?	Kiviat, observations
Lichens	Casual	ca. 10	Low	Kiviat & MacDonald, 2002; Kiviat, collections
Macrofungi	Casual	> 5	Low?	Kiviat & MacDonald, 2002; Kiviat, observations & collections

“Knowledge” indicates adequacy of study.
“Species” is number of species reported in available literature.
Question marks (?) indicate uncertain ranking or insufficient information available.

[1] Includes feral or free-ranging domestic cat and dog
[2] Loons, grebes, cormorants, waterfowl, herons, ibis, rails
[3] Excluding mosquitoes and odonates

Species Composition and Food Habits of Dominant Fish Predators in Salt Marshes of an Urbanized Estuary, the Hackensack Meadowlands, New Jersey*

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Abstract

The Hackensack Meadowlands, in heavily urbanized northern New Jersey, have undergone many types of human alteration within the past three centuries. In the last five years, attempts have been made to restore portions of the estuary to a salt marsh. To examine how fish fauna have responded to these efforts, we compared spatial and temporal patterns in the distribution and food habits of the dominant fishes collected in 457 gill-net samples during May to November 2001 from two tidal-marsh creeks in the Meadowlands. One of the creeks, Mill Creek, which has undergone two phases of mitigation since 1987, is dominated by both common reed (*Phragmites australis*) and salt-marsh cordgrass (*Spartina alterniflora*). The other, Doctor Creek, a man-made creek created in 1999–2000, is dominated solely by salt-marsh cordgrass. Water quality of the two creeks is similar in temperature but differs in salinity and dissolved oxygen: Mill Creek's salinity is 1.5 to 2 parts per thousand higher than that of Doctor Creek; it also has more frequent hypoxic conditions than Doctor Creek. We collected a total of 509 fishes representing ten species, and the dominant species (< 1% of the catch) were *Morone americana* (white perch, 46%); *Pomatomus saltatrix* (bluefish, 22%); *Alosa pseudoharengus* (alewife, 20%); *Morone saxatilis* (striped bass, 7%); and *Brevoortia tyrannus* (Atlantic menhaden, 3%). Overall fish species diversity and abundance were higher at Mill Creek than at Doctor Creek. The dominant piscivores (white perch, bluefish, striped bass) were found at almost all collection sites within each creek. The stomachs of most of these fish were 20% to 40% full, indicating that many of the fish collected had fed recently. Diet composition in both creeks was similar with respect to the consumption of fish; however, crustaceans made up a significant portion of the diet in Mill Creek fish, whereas detritus and microbenthos composed a large proportion of the diet of fish collected in Doctor Creek. Though both sites occur in a highly urbanized area, each appears to be providing fish habitat and food for typical marsh creek predators.

Key words: distribution and abundance; fish predators; food habits; Hackensack Meadowlands; *Morone americana*; *Morone saxatilis*; New York metropolitan area, *Pomatomus saltatrix*; salt-marsh creeks; urban estuary

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Introduction

Estuarine habitats, especially salt marshes and associated creeks, play an important role in the life cycle of a wide variety of fish species (Able & Fahay, 1998). However, fish use of these habitats, and the factors influencing this use, are not fully understood, especially in the case of urbanized estuaries. Recent studies show that predators use natural tidal salt-marsh creeks for feeding and coordinate their foraging movements with the tide and other environmental conditions (Wolff, Clayton & Sandee, 1981; Wirjoatmodjo & Pitcher, 1984; Raffaelli, Richner, Sumers & Northcott, 1990; Rountree & Able, 1992; Szedlmayer & Able, 1993). A large number of tidal-marsh habitats have been altered by human activities, especially those in urban areas. The Hackensack Meadowlands in northern New Jersey are a prime example: They have been altered by construction, dredging, draining, mosquito control, industrial pollution, sewage and, more recently, recreational use (Kiviat & MacDonald, 2002). Yet the impacts of these alterations on estuarine-dependent fish predators have not been well studied.

In recent years, wetland restoration and mitigation efforts performed by the New Jersey Meadowlands Commission, the former Hackensack Meadowlands Development Commission, and Marsh Resources Inc. have attempted to restore the Meadowlands to more natural conditions (Kraus & Bragin, 1989; Louis Berger & Associates, Inc., 1999; Raichel, 2001). *Phragmites australis* (common reed) was removed, and site elevations were lowered in order to reestablish tidal inundation. Channels were dredged to further enhance water exchange. These alterations were expected to reduce the risk of anoxic and hypoxic events and improve conditions for fishes. To date, the potential impacts of the alterations have not been evaluated. In fact, few evaluations of fish-predator use in marshes of this estuary have been conducted. The few studies that have been carried out include a general inventory of fisheries resources within the Hackensack River (Kraus & Bragin, 1989) and a compilation of data by the U.S. Fish and Wildlife Service to justify the establishment of a national wildlife refuge in the Hackensack Meadowlands Day, Staples, Russell, Nieminen & Milliken, 1999).

The objectives of our study were to 1) determine seasonal patterns of predatory fish use (distribution, abundance, species composition, size) in marsh creeks within the Hackensack Meadowlands that have undergone varying degrees of human alteration; and 2) examine the food habits of the dominant fish predators within the Meadowlands. We do not comment extensively on restoration success because there are no relatively undisturbed marshes in the watershed with which to make comparisons.

Material and Methods

Study Sites

Two tidal-marsh creeks (Mill Creek and Doctor Creek) in the Hackensack River in northern New Jersey (Figure 1) were divided into three study sampling areas: 1) the mouth of each creek—Mill Creek Mouth (MCM) and Doctor Creek Mouth (DCM); 2) the lower portion of each creek—Mill Creek Lower (MCL) and Doctor Creek Lower (DCL); and 3) the upper portion of each creek—Mill Creek Upper (MCU) and Doctor Creek Upper (DCU). The distance to Newark Bay (approximately 16 km) and the ocean is similar for both creeks.

Mill Creek is about 2.2 kilometers[*] long and 20 meters wide. The depth is variable and generally ranges between 4 and 8 meters at high tide with some deep spots—the deepest point near the MCL site has a maximum depth of 25 meters. Average tidal range is 1.7 meters (derived using Nobeltec nautical software). The west bank of Mill Creek and the area at the MCU site are completely dominated by *P. australis*. The east bank and the remainder of the marsh stretching up to the eastern spur of the New Jersey Turnpike have undergone two phases of mitigation. The older phase of mitigation (approximately 24 hectares; 59.3 acres) was performed by the Hartz Mountain Development Corporation in 1987–88 and is enclosed by the Hackensack River to the west, MCL to the south, Cromakill Creek to the north, and the eastern spur of the New Jersey Turnpike to the east (Figure 1). This mitigation area is dominated by seeded *Spartina alterniflora* (salt-marsh cordgrass). The second phase of mitigation took place farther up the creek and was completed by the Meadowlands Commission in 1999. The area is bordered by Mill Creek to the west, the New Jersey Turnpike eastern spur, and Mill Creek Mall to the south (Figure 1). It consists of 56 hectares (approximately 138 acres) of man-made islands and lower and upper marsh areas. At the time of this study, in summer 2001, the marsh surface had no vegetation cover. The lower marsh is covered by water at high tide.

Doctor Creek is a man-made creek about 800 meters long and 20 meters wide. Its average depth is uniformly 2 meters at high tide, with an average tidal range of 1.7 meters. The profile across the creek is uniformly steep-sided with a flat bottom, except for a sill at the entrance to the creek in the Hackensack River. There are channels and smaller creeks linking the marshes with the Hackensack River. Doctor Creek is located within the area known as Transco Marsh and is the site of the Marsh Resources Inc. Meadowlands Mitigation Bank. The area around Doctor Creek is phase one of the Marsh Resources Inc. mitigation, and the whole marsh including Doctor Creek was created in 1999–2000. This phase of the mitigation consists of 82.5 hectares (approximately 204 acres) of man-made islands and high and low marshes. Before its creation, the marsh surface was dominated by *P. australis*. The Doctor Creek marsh surface is now dominated by *S. alterniflora* and *S. patens* (saltmeadow cordgrass), which have been planted or seeded (Louis Berger & Associates, Inc. 1999).

Sampling Design and Gear

Sampling in the Hackensack Meadowlands took place from May 22 to November 19, 2001 (Table 1). Sampling was conducted using monofilament gill nets (232 sets in Mill Creek and 225 sets in Doctor Creek). Each gill net measured 2.4 meters high by 6.1 meters long and was divided into four panels. Each of these panels had a different mesh size: 1.9 centimeters, 4.4 centimeters, 8.9 centimeters, and 10.2 centimeters, respectively. Peak sampling occurred in October (71 sets in Mill Creek and 63 sets in Doctor Creek). We performed all sampling during daylight at high tide, as Doctor Creek was only accessible by boat at high tide.

We deployed four nets in each creek, two at the lower sites (MCL and DCL) and two at the upper sites (MCU and DCU). In each creek, one net was deployed across the current, as much as the floating

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[*] Measurements throughout this paper are in metric notation; conversions to U.S. equivalents can be obtained at www.onlineconversion.com/length.htm.

debris permitted. Another net was deployed across the mouth of one of the smaller side creeks. The remaining two gill nets were deployed parallel to the current in the center of the creek. When we sampled the mouths of the creeks (MCM and DCM), we deployed one net across the mouth of each creek. Because Mill Creek is a public waterway with some boat traffic, the sampling at MCM took place across the mouth of a side branch of the creek (see Figure 1). This side branch starts at the MCL site, where the remains of an old tide lock divides Mill Creek. Each net was deployed for one hour, and sampling was repeated once or twice the same day. Sampling alternated between Mill Creek and Doctor Creek, and over a typical two-week period, each creek was sampled on four days.

We identified all fish and measured their total length (TL) to the nearest millimeter. The sampling effort was measured as the number of fish captured per net per hour (CPUE, no. net-1 h-1). Spatial and temporal differences in CPUE and differences in mean lengths of the dominant predators were analyzed using analysis of variance (ANOVA) and Student-Newman-Keuls (SNK) multiple comparisons test (SAS Institute, 1990).

Stomach Contents Analysis

Selected predator species including *Morone americana* (white perch), *M. saxatilis* (striped bass), and *Pomatomus saltatrix* (bluefish), were measured and placed on ice until transfer to a land-based freezer. Subsequently, after partial defrosting, we recorded the wet weight of each whole fish. Its stomach was removed from the abdominal cavity, emptied into a finger bowl of 95% ethanol solution, and then returned to the abdominal cavity. We then reweighed the fish to determine a post–stomach extraction weight. We calculated a gravimetric index of stomach fullness by dividing the total prey weight (in grams) by the total predator weight and multiplying the proportion by 100 (Hyslop, 1980). Stomach contents were transferred to sample jars and preserved in 95% ethanol solution, with the staining agent rose bengal added to aid in identification. We looked for spatial and temporal differences in gravimetric indices for the dominant predators using ANOVA and SNK multiple comparisons test (SAS Institute, 1990).

In order to quantify stomach contents of individual predators, we determined the proportion by weight of each prey category according to the sieve fractionation method (Carr & Adams, 1972) as adapted by Nemerson and Able (2004): Stomach contents were poured through six sieves—2-millimeter, 850-micrometer, 600-micrometer, 250-micrometer, 125-micrometer, and 75-micrometer—which were mounted on a sieve shaker and rinsed with distilled water for approximately one minute. The contents were then sorted into finger bowls by sieve size. Occasionally, contents of separate sieves were combined. We identified prey constituents to the lowest possible taxonomic subdivision. Qualitative ratios based upon the weights of constituents belonging to the same taxonomic subdivision were recorded for each finger bowl. Their contents were then filtered onto dried, preweighed, and numbered filter papers using vacuum filtration. (Filter papers were dried and preweighed approximately 24 hours before use.) After filtration, the filter papers and contents were placed in an oven and dried for approximately 24 hours. We then weighed the filter papers and contents to within three significant figures of accuracy and determined gross weight.

Stomach contents (including plant matter) were divided into nine aggregated prey categories (Table 2). Consumption of prey belonging to each category is presented as gravimetric proportions (*i*) according to this formula:

$$W_i = \frac{\sum_{j=1}^{nj} W_{ij}}{\sum_{i=1}^{ni} \sum_{j=1}^{nj} W_{ij}}$$

Wij is the weight of prey summary category *i* in each sample *j; ni* is the total number of prey summary categories; and *nj* is the total number of samples examined.

Water Quality

We recorded temperature (in degrees Centigrade: °C), salinity (in parts per thousand: ‰), and dissolved oxygen concentration (in mg/L and %) using three types of stationary data loggers between June 13 and November 19, 2001. YSI 6000 data loggers were used at DCU and MCL, a YSI 600 data logger at MCU, and a Hydrolab DataSonde 3 data logger at DCL. In addition, a handheld YSI 600 unit was used October 9 to 16, 2001. Prior to the availability of data loggers, we collected surface-salinity samples with water bottles from May 22 to June 28 and later analyzed them in the laboratory using a YSI 600 data logger. In Doctor Creek, the data loggers were out of the water at low tide; therefore, no physical data are available for Doctor Creek at low tide.

Results

Physical Characteristics

Water quality was similar at Mill and Doctor creeks with respect to bottom-water temperature but different with respect to bottom salinity and dissolved oxygen (Table 3). Mean temperatures ranged from a low of approximately 12°C (53.6°F) in November to approximately 26°C (78.8°F) in August at both Mill and Doctor creeks. Mean salinity ranged from 3.1‰ in June to 11.5‰ in November at Mill Creek, and from 2.6‰ in June to 10.2‰ in November at Doctor Creek. The temporal trends (changes over time) in salinity at each site were similar, but values were 1.5 to 2.0‰ lower overall at Doctor Creek compared with Mill Creek. Mean dissolved oxygen ranged from a low of 2.0 mg/L in October to 3.5 mg/L in August at Mill Creek, and from 2.8 mg/L in June and October to 4.3 mg/L in July at Doctor Creek. Temporal trends in mean dissolved oxygen differed between sites: We recorded hypoxic conditions at Mill Creek in all months except July and August, but only during June and October at Doctor Creek.

Species Composition and Abundance

Over the sampling period, a total of 509 fish, representing ten species (Table 4), were collected using gill nets. The dominant species (< 1% of catch), ranked by their abundance, were white perch (46.17%); bluefish (21.81%); *Alosa pseudoharengus* (alewife) (19.84%); striped bass (6.68%); and *Brevoortia tyrannus* (Atlantic menhaden) (2.75%). All ten species were present in Mill Creek. In Doctor Creek, however, only six species—white perch, striped bass, bluefish, alewife, *Cyprinus carpio* (carp), *Dorosoma cepedianum* (gizzard shad)—were present.

Fish abundance also varied by season (Fig. 2a). Of the piscivorous predators, only white perch was collected during all months of the study. Striped bass was not collected in June and August, and bluefish was only collected from July to October. White perch (totaling 239 individuals) reached a peak in abundance in May and was at its lowest point in June. Abundance of white perch was significantly higher in May than in the months that followed ($p < 0.01$). Striped bass (34) peaked in abundance in October and declined to its lowest point in November. Bluefish (111) was present in collections beginning in July, peaked in abundance in September, and was absent from the collections by November. Bluefish abundance was significantly higher in September compared with all months except August ($p < 0.05$). Overall, abundance of striped bass was low compared with that of white perch or bluefish (Figure 2a).

We detected little spatial differentiation in abundance for the top three dominant piscivores, white perch, striped bass, and bluefish (Figure 2b). The only species that exhibited significant spatial differences in abundance was striped bass; catches at the mouths of both creeks were significantly higher than those in the lower and upper portions of each creek ($p < 0.01$). Abundance data for white perch and bluefish was variable, but these species tended to be least abundant at the upper creek sites (MCU and DCU) and most abundant at the MCL site. Bluefish never occurred in samples taken at the mouth of Doctor Creek. Overall abundance for all three species was higher in Mill Creek than in Doctor Creek.

Size Composition

Overall, the average sizes of piscivorous predators varied temporally for all three of the species examined and varied spatially for two of the three species examined. White perch ranged from 29 to 310 millimeters in total length (TL), but the collection was dominated by individuals ranging, on average, between 136 and 206 millimeters TL. Temporal trends in size for white perch revealed that the smallest individuals (< 60 mm TL) appeared in the collections in July, and most of the large individuals (< 250 mm TL) were collected in October and November at the MCU site ($p < 0.01$). Striped bass ranged from 145 to 570 millimeters TL, with most collections averaging between 194 and 381 millimeters TL. Most individuals of less than 300 millimeters TL were captured before October, and all individuals greater than 300 millimeters TL were captured in October and November, with the largest striped bass collected at the mouths and lower portions of the creeks (although these differences were not significant). Bluefish ranged in size from 60 to 230 millimeters TL, but the collection was dominated by individuals averaging between 147 and 186 millimeters TL. Bluefish were significantly smaller at the mouth of Mill Creek than they were at the DCU, MCL, and MCU sites ($p < 0.01$). Sizes increased progressively through the sampling season, with the smallest individuals (< 80 mm TL) appearing in August and the largest individuals (< 200 mm TL) last appearing in October.

Food Habits

Mean gravimetric indices of stomach fullness (total prey weight/predator weight 100 ± SE) ranged from 0.09 ± 0.041 for striped bass to 0.37 ± 0.118 for bluefish (Figure 3a). No significant differences in mean gravimetric indices of stomach fullness for the dominant predators existed between creeks. We detected no temporal differences in gravimetric indices of stomach fullness for white perch or striped bass; however, bluefish collected in July had significantly higher gut fullness indices compared with fish collected in the months that followed ($p < 0.01$; Figure 3b).

The degree of piscivory appeared to be similar between creeks for most of the dominant species. The percentage of stomachs that contained fish, that contained no fish but other prey items, or that were empty was similar between creeks for white perch and bluefish (Figures 4a, b). White perch stomachs contained very few fish (13% Mill Creek, 16% Doctor Creek), and a small percentage of the stomachs were empty (8% Mill and Doctor creeks). A large percentage of bluefish stomachs were empty (53% Mill Creek, 54% Doctor Creek), but when stomachs contained material, this material was predominantly fish (40% Mill Creek, 31% Doctor Creek). The percentage of fish material was higher in the stomachs of striped bass collected in Mill Creek compared with Doctor Creek (38% in Mill Creek versus 22% in Doctor Creek), while the percentage of empty striped bass stomachs was similar between creeks (Figures 4a, b).

There were species-specific differences in prey selection at the two creeks. In Mill Creek, white perch of all sizes (100–300 mm TL) consumed a large proportion of crustaceans (Figure 5a). In Doctor Creek, the stomachs of small white perch (< 160 mm TL) contained mostly microbenthos and detritus. White perch between 160 and 230 millimeters TL in Doctor Creek exhibited a more varied diet made up of fish, crustaceans, annelids, and mollusks (Figure 5b). Piscivory was evident in only large white perch (< 160 mm TL) from both creeks (Figures 5a, b). Piscivory was evident among all sizes (140–740 mm TL) of striped bass from both creeks (Figures 6a, b). Crustaceans made up a fairly large proportion of the stomach contents of smaller striped bass (< 370 mm TL) from Mill Creek. In addition to eating fish, small striped bass from Doctor Creek also consumed detritus, annelids, and microbenthos. Fish composed a large proportion of the stomach contents of bluefish greater than 140 millimeters TL from both Mill and Doctor creeks (Figures 7a, b). Bluefish less than 136 millimeters TL were only collected at Mill Creek, and they consumed detritus and unidentifiable material. We identified high proportions of crustaceans in the stomachs of bluefish from Mill Creek, but no crustaceans were identified in the stomachs of bluefish from Doctor Creek.

Discussion

Environmental Influence on Fish Abundance

With respect to water quality, dissolved oxygen (d.o.) may have had the most influence on the distribution of large predators. Dissolved oxygen readings were, in most cases, higher at Doctor Creek than at Mill Creek. The average values for both creeks were lower (Table 3) than values for oligohaline creeks in Delaware Bay (mean surface d.o. 7.2–7.9 mg/L [Able, Jones & Fox, 2004, submitted for publication]). Variation in available dissolved oxygen is normal for tidal-marsh creeks (Szedlmayer & Able, 1993; Rountree & Able, 1993) and has been implicated in directing the movements of mobile species within these systems (Bell, Eggleston & Wolcott, 2003). Fluctuations between hypoxic/anoxic and normoxic conditions have been found in other studies conducted in the Hackensack Meadowlands, but very often only average values over larger time scales (daily, monthly, annual) are reported (Kraus & Bragin, 1989; Raichel et al., 2003). With respect to fish use of marsh creeks, however, the frequency of individual events of low dissolved oxygen is probably more important than average dissolved oxygen values. Unfortunately, because dissolved oxygen values ranged widely over the course of a few hours in both creeks, it was difficult to capture the finer-scale changes in fish use of marsh creeks that may have resulted from fluctuations in dissolved oxygen levels given the relatively infrequent (less than weekly) sampling and our inability to determine individual movements of fishes over shorter time scales.

Data limitations aside, the general patterns of fish distribution suggested that the dominant predators occasionally were present in the creeks when hypoxic conditions existed. White perch appeared to tolerate the widest range of dissolved oxygen values. Relatively large numbers of white perch were collected in Mill Creek during hypoxic conditions. However, the presence of a deep hole (8 m) adjacent to one sampling site within Mill Creek may have provided a normoxic refuge. At other times when white perch were present with low dissolved oxygen conditions (< 2 mg/L), they were collected at the MCL site. It is possible that these fish were caught leaving Mill Creek on these occasions. Similarly, on the four occasions when we collected bluefish under hypoxic conditions, they were captured at the MCL site. Some of the highest bluefish catches occurred at these low dissolved oxygen levels (< 2 mg/L) when gill nets were set across the mouth of the Mill Creek. It is therefore possible that those fish were caught leaving Mill Creek. While large-scale changes in distribution and abundance patterns of mobile species have been related to hypoxia in other systems (Pihl, Baden & Diaz, 1991; Breitburg, 1992), only one study has demonstrated a fine-scale behavioral response of a mobile species to the dynamics of hypoxia (Bell et al., 2003). In our study, we rarely collected striped bass at values below about 3 milligrams per liter. This suggests that this species is less tolerant of low dissolved oxygen concentrations than white perch and bluefish, as observed in other marsh creeks (Tupper & Able, 2000).

It is likely that factors other than low dissolved oxygen contribute to differences in abundance of predators in Mill and Doctor creeks. Two possible major differences between them are food availability and water depth. Because Doctor Creek is much shallower than Mill Creek, low water levels might discourage predators from moving into Doctor Creek, especially at low tide.

Species Composition and Size

The dominant fish species (white perch, striped bass, and bluefish) observed in gill-net collections from the tidal-marsh creeks during May through November have also been found in the adjacent Hackensack River (Kraus & Bragin, 1989). These dominant species have also been observed in other low-salinity estuarine marsh systems in the northeastern United States during otter-trawl (Able et al., 2001) and gill-net collections (Tupper & Able, 2000; Able et al., 2004, submitted for publication). However, total species composition from the Hackensack River oligohaline marshes differ from polyhaline marshes. For example, in southern New Jersey marshes, the fauna is dominated by other fish species, including *Mustelus canis* (smooth dogfish), *Paralichthys dentatus* (summer flounder), *Prionotus evolans* (striped searobin), and *Alosa mediocris* (hickory shad) (Rountree & Able, 1997). A comparison with the fish fauna captured by gill nets in two naturally vegetated oligohaline marsh creeks in Delaware Bay (Able et al., 2004, submitted for publication) indicates an overlap in the composition of the dominant fish species. However, several less abundant freshwater species—*Ameiurus catus* (white catfish), *Ictalurus punctatus* (channel catfish), *Perca flavescens* (yellow perch)—and marine species—*Caranx hippos* (crevalle jack), *Leiostomus xanthurus* (spot), *Micropogonias undulatus* (Atlantic croaker), *Pogonias cromis* (black drum), *Mugil curema* (white mullet)—collected in Delaware Bay were absent from the Hackensack Meadowlands collections, suggesting reduced relative fish diversity in the Hackensack River study sites. Overall, species richness was greater in Delaware Bay marsh creeks (14 freshwater and 16 saltwater species) than in the Meadowlands marsh creeks (6 freshwater and 10 saltwater species).

Mill Creek and Doctor Creek varied in species composition, with greater species diversity present in Mill Creek. A possible explanation could be that Doctor Creek is much younger; it was created only one year prior to the start of this study. The flora and fauna may have still been developing at the time we sampled. White perch was the most abundant predator collected in this study and the only one present in all locations. This species was most common in spring and more so in Mill Creek than in Doctor Creek. Other studies confirm the year-round presence of white perch in the Hackensack Meadowlands (Kraus & Bragin, 1989). Striped bass was less abundant than the other predators, but total biomass may have been similar to other predators because individual striped bass grow much larger in size. We recorded significantly higher numbers of striped bass at the mouths of both creeks than at other locations. This pattern was evident in ultrasonically tagged individuals in Delaware Bay as well (Tupper & Able, 2000). Young-of-the-year bluefish were all of similar size when they first appeared in our collection samples. If they were resident in the summer months, as they are in other estuaries (Able, Rowe, Burlas & Byrne, 2003), it would be expected that they would increase in size over time. This they did, suggesting that the fish were foraging successfully in the creeks. Successful foraging by bluefish is also supported by the fact that they were collected in gill nets along with alewife, a species that made up a large component of bluefish diet.

Food Habits

Foraging behavior of white perch, striped bass, and bluefish between Mill and Doctor creeks, as gauged by gravimetric indices of stomach fullness, did not appear to differ between creeks. Temporal comparisons of gravimetric stomach fullness indices revealed that only bluefish exhibited a significant peak in foraging during July. While we expected that spatial and temporal differences in water quality might affect foraging rates, we found no evidence of this, despite the more frequent anoxic/hypoxic conditions in Mill Creek and lower frequency of anoxic/hypoxic conditions in July and August. There was no correlation between dissolved oxygen and gravimetric indices of stomach fullness for any species.

Species-specific patterns in diet composition between the creeks were similar in some ways but different in others. The amount of fish consumed by white perch and bluefish was similar in Mill and Doctor creeks, but more fish were consumed by striped bass in Mill Creek than in Doctor Creek. A more detailed look at the gravimetric proportions of contents in the stomachs of all species collected in both creeks revealed other differences. Fish consumption increased with increasing striped bass size in Mill Creek, as has been observed in this species in other systems (Nemerson & Able, 2003), but this pattern was not as clear in Doctor Creek. Crustaceans made up a large proportion of the diets of all species (especially striped bass and white perch) collected in Mill Creek, whereas detritus and microbenthos composed a large proportion of the material in the stomachs of fish collected in Doctor Creek. Compared with those of the other fish species, the gravimetric proportions of dietary constituents in bluefish stomachs were most similar between the sites. Other studies (Link & Almeida, 2000; Able et al., 2003) have shown that bluefish exhibit primarily piscivorous feeding over a broad size range, and this pattern was similar at the Hackensack River creeks.

The consequences of these differences in diet composition between the two creeks are uncertain. Additional studies designed to examine the movement and growth rates of fish from Mill and Doctor creeks would provide a better understanding of how diet composition, growth, and overall food-web dynamics of fish in the Hackensack Meadowlands are related. Regardless, even though both creeks occur in a heavily urbanized estuary, they provide structural habitats and feeding areas for some typical marsh-creek predators.

Acknowledgments

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Glossary

Analysis of variance (ANOVA): Statistical method that yields values that can be tested to determine whether a significant relation exists between variables.

Anoxic: Of or relating to zero dissolved-oxygen conditions, unsupportive of aerobic life.

Gravimetric: Of or relating to measurement by weight.

Hypoxic: Pertaining to, in aquatic environments, conditions in which there is a dissolved-oxygen concentration of less than 3mg per liter[*] of water; such conditions are usually harmful or deadly to aerobic life.

Microbenthos: Organisms (e.g., protozoa, nematodes) too small to be seen with the naked eye that live on or in sea or lake bottoms.

Mitigation banking: The process of preserving, enhancing, restoring, or creating habitat to compensate for (current or future) habitat disturbances elsewhere, especially due to development.

Normoxic: Of or relating to the concentration of dissolved oxygen in an organism or environment that is considered functionally normal.

Oligohaline: Of or relating to a body of water with a salinity measure of less than 5 parts per thousand (or 5 grams of salt per liter).

$p < 0.01$: An indicator of statistical significance in which the probability of the result of a study being a chance occurrence is less than 1 in 100.

Piscivore: An animal that feeds on fish.

Piscivory: The state or condition of feeding on fish.

Polyhaline: Of or relating to a body of water with a salinity measure between 18 and 30 parts per thousand (or grams of salt per liter).

Student-Newman-Keuls multiple comparison test: A statistical method for determining differences among groups of samples.

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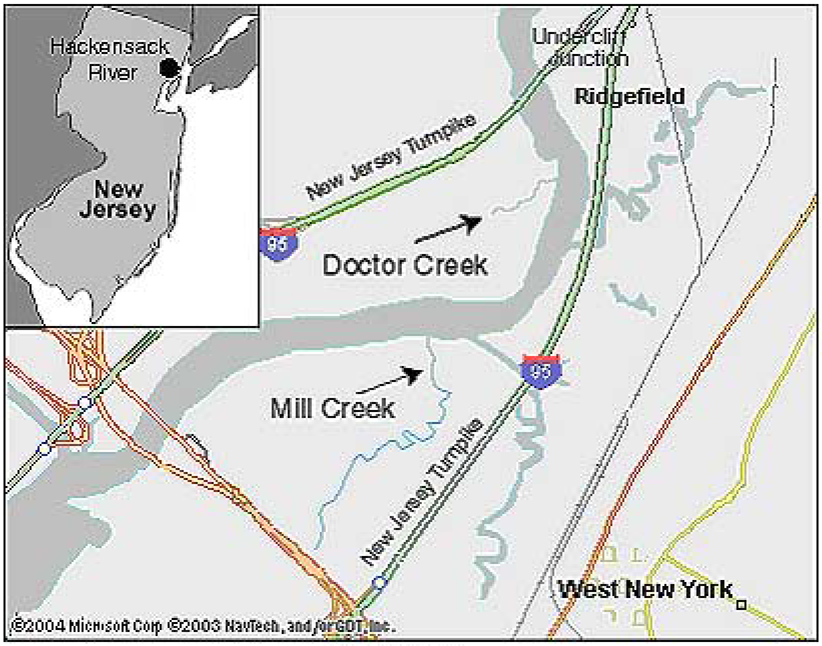
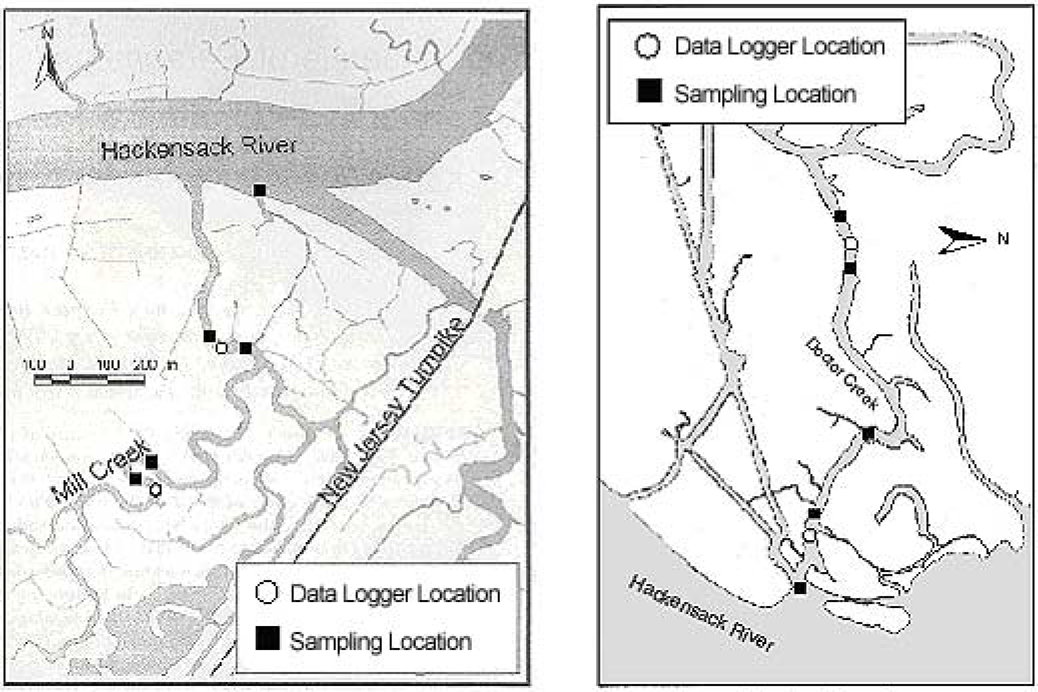
[*] Measurements throughout this paper are in metric notation; conversions to U.S. equivalents can be obtained at http://www.onlineconversion.com.

Figure 1.



Study Area



Mill Creek

Doctor Creek

Figure 1. Map of the study area in the Hackensack Meadowlands, with maps detailing the locations of Mill Creek and Doctor Creek. Data logger (O) and gill-net sampling locations (■) sampled from May to November 2001 are shown for each creek.

Figure 2a.

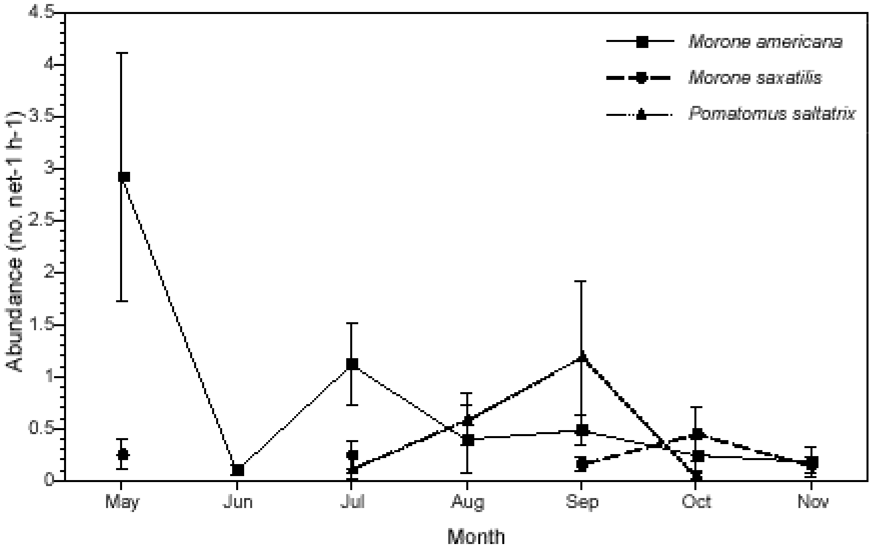


Figure 2a. Abundance (±S.E.) for *Morone americana* (white perch), *Morone saxatilis* (striped bass), and *Pomatomus saltatrix* (bluefish) in the Hackensack Meadowlands study area from May to November 2001 by month.

Figure 2b.

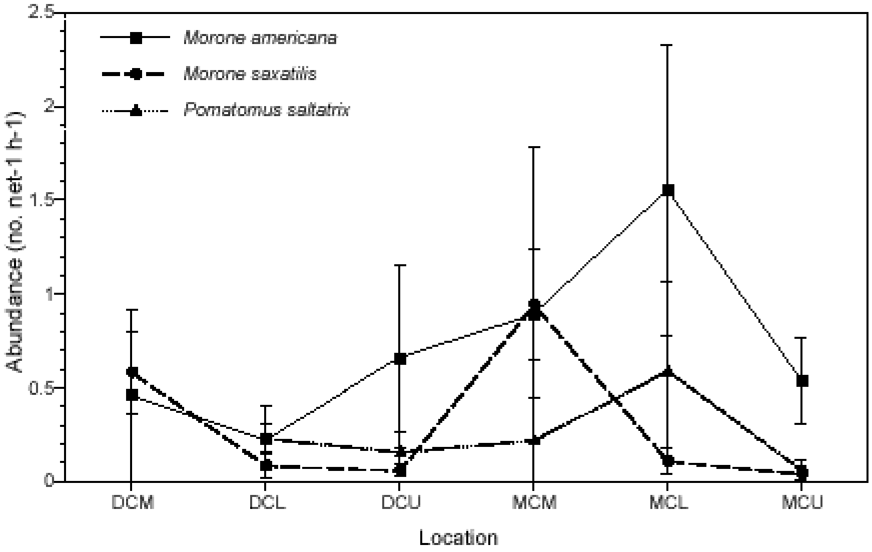


Figure 2b. Abundance (±S.E.) for *Morone americana* (white perch), *Morone saxatilis* (striped bass), and *Pomatomus saltatrix* (bluefish) in the Hackensack Meadowlands study area from May to November 2001 by location.

Abbreviations: Doctor Creek Mouth (DCM), Doctor Creek Lower (DCL), Doctor Creek Upper (DCU), Mill Creek Mouth (MCM), Mill Creek Lower (MCL), Mill Creek Upper (MCU)

Figure 3a.

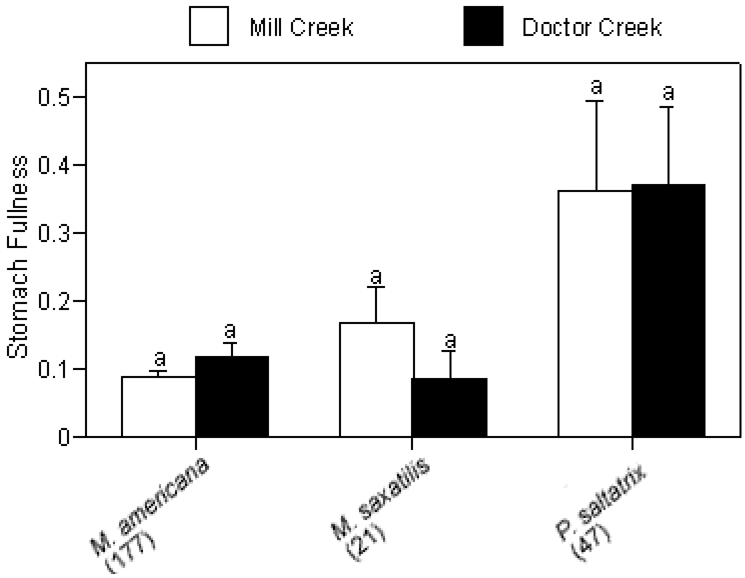


Figure 3a. Gravimetric index of stomach fullness ((total prey weight/predator weight) x 100 ± S.E.) by species for Mill and Doctor creeks. Locations within a species that share a letter (a) are not significantly different from each other.

Figure 3b.

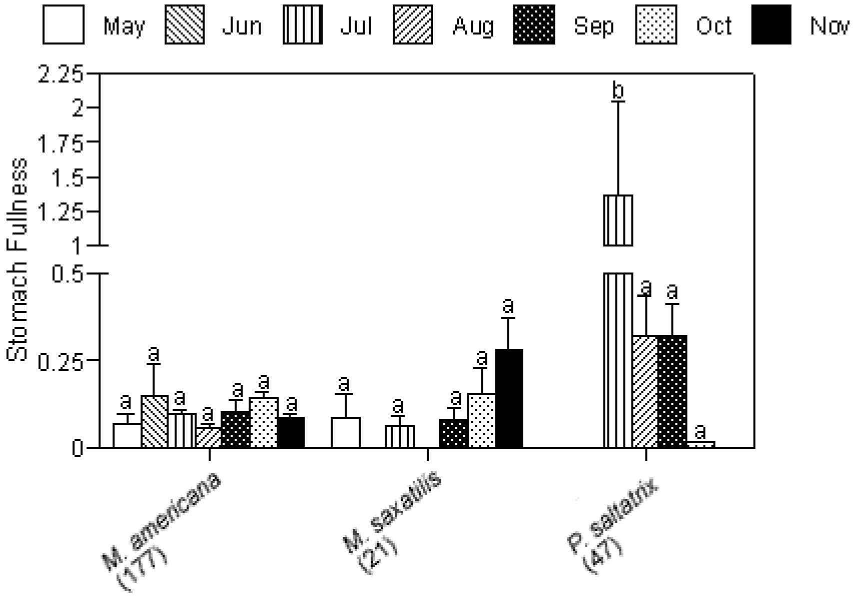


Figure 3b. Gravimetric index of stomach fullness ((total prey weight/predator weight) x100 ±; S.E.) by species for month of the year. Locations within a species that share a letter (a) are not significantly different from each other.

Figure 4a.

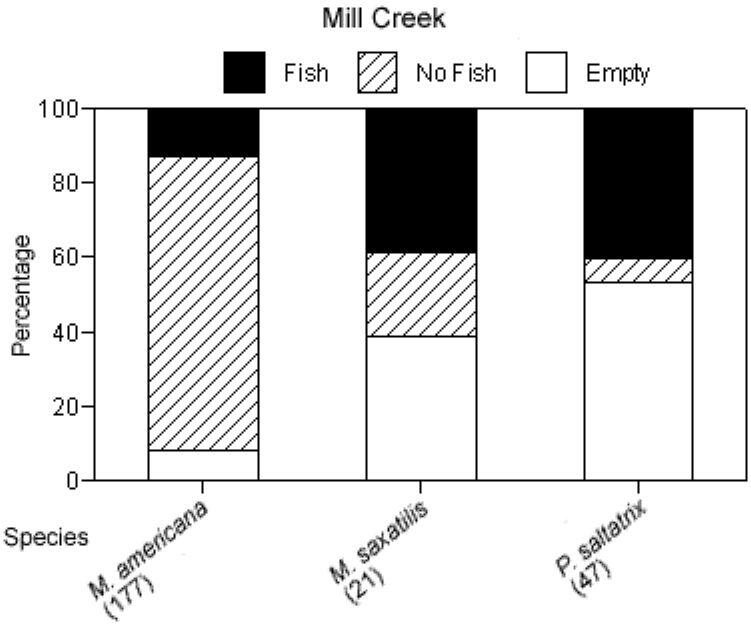


Figure 4a. Contribution (percentage of individuals) of fish to diets by species for Mill Creek. Numbers in parentheses indicate sample sizes.

Figure 4b.

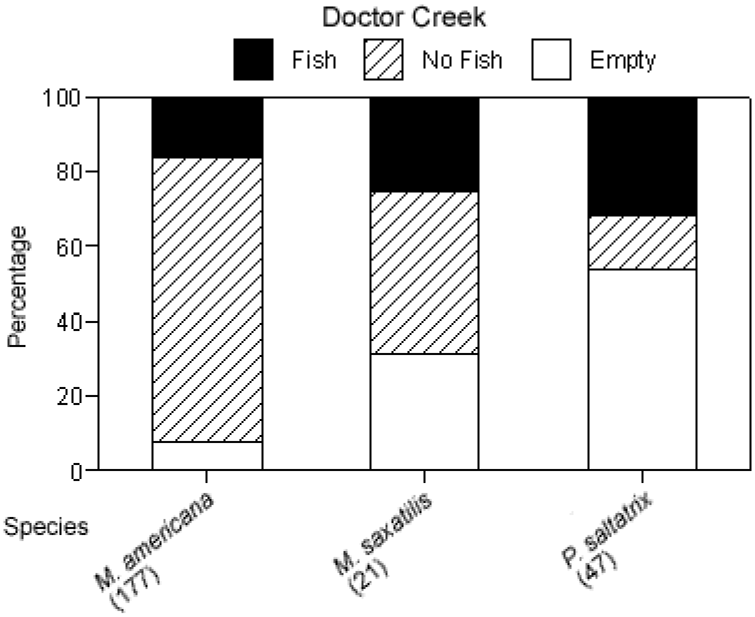


Figure 4b. Contribution (percentage of individuals) of fish to diets by species for Doctor Creek. Numbers in parentheses indicate sample sizes.

Figure 5a.

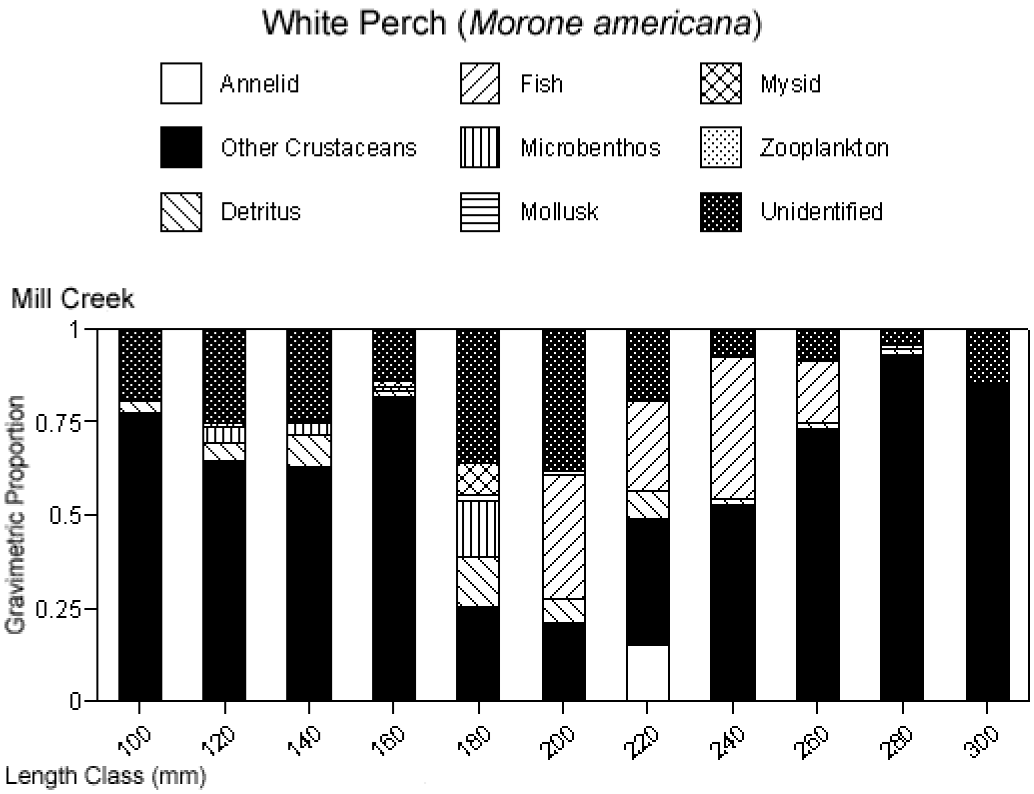


Figure 5a. Gravimetric proportion of each prey category for *Morone americana* (white perch) of different lengths in Mill Creek. Size categories displayed along the x-axis represent the midpoint of a 20-mm size range (e.g., the first category ranges from 90 to 110 mm).

Figure 5b.

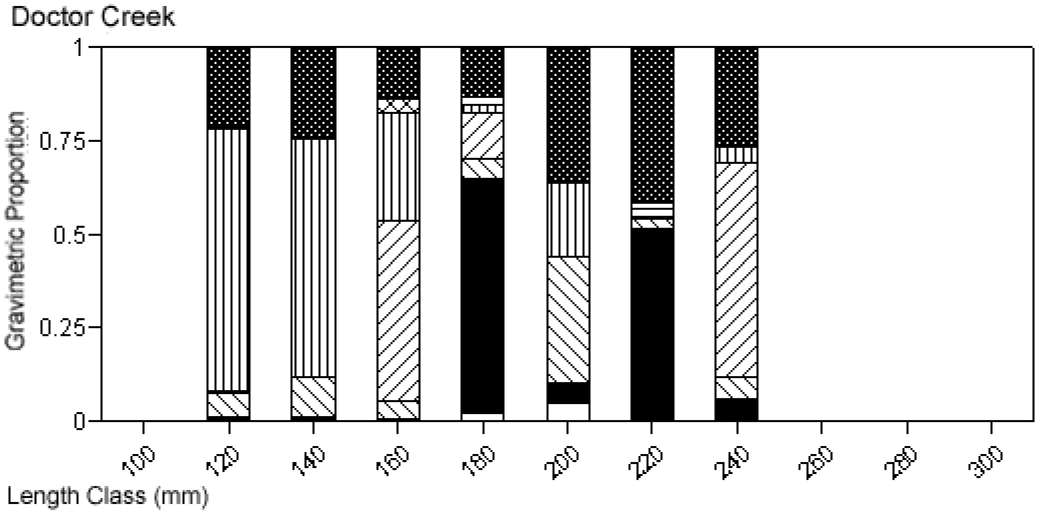


Figure 5b. Gravimetric proportion of each prey category for *Morone americana* (white perch) of different lengths in Doctor Creek. Size categories displayed along the x-axis represent the midpoint of a 20-mm size range (e.g., the first category ranges from 90 to 110 mm).

Figure 6a.

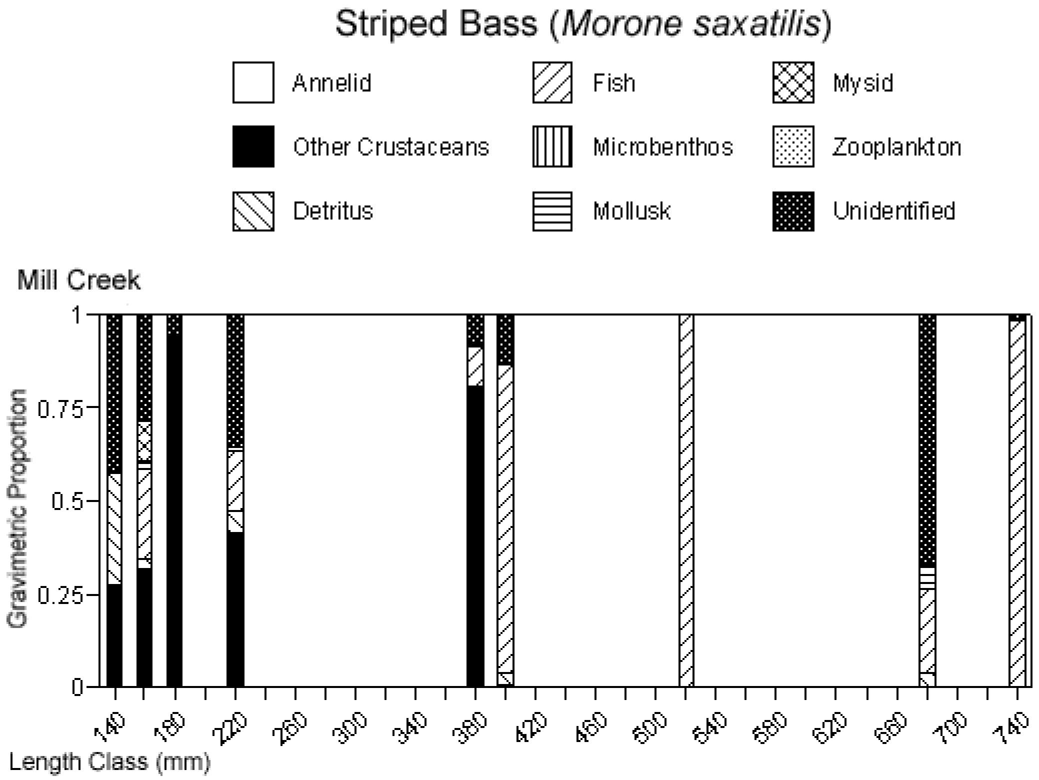


Figure 6a. Gravimetric proportion of each prey category for *Morone saxatilis* (striped bass) of different lengths in Mill Creek. Size categories displayed along the x-axis represent the midpoint of a 20-mm size range (e.g., the first category ranges from 130 to 150 mm).

Figure 6b.

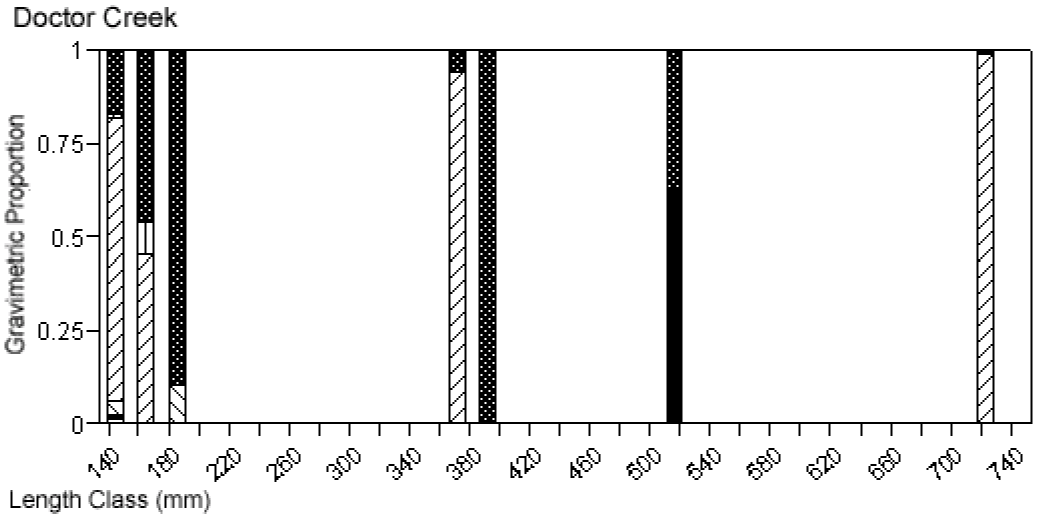


Figure 6b. Gravimetric proportion of each prey category for *Morone saxatilis* (striped bass) of different lengths in Doctor Creek. Size categories displayed along the x-axis represent the midpoint of a 20-mm size range (e.g., the first category ranges from 130 to 150 mm).

Figure 7a.

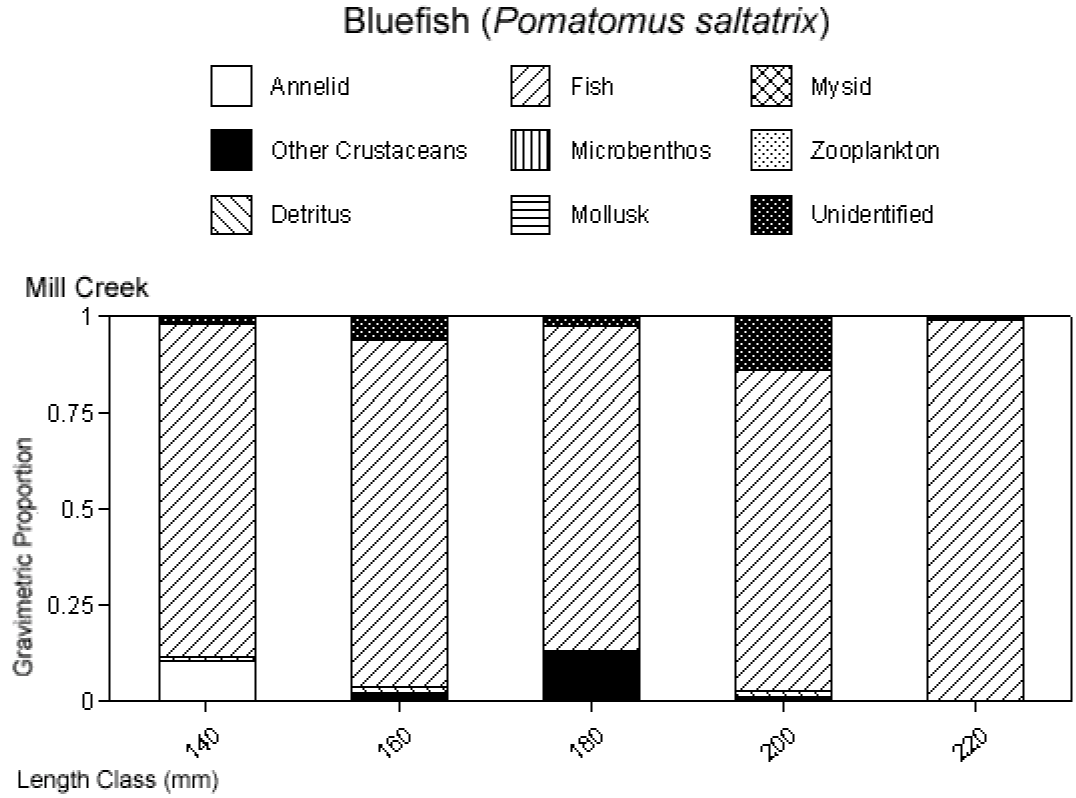


Figure 7a. Gravimetric proportion of each prey category for *Pomatomus saltatrix* (bluefish) of different lengths in Mill Creek. Size categories displayed along the x-axis represent the midpoint of a 20-mm size range (e.g., the first category ranges from 130 to 150 mm).

Figure 7b

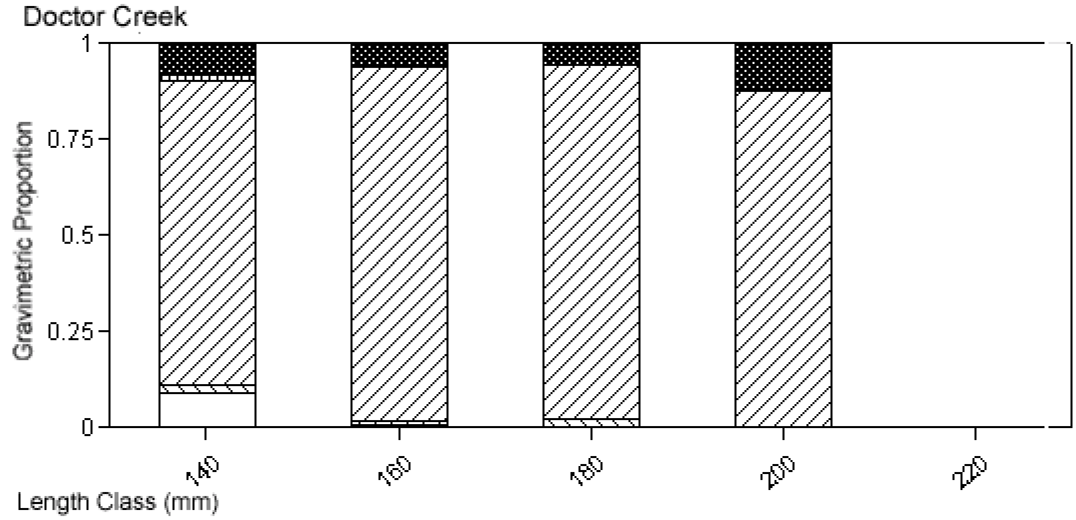


Figure 7b.
Gravimetric proportion of each prey category *Pomatomus saltatrix* (bluefish) of different lengths in Doctor Creek. Size categories displayed along the x-axis represent the midpoint of a 20-mm size range (e.g., the first category ranges from 130 to 150 mm).

Table 1.

Gill-Net Location	Month						
	May	Jun	Jul	Aug	Sep	Oct	Nov	TOTAL
Mill Creek								
MCM			6			2	4	12
MCL	2	10	27	17	10	34	14	114
MCU	3	8	18	16	12	35	14	106
Doctor Creek								
DCM			8			2	4	14
DCL	2	5	24	23	12	32	8	106
DCU	2	5	19	28	14	29	8	105
TOTAL	9	28	102	84	48	134	52	457

Table 1. Sampling effort (number of gill nets deployed) in Mill Creek at three locations (mouth of creek–MCM, lower portion of creek–MCL, and upper portion of creek–MCU) and in Doctor Creek at three locations (mouth of creek–DCM, lower portion of creek–DCL, and upper portion of creek–DCU) within the Hackensack Meadowlands study area during May to November 2001. See Figure 1 for location of sampling sites.

Table 2

Aggregated Prey Categories	Detailed Constituents
Annelid	Capitellid polychaetes, hirud leeches, unidentified annelids, unidentified oligochaetes, unidentified polychaetes
Crustacean	*Callinectes sapidus*, corophid amphipods, narrow gammarid amphipods, *Palaemonetes pugio*, *Palaemonetes* spp., *Rhithropanopeus harrisii*, typical gammarid amphipods, *Unciola* gammarid amphipods, unidentified amphipod, unidentified crab, unidentified decapod shrimp
Detritus	Detritus, plant matter
Fish	*Alosa* spp. *Dorosoma cepedianum*, *Fundulus diaphanus*, *Fundulus heteroclitus*, *Fundulus* spp., *Menidia menidia*, *Sciaenidae* spp., unidentified fish, unidentified fish scales
Microbenthos	Chrionomid larvae, dipteran pupa, nematodes, ostracods, true nemerteans
Mollusk	*Ilyanassa obsoleta*, unidentified bivalve, unidentified gastropod
Mysid	Mysid shrimp (mainly *Neomysis americana*)
Unidentified	Unidentified animal matter
Zooplankton	Calanoid copepods, unidentified eggs

Table 2. Names, category abbreviations, and descriptions of aggregated prey categories used in stomach content analysis of fish predators in the study area during May to November 2001.

Table 3

Physical Variable	Mill Creek						Doctor Creek					
	Jun	Jul	Aug	Sep	Oct	Nov	Jun	Jul	Aug	Sep	Oct	Nov
Temperature (°C)*	25.7 (0.04) (18-31)	25.6 (0.04) (13-31)	26.4 (0.03) (19-31)	22.8 (0.05) (15-27)	16.5 (0.05) (11-21)	11.6 (0.04) (8-16)	25.8 (0.07) (22-31)	25.8 (0.04) (20-32)	26.5 (0.04) (20-33)	22.6 (0.08) (14-28)	15.8 (0.07) (9-22)	11.8 (0.06) (6-17)
Salinity (‰)	3.1 (0.04) (0-7)	6.3 (0.06) (0-12)	8.2 (0.04) (0-12)	8.1 (0.03) (0-12)	9.5 (0.03) (4-13)	11.5 (0.04) (9-15)	2.6 (0.05) (0-5)	5.6 (0.06) (1-10)	7.6 (0.03) (0-10)	7.3 (0.04) (0-11)	8.1 (0.04) (3-11)	10.1 (0.04) (3-12)
Dissolved oxygen (mg/l)*	2.3 (0.06) (0-10)	3.4 (0.06) (0-14)	3.5 (0.06) (0-16)	2.4 (0.04) (0-14)	2.0 (0.03) (0-7)	2.4 (0.03) (0-5)	2.8 (0.09) (0-9)	4.3 (0.07) (0-15)	3.4 (0.07) (0-18)	4.2 (0.1) (1-18)	2.8 (0.03) (1-7)	3.9 (0.04) (2-8)

Table 3. Mean, S.E. (standard error), and range of water quality variables recorded during monthly gill-net sampling conducted at two sites in the Hackensack River system, June–November 2001.

Table 4

Species	Number	Percentage	CPUE
Morone americana	235	46.17	0.529
Pomatomus saltatrix	111	21.81	0.25
Alosa pseudoharengus	101	19.84	0.227
Morone saxatilis	34	6.68	0.077
Brevoortia tyrannus	14	2.75	0.031
Cyprinus carpio	5	0.98	0.011
Dorosoma cepedianum	4	0.79	0.009
Alosa sapidissima	2	0.39	0.005
Cynoscion regalis	2	0.39	0.005
Ameiurus natalis	1	0.2	0.0004
Total Fish	509		

Table 4. Species composition and abundance of the dominant fishes sampled with gill nets in Mill and Doctor creeks. Total number of individuals, percentage of catch (%), and catch per unit effort (CPUE) are shown for each species.

*** Measurements throughout this paper are in metric notation; conversions to U.S. equivalents can be obtained at www.onlineconversion.com/length.htm.**

Spartina alterniflora and *Phragmites australis* as Habitat for the Ribbed Mussel, *Geukensia demissa* (Dillwyn), in Saw Mill Creek of New Jersey's Hackensack Meadowlands*

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Abstract

In areas where the cordgrass *Spartina alterniflora* and the invasive common reed, *Phragmites australis*, coexist, *P. australis* is often regarded as the salt-marsh grass less populated by fauna. Although it is known that the ribbed mussel, *Geukensia demissa*, utilizes *S. alterniflora* as habitat, it was not known whether *S. alterniflora* is a preferred habitat for the mussel when both the cordgrass and *P. australis* occupy an area. To determine this, I calculated the mean number of *G. demissa* in four replicate quadrats near *P. australis* and four replicate quadrats near *S. alterniflora* in Saw Mill Creek of the Hackensack Meadowlands, New Jersey, in March, June, and October 2002 and June 2003. Ribbed mussels were significantly more numerous near *P. australis* than near *S. alterniflora* in March 2002 and tended to be somewhat more numerous near *P. australis* on the other three sampling dates, suggesting that *P. australis* provides as good, if not better, habitat for *G. demissa* as *S. alterniflora*. Since Saw Mill Creek is a unique ecosystem due to human intervention, the results of this study should not be assumed to be true in areas where *S. alterniflora* and *P. australis* coexist and similar human influence is absent.

Keywords: common reed; cordgrass; *Geukensia*; habitat; *Phragmites*; ribbed mussel; *Spartina*.

Introduction

There has been much concern about the effects the invasion of the common reed, *Phragmites australis*, has on salt marshes that have been dominated by the cordgrass *Spartina alterniflora*. The common reed flattens the marsh surface, lowers the water table and the salinity of the soil (Windham & Lathrop, 1999), and converts mosaics of vegetation into dense monotypic stands (Marks, Lapin & Randall, 1994; Chambers, Meyerson & Saltonstall, 1999; Galatowitsch, Anderson & Ascher, 1999; Windham & Lathrop, 1999; Rice, Rooth & Stevenson, 2000). It may also increase sedimentation (Buttery & Lambert, 1965) and build up the marsh plain (Windham, 1995).

These actions, and possibly others, may be altering habitat for salt-marsh plants and animals. Marks, Lapin, and Randall (1993) found that several rare and endangered plant populations were threatened by *P. australis* invasion. Benoit and Askins (1999) found that the biodiversity of flowering plants and birds was reduced in *P. australis*–dominated marshes. *Phragmites australis* is

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often regarded as a salt-marsh grass that is less populated by fauna than *S. alterniflora*. Roman, Niering, and Warren (1984) found that waterfowl usage was substantially reduced in marshes invaded by *P. australis*. Rozas and Odum (1987); Kneib (1994); Kneib and Wagner (1994); Able and Hagan (2000, 2003); Raichel, Able, and Hartman (2003); and Able, Hagan, and Brown (2003) reported that larval and juvenile fish usage of the marsh surface was affected. Angradi, Hagan, and Able (2001) found that the density of benthic macroinvertebrates was lower in *P. australis* than in *S. alterniflora* in August and October.

Concern about habitat alteration has often led to the physical removal of *P. australis* and the planting of *S. alterniflora* in its place (Marks et al., 1994; Weinstein, Balletto, Teal & Ludwig, 1997; Weinstein, Phillip & Goodwin, 2000; Weinstein, Teal, Balletto & Strait, 2001). As a restoration solution, this has been costly and sometimes less than successful (Melvin-Stefani & Webb-James, 1998).

Moreover, there is evidence supporting the view that *P. australis* does not have a deleterious effect on the ability of marshes to function as habitat for fauna. Fell et al. (1998) and Warren et al. (2001) reported that fish foraging on invertebrates and the abundance of invertebrates was not affected by the expansion of *P. australis*. Others have found that fish species composition was also not affected by common reed invasion (Able and Hagen, 2000; Meyer, Johnson & Gill, 2001). Wainright, Weinstein, Able, and Currin (2000) reported that *P. australis* may contribute to the food chain in marsh systems.

Offering weight to both sides of the issue, Talley and Levin (2001) reported that invading *P. australis* stands had more podurid insects, sabellid polychaetes, and peracarid crustaceans but fewer epifaunal gastropods, arachnids, midges, and tubificid and enchytraeid oligochaetes than uninvaded stands. Their findings varied with season, site, and salinity.

It is well known that the ribbed mussel, *Geukensia demissa*, utilizes *S. alterniflora* as habitat (Kuenzler, 1961a, b; Castagna & Chanley, 1973; Stiven & Kuenzler, 1979; Jordan & Valiela, 1982; Bertness, 1984; Bertness & Grosholz, 1985). There is evidence that ribbed mussels benefit *S. alterniflora* by attaching to the plant's root mat and strengthening it against physical disturbance and erosion. The mussels' filter-feeding activities may also oxygenate the sediments and provide them with nitrogenous wastes and minerals (Jordan & Valiela, 1982), contributing in turn to an increase in the above- and below-ground biomass of *S. alterniflora* (Bertness, 1984).

Though the associations between *S. alterniflora* and *G. demissa* are known, information about possible associations between *P. australis* and *G. demissa* is lacking. The purpose of this study was to determine if one marsh grass is more densely populated by *G. demissa* when *S. alterniflora* and *P. australis* coexist.

Materials and Methods

The study was conducted in the Hackensack Meadowlands of New Jersey, west of the Hackensack River, in a tidal tributary of Saw Mill Creek, itself a tributary of the Hackensack River (40°46′N, 74°06′W). The west side of the tidal tributary is dominated by *P. australis*, and the east side is dominated by native *S. alterniflora*. *Phragmites australis* was planted in the Meadowlands to stabilize the banks of mosquito ditches at a time when the plant was not considered invasive (Headlee, 1945). Dikes, tidal restrictions (Roman et al., 1984), drainage or mosquito ditches (Bart, 1997; Bart & Hartman, 2000), and construction creating higher ground such as roads (Bart, 1997; Keller, 2000; Ailstock, Norman & Bushmann, 2001) have been found to be associated with invasions of *P. australis*. Dikes, roads (e.g., the New Jersey Turnpike), and railroads surround Saw Mill Creek, and it is possible that such construction may have aided the expansion of *P. australis* at the study site. Prior to this construction, it is possible that the study site was dominated by *S. alterniflora*. The presence of both *P. australis* and *S. alterniflora* in Saw Mill Creek may be the result of the failure of dikes during storms, as this would have allowed the tide to come in again and the saltwater species *S. alterniflora* to recolonize. Remnants of these dikes can still be seen at the mouth of Saw Mill Creek where it drains into the Hackensack River. Their failure has also allowed tidal flushing of *P. australis* stands, and this, along with salinity changes, may be responsible for the rarely seen presence of *G. demissa* near *P. australis*.

Because of the sparse population of *G. demissa* on either side of the tidal tributary, possibly due to low salinity, quadrats were not located along a transect line. The location of each quadrat was determined by the presence of at least one mussel, and so was not random. This "chosen meter" method included nearly every mussel that was present at the site. Each quadrat measured one square meter; the number of *G. demissa* in one square meter of marsh was sampled by counting the number of mussels found within each quadrat. Four replicate quadrats, which did not overlap, were surveyed around *P. australis*, along with another four replicate quadrats around *S. alterniflora*, in March, June, and October 2002 and June 2003. The same eight quadrats were not repeatedly sampled; however, the area where they were made, consisting of a sparse population of mussels and including nearly every mussel at the site, was sampled repeatedly. The mean number of *G. demissa* in four replicates of the chosen meters around *P. australis* and four replicates of the chosen meters around *S. alterniflora* was calculated. A one-way ANOVA and a Dunnett's Multiple Comparison Test were used to determine whether the means were significantly different. The means were considered to be significantly different when $p < 0.05$. The sizes of the mussels around *P. australis* and *S. alterniflora* were not measured.

Results and Discussion

Geukensia demissa was significantly more numerous near *P. australis* than near *S. alterniflora* in March 2002 and tended to be somewhat more numerous near *P. australis* on the other three sampling dates, suggesting that *P. australis* may provide as good, if not better, habitat for *G. demissa* as *S. alterniflora* (Figure 1). These findings, from a habitat perspective, are consistent with those of Fell et al. (1998), Able and Hagen (2000), Meyer et al. (2001), and Warren et al. (2001), as outlined above.

They are not, however, consistent with the findings of other researchers, also outlined above (Roman et al., 1984; Rozas & Odum, 1987; Kneib, 1994; Kneib &Wagner, 1994; Benoit & Askins, 1999; Able & Hagan, 2000, 2003; Angradi et al., 2001; Talley & Levin, 2001; Raichel et al., 2003; Able et al., 2003). Neither are they consistent with Posey, Alphin, Meyer & Johnson (2003), who reported a slightly higher abundance of fauna in *S. alterniflora* marshes than in *P. australis* marshes.

There could be several reasons for the inconsistency. The most basic one is the difference between the species and sites studied. In this study, habitat usage was evaluated using a semisessile species, *G. demissa*. Mussels are an excellent species to use in habitat studies because they generally don't move very far from the habitat where they settle, and when they do, their rate of movement is slow. Animals such as waterfowl and fish are more difficult to use when evaluating habitats because they migrate. If their migratory patterns are not known or accounted for when sampling, this can have a profound effect on the study results. Other reasons for the inconsistency include the presence of shallow pools around *S. alterniflora* and the lack of them around *P. australis*, possible differences in food availability, and differences in stem density and/or canopy thickness (Fell, Warren, Light, Rawson & Fairley, 2003). *P. australis* populations often occur in large dense stands with 100% cover; *S. alterniflora* populations are patchy. It is possible that variations in the spatial dynamics of the population of each species from one site to the next are responsible for the variable results on the effects of *P. australis* and *S. alterniflora* as habitat for animals.

It is likely that after March 2002, there was more predation and/or other mortality of *G. demissa* near *P. australis*; and between June and October 2002, there may have been more recruitment of *G. demissa* near *S. alterniflora*. The extent of mortality and recruitment at each site is currently being studied by marking individual mussels. If recruitment of *G. demissa* to *P. australis* and *S. alterniflora* is different, future studies will determine whether this difference is due to habitat selection by larval *G. demissa* or to hydrodynamic factors. In other studies currently being conducted, half the mussel populations are being caged to gain additional information on predation of *G. demissa* near *S. alterniflora* and near *P. australis*.

The construction of mosquito ditches, roads, railroads, dikes, and their failure in storms make Saw Mill Creek of the Hackensack Meadowlands a unique ecosystem where both *S. alterniflora* and *P. australis* coexist. Although the results of this study indicate that *P. australis* may provide comparable, if not better, habitat for *G. demissa* than *S. alterniflora*, the results should not be assumed to be true in areas where *S. alterniflora* and *P. australis* coexist but the kind of human intervention that exists in Saw Mill Creek is absent. Future studies will investigate such areas and determine whether *G. demissa* is also present in other parts of the Meadowlands that are dominated by *P. australis*.

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Glossary

ANOVA (analysis of variance): Statistical method that yields values that can be tested to determine whether a significant relation exists between variables.

Benthic: Organisms (e.g., protozoa, nematodes) living on or in sea or lake bottoms.

Dunnetts Multiple Comparison Test: Statistical test used to compare a series of different treatments in an experiment with the experiment's single control.

Enchytraeid: Any of a family (Enchytraeida) of annelid worms.

Epifaunal: Pertaining to animals that live on the surface of a sediment or object.

Gastropod: Any of various mollusks of the class Gastropoda, such as the snail, slug, cowrie, or limpet, which characteristically have a single, usually coiled shell or no shell at all, a ventral muscular foot for locomotion, and eyes and feelers located on a distinct head.

Macroinvertebrate: An animal, such as an insect or mollusk, that lacks a backbone or spinal column and can be seen by the naked eye.

Oligochaetes: Any of various annelid worms of the class Oligochaeta, including the earthworms and a few small freshwater forms.

$p < 0.05$: An indicator of statistical significance in which the probability of the result of a study being a chance occurrence is less than 5 in 100.

Peracarid: Any of an order (Peracarida) of shrimplike crustaceans.

Podurid insects: Small, leaping, scaly insects (e.g., aquatic springtails) from the genus Podura or related genera.

Polychaetes: Any of various annelid worms of the class Polychaeta, including mostly marine worms such as the lugworm, characterized by fleshy-paired appendages tipped with bristles on each body segment.

Replicate quadrats: A quadrat is a small, usually rectangular or square plot used for close study of the distribution of plants or animals in an area. In order to account for variation in soil, hydrology, and topography, it is necessary that quadrat sampling be repeated (replicated) elsewhere in the study area.

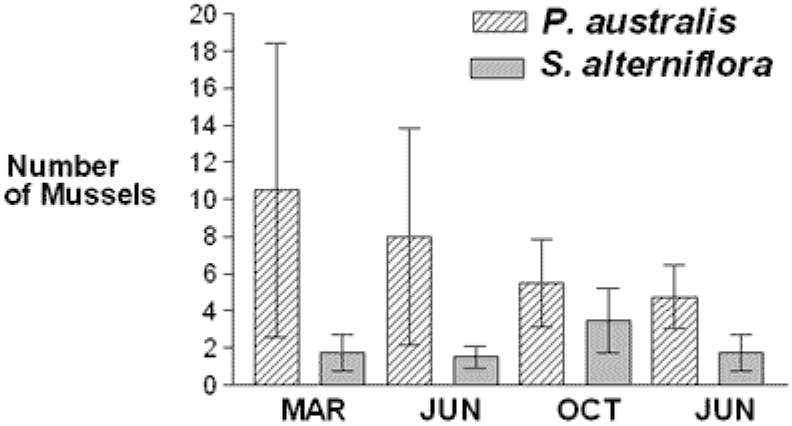
Sabellid: A fan worm in the family Sabellidae.

Semisessile: Partially fixed in its position.

Transect line: A straight line drawn through a study area for the purpose of sampling plants and animals, often to illustrate a gradient or linear pattern along which plant or animal communities change.

Tubificid: Any of a family (Tubificidae) of aquatic worms that lack a specialized head (such as *Tubifex* worms).

Figure 1. Number of Mussels near *Phragmites australis* and *spartina alterniflora*



The mean number of ribbed mussels, *Geukensia demissa*, in four replicate "chosen meter" quadrats in two habitats, *Phragmites australis* and *Spartina alterniflora*, in the months of March, June, and October 2002 and June 2003. Error bars represent the standard deviation. The results show that *P. australis* provides as good, if not better, habitat for the ribbed mussel as *S. alterniflora*.

Influence of Sediment Characteristics on Heavy Metal Toxicity in an Urban Marsh[*]

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Abstract

Remediation and protection of urban wetlands are gaining public support as the contribution of these wetlands to biodiversity, and their importance to local fisheries and wildlife, become better understood. When developing remediation strategies, it is important to consider the key parameters that influence availability and toxicity of contaminants to which plant and animal life are exposed. Kearny Marsh is an important component of the Hackensack Meadowlands, which, located as they are in one of the most populated metropolitan areas in the United States, have been subjected to urban encroachment. We undertook studies to determine what sediment and detritus characteristics might be influencing heavy metal toxicity in Kearny Marsh. Toxicity parameters included sediment grain size, percentage of total organic carbon (%TOC), SEM-AVS, and heavy metal concentrations in whole sediment and detritus. These parameters were correlated with ten-day survival and growth, under laboratory conditions, of the aquatic larvae of *Chironomus riparius* (midge fly) in order to determine what factors were having the most effect on toxicity. Data showed that both sediment and detritus were highly contaminated with heavy metals. High metal levels in detritus had a significantly negative effect on the survival and growth of *Chironomus* larvae. Conversely, high iron-to-metal ratios in both sediment and detritus were correlated with reduced toxicity. The %TOC in sediments was linked to larval growth in October but not in June. SEM-AVS and grain size were not good indicators of toxicity. We conclude that detritus and iron could prove to be important factors for controlling and remediating heavy metal toxicity in Kearny Marsh and other wetlands in highly urbanized areas.

Key words: Acid volatile sulfides; *Chironomus*; detritus; Hackensack Meadowlands; heavy metals; iron; remediation; sediment; total organic carbon; toxicity testing; wetland.

Introduction

Kearny Marsh, in New Jersey, is a 320-acre freshwater wetland within the 8,400-acre estuary system known as the Hackensack Meadowlands. It has been heavily impacted by urban sprawl, including landfill construction within the marsh, housing and commercial development around the marsh, and the 1970 extension of the New Jersey Turnpike (Interstate Highway 95) through the marsh. Extension of the turnpike involved the installation of a dike that separated the marsh from the tidal flow of the Hackensack River and left it with no natural inlet or outlet of water. This allowed contaminants to settle into and concentrate in sediments. Because of its size and uniqueness as a freshwater wetland, Kearny Marsh is an important component of the Hackensack

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Meadowlands, and there is now increased interest in preserving the remaining acreage and improving its environmental health. Wetlands are highly productive ecosystems that usually provide an abundance of food for a diversity of fish and bird species, and eventually, through the food chain, for humans. Although Kearny Marsh has been damaged due to urbanization, marshes have incredible regenerative ability in general, and intervention at Kearny might improve its productivity.

Kearny Marsh sediments are severely contaminated with heavy metals (Langan Engineering and Environmental Services, Inc., 1999), so improving the marsh might require costly sediment remediation. However, the extent to which Kearny Marsh sediments are actually toxic has not been investigated. A critical factor for sediment toxicity is contaminant bioavailability—the degree to which contaminants can be taken up by plants and animals (Ankley, Di Toro, Hansen & Berry, 1996). Sediment parameters that affect heavy metal bioavailability include cation exchange capacity (CEC), total organic carbon (TOC), iron (Fe) and manganese (Mn) oxides, as well as the relationship between acid volatile sulfides (AVS) and simultaneously extracted metals (SEM). Following is a brief explanation of these parameters.

Cation exchange capacity is based on the surface area of sediment grain particles available for binding cations, such as hydrogen (H^+) and free metal ions (e.g., Mn^{+2}). Sediments with a high percentage of small grains, such as silt and clay, have high surface-to-volume ratios and can adsorb more heavy metals than sediments composed of large grains, such as sand. Total organic carbon is added to sediments primarily through the decomposition of plant and animal matter. Organic carbon can directly adsorb heavy metals from solutions applied to sediments (Liber et al., 1996). However, it can also contain heavy metals accumulated by plants that have been exposed to contaminated sediment during their lifetimes (Peltier, Webb & Gaillard, 2003). Nonetheless, high percentages of organic matter and/or small grains in sediment are generally associated with reduced heavy metal bioavailability and toxicity (Ankley et al., 1996).

Iron and Mn are major heavy metal components of both soil and sediment and can exist as dissolved ions or various precipitates, such as oxyhydroxides (oxides) and sulfides. Both Fe and Mn oxides can remove other heavy metals from solution, thus making them less bioavailable (Fan & Wang, 2001). One way they do this is by precipitating heavy metals from solution during oxide formation (Simpson, Rosner & Ellis, 2000); another is direct adsorption onto preformed oxides (Dong, Nelson, Lion, Shuler & Ghiorse, 2000). Sulfide is known to interact with Fe under anaerobic conditions to form a solid, iron sulfide (FeS). Other heavy metals such as copper (Cu), lead (Pb), nickel (Ni), and zinc (Zn) can be removed from solution by displacing Fe and binding to the sulfide. This process has led to a relatively new parameter for evaluating sediment toxicity: simultaneous extracted metal minus acid volatile sulfide (SEM-AVS). The term AVS represents the amount of sulfide in sediments available for binding heavy metals; SEM represents the amount of heavy metals in sediment that could be available to plants and animals. If SEM exceeds AVS, the sediments are potentially toxic (Di Toro et al., 1990; Hansen et al., 1996).

Testing sediments for toxicity generally relies on the use of test organisms. A common test organism is the aquatic larva of the chironomid *Chironomus riparius* (midge fly). Chironomid larvae, such as those of *Chironomus riparius* and *Chironomus tentans* are detritivores, and they live in intimate contact with sediments. Standardized procedures have been developed that use reduced survival and weight in chironomids as indicators of toxicity in sediments (American Society for Testing and Materials [ASTM], 1992; U.S. Environmental Protection Agency, 1994). Chironomids have also been used in laboratory (Call et al., 1999) and field studies (Liber et al., 1996) to evaluate the influence of parameters such as SEM-AVS and TOC on sediment toxicity. In addition to being valuable test organisms, chironomids are environmentally important components of aquatic food webs (Armitage, Cranston & Pinder, 1995). Several species of chironomids live in Kearny Marsh (Bentivegna, personal observation).

The goals of this study were to evaluate the toxicity of Kearny Marsh sediments and investigate what sediment parameters might be associated with that toxicity. We evaluated sediment toxicity by measuring the ten-day survival and growth of chironomids. Testing was performed with either whole sediment or the detrital fraction (partially decayed organic matter) of the sediment in order to determine what contribution plant matter was making to overall sediment toxicity. Other parameters tested included grain size, TOC, SEM-AVS, and total heavy metal concentrations in sediment and detritus. Our focus was on heavy metals because previous studies had already indicated toxic levels of metals in Kearny Marsh sediments, while the same studies had shown organic contaminants (polychlorinated biphenyls, chlorinated pesticides, and polynuclear aromatic hydrocarbons) to be at lower levels (Langan Engineering and Environmental Services, Inc., 1999). We anticipated that our results would indicate whether there was a need for sediment remediation in the marsh, and if so, what the best remediation approach would be.

Materials and Methods

Site Description

Kearny Marsh is part of the Hackensack Meadowlands in northeastern New Jersey. The marsh is located just west of New York City, New York, and north of Newark, New Jersey. To the west of the marsh is the town of Kearny; to the east are the Hackensack River and its associated wetlands. The marsh is surrounded by highways and railroad tracks that serve commuter traffic in one of the most populous metropolitan areas in the United States (Figure 1).

Water-quality data collected during our study (2002–03) showed the marsh to be an oligohaline wetland, with salinity ranging from 0.5 to 2.6 parts per thousand (ppt). Our study area was shallow, with depths of 0.5 to 3 feet, and had low dissolved oxygen ranging from 0.1 to 3.5 parts per million (ppm) during the months of May through October. Water temperature during the same months ranged from 14°C to 34°C (57.2°F to 93.2°F).

Sediment and Detritus Collection and Analyses

We collected sediment and detritus from six sites in Kearny Marsh. These sampling sites were numbered 3, 7, 9, 10, 18, and 22 (see Figure 1). Substrates were collected on June 5, 2002, and October 18, 2002, using an Ekman dredge. Toxicity testing was done on whole sediment or detritus. We separated detritus from whole sediment on site by sieving the sediment through a 1,000-micrometer mesh, using site water. Substrates were stored in polypropylene containers at 4ºC (39.2°F). Sediment was used in toxicity tests within two weeks of collection; detritus was tested within one month of collection. We analyzed sediment and detritus for heavy metal content (described below), as well as for %TOC, grain size, and AVS-SEM. Samples for AVS-SEM were stored at -70°C (-94°F).

Sediment characterization was done as follows. We analyzed TOC and grain size using American Society for Testing and Materials methods (ASTM, 1992). For TOC, we measured samples by the volatile solids technique, which involved drying sediments and burning off organic matter in a furnace for 16 hours at 550°C (932°F). Percentage TOC was calculated based on the change in sediment weight before and after ignition (ASTM method D2974). We determined grain size by drying whole sediments, grinding them up, and then sieving them through different-size meshes to establish percentages of gravel, sand, and silt+clay (ASTM method D422).

We analyzed AVS and SEM according to Allen, Fu, Boothman, Di Toro, and Mahony (1994). We constructed a closed AVS apparatus consisting of an 8- to 16-vessel train linked together with Nalgene tubing. Nitrogen gas was used to volatilize and transport reactants through the train. Each station of the train consisted of one reaction vessel containing oven-dried sediment (7–14 g[*]), deionized water (200 ml), and hydrochloric acid (HCl) (10 ml of a 6 M solution) to acidify samples; one vessel containing a pH 4 buffer (potassium phosphate 0.05 M) through which gas flowed to acidify the train; and two silver nitrate traps (200 ml 0.1M $AgNO_3$) into which sulfides flowed from the reaction vessel. At the end of the train was 1 M HCl (200 ml) for acidification of sediment samples. Before being passed through the reaction vessels, the nitrogen gas was deoxygenated and acidified by passing it through an oxygen scrubber (0.02 M H_4NO_3V, 0.014 M $HgCl_2$) and a pH 4 buffer. All solutions in the train were deoxygenated before use. Reactions ran for two hours, after which vessel contents settled for 30 minutes. Sediment sulfide content (AVS) was analyzed by filtering the combined contents of the two silver nitrate traps through 1.2-millimeter filter paper (Fisher Scientific, Pittsburgh), drying the residue for 40 minutes at 104°C (219.2°F), desiccating it for 20 minutes at room temperature), and then determining the change in filter-paper weight. We analyzed the SEM by collecting 100 to 160 milliliters of the acidified water from the reaction vessel and measuring Cd, Cu, Ni, Pb, and Zn, as described below. Silver nitrate traps were standardized by adding 3 to 6 milliliters of 0.1 M sodium sulfide (NaS) to the $AgNO_3$ solution used in the train; then the AVS was analyzed as described above. The AVS from the samples was based on the micromoles (µmol) of sulfides in the traps adjusted for the standard and divided by the quantity of dried sediment added to the reaction vessel, giving µmol/g. The SEM was based on the combined µmol of Cd, Cu, Ni, Pb, and Zn divided by the quantity of dried sediment added to the reaction vessel.

Heavy Metal Analysis

For metal analysis, sediment samples were oven dried (yielding 1–2 g dry weight), weighed, and mineralized in 10 milliliters of trace-metal-grade nitric acid (HNO_3) using Teflon bombs in a microwave digester. The resulting mineralized solution was boiled off to near dryness and restored to 10 milliliters volume with 1% HNO_3. We analyzed SEM samples without further processing. Cadmium (Cd), chromium (Cr), Cu, Fe, Mn, Ni, Pb, and Zn were analyzed by flame or graphite-furnace atomic absorption spectrophotometry (using Varian Spectra AA-220FS), depending on the metal concentration. Mercury (Hg) analyses were performed by cold-vapor generation (VGA-77) using a Bacharach MAS-50D mercury analyzer. Trace Metal Standard 1 (Baker Instra-Analyzed Reagent, lot number V47419)

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[*] Except where noted, measurements throughout this paper are in metric notation; conversions to U.S. equivalents can be obtained at http://www.onlineconversion.com/length.htm

was used as a quality control sample and run with each set of samples along with a blank. Data provided were the average of two replicates.

Toxicity Testing

Subchronic toxicity tests followed standard methods (ASTM, 1992). We used second instar *Chironomus riparius* and ran the tests for ten days. Chironomids were obtained from a laboratory culture maintained by Bentivegna. Two separate subchronic tests were performed and replicated three times (for a total of six tests) on sediment and detritus collected from all sites in June and October. Each replicate started with ten chironomids, which were not fed for the duration of the experiment. Toxicity measurements were based on chironomid survival and weight. Survival was defined as the number of living individuals found after ten days. We determined chironomid weight by collecting survivors from a particular replicate, blotting them dry, and weighing them together. Initial weights were taken from a representative group of ten chironomids at the start of each experiment for comparison.

Conditions for the toxicity tests were as follows. We put 50 milliliters of sediment or 5 grams of detritus, along with 250 milliliters of test water, in one-liter polypropylene containers. The test water was particle and carbon filtered using CDPRM1206 and CDFC01204 filters (from the Millipore Corporation, Billerica, Massachusetts). Test-water hardness (i.e., its concentration of calcium and magnesium) was 130 mg/L. Substrate and water were combined and allowed to sit overnight; chironomids were added the next day. The containers were kept static, and any evaporated water was replaced daily with distilled or deionized water. The containers were exposed to 12 hours of light and 12 hours of darkness. Temperature ranged from 23°C to 26°C (73.4°F to 78.8°F). The pH was taken at the beginning and end of each experiment (using Sentron Model 2001 pH System, Sentron Inc., Gig Harbor, Washington); pH values ranged from 7.1 to 7.7 for sediments and 7.3 to 7.8 for detritus.

Controls for sediment and detritus toxicity testing were set up as follows. In the sediment tests, both positive and negative controls consisted of chironomids exposed to acid-washed sand (from American Stone-Mix, Inc., Towson, Maryland) in 250 milliliters of test water, and fed biweekly on ground fish food (three drops of 0.1 g/ml Tetracichlid; Tetra GMBH, Melle, Germany). Cadmium (Cd) was added to the positive control to a concentration of 0.3mM, while the negative control received no Cd. We fed the control chironomids because the sand had no nutritional value and would not support chironomid survival or growth over a ten-day period. Positive and negative controls for the detritus tests consisted of detritus collected from site 3, along with the same amounts of test water and fish food used in the sediment controls. The positive detritus control also had Cd added to a concentration of 0.3 mM, while the negative control had no added Cd. A positive control was not run for June detritus. We fed the detrital control chironomids in order to provide them with an alternative, uncontaminated source of food and distinguish their responses from those of the test chironomids that were exposed to site 3 detritus alone. The pH for the controls ranged from 7.3 to 7.9 in the sediment tests and 6.8 to 7.4 in the detritus tests.

Statistical Analyses

We performed statistical analyses by combining data from the two experiments run for each substrate (sediment and detritus) at each collection time (June and October). Statistical differences for survival and growth in the sediment and detritus treatments were determined by one-way ANOVA, followed by Tukey post hoc tests, $p \leq 0.05$. Differences between detritus and sediment from each site and collection time were determined by independent sample T-test, $p \leq 0.05$. The statistical relationship between chironomid survival and growth and sediment parameters was determined by bivariate correlation using the Pearson coefficient in a two-tailed test, $p \leq 0.05$. All statistical analyses were performed using SPSS software (Version 12.0).

Results

In order to investigate the role of sediment versus detritus toxicity of marsh sediments, we tested whole sediment and its detrital fraction separately. Results for the sediment toxicity tests showed significant differences in survival between sites (Table 1). In June, survival for site 7 was significantly reduced compared with the negative control (-C) and sites 3 and 22, $p \leq 0.05$. Survival in October sediment was significantly reduced in sites 7 and 22 compared with -C and sites 3, 9, 10, and 18. Results for growth also showed statistically significant differences in June and October. For June, site-7 growth was similar to the positive control (+C) growth and significantly reduced compared with growth at sites -C, 9, and 18. October results differed from June in that growth was significantly reduced in sites 9, 10, and 18 compared with -C and site 22. Results for detritus showed no statistically significant effects on survival in June or October, although site-10 survival was suppressed in both months (Table 2). Growth in site-10 detritus was significantly reduced compared with -C and sites 7 and 9 in June and October; site-10 results were similar to +C. In addition, site-18 growth was significantly reduced in October detritus.

Our toxicity test results were complicated by the difficulty of finding all the surviving chironomids due to their small size. The nutritional value of the sediment and detritus in general was poor; unfed larvae only doubled or tripled their weights. Data did show that sediment and detritus from some sites, most consistently 7 and 10, were toxic, as growth was similar to that of +C (Tables 1 and 2). Comparison of the two substrates showed that neither consistently supported growth and survival better than the other (Figures 2 and 3). However, detritus did prove superior to sand in -C.

The results of our sediment characterization tests are presented in Table 3. The TOC levels in sediments were very high, ranging from 7% to 87%. This indicated a large amount of detritus in the sediments, which was expected because of the annual dieback of wetland grasses and poor microbial degradation found in suboxic marshes. Sediments were primarily composed of sand, which ranged from 70% to 94%. When combined, the smaller particles of silt and clay ranged from 4% to 31%. Taken together, the percentage of silt+clay was similar between June and October sediments. There were two notable exceptions: At site 18, June sediments were 2.5 times higher than October sediments, and at site 22, June sediments were 6.3 times higher than those in October. This may have been due to variation in the sediment composition at our sampling sites. The SEM-AVS values were all negative, indicating that more sulfide was present than biologically available metals. The AVS values did show apparent seasonal differences: Values in October were considerably higher than in June for most samples. For example, AVS for site 3 was 385.62 µmol/g in October and 37.37 µmol/g in June.

We measured heavy metals in both sediment and detritus and then compared our results to sediment quality guidelines established by the Ontario Ministry of the Environment (1993). These guidelines provide concentrations of metals that have no effect on the majority of sediment-dwelling organisms, designated as "lowest effect level" (LEL), and concentrations that indicate polluted sediment and are likely to affect organism health, designated as "severe effect level" (SEL). Most sites had sediment concentrations of Cr, Cu, and Pb above the SEL (Table 4). Therefore, based on their heavy metal content, sediments should have been toxic. Sites 7 and 9 had the most heavy metals exceeding SEL. Site 22 had no heavy metal concentrations exceeding SEL, but Cd, Cu, Ni, and Pb exceeded LEL. Cadmium did not exceed SEL in any of the sediments but did exceed the LEL for all sites. Results for detritus showed that it was also highly contaminated (Table 5): Copper exceeded SEL in all samples; Cd exceeded SEL for all June samples and site 18 for October. Based on heavy metal concentrations, site 7 was the most contaminated and site 22 was the least contaminated. Substrate comparisons showed that detritus consistently had similar or greater concentrations of Cd, Cu, Ni, and Zn than whole sediment (Figure 4). October detritus also had greater concentrations of Fe and Pb compared with that of sediment. June detritus from site 10 had ten times more Cd than that of sediment. Clearly detritus was an important source of heavy metal contamination in marsh sediments.

We correlated sediment and detritus parameters with chironomid survival and growth in order to ascertain which parameters were having the most effect on toxicity (Table 6). Sediment toxicity was compared with silt+clay, %TOC, and total heavy metal concentrations in detritus (DT-MT) and sediment (SD-MT). Total heavy metal concentrations were the sum of Cd, Cr, Cu, Hg, Ni, Pb, and Zn. We did not include Fe and Mn because we did not consider them toxic at the levels found in this study. For June sediments, the only statistically significant correlation was for survival and DT-MT (-0.865), in that better survival correlated with low heavy metal concentrations in detritus. For October sediments, there were no significant correlations with survival. However, %TOC (-0.863) and DT-MT (-0.939) showed significant negative correlations with growth, indicating that the organic component of the sediments was toxic.

The influence of Fe was evaluated by correlating total metal concentration, AVS SEM, Fe/MT (the ratio of iron to heavy metal), and Fe in sediment and detritus with chironomid survival and growth. The results for total metals, Fe/MT, and Fe are illustrated in Figure 5. June and October sediments showed no statistically significant correlations between Fe parameters and survival. However, there were relatively strong negative correlations for June survival with total metals (-0.719) and Fe (-0.791), which suggested toxicity due to high metal concentrations in general. We found strong but not significant negative correlations for sediment growth with SEM-AVS in June (-0.649) and October (-0.863), indicating sulfides might be limiting heavy metal toxicity. Data for site 22 were not included in the correlations. This site had unusual concentrations of insoluble iron, presumably because it was located close to an old railroad track. The strongest and most significant correlation was between chironomid growth and Fe/MT (0.955) in October sediments. This indicated that sediments with a high proportion of Fe were less toxic. Total metals in detritus correlated poorly with chironomid survival and growth in June (0.392 and -0.060, respectively) and October (0.076 and -0.392, respectively). Correlations improved when Fe content was considered. There were nonsignificant positive relationships between growth and Fe/MT and between growth and Fe in both June (0.575 and 0.663, respectively) and October (0.873 and 0.676, respectively) detritus. Correlations were statistically significant for survival and Fe (0.900) in June detritus and for growth and Fe/MT (0.873) in October detritus.

Overall, our data indicates that metals in detritus are an important source of sediment toxicity and that Fe in detritus supports better growth and survival.

Discussion

We characterized Kearny Marsh sediments in terms of common parameters such as grain size, %TOC, and SEM-AVS in order to investigate to what extent they might be contributing to, or moderating, sediment toxicity. The TOC in Kearny Marsh sediments ranged from 7% to 87% and was greater than 32% in most samples. This large amount of organic matter, found primarily in the form of poorly decomposed plant matter, was probably due to suboxic conditions in the marsh. Similar TOC levels (50%–70%) have been found in oligohaline wetlands (approximately 0.5 ppt–2 ppt salinity) in Canada (Bendell-Young, Thomas & Stecko, 2002). The TOC has varied widely, even for similar ecosystems. For example, TOC in Foundry Cove, an oligohaline wetland in the Hudson River watershed, New York, was found to be 0.8% to 13% (Hansen et al., 1996), much lower than that of Kearny Marsh. Kearny Marsh grain size was dominated by sand, typically at levels greater than 80%. These sand levels were similar to those found in Massachusetts salt marshes, which averaged 80% (Hansen et al., 1996). Since Kearny Marsh was once connected to the Hackensack River estuary system, the high percentage of sand in its substrate seems reasonable. The AVS values in sediments were high: 5 to 79 µmol/g in June and 45 to 499 µmol/g in October. These AVS levels were comparable with those found in other suboxic wetlands, which ranged from 50 to 400 µmol/g (Sundelin & Eriksson, 2001). The AVS concentrations well exceeded SEM in most samples, suggesting that sediments should not be toxic. This indicates that some other factor(s) caused the poor growth of chironomids in the toxicity tests (see below).

When testing sediments for toxicity, researchers commonly use test organisms that incorporate and respond to multiple toxicity parameters and allow them to discriminate measurable concentrations of contaminants. The bulk of the literature on the subject shows that various, natural sediment components can interact with contaminants and limit their bioavailability and associated toxicity (Ankley et al., 1996). In this study, we tested whole sediment and its detrital fraction from several sites in the Kearny Marsh using larvae of a common benthic macroinvertebrate, *Chironomus riparius* (midge fly). Our data showed that neither whole sediment nor detritus supported good chironomid growth (Tables 1 and 2). Chironomids merely doubled or tripled their size over a ten-day exposure period while controls fed on an alternate food source usually grew to ten times their initial weights. Since chironomid growth correlated with several factors known to control heavy metal bioavailability (Table 6), it is likely that effects were due to sediment and detritus toxicity. The case for poor sediment quality was supported by the absence of resident organisms; only an occasional nematode was actually found in sediments. Ingestion appeared to be an important route of contaminant exposure for the larvae, as there was an excess of free sulfides (AVS) to bind up any free heavy metals that might be absorbed through larval cuticles or gills. Also, larvae grew well in sediment and detritus samples to which fish food was added (all data not shown). For example, larvae in site 3 detritus showed good mean growth (4.698 ± 0.302) with fish food but poor mean growth (0.928 ± 0.146) without it.

Previous studies have shown that the major contaminants in Kearny Marsh sediments were heavy metals (Langan Engineering and Environmental Services, Inc., 1999). In this study, five of six sites had sediments with SELs of Cr, Cu, and Pb based on established sediment quality guidelines (Table 3). Two sites, 7 and 9, were also severely contaminated with Hg. Site 9 had the highest level of total toxic metals. Metal concentrations were similar to or greater than those found in the Hackensack River and Newark Bay, which were 10±6 mg/kg Cd, 237±222 mg/kg Cu, 2.1±2.6 mg/kg Hg, 39±49 mg/kg Ni, 421±571 mg/kg Pb, and 395±403 mg/kg Zn (Bonnevie, Huntley, Found & Wenning, 1994). Surprisingly, detritus not only had heavy metal concentrations above sediment LELs, but it also contained higher concentrations of Cd, Cu, Pb, and Zn than sediments (Table 4 and Figure 4). Kearny Marsh is dominated by the wetland grass *Phragmites australis* (common reed), which actively accumulates heavy metals in its roots (Peltier et al., 2003). Decomposition of these contaminated roots over time could have contributed to the heavy metals in the marsh detritus. Alternatively, the detritus could have adsorbed the heavy metals from overlaying water. Windham and coworkers found that submerged litter from wetland plants accumulated heavy metals in excess of sediment concentrations (Windham, Weis & Weis, 2004). As in our study, they determined that Cu, Pb, and Zn adsorption was greater than that of Cr and Hg. In either case, detritus might have contributed to an unstable pool of metals that were more or less available during the year. This was supported by metal concentrations in detritus that were consistent with the release of Cd under oxic conditions (early June) and of Pb under suboxic ones (early fall) (Reddy & Patrick, 1977).

Several sediment and detrital parameters showed statistically significant correlations with chironomid survival and growth (Table 6). This indicates that the parameters were influencing toxicity even though responses between sites did not appear to be very different (Figures 2 and 3). In our sediment experiments, metal concentrations in detritus (DT-MT) correlated with chironomid survival in June samples (-0.874) and chironomid growth (-0.940) in October samples. Correlations indicate that chironomid survival and growth were better when metal concentrations in detritus were low, and that metal concentrations in whole sediment were less influential. The complexity of larval responses was shown by the lack of correlation between DT-MT and chironomid growth in June (-0.174). In this instance, it is possible that the death of some larvae allowed less sensitive ones to acquire more food and grow normally. Iron concentrations in sediment and detritus appeared to be an important factor controlling substrate toxicity. When Fe levels increased or exceeded relative to the combined total of other metals (Fe/MT), toxicity was reduced. This relationship was seen in October sediment and detritus and in June detritus (Figure 5). Iron chemistry of sediments is known to control heavy metal bioavailability. Research has shown that Fe oxide precipitates can adsorb heavy metals (Dong et al., 2000) and that sulfides can exchange Fe for other toxic metals, forming less available metal sulfide precipitates (Hansen et al., 1996). The formation of metal sulfides has been used to explain the apparent lack of toxicity for anaerobic sediments that are highly contaminated with heavy metals (Lau & Chu, 2000). In our studies, sulfides did not appear to be a significant factor as measured by SEM-AVS. The AVS values did show seasonal variation, being lower in June and higher in October (Table 3). Research has shown that wetland plants create oxygenated microenvironments around their roots and thereby release sulfides from sediments (Azzoni, Giordani, Bartoli, Welsh & Viaroli, 2001). Data presented here support the idea of oxygenated microenvironments, in that there were fewer sulfides in sediment during active plant growth (June) and more when plants are less active (October). However, sediments were toxic even when there were high levels of sulfides (AVS) available to bind heavy metals. Correlations with detrital parameters indicate that organic Fe complexes are more important for moderating the toxic effect of heavy metals.

The results of this project show Fe and detritus to be controlling factors of toxicity at Kearny Marsh. These findings suggest several approaches for remediating Kearny Marsh. The marsh is suboxic, which is the primary factor limiting biodiversity. Increasing water circulation by reconnecting it to the Hackensack estuary and/or increasing coverage by wetlands plants would likely improve dissolved oxygen levels. One concern about increased circulation would be the release of heavy metals from metal sulfides and detritus into the water column and the subsequent contamination of the Hackensack estuary. However, the substantial amount of Fe in marsh sediments and the production of metal-binding Fe oxides under more aerobic conditions would probably limit the redistribution of toxic heavy metals (Liang, McNabb, Paulk, Gu & McCarthy, 1993). Another approach would be to cap sediments. In aquatic ecosystems this is usually achieved with sand. However, sand does not provide an appropriate substrate for the type of macroinvertebrates found in oligohaline wetlands. Capping with clay-based substrates amended with Fe and organic matter would complement the natural chemistry of the area and provide a better substrate for macroinvertebrate colonization. We recommend further studies of metals in the sediment of Kearny Marsh and also an investigation of the potential contribution of organic contaminants to sediment toxicity.

Acknowledgments

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Glossary

Analysis of variance (ANOVA): Statistical method that yields values that can be tested to determine whether a significant relation exists between variables.

Atomic absorption spectrophotometry: An analytical technique used to measure a wide range of elements in materials such as metals, pottery, soils, and glass. A sample solution of material is atomized in a spectrophotometer (for example, in a flame burner or graphite furnace). Light of a suitable wavelength is then applied. The amount of light absorbed by the atoms of the sample is proportional to the concentration of the element in the solution, and hence in the original material.

Benthic: Of or related to organisms (e.g., protozoa, nematodes) living on or in sea or lake bottoms.

Bivariate correlation: The degree to which two variables are related.

Cation: An ion (charged atom) or group of ions having a positive charge.

Chironomid: A member of the freshwater insect family Chironomideae.

Cold-vapor generation: An analytical technique used to measure mercury and other metals that can be easily volatilized. A sample solution of material (such as sediment or detritus) is treated so as to put the mercury in its elemental state. Then air is bubbled through the solution and a mercury vapor is formed. The mercury vapor is collected in a cell through which a suitable light wavelength is passed. The amount of light absorbed by the atoms of mercury is proportional to the concentration of the element in the solution, and hence in the original material.

Control: A parallel experiment used as a standard of comparison to judge the effects of the actual experiment. Controls can be negative or positive. Subjects in a negative control undergo the same treatment as subjects in the actual experiment except for the omission of the procedure or agent (e.g., a heavy metal) that is being tested. Subjects in a positive control are treated with a surrogate of the procedure or agent that's being tested in the actual experiment (e.g., a heavy metal toxicant) in order produce a biological effect and confirm the basic conditions of the actual experiment (e.g., that heavy metals cause reduced growth and mortality in midge larvae).

Detritivore: An animal that feeds on detritus, the organic debris from decomposing organisms and their products.

Instar: A stage in the life of an insect or other arthropod between two successive molts.

Macroinvertebrate: An animal, such as an insect or mollusk, that lacks a backbone or spinal column and can be seen with the naked eye.

mM (millimole): One one-thousanth of a mole (see below).

M (mole): The amount of a substance that contains as many atoms, molecules, ions, or other elementary units as the number of atoms in 0.012 kilograms of carbon 12. The number is 6.0225×10^{23}, or Avogadro's number. It is also called a gram molecule.

Negative control: A control (see definition above) in which the procedure or agent that's being tested in the actual experiment (e.g., a heavy metal toxicant) is omitted.

Oligohaline: Describing a body of water with a salinity measure of 0.5 to 2.5 parts per thousand (or 0.5 to 2.5 grams of salt per liter).

Oxic: Describing concentrations of oxygen in water or sediment that are normal.

Pearson coefficient: Statistical measure reflecting the degree of linear relationship (as plotted on a graph) between two variables. Also called the Pearson product moment correlation.

$p \leq 0.05$: An indicator of statistical significance in which the probability of achieving the result due to chance alone is less than or equal to 5 in 100.

pH buffer: A substance that minimizes change in the acidity or basicity of a solution when an acid or base is added to the solution.

SEM-AVS: Simultaneous extracted metal (SEM) minus (-) acid volatile sulfide (AVS): a measure of sediment toxicity based on the amount of sulfide in the sediment that can bind with toxic heavy metals and make them unavailable to plants and animals.

Subchronic toxicity: Adverse effects in an organism resulting from repeated dosage or exposure to a substance over a short period, usually about 10% of the organism's lifespan.

Suboxic: Describing concentrations of oxygen in water or sediment that are extremely low and have no perceptible gradients. These amounts of oxygen support limited types of aquatic plants and animals.

T-test: Statistical technique used to analyze the differences in means between two groups.

Trace Metal Standard 1: A solution, approved by the U.S. Environmental Protection Agency, known to contain certain amounts of metals. It is used to verify that metal concentrations are being measured accurately.

Tukey post hoc test: Statistical method that compares two means to determine whether or not they are significantly different.

Volatilize: To make volatile (turn into vapor).

Figure 1.

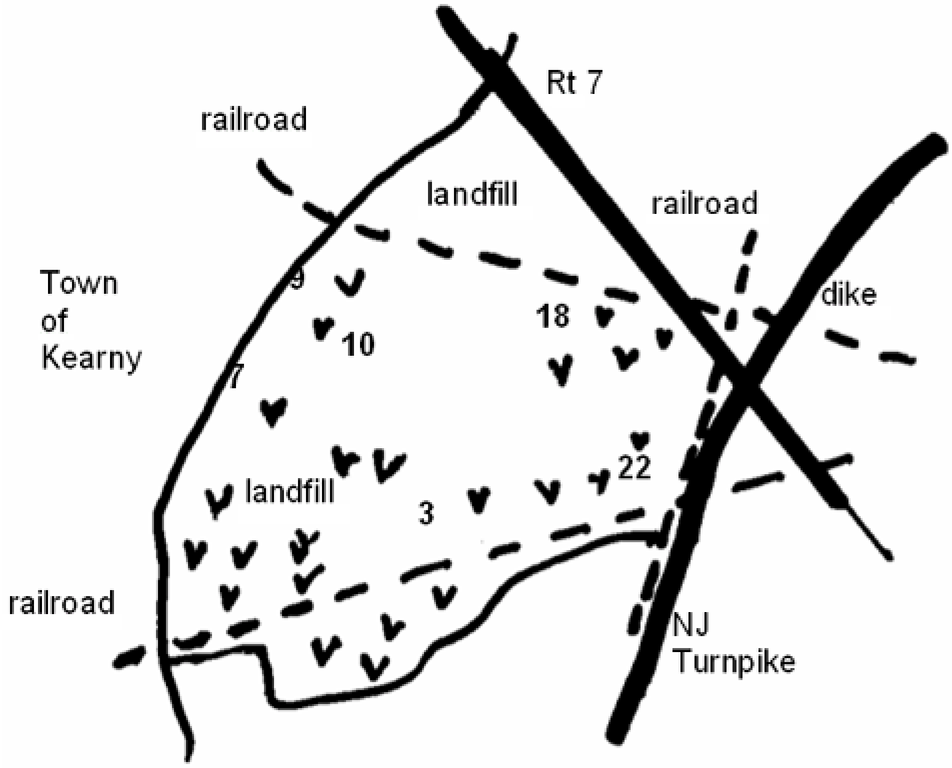

Figure 1. Map of Kearny Marsh showing sampling sites and significant landmarks. Sediment and detritus were collected from six sites—3, 7, 9, 10, 18, and 22—in June and October of 2002. Wetland vegetation is marked.

Figure 2.

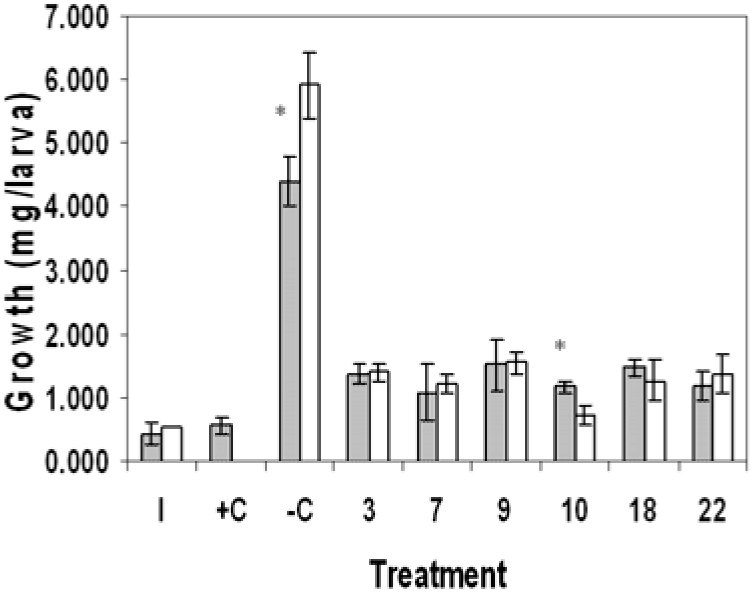

Figure 2. Effect of June sediment and detritus from different sites on growth of chironomids (mg/larva) after ten days. Sediment data are in closed columns; detritus in open columns. Data represent average ± SD, n = 4–6. Asterisks indicate a significant difference between detritus and sediment, $p \geq 0.05$. I = initial weight; +C = positive control; -C = negative control.

Figure 3.

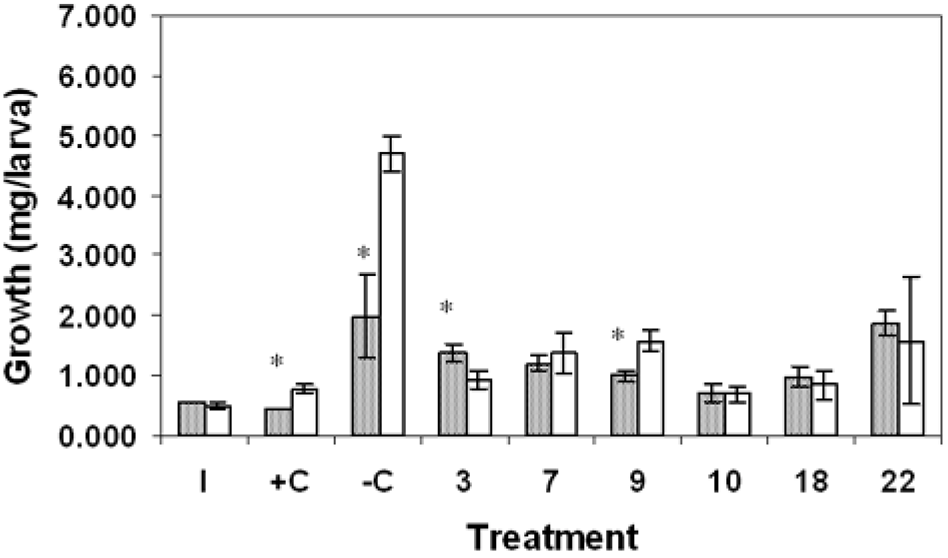

Figure 3. Effect of October sediment and detritus from different sites on chironomid growth (mg/larva) after ten days. Sediment data are in closed columns; detritus in open columns. Data represent average ± SD; n = 4–6. Asterisks indicate a significant difference between detritus and sediment, $p \geq 0.05$. I = initial weight; +C = positive control; -C = negative control.

Figure 4.

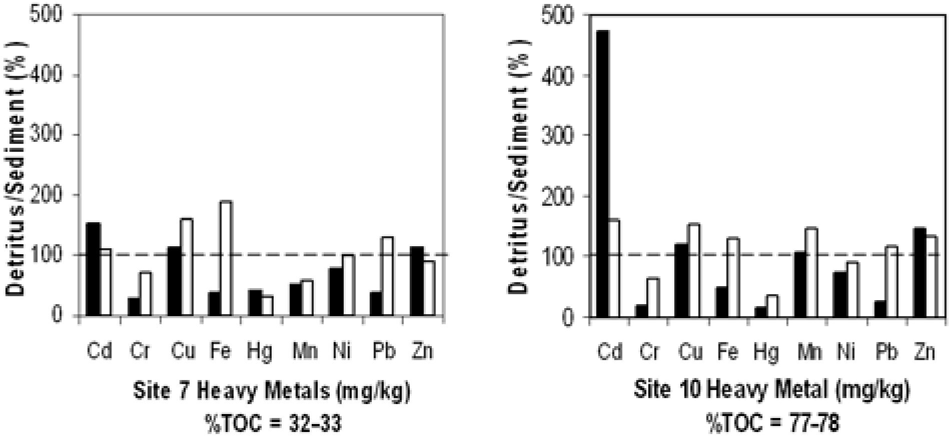

Figure 4. Comparison of heavy metals in detritus and sediment. The ratios of heavy metals in detritus versus whole sediment (%) are shown for sites 7 and 10 collected in June (closed column) and October (open column). A reference line for equivalent levels of metals in detritus and sediments is provided. The two sites had different levels of TOC, which did not appear to influence detritus-to-sediment ratios overall.

Figure 5.

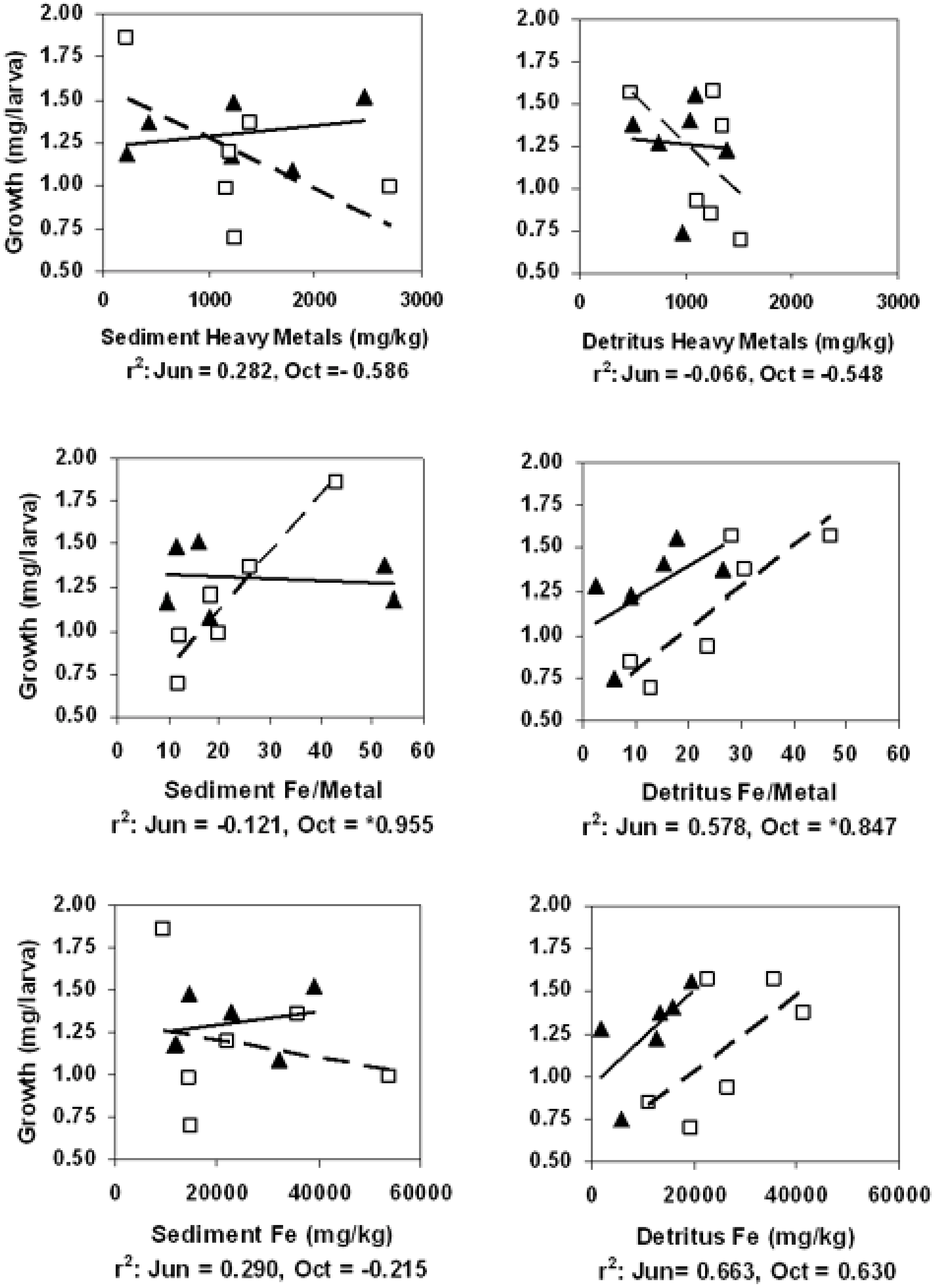

Figure 5. Correlations of sediment or detritus growth in chironomids (mg/larva) with heavy metal parameters. Open squares and dashed lines represent October substrates. Closed triangles and solid lines represent June substrates. Sediment growth is shown on left; detritus growth on right. Correlations were calculated using Pearson two-tailed test. Asterisks indicate statistically significant correlation, $p \geq 0.05$.

Table 1.

	June		October	
Treatment	Survival (mean ± SD)	Growth (mean ± SD)	Survival (mean ± SD)	Growth (mean ± SD)
I		0.435 ± 0.177^{ab}		0.540 ± 0.000^{a}
+C	76.7 ± 20.7^{ab}	0.613 ± 0.173^{b}	21.7 ± 20.4^{a}	0.502 ± 0.146^{a}
–C	91.7 ± 9.8^{a}	4.406 ± 0.380^{c}	83.3 ± 10.3^{b}	1.980 ± 0.694^{b}
3	88.3 ± 11.7^{a}	1.370 ± 0.162^{d}	88.3 ± 4.1^{b}	1.364 ± 0.147^{bc}
7	46.7 ± 38.2^{b}	1.084 ± 0.434^{abd}	55.0 ± 35.1^{a}	1.197 ± 0.128^{ab}
9	68.3 ± 24.8^{ab}	1.517 ± 0.393^{d}	68.3 ± 16.0^{b}	0.991 ± 0.090^{ac}
10	86.7 ± 10.3^{a}	1.174 ± 0.094^{bd}	75.0 ± 15.2^{b}	0.697 ± 0.150^{a}
18	90.0 ± 7.1^{a}	1.483 ± 0.141^{d}	65.0 ± 27.4^{b}	0.980 ± 0.163^{ac}
22	95.0 ± 8.4^{a}	1.184 ± 0.244^{d}	50.0 ± 36.3^{a}	1.863 ± 0.205^{b}

I = initial weight of representative larvae.

*Control treatments consisted of acid-washed sand plus food with 0.3mM Cd (+C) and without (-C).

Means that share a common letter were not statistically different, n = 5–6, p. ≥ 0.05.

Table 1. Effect of sediments on ten-day survival (%) and growth (mg/larva) of chironomids. Larvae exposed to sediment from different sites and months of collection were unfed. Controls received food.*

Table 2.

	June		October	
Treatment	Survival (mean ± SD)	Growth (mean ± SD)	Survival (mean ± SD)	Growth (mean ± SD)
I		0.527 ± 0.000^{a}		0.501 ± 0.040^{a}
+C	NA	NA	84.0 ± 25.1	0.609 ± 0.126^{a}
–C	74.0 ± 11.4	5.914 ± 0.504^{b}	91.7 ± 7.5	4.698 ± 0.302^{b}
3	76.7 ± 15.1	1.406 ± 0.139^{c}	76.7 ± 8.2	0.928 ± 0.146^{ac}
7	72.0 ± 8.4	1.226 ± 0.141^{c}	90.0 ± 7.1	1.374 ± 0.345^{cd}
9	75.0 ± 17.3	1.555 ± 0.163^{c}	86.5 ± 5.5	1.573 ± 0.162^{d}
10	48.3 ± 20.4	0.743 ± 0.154^{a}	64.0± 8.9	0.691 ± 0.139^{a}
18	63.3 ± 38.8	1.272 ± 0.319^{c}	70.0 ± 23.7	0.848 ± 0.245^{a}
22	74 ± 19.5	1.378 ± 0.323^{c}	75.0 ± 18.7	1.566 ± 1.062^{ad}

I = initial weight of representative larvae.

*Control treatments consisted of acid-washed sand plus food with 0.3mM Cd (+C) and without (-C).

Means that share a common letter were not statistically different; n = 4–6, p ≥ 0.05.

NA = Not analyzed.

Table 2. Effect of detritus on chironomid survival (%) and growth (mg/larva) after ten days. Larvae exposed to detritus from different sites and months of collection were unfed. Controls received food.*

Table 3.

Site	Mon	Gravel	Sand	Silt+Clay	TOC	SEM[a]	AVS[a]	SEM–AVS[a]
3	Jun	1.27	89.3	9.9	23.2	9.0	37.4	-28.4
	Oct	0.07	89.1	10.9	44.9	18.5	385.6	-367.1
7	Jun	1.67	87.2	11.2	32.0	11.7	46.4	-34.7
	Oct	0.91	80.9	18.2	33.0	46.6	499.0	-452.4
9	Jun	0.01	84.2	15.8	52.9	24.6	79.1	-54.5
	Oct	1.90	80.4	17.9	43.8	33.8	116.9	-83.1
10	Jun	0.93	86.7	12.9	77.0	36.8	46.2	-9.3
	Oct	3.60	86.2	9.1	78.2	8.8	45.0	-36.2
18	Jun	2.47	91.0	16.1	87.2	44.2	55.4	-9.2
	Oct	0.82	98.3	6.4	83.2	63.4	254.9	-191.5
22	Jun	0.48	69.5	30.1	11.8	1.7	5.7	-4.0
	Oct	1.51	94.0	4.5	7.1	25.4	80.4	-55.0

[a] SEM, AVS, and SEM-AVS were the average of two replicate analyses. Units were µmol/g.

TOC = % of volatile solids in dried sediments.

SEM = Simultaneous extracted metals (Cd, Cu, Hg, Pb, and Zn).

AVS = Acid volatile sulfides.

NA = Not analyzed.

Mon = Month collected.

Table 3. Characterization of sediments from June and October collections. Parameters included TOC (%), AVS, SEM-AVS, and grain size (% gravel, sand, silt+clay).

Table 4.

Site	Mon	Cd	Cr	Cu	Fe	Hg	Mn	Ni	Pb	Zn	Total[a]
3	Jun	3.13	*120	56	22822	0.55	168	31	153	172	435
	Oct	5.83	100	*177	35909	1.78	321	68	*385	646	1383
7	Jun	7.98	*232	*210	32206	*8.32	262	73	*591	671	1792
	Oct	5.75	101	*159	21885	*6.97	254	56	*415	447	1190
9	Jun	8.25	*502	*243	38983	*2.23	407	*97	*661	*955	2468
	Oct	9.75	*512	*295	53968	*3.40	542	*93	*777	*1019	2708
10	Jun	5.32	*182	*153	11701	1.61	183	57	*435	385	1218
	Oct	4.87	*128	*137	14819	1.29	386	61	*458	464	1255
18	Jun	4.27	66	*148	16227	1.22	382	66	*526	428	1240
	Oct	4.34	52	*142	14304	0.89	311	55	*497	410	1161
22	Jun	1.94	16	41	12032	0.21	183	23	61	79	222
	Oct	1.53	6	39	9386	0.16	148	22	70	78	218
LEL		0.60	26	16	NS	0.20	NS	16.0	31	120	
SEL		10.00	110	110	NS	2.00	NS	75.0	250	820	

[a] Total = Includes concentrations for Cd, Cr, Cu, Hg, Ni, Pb, and Zn but not Fe and Mn.

LEL = Lowest Effects Limit based on Ontario Ministry of the Environment guidelines.

SEL = Severe Effects Limit based on Ontario Ministry of the Environment guidelines.

NS = No sediment criterion.

Mon = Month collected.

*Metal concentration exceeds SEL.

Table 4. Heavy metal concentrations (mg/kg) in Kearny Marsh sediments.

Table 5.

Site	Mon	Cd	Cr	Cu	Fe	Hg	Mn	Ni	Pb	Zn	Total[a]
3	Jun	*18.2	27	*270	15816	0.97	446	40	*256	409	1021
	Oct	6.4	40	*219	26474	0.51	297	47	*490	314	1117
7	Jun	*12.2	66	*240	12636	*3.56	136	56	239	771	1389
	Oct	6.4	71	*257	41325	*2.18	149	57	*546	409	1349
9	Jun	*22.2	95	*211	19528	0.15	253	50	235	477	1090
	Oct	9.1	*233	*205	35481	*2.23	200	62	*321	428	1261
10	Jun	*25.2	37	*187	5677	0.27	194	43	108	567	968
	Oct	7.8	82	*212	19403	0.49	567	56	*536	628	1522
18	Jun	*16.3	9	*223	1896	0.56	89	27	71	394	741
	Oct	*19.2	50	*278	11209	0.55	220	47	*496	363	1253
22	Jun	8.8	18	*145	13220	0.84	212	28	49	249	499
	Oct	2.3	19	*120	22515	0.08	268	3	136	168	477
LEL		0.6	26	16	NS	0.20	NS	16	31	120	
SEL		10.0	110	110	NS	2.00	NS	75	250	820	

[a] Total = Includes concentrations for Cd, Cr, Cu, Hg, Ni, Pb, and Zn but not Fe and Mn (mg/kg).

LEL = Lowest Effects Limit based on Ontario Ministry of the Environment guidelines.

SEL = Severe Effects Limit based on Ontario Ministry of the Environment guidelines.

NS = No sediment criterion.

Mon = Month collected.

*Metal concentration exceeds SEL.

Table 5. Heavy metal concentrations (mg/kg) in Kearny Marsh detritus.

Table 6.

Treat.	Mon.	Silt+Clay	%TOC	SEM–AVS	DT-MT	SD-MT	FE/MT	FE
SD-SV	Jun	0.452	0.116	0.696	*-0.874	-0.719	0.420	-0.791
SD-GR	Jun	-0.102	0.386	-0.348	-0.174	0.282	-0.121	0.290
SD-SV	Oct	0.063	0.494	0.152	0.451	0.421	-0.368	0.439
SD-GR	Oct	-0.328	*-0.863	-0.861[b]	*-0.940	-0.586	*0.955	-0.210
DT-SV	Jun				0.380		0.351	0.723
DT-GR	Jun				-0.066		0.578	0.663
DT-SV	Oct				-0.035		0.494	*0.904
DT-GR	Oct				-0.548		*0.847	0.630

*Pearson correlation coefficient was statistically significant; $p \leq 0.05$.

SD = sediment toxicity test

DT = detritus toxicity test

SV = survival (%)

GR = growth (mg/larvae)

Treat. = treatment

Mon. = month collected

Silt + Clay = sum of % silt and clay in sediment

DT-MT = metal[a] concentration in detritus (mg/kg)

SD-MT = metal[a] concentration in sediment (mg/kg)

FE/MT = [Fe] divided by [MT][a] in test substrate

%TOC divided by [MT][a] in sediment

[a]Total = Includes concentrations for Cd, Cr, Cu, Hg, Ni, Pb, and Zn but not Fe and Mn (mg/kg).

[b]Site 22 data were not included in correlation; see text for explanation.

Table 6. Correlations of toxicity test endpoints (chironomid survival and growth) with different sediment and detritus parameters; r = Pearson correlation coefficient.

Hyperspectral Remote Sensing of Habitat Heterogeneity Between Tide-Restricted and Tide-Open Areas in the New Jersey Meadowlands*

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Abstract

The restriction of tidal flow by roads, rail beds, dikes, and tide gates can significantly alter the integrity, spatial configuration, and ultimately the biodiversity of salt marshes. In our study we evaluated the effects of tide restriction on marsh habitat heterogeneity using hyperspectral remote sensing. Field-collected reflectance spectra of marsh surfaces and advanced image-classification techniques were applied to derive a thematic map of marsh surface types in the New Jersey Meadowlands from hyperspectral images captured by an airborne imaging spectroradiometer (AISA). Forty sampling sites were randomly selected in tide-restricted and tide-open areas and used to identify several landscape metrics for spatial pattern analysis. The results of this analysis showed significant differences in landscape metrics between tide-restricted and tide-open sites; open sites had a greater number, and a more even distribution, of landscape patch types. We found that the number of patches and the total edge were the best metrics for differentiating between tide-restricted and tide-open areas, and these may be used as surrogates for salt marsh biodiversity. The study indicated that hyperspectral images might be used on their own to detect marsh features that are ecologically significant.

Key words: hyperspectral remote sensing; landscape metrics; marsh; New Jersey Meadowlands; reflectance spectra; urban wetlands

Introduction

Tidal cycles of inundation and drainage are essential to the vitality of salt marshes as habitats for animal and plant species (Teal & Teal, 1969). The hydrological changes caused by restricting the flow of the tide with roads, rail beds, dikes, and tide gates significantly alter the integrity and spatial configuration of salt marshes in the northeastern United States. Visual interpretation of aerial photographs of marsh surfaces reveals an apparent decrease in marsh surface heterogeneity in tide-restricted regions (Thiesing, 2002). Coastal wetland restoration often involves reopening areas to the tide and creating new, more heterogeneous habitat to attract wildlife. Restoring surface habitat heterogeneity has been linked to an increase in the diversity of marsh species. For example, observations of bird-community composition in pre- and post-

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marsh-restoration projects have indicated that increased habitat heterogeneity after restoration significantly increased bird species richness (Delphey & Dinsmore, 1993; Brawley, Warren & Askins, 1998; Ratti, Rocklage, Giudice, Garton & Golner, 2001; Fletcher & Koford, 2003).

It is difficult to distinguish between various kinds of marsh surface types using traditional remote sensing technologies like aerial photography interpretation. Moderate-resolution remote sensors mounted on orbiting satellites (e.g., Landsat, with 30-meter* spatial resolution) are able to discriminate between surface types covering relatively large areas (Harvey & Hill, 2001; Berberoglu, Yilmaz & Ozkan, 2004), but they cannot reveal marsh features such as ponds, pannes, and levees whose extension is smaller than the image pixel size. Recently, imagery collected by hyperspectral sensors and near-infrared cameras and video technology mounted on low-altitude platforms (e.g., fixed-wing aircraft and balloons) has been widely applied in classifying wetland features in great detail (Miyamoto, Yoshino & Kushida, 2001; Shmidt & Skidmore, 2003). Using this new technology, it is possible to identify marsh surface types such as ponds. It is even possible to map plant species in coastal wetlands and relate their configuration and spatial arrangement to hydrological conditions influencing habitat heterogeneity—and ultimately, biodiversity.

We hypothesized that tide restriction causes the configuration and spatial arrangement of marsh surfaces to change, and that this rearrangement influences habitat heterogeneity. In order to characterize habitat heterogeneity based on the spectral reflectance of marsh surfaces, we identified a set of landscape metrics commonly used in the classification of hyperspectral imagery. These landscape metrics should illustrate that tide-restricted areas in marshlands have lower habitat heterogeneity than tide-open areas. Furthermore, we set out to show that it is possible to detect and identify tide-restricted and tide-open marshlands based only on landscape metrics derived from hyperspectral imagery. Demonstrating this could prove useful in the planning of coastal marsh preserves in fragmented urban wetlands, as discussed below.

The ramifications of scale are profound in studies in which habitat heterogeneity measurements are based on spatial metrics (Levin, 1992). Scale in our study had two components: the minimum mapping unit (2.5-meter pixel size) and the sample size (one-hectare—or 100-by-100-meter—plots). We selected 40 one-hectare sampling plots (20 in tide-restricted areas and 20 in tide-open areas) in the New Jersey Meadowlands from which to identify and calculate landscape metrics. We then compared the differences of these metrics between the tide-restricted and tide-open sites and evaluated the effects of tide restriction on habitat heterogeneity using spatial pattern analysis.

Methods

Study Area

Our study focused on the remaining marshlands of the New Jersey Meadowlands in northern New Jersey. Originally, the Meadowlands consisted of approximately 17,000 acres of wetlands and waterways and included a diverse array of marsh surface types (Wong, 2002). By the beginning of the 17th century, the wetlands were being diked, drained, farmed, and filled, causing drastic changes in the configuration and spatial arrangement of marsh surface types. Today the Meadowlands comprise 8,400 acres of marshlands and mudflats surrounded

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*Except where noted, measurements throughout this paper are in metric notation; conversions to U.S. equivalents can be obtained at http://www.onlineconversion.com/length.htm.

by intense industrialization. The salt marsh ecosystem here includes high marsh areas, dominated by *Spartina patens* (saltmeadow cordgrass) and *Distichlis spicata* (inland saltgrass), and undisturbed low marsh areas dominated by *Spartina alterniflora* (saltmarsh cordgrass). The invasive species *Phragmites australis* (common reed) occupies the higher-elevation dredge spoil islands, tidal creek banks, and levees. The seemingly uniform high and low marsh vegetation cover is interrupted by patches of exposed mud and water-filled depressions that create an intricate pattern of surface types at low tide.

Hyperspectral Images

Unlike multispectral imagery, which consists of disjointed spectral bands, hyperspectral imagery contains a larger number of images from contiguous regions of the spectrum. This increased sampling in spectrum provides a significant increase in image resolution—and thus in information about the objects being viewed.

In our study, we used 22 flight lines (strips) of hyperspectral imagery covering the entire Meadowlands. The images were collected between 11 a.m. and 2 p.m. on October 11, 2000, using an Airborne Imaging Spectroradiometer for Applications (AISA). Atmospheric conditions on the day of image capture included clear skies with 660 watts/m2 of solar irradiation at high sun, 55% relative humidity, and a surface temperature of 18°C (64.4°F).

The AISA is a remote-sensing instrument capable of collecting data within a spectral range of 430 to 900 nanometers (nm) in up to 286 spectral channels (Spectrum, 2003). The sensor was configured for 34 spectral bands from 452 to 886 nanometers. Bandwidths varied 4.86 nanometers from bands 1 to 9 (452–562 nm), 5.20 nanometers from bands 10 to 27 (578–800 nm), and 3.54 nanometers from bands 28 to 34 (805–886 nm). The AISA sensor had a 20-degree field of view (FOV) at an altitude of 2,500 meters, which corresponded to a swath width of 881.6 meters and a pixel size of 2.5 by 2.5 meters. Final images were stored in a band-interleaved-by-line (BIL) format and distributed in six CD-ROMs.

Reflectance of Marsh Surface Types

Close examination of marsh surface texture from aerial photography and field inspection revealed seven dominant surface types in the New Jersey Meadowlands. Each surface type was characterized by a unique plant community composition and/or substrate. These seven marsh types were found throughout the Meadowlands and accounted for more than 95% of the marsh surface (Table 1).

We used a hand-held FieldSpec Pro Full Range spectroradiometer from Analytical Spectral Devices, which measures reflectance in the visible, short-wave infrared region of the electromagnetic spectrum (350–2500 nm), to record surface reflectance spectra in 10-by-10-meter plots of these seven marsh surfaces. These field-spectra measurements were collected at six locations under clear skies in late September and early October 2000 to roughly parallel with the AISA hyperspectral imagery collections. We made 25 readings at one-second intervals in each plot and calculated final measurements based on the averages of these readings. The measurements were also referenced to a Spectralon white reference panel before each sampling period to ensure calibration accuracy. The average reflectance spectra of the seven marsh surface types are presented in Figure 1. These field-collected spectra were used to classify the hyperspectral imagery into a thematic map showing the distribution of the seven surface types in the Meadowlands.

To compare landscape metrics between tide-restricted and tide-open areas in the Meadowlands, we randomly selected 20 one-hectare sampling plots from the AISA hyperspectral imagery within both tide-restricted and tide-open areas (Figure 2)—a total of 40 plots. (It was determined that one hectare was the largest size for plots that could fit in the wetland fragments of the Meadowlands while also remaining immune from any edge effects associated with mosquito control ditches.) We used maps and aerial photography showing tide gates, roads, and culvert locations, in addition to field observations, as the basis for distinguishing between tide-restricted and tide-open areas in the hyperspectral imagery.

Hyperspectral Image Processing

We used an AISA to capture both radiance and reflectance images of the New Jersey Meadowlands. We also employed the AISA sensor's Fiber Optic Downwelling Irradiance System (FODIS) to perform atmospheric correction and convert concurrent measurements of downwelling and upwelling radiance to apparent reflectance (AISA, 2003).

We employed ENVI software to perform image preprocessing and further image analysis (RSI, Version 4.0). Although the AISA images were georeferenced, geographic distortions existed between most strips. Therefore, each strip image was corrected using a one-foot pixel-size orthophoto and registered to New Jersey's state plane coordinate system using North American Datum 83. We also found obvious brightness distortion (dark edges) among strips and used a histogram-matching technique to correct them. After corrections, the 22 strips of hyperspectral imagery were mosaicked into a single seamless image and subsetted to the Meadowlands district (Figure 3). Since not all 34 spectral bands were contributing useful information, a minimum noise fraction (MNF) rotation was applied (Underwood, Ustin & DiPietro, 2003) and the first 7 MNF bands (minus MNF band 2) were selected for use in subsequent spectral analysis.

We used our field-collected spectral library and a Spectral Angle Mapper (SAM) to classify the remaining MNF bands into a thematic map showing the location and spatial arrangement of the seven dominant marsh surface types in the Meadowlands (Kruse, Lefkoff & Dietz, 1993). The SAM determines the similarity of two spectra by calculating the "spectral angle" between each pixel in the MNF images and the field-collected spectra. In other words, the SAM scores each pixel in the MNF band image according to how similar it is to any of the field-collected spectra. Each pixel in the image is assigned to a marsh surface according to its highest SAM score.

Landscape Metrics and Spatial Pattern Analysis

Spatial pattern metrics were calculated from the 40 sampled sites using Fragstats, analysis software that can calculate a wide variety of landscape metrics from a thematic map (McGarigal & Marks, 1995). Metrics calculated in this study were class-level metrics of total class area per hectare (CA), number of patches (NP), total edge in meters (TE), and fractal dimension index (FDI), as well as the landscape-level metrics of patch richness (PR) and the Shannon Diversity Index (SHDI). Descriptions of, and calculation equations for, these metrics are presented in Table 2.

Results

Marsh Surface Classification

Each spectral class in the MNF band image represented a relatively homogenous and distinct plant assemblage or substrate type in the Meadowlands marsh. We scored each class against known surface spectra with the SAM, and each pixel in the thematic map was accordingly assigned to a single marsh surface. We then merged and renamed the classes into the following seven predefined surface area types (Figure 4): *Distichlis spicata* and *Spartina patens* were defined as a single High Marsh type, since these two species define the high marsh community in the Meadowlands. The *Phragmites* type was characterized by tall (≥ 2 m) dense monotypic stands of *Phragmites australis* with 100% cover. The Stunted *Phragmites* type was characterized by a monoculture of low-density *Phragmites* not exceeding two meters in height and a vegetation-to-mud-cover ratio of 50:50 or greater. The High Marsh/*Phragmites* type was defined as a mixture of sparse *Phragmites* stems with an understory of high marsh grasses (*Spartina patens* and *Distichlis spicata*). The *Spartina* type was characterized by dense stands of *Spartina alterniflora* with 90% or more vegetation cover. Exposed mud surfaces were classified into a single Mud type. These mud surfaces were exposed at low tide and free of vascular vegetation. The Water type included open-surface waters in ponds, channels, and creeks. Though no quantitative accuracy assessment was performed, historical vegetation studies (Sipple, 1972) and visual assessments (using one-foot infrared orthophotos) by ecologists familiar with the Meadowlands confirmed that our seven designations of surface-area type closely matched the actual surfaces of several well-known marsh sites.

Class-Level Metrics

We calculated descriptive and test statistics of class-level metrics (CA, NP, TE, and FDI) for five of the seven marsh surface types in tide-open and tide-restricted sites (Table 3). We found that Stunted *Phragmites* was the most common surface type and existed in both tide-open and tide-restricted sites (N=20 and N=19, respectively). All other surface types were more common in tide-open sites than in tide-restricted sites. Mud was five times more likely to occur in tide-open sites than in tide-restricted sites (N=3 compared with N=15). In terms of class-level metrics, the amount of High Marsh varied most widely between tide-open and tide-restricted sampling sites. High Marsh occupied approximately 13% of the tide-open sites and only 5% of tide-restricted sites. The NP in tide-open sites was almost double that in tide-restricted sites, and consequently the TE was longer at tide-open sites than in tide-restricted sites. The FDI, a measure of patch-shape complexity, was also higher at tide-open sites than at tide-restricted sites (1.11 compared with 1.07; $p < 0.05$). The CAs of Stunted *Phragmites* and Water were not significantly different between the two tidal regimes. However, the NP and TE of both Stunted *Phragmites* and Water were twice as high in tide-open sites. In other words, twice as many patches of these two surface types were found in tide-open sites than in tide-restricted sites, but the total area of these types was no different based on tidal regime. The CA of the *Phragmites* surface type was similar in both tidal regimes, and so were the NP and the FDI. The only exception was the TE, which was marginally significant (at $p < 0.05$).

Landscape-Level Metrics

Table 4 presents the descriptive and test statistics calculated for the landscape-level metrics (PR and SHDI) between tide-restricted and tide-open sites. PR is simply the number of different patch types. Overall, tide-open sites had a larger mean number of patch types (4.85) than the tide-restricted sites (3.60). Similarly, tide-open sites had a significantly higher SHDI than tide-restricted sites (1.135 compared with 0.679). This indicates that the distribution of area among patch types was more even in tide-open sites than in tide-restricted sites. The distribution of the SHDI between tide-restricted and tide-open sites was also graphed in a Q-Q plot (Figure 5). All points in the graph were above the y = x line, indicating SHDI in tide-open sites was on average 0.6 larger than that in tide-restricted sites (points would be gathered around the y = x line if the sites showed similar distribution).

Discussion

Our approach consisted of classifying hyperspectral imagery based on field-collected spectra of the dominant marsh surface types that make up the ecologically significant surfaces and plant communities in the New Jersey Meadowlands. Based on the scale of this study, it was clear that there were significant differences in landscape metrics between tide-restricted and tide-open sites. At the landscape level, tide-open sites had a greater number of patch types, and the distribution of these patches was more even. At the class level, Stunted *Phragmites* was the most common surface type under both tidal regimes. Another significant feature at the class level was the extent and configuration of the High Marsh type. There was more CA, NP, and TE of this type in tide-open sites than in tide-restricted sites. There were no significant differences in the total area and spatial arrangement of the *Phragmites* surface type between tide-restricted and tide-open sites. Overall, we found that at the class level, the NP and TE were the best landscape metrics for determining whether marsh surface types are tide-open or tide-restricted.

The results also indicated that it might be possible to determine tide restriction from hyperspectral remote sensing images alone using landscape metrics. The images were able to reveal marsh features such as ponds, pannes, levees, and back marsh stands that are ecologically significant and measurable. This implies that an unsupervised computer-learning algorithm might be developed to calculate landscape metrics from remote sensing images and then automatically classify tide-restricted areas from the images to arrive at an assessment of the overall biodiversity or state of a given ecosystem. Similar methods could be devised to detect and assess habitat availability and biodiversity of riverbank vegetation that has been modified by flooding or by other disturbances, such as fires, landslides, and erosion, that might periodically affect the spatial arrangements of land cover.

In our case, we assumed the minimum mapping unit to be 2.5 by 2.5 meters (image pixel size) and the sample size to be 100 by 100 meters. It was within these resolutions that classes and patches were identified. It is not clear how altering the mapping unit and sample size might affect the identification of spectral classes and surface patches within the hyperspectral imagery. This is important because marsh species diversity has been found to be proportional to the size of the marsh patches (Kane, 1987). It appears safe to assume that sample size ultimately has a direct effect on the overall estimation of habitat heterogeneity (Mayer & Cameron, 2003). Our chosen scale may be appropriate to address the persistence of vascular plant and vertebrate animal species but inadequate for addressing species that operate at larger and smaller scales, such as migrating birds and microinvertebrates.

Instead of using fixed plots in future studies, we suggest selecting sampling sites—especially irregular polygons—from existing patches, as they would be a better reflection of the nature of marsh fragments. Irregular polygons would allow the inclusion of information on marsh edges as additional metrics for identifying and characterizing marsh fragments in the landscape. Further studies are needed to establish a reliable relationship between scale, habitat heterogeneity, and biodiversity.

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Glossary

Accuracy assessment: Accuracy assessment in remote sensing refers to the comparison of a classification to a geographical image that is assumed to be true. Usually, the assumed-true data are derived from field observations.

Class-level metrics: A set of metrics used in landscape ecology to measure the aggregate properties of the landscape patches belonging to a single class or patch type (see below).

Downwelling radiance: See upwelling and downwelling radiance, below.

Dredge spoils: The sediment removed from a body of water during dredging.

Edge effects: Altered environmental and biological conditions at the edge of fragmented habitat.

Georeference: Also referred to as registering, this is the establishment of the relationship between page coordinates (i.e., x, y) of a planar map of an image with known real-world coordinates (i.e., longitude, latitude, etc.).

Heterogeneity: The quality or state of being heterogeneous, or consisting of dissimilar elements or parts.

Histogram matching: An equalization technique often used to correct the brightness difference among flight lines (images) captured at different times of the day.

Hyperspectral remote sensing: Also known as imaging spectroscopy, this relatively new technology can simultaneously acquire images of the earth's surface in many narrow, contiguous, spectral bands.

Irregular polygon: Any shape or figure on a plane that has many straight sides of no regular length.

Landscape-level metrics: Metrics used in landscape ecology to measure the aggregate properties of an entire mosaic of landscape patches.

Landscape Metrics: Algorithms that quantify specific spatial characteristics of landscape patches, classes of these patches, or entire landscape mosaics. They include landscape-level and class-level metrics (see above).

Microinvertebrate: An animal without a backbone that is too small to be seen with the naked eye.

Minimum Noise Fraction (MNF) rotation: A method used to separate hyperspectral image noise from signals and compress spectral information of the image into a few informative bands.

Mosaic: An assemblage of overlapping aerial or space photographs or images whose edges have been matched to form a continuous pictorial representation of a portion of the earth's surface.

Nanometer (nm): 10^{9}meters, or one billionth of a meter. It is commonly used in measuring the wavelengths of visible light (400 nm to 700 nm).

North American Datum 83: A commonly used geographic coordinate system based on ground and satellite data.

Orthophoto: A photograph derived from a conventional-perspective photograph by simple or differential rectification so that image displacements caused by camera tilt and relief of terrain are removed.

$p < 0.05$: An indicator of statistical significance in which the probability of the result of a study's being a chance occurrence is less than 5 in 100.

Panne (or salt panne): A small pond or pool in a marsh that usually holds water as the tide recedes.

Patch types: Discrete areas of landscape with relatively homogeneous surface composition and environmental conditions.

Pixel: A two-dimensional picture element that is the smallest nondivisible element of a digital image.

Q-Q plot (quantile-quantile plot): A graphing technique for determining if two sets of data come from populations with the same distribution.

Radiance: A measure of the energy radiated by the object together with the frequency distribution of that radiation.

Reflectance: The fraction of radiant energy that is reflected from a surface.

Shannon Diversity Index: An algorithm for quantifying the diversity of a landscape based on two components: the number of different patch types and the proportional distribution of area among these patch types.

Spectrum (pl. spectra): The distribution of energy emitted by a radiant source arranged in order of wavelengths.

Subset: The process of clipping an image into the area of interest.

Upwelling and downwelling radiance: Upwelling radiance is the amount of electromagnetic radiation reflected upward from the ground's surface. It includes downwelling radiance, which is the thermal energy radiated onto the ground by all objects in a hemisphere surrounding it, including topography and atmospheric gases and aerosols. To obtain an atmospherically corrected reflectance, downwelling radiance must be subtracted from upwelling radiance.

White reference panel: A standard reference panel made of a special white material and used to fix the maximum reflectance value for each sampling period. This way measurements made at different dates can be compared regardless of the slight changes in illumination that may occur from one day to another.

Figure 1.

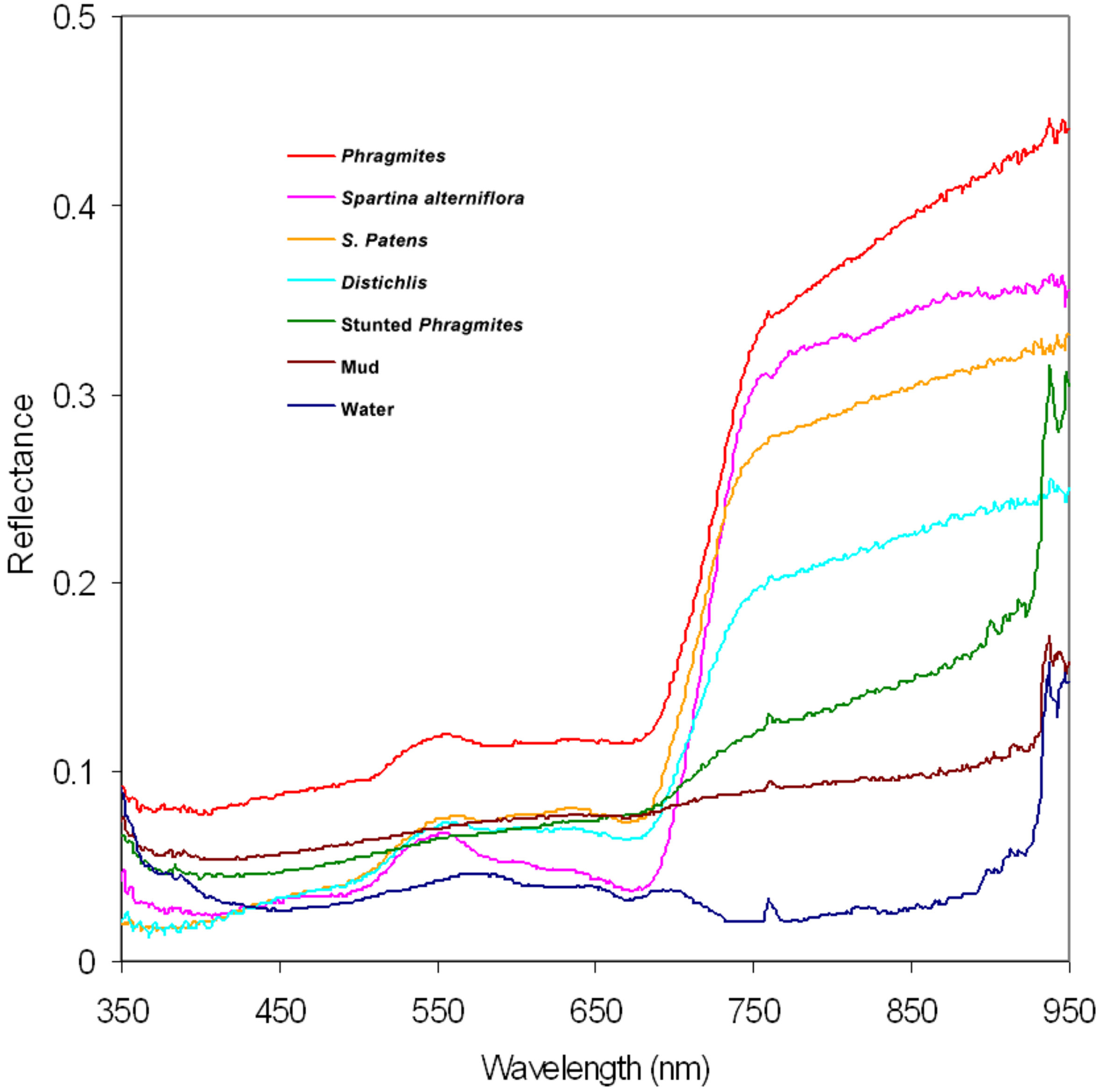

Figure 1. Field-collected reflectance spectra of marsh surface types in the New Jersey Meadowlands. These curves were used to identify the marsh surface types and classify the AISA hyperspectral imagery.

Figure 2.

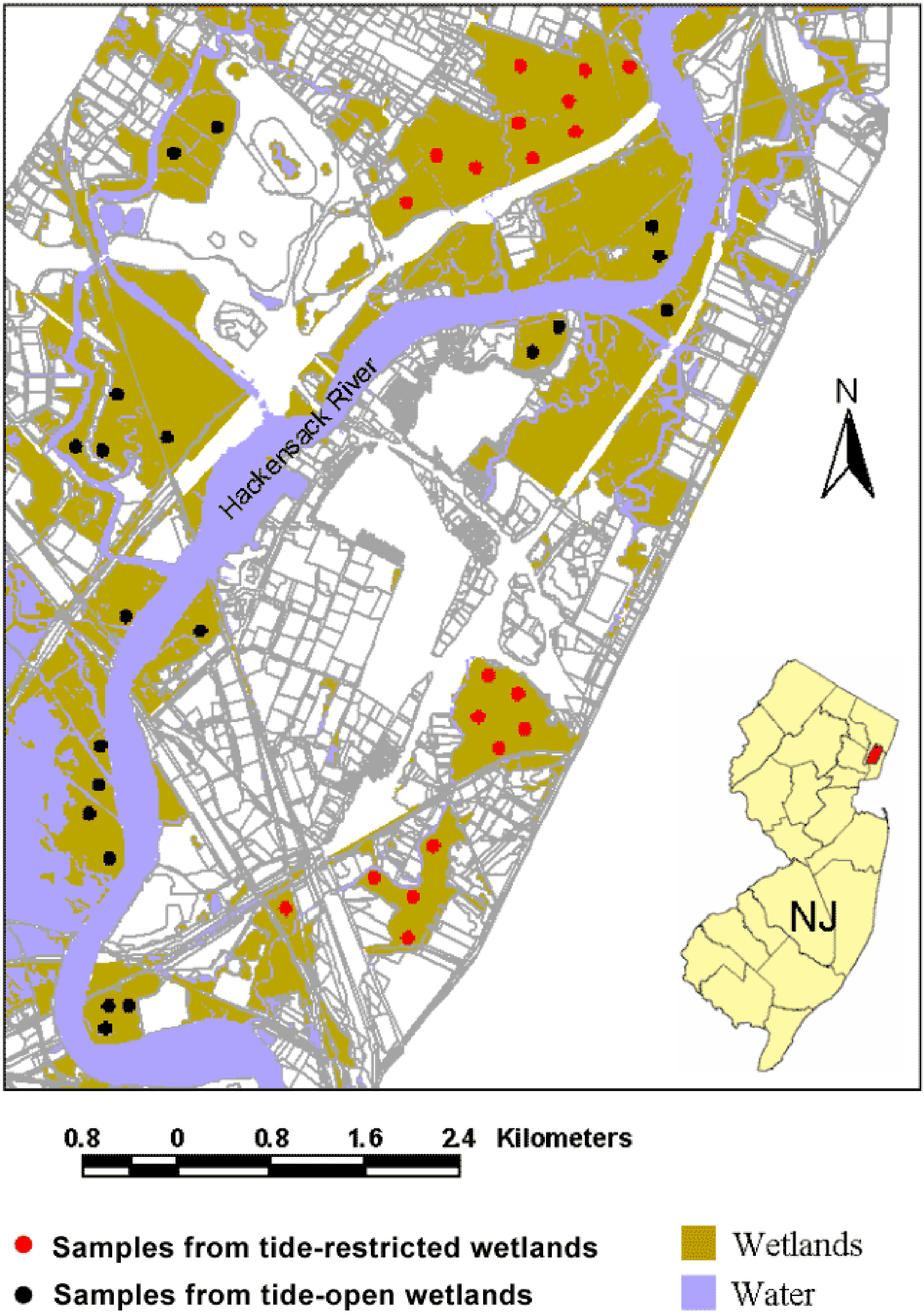

Figure 2. Twenty 100 × 100 m plots sampled in both tide-open wetlands (black) and 20 in tide-restricted wetlands (red) in the New Jersey Meadowlands.

Figure 3.

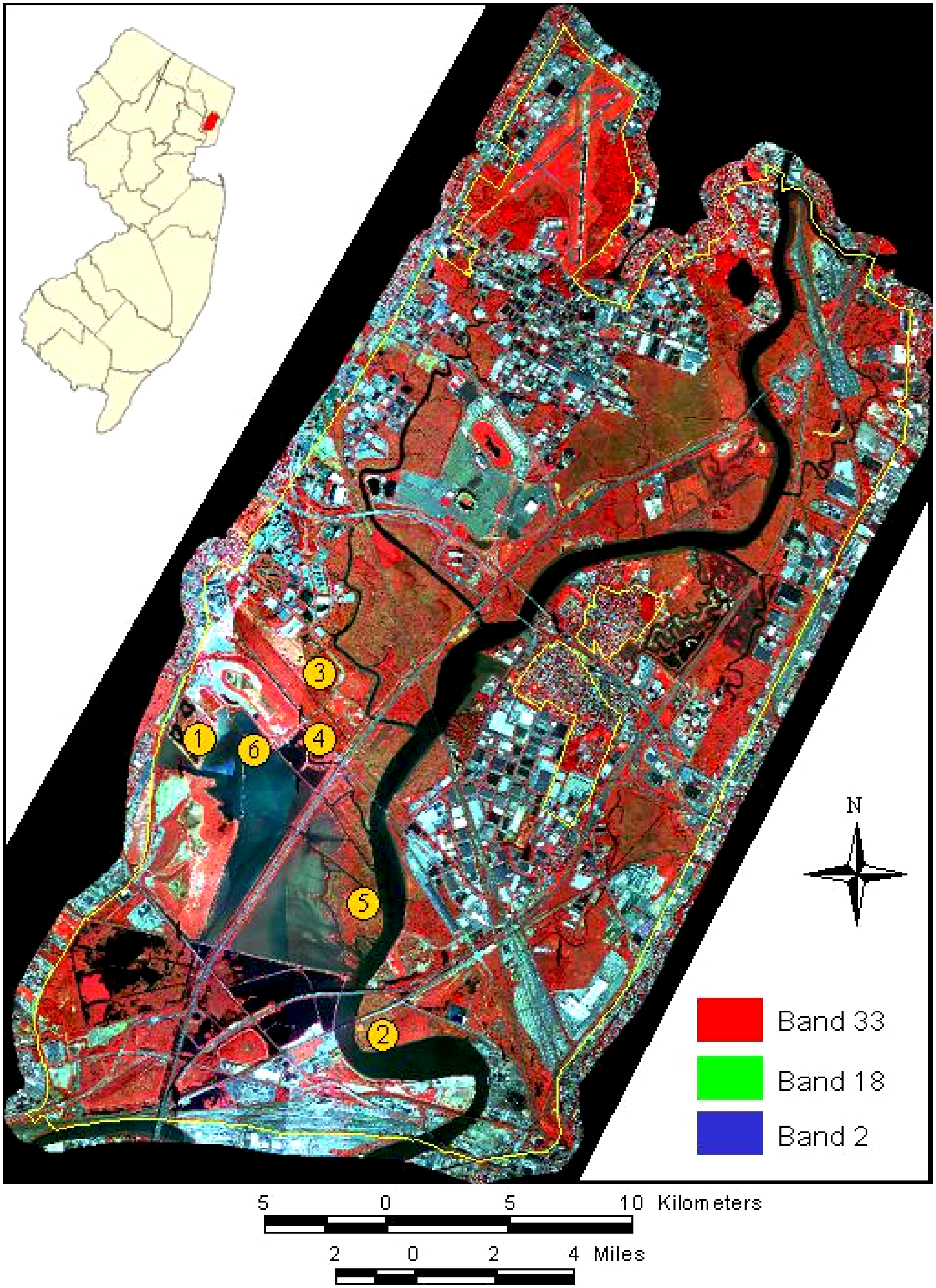

Figure 3. AISA imagery of the New Jersey Meadowlands and the six sites where field spectra were collected (site 1—Harrier Meadow; site 2—The Bend; site 3—The Turn; site 4—Station 8; site 5—Saw Mill Creek; and site 6—The Dock).

Figure 4.

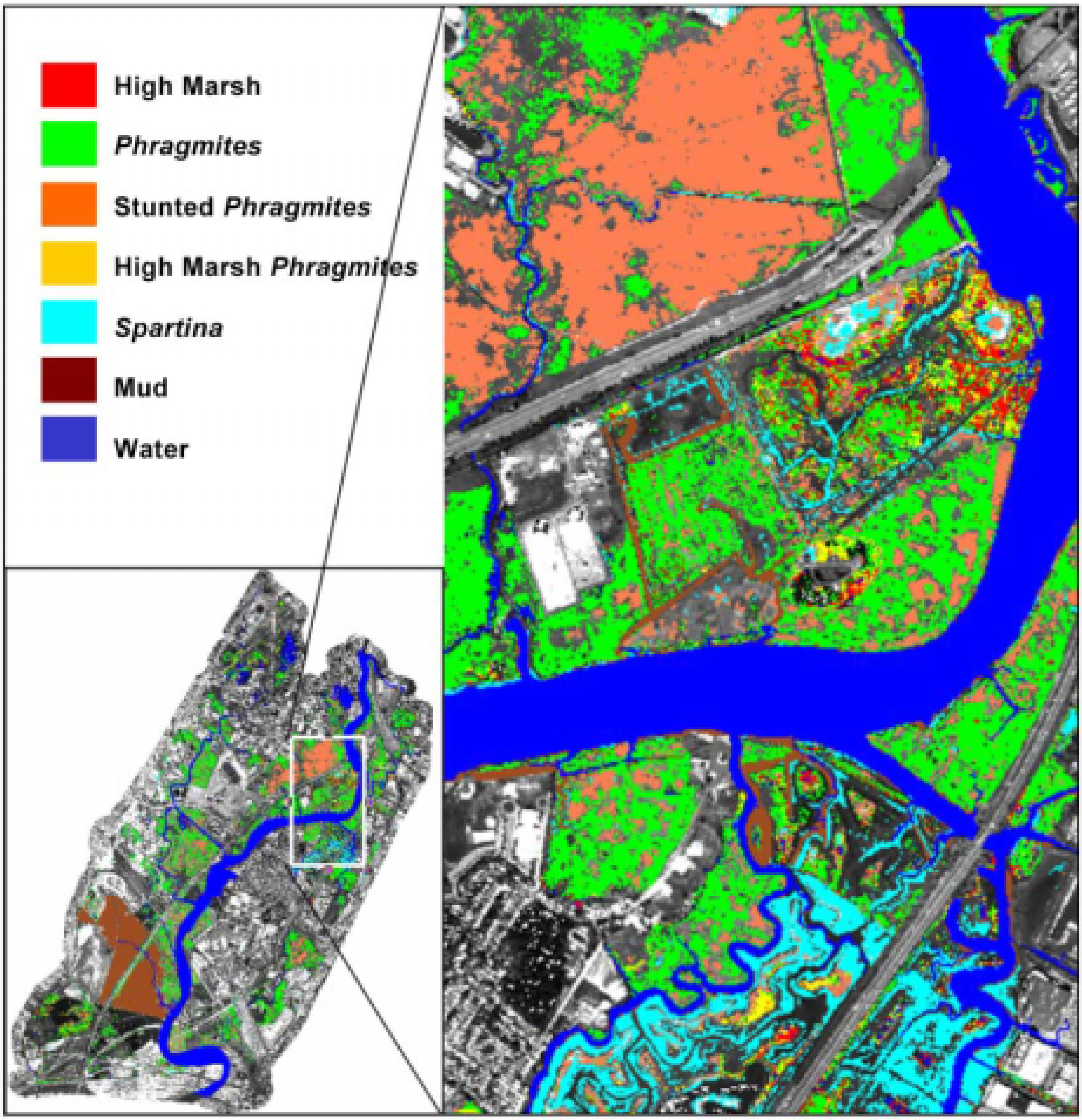

Figure 4. Marsh surface types in the Meadowlands classified using AISA imagery and field-collected spectra.

Figure 5.

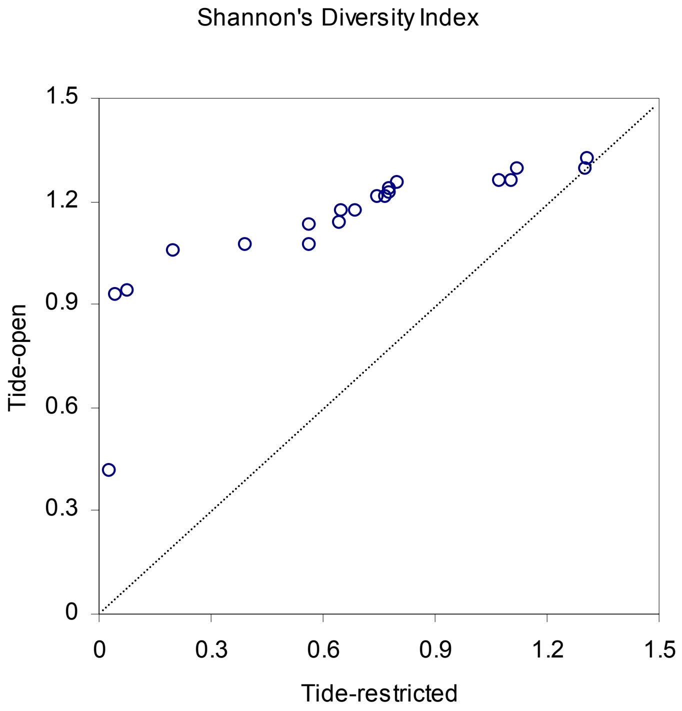

Figure 5. Q-Q plot of the Shannon Diversity Index (SHDI) calculated for tide-open and tide-restricted marsh in the Meadowlands. The SHDI is on average 0.6 higher in tide-open marsh than in tide-restricted marsh.

Table 1.

Predefined Marsh Surface Types	**Spectral Library**	**Surface Types and Location**
High Marsh	Dis1	Pure *Distichlis* at site 1
	Dis2	Pure *Distichlis* at site 2
	Pa1	Pure *Spartina patens* at site 2
	Pa2	Pure *S. patens* at site 1
Phragmites	Phrag1	Pure *Phragmites* at site 3
	Phrag2	Pure *Phragmites* at site 4
	Phrag3	Pure *Phragmites* at site 4
	Phrag4	Pure *Phragmites* at site 4
	Phrag/Dis	*Phragmites* and *Distichlis* mixture at site 2
Stunted *Phragmites*	SPhrag1	Stunted *Phragmites* with Mud1 at site 5
	SPhrag2	Stunted *Phragmites* with Mud2 at site 5
High marsh*/Phragmites*	Pa/Phrag	*S. patens* and *Phragmites* mixture at site 2
	Phrag/Pa	*Phragmites* and *S. patens* mixture at site 2
Spartina	Sp1	Pure *Spartina alterniflora* at site 6
	Sp2	*S. alterniflora* type 1 at site 2
	Sp3	*S. alterniflora* type 2 at site 2
	Sp/Phrag	*S. alterniflora/Phragmites* mixture at site 2
Mud	Mud1	Mud type at site 5
	Mud2	Mud type 1 at site 2
	Mud3	Mud type 2 at site 2
	Mud4	Mud type 3 at site 2
Water	Water	Open Water at site 2

Table 1. Seven predefined marsh surface types and their reflectance spectra collected from the Meadowlands at six sampling sites (site 1—Harrier Meadow; site 2—The Bend; site 3—The Turn; site 4—Station 8; site 5—Saw Mill Creek; and site 6—The Dock).

Table 2.

Total Class Area (CA)

$$CA = \sum_{j=1}^{n} a_{ij} \left(\frac{1}{10{,}000} \right)$$

a_{ij} = area (m^2) of patch ij.

CA is a measure of landscape composition; specifically, how much of the landscape is comprised of a particular patch type.

Number of Patches (NP)

NP = n_i n_i is the number of patches in the landscape of patch type (class) i.

NP of a particular patch type is a simple measure of the extent of subdivision or fragmentation of the patch type.

Total Edge (TE)

$$TE = \sum_{k=1}^{m} e_{ik}$$

e_{ik} is total length of edge in landscape involving patch type i.

TE at the class level is an absolute measure of total edge length of a particular patch type.

Fractal Dimension Index (FDI)

$$FDI = \frac{2 \ln(.25 p_{ij})}{\ln a_{ij}}$$

p_{ij} is perimeter (m) of patch ij; a_{ij} is area (m^2) of patch ij.

FDI reflects shape complexity across a range of spatial scales (patch sizes).

Patch Richness (PR)

PR = m m = number of patch types (classes) present in the landscape, excluding the landscape border if present.

PR is the simplest measure of landscape composition.

Shannon's Diversity Index (SHDI)

$$SHDI = -\sum_{i=1}^{m} \left(P_i \ln P_i \right)$$

P_i is proportion of the landscape occupied by class i.

SHDI is a popular measure of diversity in community ecology, applied here to landscapes.

Table 2. Calculation and brief description of the landscape metrics used in this study (retrieved December 12, 2003, from the University of Massachusetts, Amherst, Landscape Ecology Program Web site: http://www.umass.edu/landeco/research/fragstats/fragstats.html).

Table 3.

Metrics	Tide-open sites			Tide-restricted sites			t-test for Equality of Means
	N	Mean	Std. Deviation	N	Mean	Std. Deviation	Sig. (2-tailed)
High Marsh							
CA	20	0.13	0.10	14	0.05	0.08	**.032**
NP	20	19.95	5.96	14	8.57	8.56	**.000**
TE	20	791.00	443.40	14	343.75	415.59	**.005**
FDI	20	1.11	0.04	14	1.07	0.06	**.047**
Mud							
CA	15	0.01	0.01	3	0.02	0.03	.544
NP	15	3.40	1.96	3	4.67	4.04	.645
TE	15	79.67	77.19	3	146.67	132.70	.477
FDI	15	1.08	0.05	3	1.07	0.03	.801
Stunted *Phragmites*							
CA	20	0.31	0.17	19	0.46	0.34	.093
NP	20	10.25	7.34	19	4.21	2.62	**.002**
TE	20	786.63	365.69	19	404.21	260.22	**.001**
FDI	20	1.14	0.04	19	1.11	0.05	.095
Phragmites							
CA	20	0.39	0.22	16	0.38	0.34	.948
NP	20	8.30	5.30	16	5.19	4.67	.070
TE	20	781.13	356.44	16	521.56	394.61	**.049**
FDI	20	1.14	0.04	16	1.13	0.07	.395
Water							
CA	20	0.18	0.14	20	0.21	0.20	.585
NP	20	27.60	10.49	20	12.15	9.99	**.000**
TE	20	1135.25	594.81	20	683.38	456.83	**.011**
FDI	20	1.13	0.04	20	1.13	0.06	.672

Table 3. Descriptive and test statistics of class-level metrics—total class area in hectares (CA), number of patches (NP), total edge in meters (TE), and fractal dimension index (FDI)—for five marsh surface types in tide-open and tide-restricted sites. (Boldface numbers in the t-test column are statistically significant; $p < 0.05$.)

Table 4.

Metrics	Tide-open sites			Tide-restricted sites			t-test for Equality of Means
	N	Mean	Std. Deviation	N	Mean	Std. Deviation	Sig. (2-tailed)
PR	20	4.85	.587	20	3.60	.821	**0.00**
SHDI	20	1.135	.202	20	.679	.390	**0.00**

Table 4. Descriptive and test statistics of landscape-level metrics—patch richness (PR) and Shannon's Diversity Index (SHDI)—in tide-open and tide-restricted sites. (Boldface numbers in the t-test column are statistically significant; $p < 0.05$.)

Evaluating Urban Wetland Restorations: Case Studies for Assessing Connectivity and Function*

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Abstract

Restoration of urban intertidal wetlands such as the Hackensack Meadowlands of New Jersey typically involves the return of tidal flow to diked or gated land, the removal of dredge spoils to lower elevations, and/or the replacement of invasive plant species (e.g., *Phragmites australis*) with preferred marsh plants. Restoration of preferred vegetation and hydrology is expected to net an overall improvement in habitat quality for fishery and wildlife species. Common metrics have been identified for evaluating the functional success of restoration on individual sites in urban wetlands. We argue, however, that alternative, larger-scale metrics are needed in order to monitor and evaluate the success of restoring functional connectivity to the patchwork of wetlands that compose urban estuarine systems. We present here a literature review of measurements that have been used in wetland restorations throughout the United States to assess restoration success of ecological functions at the ecosystem and/or landscape scale. Our goal is to stimulate discussion of alternative metrics to be included in future and ongoing assessments of urban restoration sites, especially those in the Meadowlands.

Key words: Hackensack Meadowlands, landscape, restoration, salt marsh

Introduction

Functional assessment of undisturbed wetland systems is an intricate task, and assessment of urban wetland systems can be even more complex. As discussed by Ehrenfeld (2000) and Baldwin (2004), urban habitats are generally physically and biologically different from nonurban systems in a number of ways. First, urban systems are often subject to different climate and air quality than nonurban systems (for example, warmer temperatures, lower wind speeds, and higher concentrations of nutrients and toxicants). Physical alteration of wetland habitats, such as ditching and diking, is also common in urban habitats. In addition, the species pool in urban habitats is often limited in its seed-dispersal capabilities or mutualistic interactions, such as pollination, and the possible range of habitat types is often limited. Finally, wetlands, especially small isolated patches, may play different roles for wildlife in urban habitats than their nonurban counterparts. Specifically, while isolated wetlands in nonurban areas may have lower species richness and be underutilized by wildlife, similar habitats in an urban setting may provide an oasis used by a wide variety of species (Ehrenfeld, 2000).

The Hackensack Meadowlands, located in northeastern New Jersey, provide a prime example of these differences. This wetland complex has been dramatically affected by urbanization during the last 200 years: The hydrology has been so altered that this once freshwater-brackish system is now brackish to saline. The roughly 7,000-hectare (17,300-acre) marsh complex is traversed by railroads and highways and has been subject to human intervention ranging from heavy industry and landfills to sports complexes and residential developments. It includes sites contaminated with a variety of toxicants (Sipple, 1971; Roman, Niering & Warren, 1984; Ehrenfeld, 2000), including over 200 known or suspected hazardous waste sites, among which are three Superfund sites. There are also numerous combined sewer overflows, which cause continued degradation of the Meadowlands environment (Thiesing & Hargrove, 1996). As a result of the intensive land use and related habitat degradation in the area, numerous restoration projects are being implemented, primarily to restore hydrology and replace the *Phragmites*-dominated ecosystem with a more diverse blend of vegetation in the interest of providing higher-quality habitat for fishery resources and other wildlife (New Jersey Meadowlands Commission [NJMC], 2004). The urban nature of the Meadowlands presents a challenge in identifying reference sites for gauging restoration success. The existing brackish to saline habitat is itself a product of urbanization, and therefore, undisturbed analogous sites for this habitat are not available nearby to serve as references. Because of this lack of suitable reference sites and the fact that restoration in the Meadowlands is targeted on ecosystem-scale improvements, there is a need to develop landscape-scale metrics for monitoring restoration progress and assessing wetland function.

The challenge of finding ways to measure restoration success on such a large scale is not restricted to the Hackensack Meadowlands; national symposia have been called to evaluate landscape-scale wetland assessment and management (e.g., the Association of Wetland Managers symposium "Landscape Scale Assessment and Management," Nashua, New Hampshire, October 20–23, 2003). As described by Kentula (2000) and the National Research Council (NRC, 2001), a fundamental goal of wetland restoration is that site-specific improvements relay to connected ecosystems. Wetland restoration, enhancement, and creation are regularly undertaken in this country and others to compensate for losses due to development or other habitat degradation. In the United States, federal and state regulatory programs require mitigation or compensation for certain types of disturbances and ecological injury with the ultimate goal of retaining or restoring the ecosystem services provided by aquatic habitats. However, despite the no-net-loss requirements of the federal Clean Water Act and the restoration components of CERCLA (the Comprehensive Environmental Response, Compensation, and Liability Act, also known as Superfund) and RCRA (the Resource Conservation and Recovery Act), wetlands are still being lost at a significant rate (NRC, 2001), and no metrics are being collected universally to demonstrate the contribution of restored wetlands to larger ecosystem and landscape functions. While contiguity and large size are commonly recognized as positive influences on the likelihood of restoration influencing the larger landscape, small isolated wetlands may also be important, especially for maintenance of regional biodiversity (e.g., rare plants; Zedler, 2003). Connectivity, or the degree to which the landscape patches interact, is difficult to measure but is a vital element of wetland sustainability.

Wetland acreage and function continue to be lost, and finding out why is made more difficult by the lack of effective postconstruction monitoring and adaptive management of wetland mitigation and restoration processes (Race & Fonseca, 1996; Zedler, 2000). Regulations typically require only limited evaluation of created or restored wetlands, with an emphasis on rapid-assessment methodologies, such as the Wetland Evaluation Technique (WET) or the Habitat Evaluation Procedure (HEP). With their focus on vegetation-related parameters such as plant height, percentage cover, and invasive species (see Craft, Reader, Sacco & Broome, 2003; Zedler, 2000), these correlative methodologies are good for rapid, qualitative screening of basic trends and for predicting the likelihood that a function is occurring. However, they don’t allow us to examine key large-scale interactions, such as nutrient retention or the dynamics of wildlife metapopulations), and their qualitative data are difficult to feed into models of adaptive management. Thus, while rapid-assessment methodologies are useful for broad oversight of the three basic wetland parameters (soil, water, and vegetation), they are of little use in assessing the participation of a given restored wetland in larger ecosystem services or functions. Achieving this functional connectivity is, after all, the goal of most wetland restoration and creation projects, both urban and "pristine" (Morgan & Short, 2002).

The time frame of current monitoring protocols also limits their use in landscape-scale assessments. Postrestoration monitoring is often only conducted for three to five years after construction. There is increasing awareness that this period of time is too short to adequately gauge the development of many important ecosystem attributes (Siegel, Laska, Hatfield & Hartman, unpublished data). Numerous studies have indicated that ecosystem attributes such as soil organic carbon, soil nitrogen, and biological communities require at least 5 to 25 years (or much more) to achieve relative equivalence with natural reference systems (Craft et al., 2003; Craft et al., 1999; Zedler, 2000; Warren et al., 2002). Moreover, establishment and measurement of larger-scale landscape interactions may take many more years to achieve (Zedler, 2001). As it stands today, monitoring is often conducted in a vacuum, so to speak, with little consideration given to the role of a specific site in the larger ecosystem context (Zedler, 2003).

Longer monitoring and better metrics for assessment of landscape-scale functions are especially important in patchy urban settings, where restoration may take a substantially different trajectory than that taken in more contiguous, nonurban sites. Furthermore, due to their ecological importance in disturbed landscapes, urban wetlands may contribute more at the landscape scale than independent wetlands in less disturbed settings (Callaway & Zedler, 2004). Thiesing (2001) and Zedler (2001), among others, have called for improved assessment of wetland functions at the landscape scale, but very few studies have developed techniques for large-scale assessment. Our objective is to present an outline of the common metrics of compliance success (i.e., achievement of restoration goals as set forth by a regulatory agency) in current use and to review alternative methods for assessing wetland functional progress. By reviewing published studies of creative monitoring techniques throughout the U.S., it is our goal to provide a general overview of possible means for improving the methods used in judging success in urban wetland creation and restoration.

We propose that ideal metrics for measuring urban restoration success at the landscape level have the following attributes:

- Metrics should have low spatial and temporal variability (outside of recognized gradients);
- Metrics should be measured regularly (at least annually);
- Metrics should quantitatively predict or measure a critical ecosystem function;
- Data should fit into an adaptive measurement strategy.

We recognize that not all metrics will have all these attributes, but a composite of improved metrics will allow for improved prediction and management of connectivity and function. Further, we recognize that metrics are chosen for more than scientific reasons and that the choices may affect the interpretation of restoration outcomes, a thorny issue to resolve in the restoration community.

Current Metrics of Compliance Success

Thiesing (2001) provides an excellent overview of the methods currently used to evaluate compliance success in wetland restoration and creation. She classifies the methods into four approaches: 1) inventory and classification, 2) rapid assessment protocols, 3) data-driven assessment models, and 4) bioindicators. While the approach implemented at a given site is generally specified by the regulatory agency overseeing the project, multifunction rapid assessment is the most common one used. Data collection for rapid assessment is usually a ranking for a given wetland function (e.g., high–medium–low) based on field observations or data (e.g., vegetation cover) specifically collected for compliance success. Below, we list common measurements for compliance success and review how they may be incorporated into a larger composite metric of landscape success.

Vegetation Cover and Composition

Vegetation cover and composition are the most common monitoring metrics used in most restoration projects. Indeed, they are the sole field-based metrics for many projects, particularly those driven by 404 permits (i.e., permits issued under the Clean Water Act). Factors such as percentage survival, percentage cover, and the presence of target species are relatively easy to assess in a single site visit. Monitoring vegetation cover and composition is useful because it provides a general idea of whether a restoration or construction project is establishing vegetation as expected or required. Regular vegetation monitoring can potentially help identify problems, such as low plant survivorship or the presence of invasive species, early in a project and allow for corrective action. In the New Jersey Meadowlands, for example, annual vegetation sampling in the Harrier Meadow wetland enhancement area is helping prevent *Phragmites* invasions by allowing modifications in planting and hydrologic patterns (Hicks & Hartman, 2004). In contrast, vegetation monitoring of the Eastern Brackish Marsh restoration site was limited to the first few years of vegetation establishment (1989–91), after which *Phragmites* returned as the dominant species (Laska, personal observation).

However, vegetation in and of itself can be misleading. Percentage cover and the presence of any one species, including invasive species, cannot fully determine how an ecosystem is functioning (Zedler, 2001). Measuring the fertilization of plants in their early stages of establishment may also give a false assessment of future vegetation sustainability (Zedler, 2001). Furthermore, vegetation biomass and structure, while providing a rough index of macrophyte primary production, are not always correlated with larger-scale functions such as fisheries habitat, trophic support, etc. (Weinstein, Balletto, Teal & Ludwig, 1997; Weinstein & Kreeger, 2000). Monitoring for the presence of invasive plant species (e.g., *Phragmites australis*, *Lythrum salicaria*, *Arundo donax*) is a necessary part of any wetland restoration or construction project, as invasives thrive in disturbed habitats and may limit floral and faunal recovery. While monitoring for invasive species is generally a site-specific process, the invasion pressure is a function of propagule density in the surrounding landscape. Evaluating the rate of return of *Phragmites* is critical in Meadowlands habitat, where more than 5,000 acres are dominated by this species (see Weinstein, Guntenspergen, Keough & Litvin, 2003, for additional commentary on *Phragmites* removal in New Jersey).

Wildlife Species Composition

The recovery of animal populations is often the focal goal of restoration (e.g., the northern harrier, *Circus cyaneus*, in Laska, Baxter & Graves, 2003; the California clapper rail, *Rallus longirostris obsoletus*, in Zedler, 1998), but typically monitoring efforts are minimal at best and often don't occur at all unless directly required by the overseeing regulatory agency. More than 225 species of birds occur in the Meadowlands (Kiviat & MacDonald, 2002), indicating great potential for avian responses to restoration efforts there. Generally, bird diversity or population attributes are good indicators of habitat quality (Croonquist & Brooks, 1991; Bryce, Hughes & Kaufmann, 2002); therefore, monitoring avian population responses to or habitat uses of restoration sites can be a valuable tool in evaluating restoration success (Neckles, 2002). The effectiveness of these evaluations increases when attributes are properly compared temporally (such as current versus prerestoration conditions) or spatially (restored site versus reference site over multiple years). Animal populations are rarely (if ever) in equilibrium (Wiens, 1984) and thus are extremely variable between years. Animal populations from fish to mammals must be monitored for at least five to ten years to account for high interannual variability (Elzinga, Salzer, Willoughby & Gibbs, 2001). Even with eight years of demographic study, Petranka, Murray, and Kennedy (2003) were unable to assess the response of two key amphibians to a wetland restoration in North Carolina.

Despite the difficulties in monitoring animal populations, though, they are one of the best landscape-scale indicators. This is true for both fully mobile vertebrate animals that use multiple habitats within an urban watershed and benthic invertebrates that are motile only in early life stages.

Water- and Soil-Quality Parameters

Monitoring of parameters such as salinity, pH, nutrient concentration, dissolved oxygen, and temperature can also help to identify major problems like nutrient overload, lack of dissolved oxygen, or high or low salinity and enable corrective action.

Unfortunately, these factors are not usually measured continuously and can be extremely variable over the course of even a day. Results also depend on season, precipitation, tidal amplitude, etc. As such, mean values of these factors do not provide a predictable or linear measure of conditions (Ayers, Kennen & Stackelberg, 2001). Soil chemistry can also be highly variable at the submeter scale due to small microtopographic differences. While these physiochemical parameters are fundamental to achieving restoration goals, monitoring them is only valuable when they are 1) measured together, as a suite of parameters; 2) replicated spatially in accordance with background levels of variability; and 3) replicated temporally across important gradients of time (day, tide, season, year).

Hydrology

Tidal inundation, tidal prism, water velocity, and seasonal hydrologic patterns can be monitored to ensure that a site is complying with the regulatory definition for wetland hydrology. Detailed hydrologic studies and/or hydrogeomorphic classification (HGM) are time-consuming and rarely included in long-term monitoring plans. An HGM model was recently completed for multiple sites within the New Jersey Meadowlands (see McBrien, 2003), and it will allow quantification, and thus comparison, of key hydrologic parameters between reference and restored sites. HGM models are developed iteratively (i.e., through repeated processes) with validation from field data and so are better refined and more objective than rapid assessment models. However, they are still based on comparisons with undisturbed reference wetlands, which may be outperformed by urban wetlands in functions such as pollutant retention (due to higher incidence of pollutants in urban areas). Further, although they are highly useful for determining the physical underpinnings of a marsh restoration, HGM models are not particularly useful for assessing the role of the wetland within the larger landscape.

Proposed Metrics of Functional Progress

Extensive research by both the scientific community and government agencies involved in the wetland permitting process has demonstrated that the current system of wetland mitigation and monitoring is failing to accomplish the no-net-loss goals set forth by the Clean Water Act (Race & Fonseca, 1996; NRC, 2001). This failure is due not only to the shortage of disturbed wetland acres being replaced but also to the inadequacies of currently applied monitoring techniques. With these techniques, it’s difficult to identify whether functional success has been achieved at a particular restoration site. It is also difficult to assess how restoration of one parcel influences other parcels within the landscape. Here, we review a number of metrics that have been used in the assessment of wetland functionality in ecosystem or landscape contexts.

Wildlife Assemblage and Abundance

Bird Populations

Siegel et al. (unpublished data) are monitoring avian habitat use at Meadowlands restoration sites both before and after restoration across multiple years and seasons, providing one of the few direct comparisons of wildlife responses to restoration at a landscape scale in the region. The researchers present results of pre- and post-restoration monitoring of avian communities at two tidal marshes in the

Meadowlands, Harrier Meadow and Mill Creek Marsh. Both sites were dominated by *Phragmites australis* at the beginning of the restoration effort. Restoration efforts included creating more open-water areas and upland islands, reducing invasive species, regrading to create new emergent marsh habitat, and increasing connectivity of more diverse habitats. The sites were surveyed for avian usage for at least one year prior to restoration and during a five-year postrestoration monitoring phase (Feltes & Hartman, 2002). By comparing the changes in each of these sites, as well as the differences between them, the monitoring demonstrated a significant increase in avian species richness in habitats that had been restored and presumably a relationship between type of restored habitat and avian guild. These results also indicate a tangible benefit to urban intertidal wetland restoration for avian communities in the Meadowlands.

Fish Populations

While fish productivity is often challenging to quantify, many large restoration projects have used them as indices of landscape function and restoration success. In Delaware Bay, New Jersey, a long-term study of fish response to a 10,000-acre wetland restoration has been ongoing for seven years (Weinstein et al., 2000; Grothues & Able, 2003). In this study, a broad variety of ecological patterns were quantified to demonstrate that multiple trophic levels of fish were able to breed, grow, move, and behave in similar ways in both restored and reference marshes. The researchers' methods included tracking juvenile fish movements and isotopic signatures (of carbon, nitrogen, and sulfur) in fish to determine whether the food chain had been altered by restoration. At four sites in Oregon's Salmon River estuary, researchers assessed the rate and pattern of juvenile chinook salmon (*Oncorhynchus tshawytscha*) by measuring fish density, available prey resources, and diet composition using a chronosequence approach (Gray, Simenstad, Bottom & Cornwell, 2002). Dikes had been removed from three of the sites at different times between 1978 and 1996; the fourth site was an undiked reference site. The study revealed differences in measured factors between the four sites but indicated that early habitat functionality was attained within two to three years after dike removal in the restored estuaries.

Invertebrate Populations

Benthic invertebrate populations are common indicators of water quality and for trajectories of succession (Levin, Talley & Thayer, 1996). The Massachusetts Office of Coastal Zone Management developed a macroinvertebrate index to assess the condition of salt marshes both along a gradient of human disturbance and in response to tide restoration (United States Environmental Protection Agency, 2003). However, as with all animals, invertebrates are controlled by top-down and bottom-up forces (predation pressure and food supply, respectively), and this can obscure population differences during the monitoring phase. In a southern California marsh, for example, Talley and Levin (1999) found greater populations of macroinvertebrates in newly restored marshes, so-called "density overshoots." While invertebrates in isolated wetlands and other enclosed water bodies are easily tracked between years and can give strong evidence of restoration success (Dodson & Lillie, 2001), populations of invertebrates in tidal wetlands are difficult to monitor due to constant resuspension and resettlement of their planktonic larval stages. Given these difficulties in interpreting invertebrate populations, we suggest that agencies focus on the wetland function itself: nursery habitat. Intertidal marshes should function as nursery habitat for soft-sediment invertebrates (as well as fish), and rates of infaunal colonization are a quantitative indicator of habitat selection over the course of succession (Mosemen, Levin, Currin & Forder, in press). Placement of sampling devices for key invertebrates within restored and reference wetlands, while accounting for seasonal variability in their dispersal and growth, allows regulatory agencies to count and compare the frequency of settlement and the relative growth rate for these organisms throughout an estuary. For a more detailed understanding of macroinvertebrate population dynamics, Levin (2004) is performing trace-metal analyses of mussel and clam tissue of invertebrate populations in a southern California estuary to determine connectivity (i.e., how many of the invertebrates are coming from afar as opposed to occurring locally, by self-seeding).

Natural Abundance Stable Isotopes

Analysis of the natural abundance of stable isotopes of carbon, nitrogen, and sulfur in organic matter provides a useful and powerful in situ tracer for wastewater nitrogen (N) as well as for trophic relationships (what is eating what). Since isotopes are atoms with the same number of protons but different number of neutrons, the heavy-to-light-isotope ratio (e.g., ^{15}N: ^{14}N) is generally expressed as the per mil (‰) deviation of that sample from the isotopic composition of a reference compound. For example, the natural abundance of ^{15}N ($\delta^{15}N$) in wastewater is generally high, so the nitrogen signature is considered "heavy." This $\delta^{15}N$ can be compared with other pools of nitrogen, in plants or animals, so that one can determine how much nitrogen nutrition these organisms are getting from wastewater. It is known that biologically mediated nitrogen transformations (e.g., trophic assimilation of N) discriminate slightly against molecules containing the heavy isotope of N; when one considers the reaction rates for the different isotopes, the isotopic signatures can be used to determine such data as the source of nitrogen and/or the trophic level of a consumer.

Comparing Trophic Pathways

University of Rhode Island (URI) researchers (Wozniak, Roman, James-Pirril, Wainright & McKinney, 2003) are using $\delta\ ^{13}C$:$\delta\ ^{15}N$ ratios to track the food source of mummichogs (*Fundulus heteroclitus*) and fiddler crabs (*Uca pugnax*) in restored marshes of different ages (e.g., Sachuest Point, Rhode Island, and Hatches Harbor, Massachusetts) and referencing their findings to an undisturbed marsh (Herring River). Both reflect a *Spartina* species–dominated food chain in the reference marsh. However, in the restored marshes, mummichogs and crabs show little evidence of a *Spartina*-dominated diet. The URI researchers and the Center for Coastal Studies (Provincetown, Massachusetts) are developing a multisite model of isotope data from restorations on the eastern seaboard, for comparison between sites and between years in both the restored and reference sites. This approach would be extremely valuable for almost all Meadowlands restoration sites.

Nitrogen Retention

Cole et al. (2004) have reported on the use of $\delta^{15}N$ signatures in identifying sources of N for macrophytes and algae in salt marshes across the U.S. By tracking tissue concentrations of $\delta\ ^{15}N$ over time and comparing the signatures between wetlands at different successional stages, it is possible to determine the N dynamics of different marshes and infer whether a marsh is functioning as a sink for excess bioavailable N, or as a source through N fixation. For example, Cole et al. (2004) found that both developing and historic marshes in the heavily impacted urban watersheds of San Diego County, California, are important sinks for N.

Plant Assemblage and Biomass

Vegetation monitoring is both a site-specific metric and a landscape-scale metric, in that propagules of plant species are dispersed throughout watersheds by air, water, and animals. However, percentage cover and biomass of a given year are less valuable indicators than changes in species composition or nitrogen concentrations over time. Variation in species presence over time can be a simple but useful indicator of ecosystem function, with systematic loss or decline suggesting environmental stress (Zedler, 2001). This is especially true for perennial species, which are the dominant plants in salt marshes.

Vegetation percentage cover is important in terms of determining any glaring soil-related problems limiting plant survival. However, since most relatively successful restorations quickly achieve vegetation coverage, subsequent assessment is more likely to focus on biomass or plant height. One study measured macrophyte biomass and tissue concentrations for three years at 12 Chesapeake Bay tidal marshes varying in postrestoration age between 0 and 17 years (Whigham, Pittek, Hofmockel, Jordan & Pepin, 2002). They found that biomass was highly variable year to year and a poor indicator of marsh restoration over time. By contrast, they found that nitrogen concentration in plant tissue (N retention) was quick to recover, and it was a more stable, consistent indicator of recovery. Zedler (2001) has demonstrated that the accumulation of nitrogen into biomass of newly established tidal wetlands is intimately tied to ecosystem development. Monitoring nitrogen and other nutrients in plant tissue may therefore be a useful metric of wetland recovery following restoration (Whigham et al., 2002).

Soil Parameters

Soil development in wetlands is both autochonous (e.g., organic production) and allochthonous (e.g., sedimentation). Thus, soil metrics are valuable both for determining site-specific production and landscape-scale retention of sediment, including nutrients and pollutants. Finally, soil microbes are at the core of wetland biogeochemical functions, and their activities can be monitored through a variety of new techniques.

Soil Organic Matter Accumulation and Quality

Whereas macrophytic vegetation may reestablish in restored wetlands within 2 to 5 years, nitrogen and carbon pools in soil organic matter may take more than 25 years to approach natural marsh conditions (Broome & Craft, 1998; Craft et al., 1999; NRC, 2001), even with organic amendments. Craft et al. (2003) conducted a detailed analysis of ecological attributes in restored North Carolina marshes and compared the results to adjacent reference sites. Based on a comparison of measured parameters (e.g., soil carbon and nitrogen pools; C:N ratios; benthic invertebrate, algal, and diatom communities; and vegetation), they identified soil organic carbon as an ideal indicator of salt marsh development. Soil organic carbon—also called soil organic matter

(SOM)—was singled out in this study because it correlated well with other measured parameters, and it is predictable, easy to use, and inexpensive (Craft et al., 2003). Overall, soil organic matter is both a cause and result of proper tidal marsh functioning and thus should be considered the key factor for demonstrating ecosystem functionality.

Since it may take 25-plus years for a restored site to reach reference conditions for SOM, we propose modeling a trajectory by which to assess rates of change. This trajectory design should be based on data from analogous, but older, restoration sites (e.g., Eastern Brackish Marsh). For forested wetland restoration, researchers combined soil data from multiple references and restored sites to create a Soil Perturbation Index (SPI), basically a measure of how different the reference soils were from restored soils of various ages (Maul, Holland, Mikell & Cooper, 1999). Using composite data for soil organic matter, total nitrogen, and total phosphorus concentrations, they compared data from restoration sites with the index to estimate progress in soil development.

Sedimentation Rates

Sediment deposition is commonly measured by gauging sediment accumulation upon a feldspar marker horizon (http://www.pwrc.usgs.gov/set/installation/markers.html; Zedler, 2001). Measurement of rates of sediment deposition can be performed simply with a knife and a ruler if 1) the sediments are firm, 2) the surface is free of standing water, and 3) the marker horizon is not deeper than the knife is long. The simplest technique consists of placing a layer of feldspar approximately 0.25 inches in depth in a small plot (~1 m^2) on the sediment surface and returning at various sampling intervals to cut a four-sided plug of sediment; the average depth of sediment on all four sides of the plug will indicate an average sediment accumulation rate in the plot.

Horizon markers indicate rates of marsh buildup and provide the ability to sample the quantity and quality of sediment inputs to the system by keeping them physically separate from the underlying soils. Given the historic problems of remobilization of sediments from multiple development and restoration projects in the Meadowlands, we propose that restorations be required to place a marker horizon within small plots in order to track accumulation over time, thus providing a point from which to measure adverse effects.

Microbial Community

Microbial community metabolism, measured as the diurnal fluxes of dissolved oxygen in surface water, is expected to increase over time as a restored wetland develops from a net heterotrophic system to a net autotrophic system (Cronk & Mitsch, 1994). Four years of succession in a restored wetland in Montezuma National Wildlife Refuge, New York, was not sufficient for McKenna (2003) to detect this shift. Following concepts from del Giorgio and Cole (1998), del Giorgio and Newell (Marsh Ecology Research Program, unpublished; R.I. Newell, personal communication) have proposed bacterial growth efficiency (BGE) as a consistent and sensitive indicator of SOM quantity and quality in salt marshes. Another functional approach to biogeochemical processes is through analysis of microbial biochemical products. Specific microbial populations and activities can be assessed with fatty-acid analysis for functional group identification (Ravit, Ehrenfeld & Häggblom, 2003) or enzyme analysis for estimating microbial activity (Prenger & Debusk, 2003). While microbial processes may be highly variable in space and time, they may prove a valuable metric when used for detection of specific wetland functions (e.g., denitrification, sulfate reduction) in a comparative framework between restored and reference sites.

Analysis of Metrics

In Table 1, we review all metrics with the considerations listed earlier. We find that while no metric in and of itself satisfies all monitoring needs, six metrics are relatively inexpensive and together satisfy the needs of measuring at the ecosystem and landscape scales. Basic vegetation indices, coupled with measurement of surface SOM and sedimentation rates, provide quantitative values of key autochthonous and allochthonous processes. In addition, measuring invertebrate colonization and analyzing stable isotopes of key organisms and plants, though time consuming, directly targets processes of habitat production, energy transfer, and nitrogen retention. These alternative metrics, used by other researchers and reported here, are perhaps the most useful new techniques for researchers and regulatory agencies looking to establish relationships between restoration sites and the larger estuarine system.

Of all the metrics reviewed, SOM accumulation is probably the most consistent and meaningful metric of ecosystem function. Intra-annual variability of this metric is minimal, and since SOM is strictly cumulative (unlike, say, the biomass of aboveground vegetation), it generally increases with time. For landscape function, only metrics of mobile elements within the estuary—organisms, isotopes, and sediment particulates—are useful for tracking the interaction between restoration sites and the larger estuarine system. Finally, though no one metric can achieve all monitoring goals, each of the metrics has some inherent value. This is especially true when the goals are specific to a given restoration project, e.g., creating habitat for an endangered species.

Conclusions

Landscape- and ecosystem-scale metrics are important means of assessing urban restoration success in the Hackensack Meadowlands of New Jersey. This is because, as in most urbanized wetland systems, the wetlands there are largely surrounded by human-altered land and affected by human land use, and because restored Meadowland wetlands are potentially isolated from more natural wetland reference areas. Moreover, wetland restoration techniques in general can be improved by knowledge of how restored wetlands contribute to the larger estuarine system.

We suggest that, where possible, simple metrics of ecosystem function (SOM, sedimentation rates) and of landscape connectivity ($\delta^{15}N$ in plant tissues, benthic colonization) be incorporated into annual monitoring plans. We also suggest that landscape-scale monitoring data be incorporated into site-specific assessments. For example, water-quality monitoring in the Meadowlands is relatively extensive; regulators have had to respond to severe pollution distress from immense landfills and unregulated solid-waste dumping, wastewater discharges, sewer discharges from two counties, and haphazard filling for development (Thiesing & Hargrove, 1996). Leveraging data from larger-scale monitoring projects such as this can improve the utility and predictive capacity of monitoring efforts (Holl, Crone & Schultz, 2004).

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Glossary

Allochthonous: Of or relating to nonindigenous material (e.g., sediment deposits in a river). Opposite of autochthonous (see below).

Autochthonous: Of or relating to material that originated in its present position (e.g., from the decomposition of plants). Opposite of allochthonous (see above).

Autotrophic: Of or relating to autotrophs, organisms capable of synthesizing their own food from inorganic substances using light or chemical energy (e.g., green plants, algae, and certain bacteria).

Bacterial growth efficiency (BGE): The fraction of organic carbon consumed by bacteria that is incorporated into biomass.

Benthic: Of or related to organisms (e.g., protozoa, nematodes) living on the sediment surface under a water column, such as sea or lake bottoms.

Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA): Enacted in 1980, this law (also known as Superfund) created a tax on the chemical and petroleum industries and provided broad federal authority to respond directly to releases or threatened releases of hazardous substances that may endanger public health or the environment. (Source: www.epa.gov.)

Chronosequence approach: A "space-for-time" substitution used to examine long-term trends in which systems of different ages are compared to determine the trajectory of a metric, instead of monitoring a single system over time.

Combined sewer overflow: The discharge into waterways during rainstorms of untreated sewage and other pollutants via combined sewers carrying both sanitary sewage and storm-water runoff from streets, parking lots, and rooftops.

Dredge spoils: The sediment removed from beneath a body of water during dredging.

Habitat Evaluation Procedure (HEP): A technique developed by the U.S. Fish and Wildlife Service for evaluating and predicting the suitability of changing habitats for species and communities based on ecological principles.

Heterotrophic: Of or relating to heterotrophs, organisms that cannot synthesize their own food and are dependent on complex organic substances for nutrition (e.g., fish, humans).

Horizon markers: Visually distinct substances (such as feldspar) laid down on surfaces of aquatic study areas to measure the vertical accumulation (buildup) of sediment.

Infaunal: Of or relating to infauna, benthic organisms (see above) that dig into the sediment bed or construct tubes or burrows.

Isotopes: Various forms of a chemical element (e.g., carbon) that have different numbers of neutrons and therefore different atomic mass.

Isotopic signatures: Ratios of certain isotopes (see above) that accumulate in organisms and can be used by researchers to profile food webs.

Macroinvertebrate: An animal, such as an insect or mollusk, that lacks a backbone or spinal column and can be seen by the naked eye.

Macrophyte: Water-loving vascular plants (grasses, rushes, shrubs, etc.).

Metapopulation: A group of populations of the same species that exist at the same time but in different places.

Metric: A standard of measurement for estimating or indicating a specific characteristic or process.

Mutualistic: Of or pertaining to mutualism, an interaction between two species that is beneficial to both.

Nitrogen fixation: The transformation of gaseous nitrogen into nitrogenous compounds (e.g., ammonia), usually by way of nitrogen-fixing soil and/or aquatic bacteria.

Planktonic: Of or relating to plankton—tiny aquatic organisms that drift with water movements, generally having no locomotive organs.

Primary production: The rate at which biomass is produced by photosynthetic or chemosynthetic organisms.

Propagule: Any structure that functions in plant propagation or dispersal (e.g., a spore or seed).

Resource Conservation and Recovery Act (RCRA): Enacted in 1976, RCRA (often pronounced "rick-rah") gave the U.S. Environmental Protection Agency control over the generation, transportation, treatment, storage, and disposal of hazardous waste.

Sink: A natural reservoir that can receive energy, species, or materials without undergoing change. Opposite of "source" (see below).

Source: A natural net exporter of energy, species, or materials (see above).

Stable isotope: Any naturally occurring, nondecaying isotope (see above) of an element. Many elements have several stable isotopes. For example, carbon (C) has carbon 12 (^{12}C) and carbon 13 (^{13}C).

Succession: The sequential change in vegetation and the animals associated with it, either in response to an environmental change or induced by the intrinsic properties of the organisms themselves.

Tidal prism: Volume of water that is drawn into a bay or estuary from the ocean during flood tide (i.e., a rising tide).

Trophic: Of or relating to feeding habits or the food relationship between different organisms in a food chain. Organisms can be divided into different trophic levels such as herbivores and predators.

Wetland Evaluation Technique (WET): A water-quality and watershed analytical model developed for the Federal Highway Administration for conducting assessment of wetland functions and values.

Table 1.

	Low spatial and temporal variability	Relative annual cost (ease of use)	Number of annual samples suggested	Indicates landscape connectivity	Indicates ecosystem function
Vegetation cover/composition	Yes	$	3	No	No
Wildlife species composition	No	$$	2	Maybe	Maybe
Water and soil chemistry	No	$$	>30	No	No
Hydrology	No	$$	>30	No	No
Bird population dynamics	No	$$$	2	Yes	Yes
Fish population dynamics	No	$$$	2	Yes	Yes
Invertebrate colonization	No	$$	2	Yes	Yes
Trophic pathways	Yes	$$	1	Yes	Yes
Nitrogen retention	Yes	$$	1	Yes	Yes
Soil organic matter (SOM)	Yes	$	1	No	Yes
Sedimentation rates	Yes	$	1	Yes	Yes
Microbial community	No	$$$$	3	No	Yes

$	0–$1,000 per year (nearly free, can be performed by volunteers)
$$	$1–10,000 per year (low cost, can be performed by general scientist)
$$$	$10–100,000 per year (high cost, must be performed by wetland scientist)
$$$$	>$100,000 per year (prohibitively expensive, performed by specialist)

Table 1. Overview and comparison of both currently used and alternative metrics.

Historical and Current Ecology of the Lower Passaic River[*]

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Abstract

The lower portion of the Passaic River (the river) is a tributary leading to Newark Bay and part of the New York–New Jersey Harbor estuary. The river is part of a highly urbanized ecosystem that has been severely degraded by more than 200 years of urbanization and industrialization. We conducted multiseason studies in 1999 and 2000 to characterize the present ecology of the river. These included detailed habitat profiles and surveys of benthic invertebrate, fish, and bird communities. In addition, we completed a detailed environmental-history study chronicling changes in ecology and human use in the lower Passaic River and the adjacent meadowlands habitats from pre-Columbian times to the present. Nearly all of the wetland and tidal tributary habitats that were once associated with the river have been removed by land-reclamation activities. In addition, water and sediment quality in the Passaic River were severely degraded in the late 19th and early 20th centuries due to industrial and municipal waste disposal associated with population growth and the industrial revolution in the Newark, New Jersey, metropolitan area. Current invertebrate and fish communities are not particularly diverse relative to other areas in the New York–New Jersey Harbor estuary and are dominated by pollution-tolerant organisms such as tubificid worms, mummichog (*Fundulus heteroclitis*), blue crab (*Callinectes sapidus*), and white perch (*Morone americana*). Similarly, bird use of the river is relatively low compared with other estuarine areas of New Jersey.

Key Words: Passaic River, Newark, New Jersey, habitats, benthic invertebrates, fish, birds, historical ecology

Introduction

The lower Passaic River (the river) in New Jersey (Figure 1) is a tributary leading to Newark Bay and part of the New York–New Jersey (NY–NJ) Harbor estuary. The river is part of a highly urbanized landscape that has been severely degraded since the time of European settlement in the early 1700s. The river is tidal throughout the 17-mile stretch from its confluence with Newark Bay upstream to the Dundee Dam in Garfield, New Jersey.

The story of the lower Passaic is one of a highly industrialized river. Once a rich ecosystem inhabited by a diverse and abundant community of invertebrates and vertebrates, the river has suffered severe deleterious effects from more than 200 years of industrialization and urbanization. Nearly all of the wetland and tidal-creek habitats once present have been destroyed by land-reclamation activities (Table 1). In addition, water and sediment quality in the river were severely degraded in the late 19th and early 20th centuries by industrial and municipal waste disposal associated with population growth and

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the industrial revolution in the Newark, New Jersey, metropolitan area. These conditions have steadily improved since the passage of the federal Clean Water Act in 1970. However, given the large human population of the region and the high density of industrial facilities lining its shores, the Passaic continues to be one of the most polluted rivers in the United States. Iannuzzi et al. (2002) provide a detailed description of the historical uses of the river and the associated impacts from pre-Columbian times to the 1990s.

Land-use patterns adjacent to the lower Passaic River are illustrated in Figure 2. The surrounding urban landscape has a tremendous influence on the extent and quality of the habitats in the river itself. The few remaining habitats are for the most part fragmented and degraded. This, in turn, has a great effect on the types and abundance of plant and animal communities that the lower Passaic River can support.

In this paper, we summarize historical ecological information on the lower Passaic River and present data and other information from habitat and biological surveys conducted in 1999 and 2000 as part of ongoing investigations conducted by the United States Environmental Protection Agency and other government agencies and private parties under the Comprehensive Environmental Response, Compensation, and Liability Act. The objective of this study is to combine historical information with the recently collected data to show ecosystem alterations in this intensely urbanized waterway. We believe that an understanding of both the historical and current conditions is necessary not only to help determine causes of the present ecological conditions in the lower Passaic but also to help define the potential scope for restoration of the river.

Methods

This section summarizes the methods we used to compile data and information on the ecology of the lower Passaic River.

Habitat Characterization

Habitat studies were undertaken in the late summer of 1999 and again in the spring of 2000. Our objectives were to document, quantify, and characterize the location and extent of available aquatic, wetland, and terrestrial habitats in the lower Passaic River. We used remote sensing and direct observation to quantify the present distribution of habitats. To document the distribution of shoreline habitat types, we analyzed aerial photographs and videotapes (aligned with Global Positioning System location records taken simultaneously) of the entire study area. The videotapes (which provide the greatest spatial resolution) were checked against the aerial photography and extensive direct observation.

We also did archival research to evaluate changes in habitat conditions over time. Maps and other records provided quantitative documentation of the nature and extent of key components of the estuarine habitat complex (wetlands, drainage tributaries, aquatic/terrestrial ecotones) of the lower Passaic River from presettlement to the present. We compiled the available information, did the systematic calculations necessary to make the data comparable and uniform in spatial and temporal terms, and prepared synoptic maps illustrating the habitat changes. Much of this information is presented in detail in Iannuzzi et al. (2002).

Benthic Invertebrate Community Surveys

Benthic invertebrate community surveys were conducted in the fall of 1999 and spring of 2000. We collected three surface-sediment samples from each of 15 stations throughout the lower Passaic River during the fall of 1999 and from 14 stations in the spring of 2000. A Petite Ponar grab sampler was used to collect the samples. The samples were sieved and sorted, and invertebrates were identified to the lowest practicable taxon. We analyzed the resulting data for various measures of community diversity and abundance.

Similar community surveys were conducted during the same time frames in the Mullica River, a tidal tributary leading to Great Bay in southern New Jersey, which we used as a relatively nonpolluted reference area for some of the lower Passaic River studies, including the benthic invertebrate community survey. Three surface-sediment samples were collected and analyzed (as described above) from each of three stations throughout the lower Mullica River during each of the two seasonal samplings. The data from the lower Passaic and Mullica rivers are compared in this study.

Fish and Blue Crab Community Surveys

Fish and blue crab community surveys were also conducted in the fall of 1999 and spring of 2000. For these surveys, we divided the lower river into upper, middle, and lower sections. Fish and blue crab of various sizes and life stages were captured using a variety of gear, including gill nets, baited crab pots, eel pots, and minnow traps. This variety of gear types was selected to maximize the number of species captured in the various habitats and depths of the river. Sampling was confined to areas outside the main navigation channel, in accordance with United States Coast Guard requirements.

We deployed each gear type in each sampling section of the lower river on a daily basis for about two weeks during each season. Captured fish were identified, weighed to the nearest gram,[*] and measured to the nearest millimeter. The resulting data were compiled and analyzed to provide estimates of catch per unit effort, diversity, abundance, and dominance. A list of the fish caught during the fall 1999 and spring 2000 surveys is in Table 2.

Bird Community Surveys

We conducted bird surveys for one year, beginning in the fall of 1999 and ending in the summer of 2000. Four seasonal surveys (spring, summer, autumn, and winter) were done. Each survey included multiple counts of all birds observed on mudflats, along the shoreline, and on bridge abutments. Spring, summer, and fall surveys included counts taken at both low and high tides, in the morning, at midday, and at dusk, thus incorporating the range of expected bird activity periods (morning and evening low tides normally being the periods of highest activity, and midday high tides the time of minimum activity). The winter survey was a one-day effort encompassing morning and evening low tides and midday high tide. Each survey included an estimate of the number of gulls flying over a defined "volume" of space at the central portion of each bird survey area, in addition to total counts of perched, swimming, and foraging birds. The bird survey was conducted using methods provided in Bibby, Burgess, and Hill (1992), as described in Ludwig and Iannuzzi (2002).

The results of the seasonal bird surveys were compiled and analyzed for various patterns of diversity, abundance, and habitat use. To the extent possible, these data were compared with other reported bird diversity and abundance data from nearby areas and along the New Jersey coast. A

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[*] *Except where noted, measurements throughout this paper are in metric notation; conversions to U.S. equivalents can be obtained at http://www.onlineconversion.com/length.htm.

summary of the birds observed during the 1999–2000 surveys is in Table 3.

Results and Discussion

Habitats

The majority of wetlands and associated habitats once present in the lower Passaic River are now gone (Figure 3). These were altered or removed by land "reclamation" activities and mosquito ditching. Most notably, a long stretch of the south shore of the lower Passaic River was once a large intertidal salt marsh and likely a key habitat in this ecosystem. Between 1873 and 1890, this area was covered with 8 to 12 feet of mixed fill material from coal gasification facilities, eliminating the marsh habitat (Iannuzzi et al., 2002). In addition, more than 25.1 miles of tributaries leading to the lower Passaic environs were lost (Table 1). This loss of wetland and tidal-creek habitats had a substantial impact on the biological productivity of the lower Passaic River.

In addition, dredging caused major disruption of the river bottom between 1874 and 1983. This, combined with bridge construction, commercial shipping, and municipal and industrial pollution, had a substantial adverse impact on the benthic communities of the lower Passaic River.

The remaining habitats are limited primarily to degraded intertidal mudflats and subtidal bottom. There are a number of small patches of vegetated wetland scattered throughout the lower Passaic River. These are dominated by *Phragmites australis* (common reed), although *Spartina alterniflora* (saltmarsh cordgrass) and other species are also present. The total area of vegetated wetlands along the first six miles of shoreline in the lower Passaic River is less than one acre.

All of the historical natural shoreline of the lower Passaic River has been substantially modified. Today, the shoreline is highly industrialized and abutted along much of its length by buildings and parking lots. In a few areas, corridors of weedy vegetation line the shore. These remnant riparian communities are dominated by *Phragmites australis* in low-lying areas adjacent to the water or mudflats and by mixed tree and scrub-shrub communities at higher elevations. Ruderal species, including *Ailanthus altissima* (tree of heaven), *Artemisia* species, and *Solidago* species (goldenrods) dominate.

Using data collected during the 1999 and 2000 surveys, we categorized the lower six miles of Passaic River shorelines as bulkhead, riprap, mixed vegetation, or aquatic vegetation. Bulkhead consists of horizontal or vertical wood timbers, metal sheet pile, or large stone blocks constructed to form a vertical face perpendicular to the water surface. Riprap includes cobble- to boulder-size stone and/or concrete rubble placed along the shoreline on a sloped bank. Mixed vegetation refers either to areas with aquatic/riparian vegetation interspersed with bulkhead and/or riprap or areas of riprap with substantial overhanging riparian vegetation. Aquatic vegetation refers to areas with emergent wetland plant species such as *Spartina alterniflora* or *Phragmites australis*. These categories distinguish between weedy, disturbed shoreline areas with upland vegetation (mixed vegetation) and areas that are clearly wetlands (aquatic vegetation).

The number of linear feet of each shoreline category is presented in Table 4. Most of the shoreline in the lower Passaic River (82%) consists of bulkhead (52%) and riprap (30%). These are used to stabilize the shoreline and protect the industrial and urban properties that line the river's banks. While riprap can provide refuge for some organisms, its habitat quality, particularly in low-salinity areas like the lower Passaic River, is minimal. Bulkheads, which are typically built using either metal sheet piling or pressure-treated wood, have no habitat value and reduce the value of adjoining habitats. The prevalence of bulkhead and riprap along its shorelines is a substantial limitation to the ecology of the lower Passaic River.

About 12% of the total lower Passaic River shoreline is composed of mixed vegetation areas. Only about 6% supports any kind of wetlands. The latter is divided almost equally between small patches of *Phragmites* and *Spartina*. The mixed vegetation areas are interspersed with riprap shoreline or are adjacent to mudflats where the elevation grades above the high-tide line. The low percentages of vegetated shoreline areas and wetlands are clear indicators of the lack of foraging and cover habitat in the lower Passaic River, and therefore the constraints on its biological productivity.

The primary aquatic habitats are intertidal mudflats and subtidal bottom, 8% and 92%, respectively, of the lower Passaic River bottom area. The intertidal mudflats and their associated shallow-water subtidal areas are the most important habitats left for estuarine organisms, providing the only available foraging habitat for fish, blue crab, and waterbirds.

Although wetland areas are small and patchy in the lower Passaic River, three such areas appear to be functional habitats supporting biological production. These are Lawyers Creek (approximate river mile 0.5) and the associated marshes near its confluence with the Passaic River (Figure 4); a small marsh remnant downstream of the Worthington Avenue combined sewer overflow (CSO) at approximately river mile 2.5 (Figure 5); and a small, unnamed creek remnant and adjacent shoreline area at approximately river mile 3.5 (Figure 6). These three areas each represent a small habitat complex.

Lawyers Creek is one of the few historical tidal creeks that remain in the lower Passaic River, albeit substantially altered and reduced in size from its original configuration. The confluence of Lawyers Creek and the Passaic River contains a large expanse of mudflat and a *Phragmites* marsh, with some *Spartina* fringing the *Phragmites* stand. The creek and its associated wetland complex provide refuge and possibly spawning habitat for aquatic organisms and wading birds.

The Worthington Avenue CSO area is a small cove that supports wetland vegetation (*Phragmites* and *Spartina*) and an unvegetated intertidal flat. The stand of intertidal wetland provides cover and possibly spawning habitat for a variety of estuarine organisms.

The creek remnant at river mile 5.3 supports a small habitat complex including intertidal mudflat, artificial hard-bottom substrate, and upland vegetation. The habitat heterogeneity makes this a unique site in the lower Passaic River. In addition, this area is contiguous with one of the larger and more ecologically valuable mudflats in the lower river.

Benthic Invertebrate Communities

No quantitative studies of the benthic community in the lower Passaic River, either pre- or post-industrialization, are available in the historical literature. However, based on the habitat characterization and the history of sediment degradation, it can be inferred that the benthic communities of the lower Passaic River have suffered adverse effects since at least the mid-19th century. It is also likely that the sewage and industrial and municipal wastes dumped into the river through the mid-20th century limited the benthic communities. Another major impact was the dredging of large stretches of the river throughout most of the 20th century.

Since passage of the federal Clean Water Act of 1970, waste disposal in the river has decreased substantially, and water and sediment quality has improved considerably. While municipal and industrial wastes continue to be discharged into the river through CSOs and storm-water drains, water and sediment are cleaner now than they have been for decades. In addition, the river has not been dredged since 1983. Thus, it is likely that benthic communities are more robust now than they have been for years.

Using the fall 1999 and spring 2000 data sets for the lower Passaic River and the Mullica River reference area, we characterized the benthic communities. Figures 7, 8, 9, and 10 include selected measures of the structure and composition of the benthic invertebrate communities in the lower Passaic River and the reference area. Bars in these figures represent the maximum and minimum numbers of individuals, and the symbols within the bars represent the averages. The results of the surveys indicate that the lower Passaic River benthic communities are somewhat variable in structure and composition. We found a tendency toward greater abundance of invertebrates in the lower Passaic than in the Mullica, a result of large numbers of tubificid worms in several of the Passaic samples (Figure 7). The average number of taxa per sample in each of the two rivers is generally similar (Figure 8).

Lower Passaic River benthic communities are composed primarily of pollution-tolerant organisms from a variety of functional feeding groups (Figure 9). Few pollution-sensitive species (e.g., crustaceans) were found in the lower Passaic River, compared with the Mullica (Figure 10). In general, habitat does not appear to control benthic community structure in the Passaic, as bottom conditions, including grain size and organic carbon content of the sediments, don't vary greatly among sites.

We developed a qualitative classification system for the benthos based on a comparison of various measures of community structure in the lower Passaic River relative to those in the Mullica River. Based on this system, each measure in the lower Passaic River was scored as "excellent," "good," or "poor." This approach is similar in some ways to that described by Deshon (1995) for comparing invertebrate community indices (ICIs) within river stretches of various watersheds. The results (Figure 11) suggest that the quality of the benthic communities in the lower Passaic River varies among sites, ranging from diverse to quite depauperate (ie., species-poor). This finding is typical of the heterogeneous nature of infaunal communities in estuaries, reflecting the patchy distribution of benthic species in this kind of ecosystem.

Fish and Shellfish Communities

Overharvesting, loss of habitat, and pollution have had a substantial impact on fish and shellfish populations in the lower Passaic River and surrounding environs (Iannuzzi et al., 2002). Tidal creeks and wetlands provide vital nursery and foraging habitat for these organisms, and it is likely that the historical losses of these habitats in the lower Passaic River have resulted in a fishery substantially reduced from preindustrial levels. Historical documentation of fish and shellfish communities in the Passaic River is limited from both a spatial and temporal standpoint and is largely qualitative in nature. The fish and crustacean community surveys we conducted in 1999 and 2000 were the most detailed and quantitative fisheries surveys conducted in the lower portion of the Passaic River to date.

Historical fish and shellfish harvests in the lower Passaic River included striped bass (*Morone saxatilis*), rainbow smelt (*Osmerus mordax*), American shad (*Alosa sapidissima*), sturgeon

(*Acipenser* species), perch (family Percidae), and a number of freshwater fish species, as well as American oysters (*Crassostrea virginiana*) and various clams, shrimp, and crabs (Iannuzzi et al., 2002). Steady declines in the fish and shellfish harvests occurred during the late 1800s due to a number of factors, including chronic sewage pollution, low dissolved oxygen (DO) levels, toxic levels of various petroleum hydrocarbon and metals contaminants, habitat destruction from shoreline modification and wetlands loss, and dredging activities (Steimle & Caracciolo-Ward, 1989). By the early 1900s, commercial harvests of fish and shellfish from the Passaic River had ceased (Iannuzzi et al., 2002). A February 1897 Passaic Valley Sewerage Commission (PVSC) report on sewage disposal revealed that fish life, except for a few hardy species, had disappeared from the Passaic River prior to the turn of the 20th century (PVSC, 1897).

Only anecdotal information exists on the Passaic River fishery during the mid-1900s. There was little interest in investigation—few fish were present, as habitat destruction and sewage and contaminant pollution had severely limited the river's ability to support most of the species that once inhabited it. In addition, there was little human access to the lower Passaic River and limited recreational use, since industry dominated the shoreline (Iannuzzi et al., 2002).

Some recovery of the fishery occurred in the early 1970s following the authorization and implementation of the Clean Water Act. Several species returned to the river in limited numbers, including anadromous fish such as American shad and river herring. With the onset of federal and state environmental regulations beginning in the 1970s, there was a new focus on improving the water quality of America's rivers, including the Passaic. As a result, scientists and regulators began to study the fishery of the river and provide the first quantitative documentation of its condition. Water-quality tests conducted as part of the New Jersey Bureau of Freshwater Fisheries study (NJBFF, 1981) indicated that levels of DO were critically low in much of the water column of the lower Passaic River. Dissolved oxygen is still limiting on a seasonal basis. Low DO remains a physical impediment to fish and crustacean communities in the river today, and it limits the ability of many fish to survive in affected portions of the water column, at least in the summer. It also impedes migrating fish attempting to reach spawning areas of the river and its tributaries.

A total of 22 fish species and blue crab were captured in the lower Passaic River during the 1999 and 2000 community surveys (Table 2). Sixteen fish species were captured in the fall 1999 survey and 12 species in the spring 2000 survey. Six species made up 98% of the total catch from the two surveys (Figure 12). The mummichog (*Fundulus heteroclitis*), a small forage fish that is very common in East Coast estuaries, composed more than 75% of the total catch. Other dominant species included inland silverside (*Menidia beryllina*), white perch (*Morone americana*), Atlantic menhaden (*Brevoortia tyrannus*), striped bass, and gizzard shad (*Dorosoma cepedianum*). The only resident species in this group are the mummichog and white perch. The remaining four species are migratory and typically occur in the lower Passaic River from late spring to early fall (which is why many were captured in both of the surveys).

Resident and migratory species of the lower Passaic River are listed in Table 3. Resident species are found throughout the year. Migrant species occur seasonally. Rare or exotic species are not common in the Passaic River, but they may enter its waters during periods of drought (when water salinity is higher) or during periods of significant rain events (when water salinity is lower). Several functional feeding groups are represented in the fish community, including detritivores (e.g., common carp), piscivores (e.g., striped bass, bluefish), and omnivores (e.g., mummichog, white perch).

Overall, the diversity and abundance of fishes in the lower Passaic River is low relative to species reported in other greater New York–New Jersey area estuaries (see Iannuzzi et al., 2002) and historical reports for the lower Passaic River itself. This is likely due to the continued combined effects of habitat limitations and poor water and sediment quality.

Bird Communities

Like fish and invertebrates, birds have been adversely affected by industrialization and urbanization and associated habitat losses and degradation in the lower Passaic River. Historically, the NY–NJ Harbor estuary has been a focal point for migration, important for both land birds and many kinds of waterbirds (Shriner, 1896; Leck, 1984; Iannuzzi et al., 2002). The highly urbanized nature of the present landscape has important consequences for the bird fauna. Ecological resources are depauperate in urban settings (Gill & Bonnett, 1973), and bird populations and communities in the NY–NJ Harbor estuary area reflect the general trend of decreasing bird diversity with increasing urbanization (Barrett, 1990).

The effect of urbanization on habitats is graphically illustrated in Figure 2. This aerial photograph shows the intensely developed landscape of the lower Passaic River. With the exception of scattered remnants of open space (all subject to more or less intense human disturbance), the entire area consists of buildings and impervious surfaces. The same is true throughout much of the Newark Bay region. The few remaining fragments of green space provide little habitat for diverse bird communities and essentially no habitat for aquatic bird species.

Dominant habitat types in the lower Passaic River are all urban in nature, and available intertidal foraging areas for birds are limited to the isolated intertidal flats. These flats represent the only truly functional habitat for aquatic birds in the lower Passaic River. Many of the flats border vertical upland, bulkhead, or riprap shoreline or are near bridges and roadways and therefore have reduced foraging value for some waterbird species (Kane, Kerlinger & Radis, 1991). The few flats that front patches of wetland have greater value as foraging habitat for aquatic birds, although they represent a relatively small area and are spatially isolated.

A quantitative answer to the larger question, how does urbanization affect bird community structure? would require comparative observations of bird use of the lower Passaic River and a similar but less urbanized river system. Such a quantitative survey has yet to be conducted, so a complete answer to the question is not possible at the present time. However, a qualitative, partial answer can be obtained by evaluating available information on birds in the region.

One approach to answering this question is to use breeding bird survey data published in Walsh, Elia, Kane, and Halliwell (1999). Survey blocks in the lower Passaic and Hackensack river systems can be compared based on the general availability of open land and wetland habitat. It would be expected that survey blocks with greater open and/or wetland areas would support a higher diversity of breeding birds. This does appear to be the case. Figure 13 shows the number of breeding bird species reported by survey block in the lower Passaic-Hackensack river area. All blocks with a substantial remaining component of wetland habitat (either Hackensack Meadowlands or Kearny Marsh, the latter within the Passaic River watershed but not connected at the surface) have a substantially greater diversity of breeding birds than the single block of lower Passaic River habitat without wetlands. It may be concluded that the relative lack of open space and/or wetlands does indeed constrain breeding bird diversity in the lower Passaic River.

A second approach is to compare the number of foraging bird species per unit area and the density of individuals between similar habitats on the Passaic River and in a less urbanized setting elsewhere. An analysis provided by Hoden (1997) makes this second approach possible. The report includes observations of bird diversity and density on a small intertidal mudflat located in Great Bay near the town of Tuckerton (in the estuary of the Mullica River). These observations can be compared on a qualitative basis with similar data recorded during the bird survey of the lower Passaic River. Figure 14 presents this comparison. It is clear that, on a unit area basis, the urbanized ecosystem of the lower Passaic River supports a waterbird fauna depauperate in both individuals and species relative to that of the Great Bay system.

During the four seasonal surveys of the lower Passaic River in 1999 and 2000, 49 species of birds were observed (Table 3). This is a small fraction of the 443 species that have been recorded statewide or the 340 species that occur annually throughout the state (Walsh, Elia, Kane & Halliwell, 1999). Indeed, it is a small fraction of the 313 species that have been reported in the NY–NJ Harbor estuary. Of the 49 species observed during the lower Passaic River surveys, 19 are strictly terrestrial (including a single observation of an escaped domestic budgerigar). The remaining 30 species are primarily associated with aquatic ecosystems.

Gulls are by far the most abundant birds in the lower Passaic River, followed by common species of duck and bridge-nesting swallows. Among birds feeding at relatively high levels in the aquatic food web, the double-crested cormorant, herons, and egrets are most abundant. Key fish-eating birds (herons and egrets) are present in the lower Passaic River in spring, summer, and autumn only, as expected for such migratory species. The kingfisher, while not observed in winter, is likely present year-round (Walsh, Elia, Kane & Halliwell, 1999).

Conclusion

The lower Passaic River is an intensely urbanized ecosystem with severe constraints on plant and animal life (Figure 15). The diversity and abundance of many groups of organisms is low. While this may not be unexpected in a river draining this landscape (Figure 2), it is not inevitable. The depauperate nature of the biological communities is not attributable to a single cause. Habitat losses, non-point- and point-source pollutants, and ongoing human disturbance are all factors. Restoring some measure of ecological health to the lower Passaic River ecosystem will require amelioration of each constraint—a difficult, but achievable, goal.

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Glossary

Benthic invertebrates: The community of organisms living on or in bottom sediments in freshwater and marine ecosystems.

Catch per unit effort (CPUE): A sampling method used to compare the relative abundance of fish between one area of habitat and another where the only common link is the method used to catch the fish. Catch per unit effort is typically expressed as the number of fish captured divided by the amount of time it took to catch the fish (e.g., fish per hour) or the number of fish captured per net set.

Combined sewer overflow: The discharge into waterways during rainstorms of untreated sewage and other pollutants via combined sewers carrying both sanitary sewage and storm-water runoff from streets, parking lots, and rooftops.

Detritivores: Animals that feed on detritus, or dead material, typically but not always of plant origin.

Ecotone: A narrow and fairly sharply defined transition zone between two or more ecological communities, e.g., land-water interfaces.

Infauna: Organisms that bore or burrow into bottom sediments.

Omnivores: Animals that feed on both plants and animals.

Grab sampler: A grabbing device often used for collecting quantitative samples of materials from underwater.

Piscivores: Animals that feed on fish.

Point-source and non-point-source pollutants: Point-source pollutants are those that originate from a concentrated point, such as a pipe from a factory. Non-point-source pollutants come from a more dispersed area-for example, in storm water running off roads.

Ruderal species: Species characteristic of lands that are highly disturbed but rich in water, nutrients, and other resources.

Synoptic: Presenting a summary of the principal parts or a general view of the whole.

Taxon: A taxonomic rank, such as family, genus, or species.

Tubificid: Any of a family (Tubificidae) of aquatic worms that lack a specialized head (such as *Tubifex* worms).

Figure 1.

Figure 1. Lower Passaic River, New Jersey

Figure 2.

Figure 2. Passaic River Landscape

Figure 3.

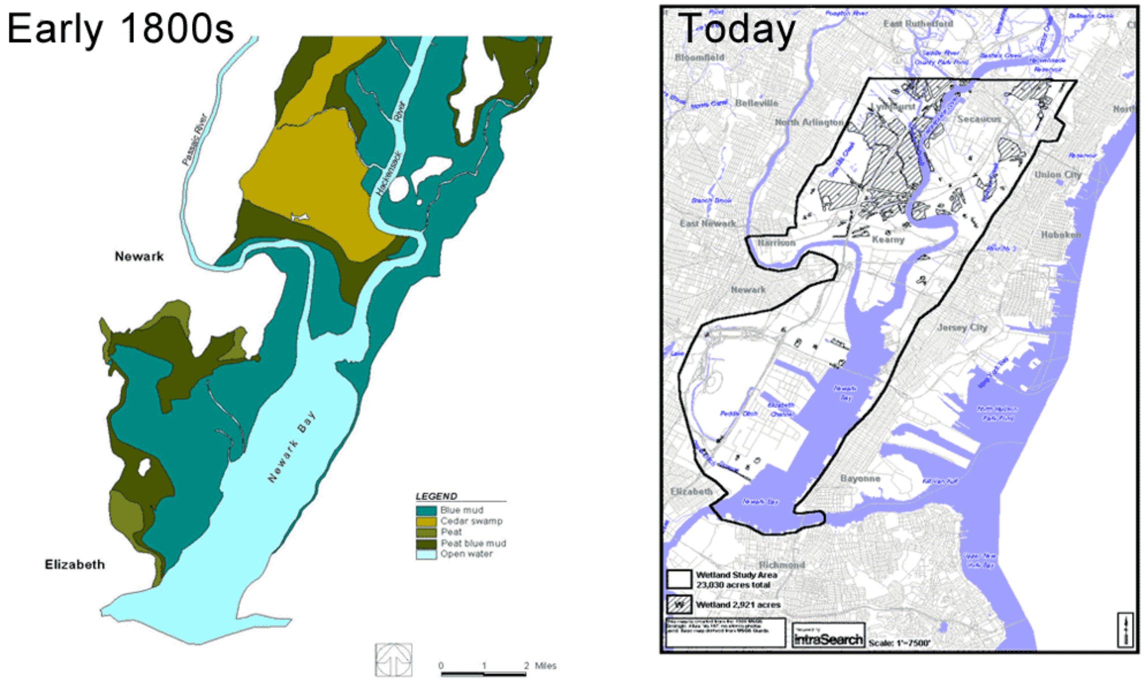


Figure 3. A Comparison of the Extent of Wetlands in Lower Passaic River Environs: Early 1800s and Today

Figure 4.

Figure 4. A Small Remnant Marsh Found at the Confluence of Lawyers Creek and the Passaic River

Figure 5.

Figure 5. Worthington Avenue Combined Sewer Overflow Area

Figure 6

Figure 6. Large Mudflat System Adjacent to Unnamed Creek

Figure 7. Benthic Invertebrate Community Assessment: Number of Individuals

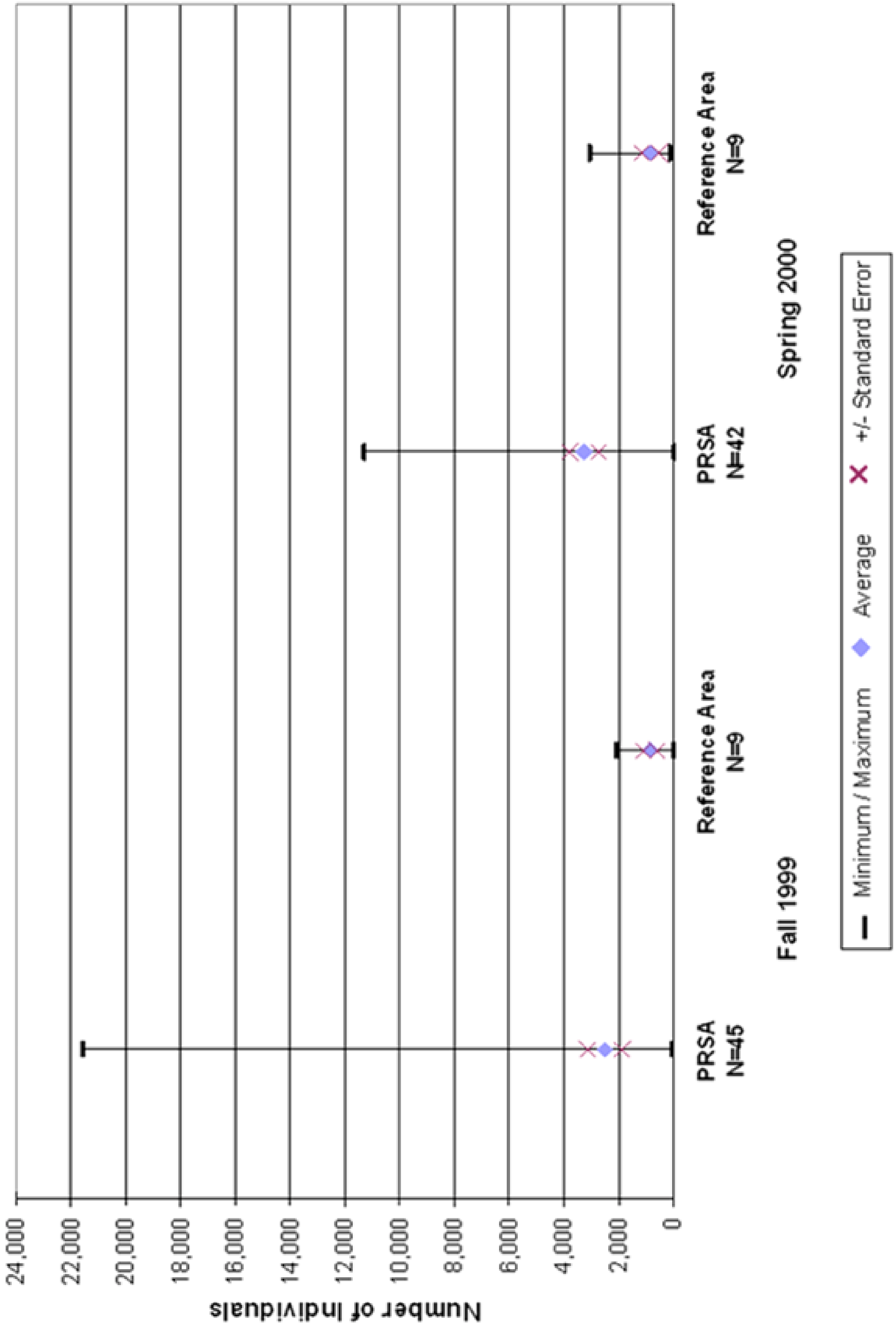


Figure 8. Benthic Invertebrate Community Assessment: Number of Taxa

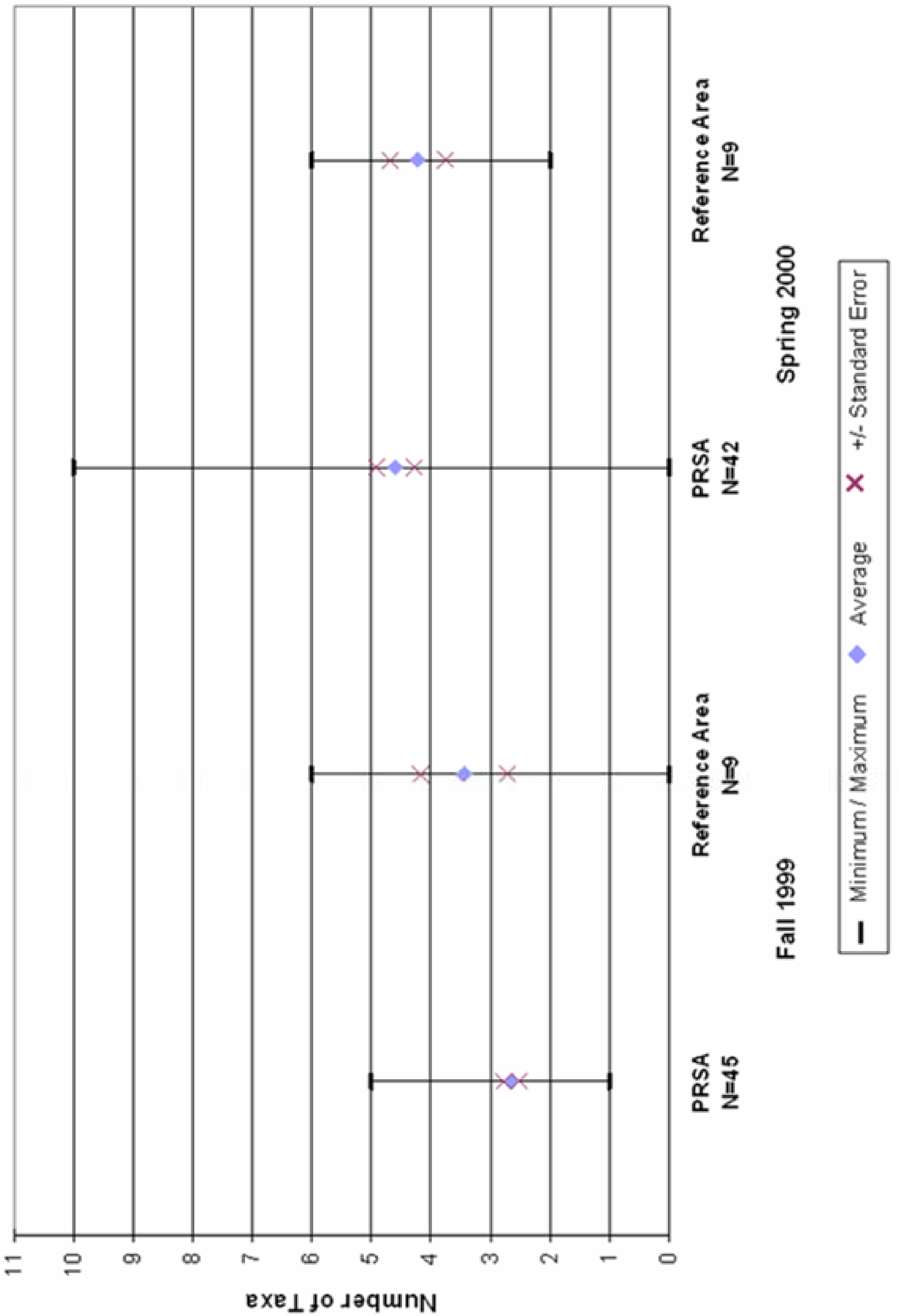


Figure 9. Pollution Tolerance of Benthic Invertebrates

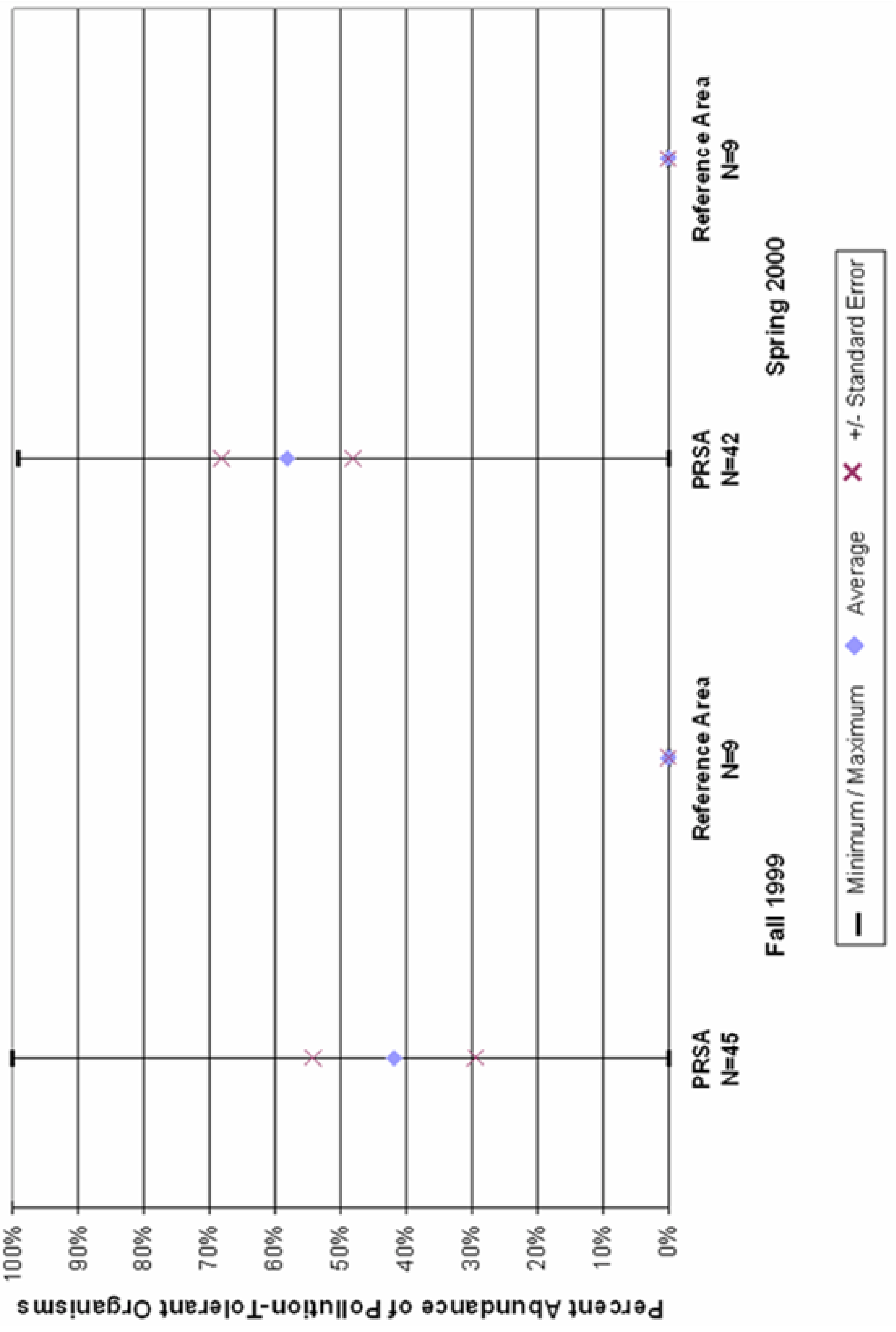


Figure 10. Benthic Invertebrate Community Assessment: Percent Abundance of Crustacea

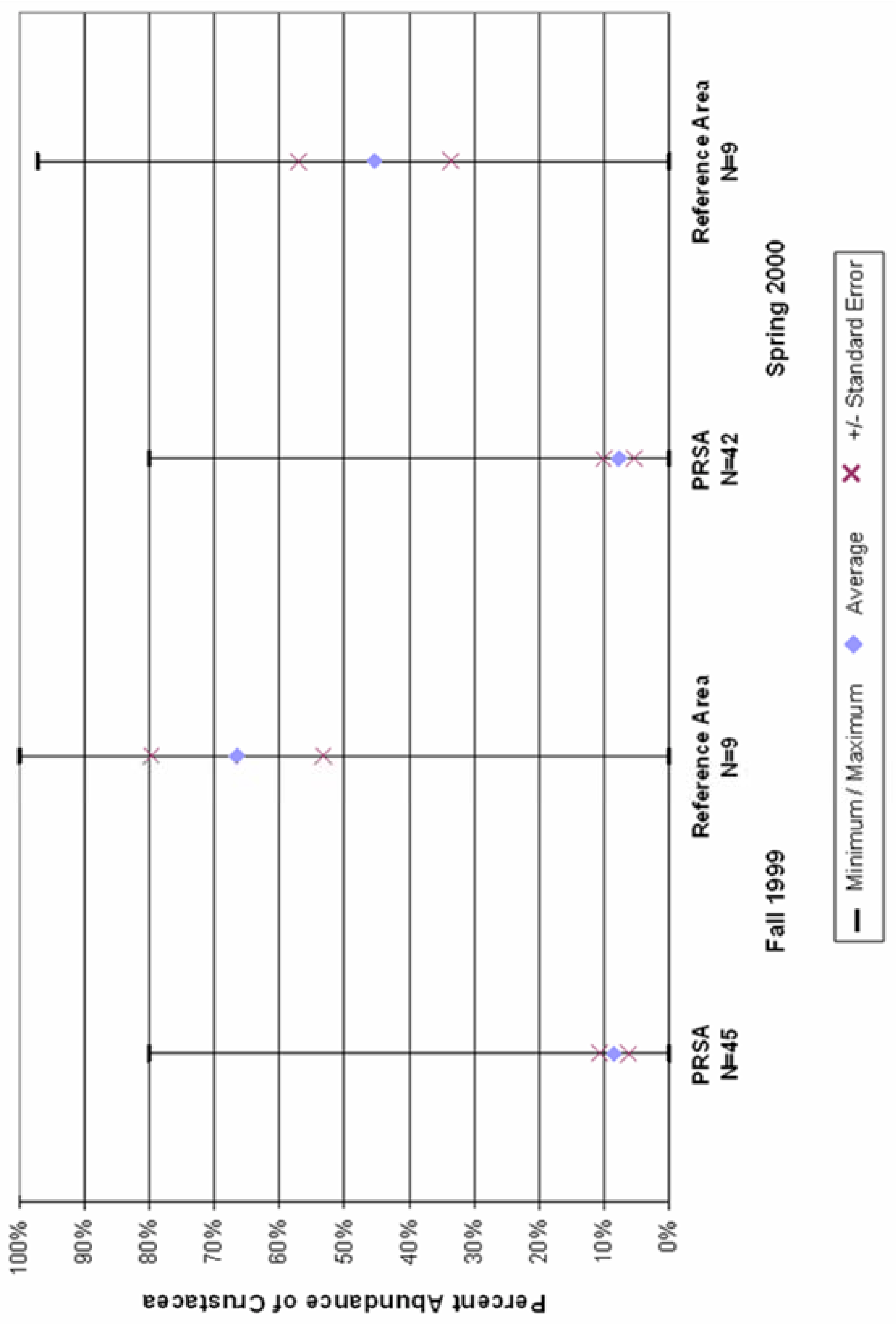


Figure 11. Benthic Invertebrate Community Condition

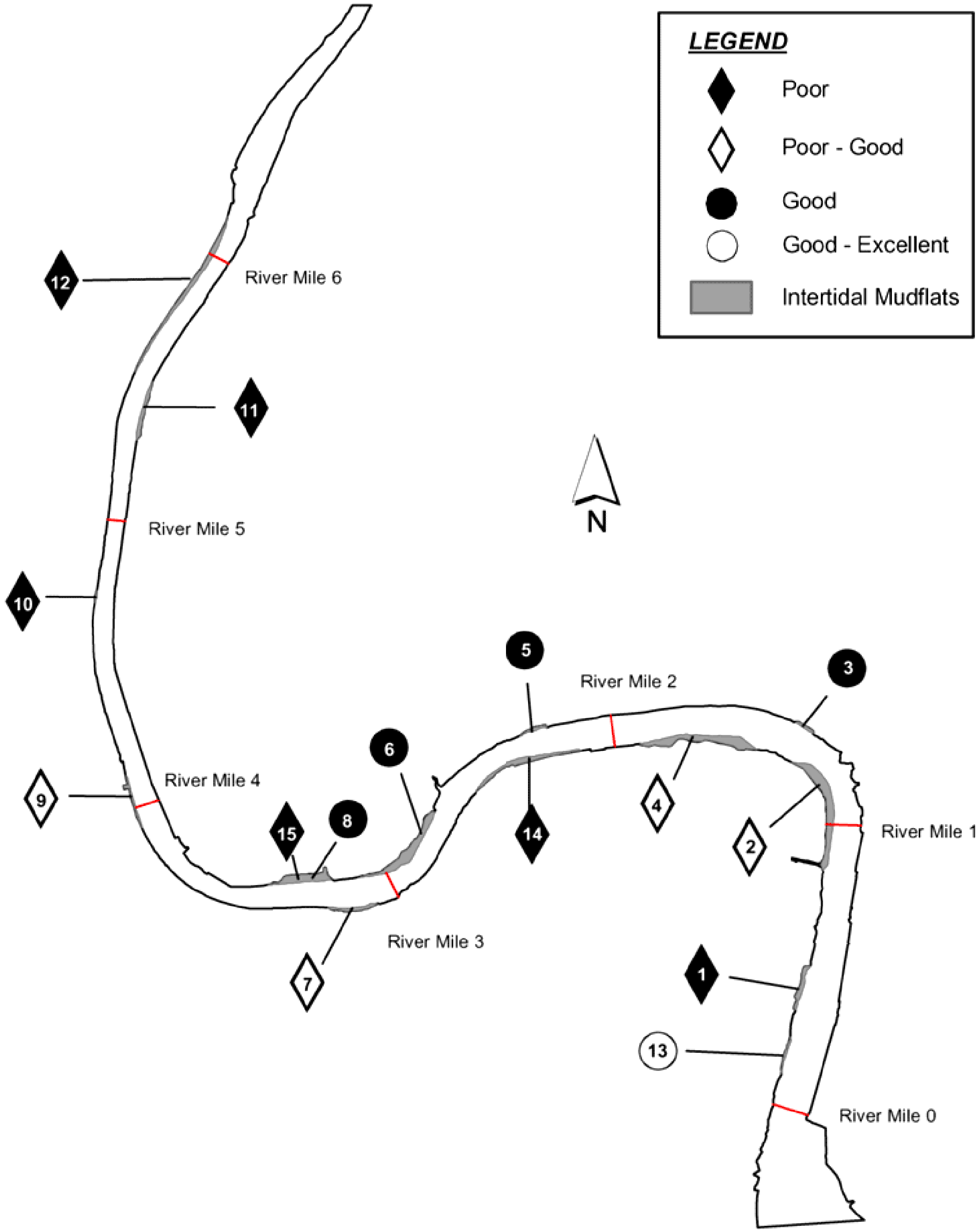


Figure 12. The Current Fishery of the Lower Passaic River

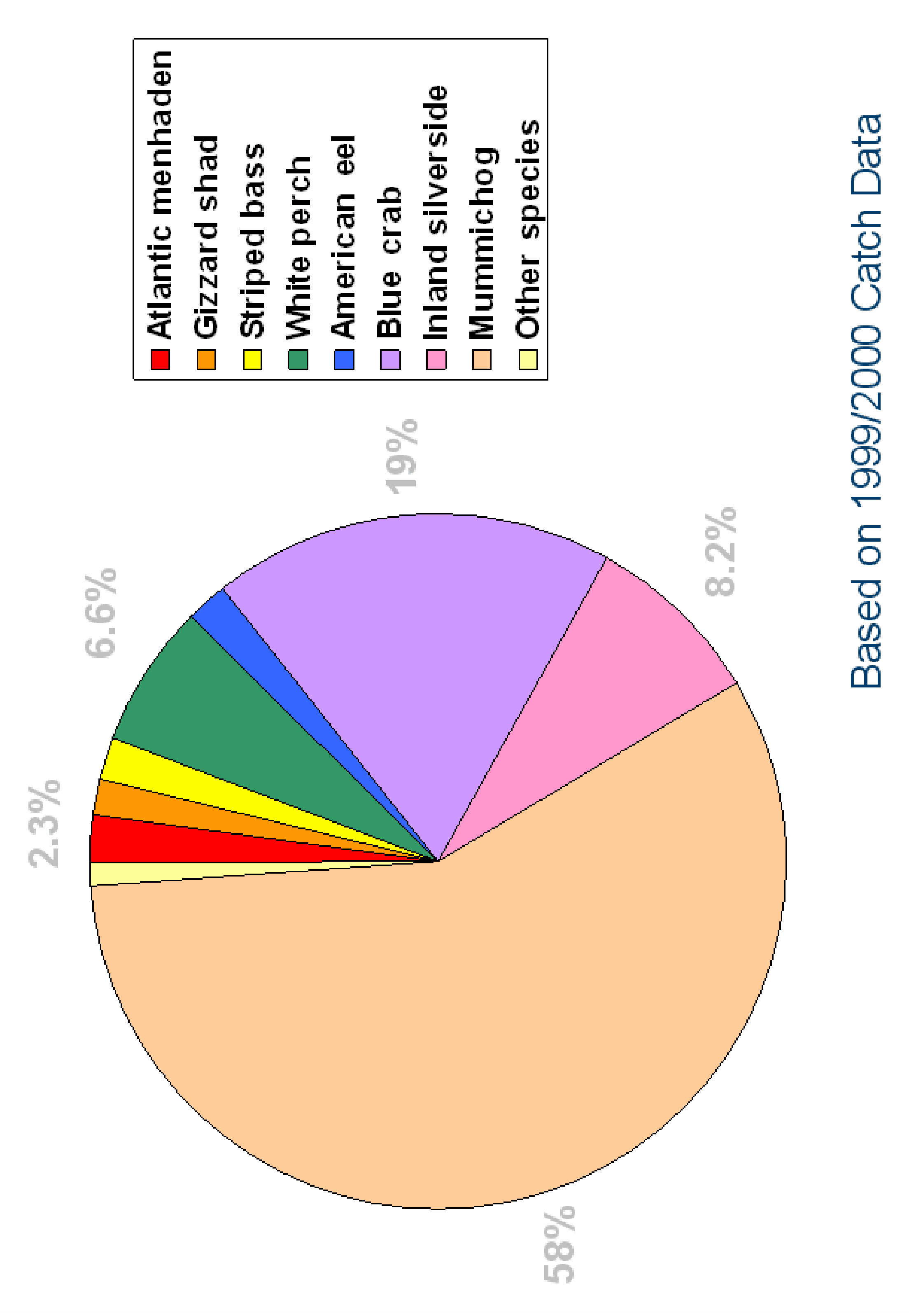
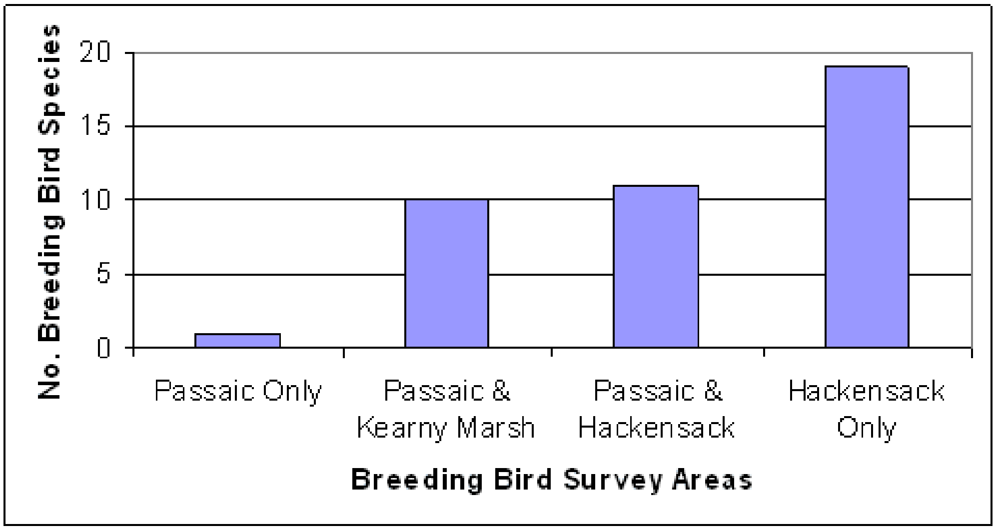


Figure 13. Relative Waterbird Use of Lower Passaic River



Area	**Breeding Bird Survey Block**	**# Breeding Species**
Passaic Only	Elizabeth North East	1
Passaic & Kearny Marsh	Orange South East	10
Passaic & Hackensack	Jersey City North West, Weehauken Central West	8-11
Hackensack Only	Weehauken South West	19

Figure 14. Waterbird Mudflat Use in Lower Passaic River and Great Bay

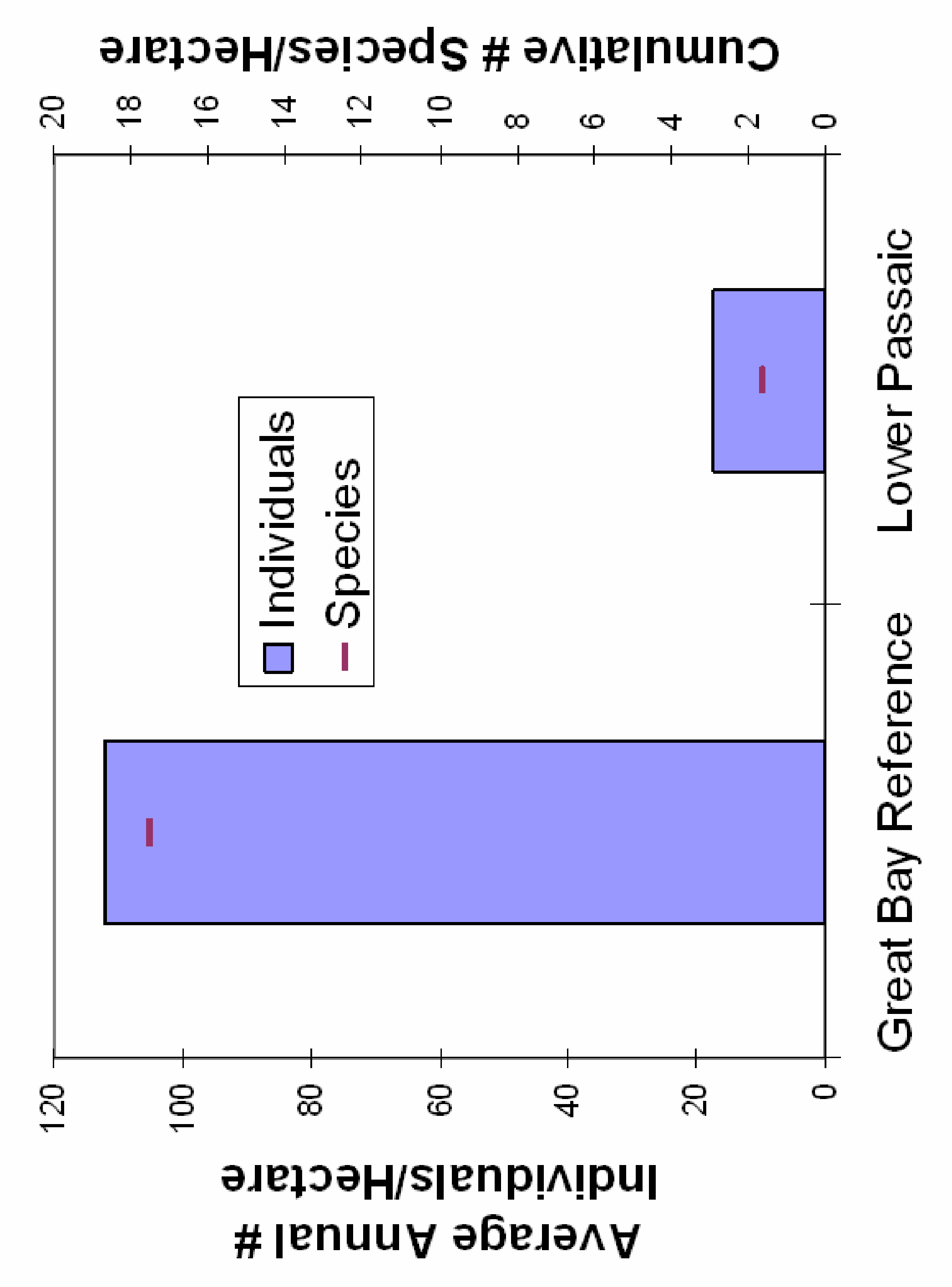


Figure 15. Urban Nature of Lower Passaic River

Table 1. Losses of Historical Rivers, Creeks, and Tributaries

River/Creek	**Estimated Length Lost (mi)**
First River and Tributaries	6
Unnamed Passaic Tributary Creeks	0.7
Kearny Marsh Tributaries	1.2
Great Meadow Brook and Tributaries	6.3
Upper Newark Bay Tributaries	10.9
Total Lost	**25.1**

Table 2 Summary of Fish Caught in the Lower Passaic River During the Fall 1999 and Spring 2000 Surveys

				Number of Fish Caught					
				Fall 1999		**Spring 2000**		**1999 / 2000 Combined**	
Common Name	**Scientific Name**	**Type of River User**	**Type of Feeder**	**N**	**% of Total**	**N**	**% of Total**	**N**	**% of Total**
American eel	*Anguilla rostrata*	M	P/I	0	0	20	3.5	20	0.46
Atlantic menhaden	*Brevoortia tyrannus*	M	D/O	67	1.8	12	2.1	79	1.8
Blueback herring	*Alosa aestivalis*	M	I	1	0.03	11	1.9	12	0.28
Bluefish	*Pomatomus saltatrix*	M	P	14	0.37	0	0	14	0.32
Bluegill	*Lepomis macrochirus*	R / FW	O	3	0.08	0	0	3	0.069
Brown bullhead	*Ameiurus nebulosus*	R / FW	P/I	0	0	2	0.35	2	0.046
Channel catfish	*Ictalurus punctatus*	R	D	1	0.027	0	0	1	0.023
Common carp	*Cyprinus carpio*	R / FW	D	0	0	7	1.2	7	0.16
Gizzard shad	*Dorosoma cepedianum*	M	D/O	6	0.16	50	8.8	56	1.3
Green sunfish	*Lepomis cyanellus*	R / FW	I	4	0.11	0	0	4	0.092
Inland silverside	*Menidia beryllina*	M	O	477	13	0	0	477	11
Largemouth bass	*Micropterus salmoides*	R / FW	P	1	0.027	0	0	1	0.023
Mummichog	*Fundulus heteroclitus*	R	O	3,021	80	316	55	3,337	77
Redear sunfish	*Lepomis microlophus*	R / FW	O	4	0.11	0	0	4	0.092
Spotted hake	*Urophycis regio*	M	P/I	0	0	1	0.18	1	0.023
Striped bass	*Morone saxatilis*	M	P/I	51	1.4	14	2.5	65	1.5
Striped killifish	*Fundulus majalis*	R	O	3	0.080	0	0	3	0.069
Summer flounder	*Paralichthys dentatus*	M	P/I	4	0.11	0	0	4	0.092
Weakfish	*Cynoscion regalis*	M	P	2	0.05	0	0	2	0.046
White catfish	*Ameiurus catus*	M / R	D	0	0	4	0.70	4	0.092
White perch	*Morone americana*	R	O	94	2.5	132	23	232	5.4
White sucker	*Catastomus commersoni*	R / FW	O	0	0	1	0.18	1	0.023
	Total Species Number			16	100%	12	100%	22	100%
	Total Species Count			3,753	100%	570	100%	4,329	100%

Key:

D = Detritivore
H = Herbivore
I = Insectivore
O = Omnivore

FW = Freshwater species
M = Migratory species
R = Resident species
P = Piscivore

Table 3. Summary of Birds Observed During the 1999–2000 Lower Passaic River Bird Surveys

Pelicaniformes
- Double-crested cormorant (*Phalacrocorax auritus*)

Wading Birds
- Egret, great (*Ardea alba*)
- Egret, snowy (*Egretta thula*)
- Heron, black-crowned night- (*Nycticorax nycticorax*)
- Heron, great blue (*Ardea herodias*)
- Heron, green (*Butorides virescens*)
- Heron, little blue (*Egretta caerulea*)

Swans, Geese and Ducks
- Canada goose (*Branta canadensis*)
- Common merganser (*Mergus merganser*)
- Duck, American black (*Anas rubripes*)
- Duck, wood (*Aix sponsa*)
- Mallard (*Anas platyrhynchos*)
- Mallard, domestic (*Anas platyrhynchos*)
- Scoter, black (*Melanitta nigra*)
- Scoter, white-winged (*Melanitta fusca*)

Diurnal Raptors
- Osprey (*Pandion haliaetus*)
- Peregrine falcon (*Falco peregrinus*)
- Red-tailed hawk (*Buteo jamaicensis*)

Shorebirds
- Killdeer (*Charadrius vociferus*)
- Sandpiper, least (*Calidris minutilla*)
- Sandpiper, spotted (*Actitis macularia*)
- Yellowlegs, greater (*Tringa melanoleuca*)
- Yellowlegs, lesser (*Tringa flavipes*)

Gulls
- Gull, great black-backed (*Larus marinus*)
- Gull, herring (*Larus argentatus*)
- Gull, laughing (*Larus atricilla*)
- Gull, ring-billed (*Larus delawarensis*)

Old World Parrots
- Budgerigar (*Melopsittacus undulatus*)

Pigeons and Doves
- Dove, mourning (*Zenaida macroura*)
- Dove, rock (common pigeon) (*Columba livia*)

Kingfishers
- Belted kingfisher (*Ceryle alcyon*)

Tyrant Flycatchers
- Eastern kingbird (*Tyrannus tyrannus*)

Jays and Crows
- Jay, blue (*Cyanocitta cristata*)
- Crow, American (*Corvus brachyrhynchos*)
- Crow, fish (*Corvus ossifragus*)

Swallows
- Swallow, barn (*Hirundo rustica*)
- Swallow, northern rough-winged (*Stelgidopteryx serripennis*)

Mimids
- Gray catbird (*Dumetella carolinensis*)
- Northern mockingbird (*Mimus polyglottos*)

Starlings
- European starling (*Sturnus vulgaris*)

Cardinals
- Northern cardinal (*Cardinalis cardinalis*)

Emberizine Sparrows and Allies
- Sparrow, American tree (*Spizella arborea*)
- Sparrow, song (*Melospiza melodia*)
- Sparrow, white-throated (*Zonotrichia albicollis*)

Icterids
- Grackle, common (*Quiscalus quiscula*)
- Red-winged blackbird (*Angelaius phoeniceus*)

Finches and Old World Sparrows
- Goldfinch, American (*Carduelis tristis*)
- House finch (*Carpodacus mexicanus*)
- Sparrow, house (*Passer montanus*)

Total Number of Species Observed = 49

Table 4. Present Shoreline Characterization—Lower Six Miles of Passaic River

Shoreline Habitat Type	Linear Feet	Percent of Total
Bulkhead	35,290	52
Riprap	20,330	30
Mixed vegetation	8,307	12
Aquatic vegetation	3,843	6
Total shoreline (feet)	67,700	

Floristic Investigations of Historical Parks in St. Petersburg, Russia*

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Abstract

From 1989 to 1998, our team of researchers conducted comprehensive floristic and phytocoenological investigations in 18 historical parks in St. Petersburg, Russia. We used sample quadrats to look at plant communities; we also studied native species, nonnative species, “garden escapees,” and exotic nonnaturalized woody species in numerous types of park habitat. Rare and endangered plants were mapped and photographed, and we analyzed components of the flora according to their ecological peculiarities, reaction to human influences (anthropotolerance), and origin. The entire park flora consisted of 646 species of vascular plants belonging to 307 genera and 98 families. Our analysis of species distribution in the parks showed a clear tendency toward a decrease in the number of species from the suburbs to the city center. The flora of gardens in the center of St. Petersburg was comprised mainly of weedy, meadow, and forest-meadow species and plants of open disturbed habitats. Rare herbaceous species were registered in almost all historical parks. Our study found large percentages of wetland and aquatic plants in most suburban parks, indicating that disturbances or management practices have impeded the parks’ drainage systems. Our floristic investigations led us to identify ten plant indicator groups. These groups can be used for future analysis and monitoring of environmental conditions in the parks. This paper also includes analyses of plant communities in 3 of the 18 parks. Such analyses are useful for determining the success of past restoration projects in parks and other habitats and for planning and implementing future projects.

Key words: floristic and phytoencological investigations, St. Petersburg, Russia, park, flora, anthropogenic, anthropotolerance, urbanophyle

Introduction

The historical gardens and parks of St. Petersburg, Russia, are valued as monuments of landscape architecture and components of the city’s urban ecosystems. They date back to the early 18th century, when Peter the Great (1672–1725) oversaw the construction of the city (his “Venice of the North”) on the marshy delta of the Neva River. After World War II, intensive restoration and reconstruction was begun in almost all of St. Petersburg’s historical parks. This effort has continued to this day and has employed advanced scientific methods (Ilinskaya, 1993).

The original restoration and reconstruction projects were based on detailed analyses of historic documents and on field research of plant communities (mostly inventories of canopy layers and soil maps). However, during the implementation of the projects, some mistakes were made due to misunderstandings about the ecological peculiarities of the park ecosystems. For example, light-demanding grasses were planted under the dense canopy of large deciduous trees in the Summer Garden and Tavrichesky Garden, and after only one season they began to die. In addition, heavy machinery used during construction work in many of St. Petersburg's historical parks compacted the soil and destroyed tree root systems. Consequently, there was degradation of woody plants and groundcover, including mass mortality in Tavrichesky Garden (Ignatieva, Reiman & Vorontsova, 1996) and Alexandrino Park (Subota, 1998); an intensive transition to swamp vegetation in the Nizhny (lower) Park (Rubtsova, 1996) and Alexandria Park (Ivanova & Ivanova, 1992) in Peterhof; and dying conifer species in Pavlovsky Park (Bodjurova & Karpeeva, 1995).

Because of these mistakes, and because of unfavorable environmental factors associated with modern cities in general (air and water pollution, permanent anthropogenic pressure, and harsh hydrological and climatic regimes), more restoration and reconstruction will be needed in St. Petersburg's parks. Detailed preliminary investigations of the ecology of the parks are required to avoid the mistakes of past projects—and to avoid the destruction of valuable plant communities during the design and implementation phases of future projects.

From 1989 to 1998, we and other researchers (students completing their master's thesis work under our supervision) at the St. Petersburg State Forest Technical Academy and the V.L. Komarov Botanical Institute conducted comprehensive floristic and phytocoenological investigations of the city's historic gardens (Ignatieva, 1994a, 1999; Konechnaya & Ignatieva, 1996; Rubtsova, 1996; Bodjurova & Karpeeva, 1995; Kotlyar, 1995; Volkova & Dorochova, 1994; Skosireva, 1993; Mal'kova, 1993; Starkova, 1992; Ivanova & Ivanova, 1992; Gorlanova, 1991). Eighteen of the most famous historic parks were investigated—a total research area of 2,378 hectares (5,876 acres). These were Letny Sad (the Summer Garden); Tavrichesky Garden; Mikhailovsky Garden; Shuvalovsky Park; the Verkhny (upper) and Nizhny (lower) parks in Peterhof; Alexandria Park in Peterhof; the Verkny (upper) and Nizhny (lower) parks of Oranienbaum, Ekaterininsky, and Alexandrovsky parks in Tsarskoye Selo; Pavlovsky Park; Konstantinovsky Park in Strelna; and Dvortsovy, Sylvia, Zverinets, and Prioratsky parks in Gatchina. Two other parks (those of the St. Petersburg State Forest Technical Academy and the V.L. Komarov Botanical Institute) were also included in this research because of their landscape-architectural heritage and unique botanical collections (Figures 1 and 2).

This paper compiles and analyzes the findings of these investigations. It also presents case studies examining plant communities in three of St. Petersburg's historical parks: the Summer Garden, Alexandria Park, and the White Birch region of Pavlovsky Park.

Methods

In our study of the parks, we looked at the following types of habitats: lawns, hedges, woodlands (in landscape parks), bosquets and parterres (in formal parks), flower beds, aquatic habitats (canals, ponds, and lakes), roads, and cracks in hard surfaces. Standardized quadrats were used in all the studies to sample plant communities. For surveying the canopy layer of woody vegetation, we marked off 50-by-50-meter[*] quadrats and recorded the trees' composition, height, diameter, and degree of sheltering. For surveying woodland groundcover layers, we used 1-by-1-meter quadrats and recorded the general density of groundcover, along with the identity, density, height, and phenological phase of each species. For investigating meadows and lawns, we also used 1-by-1-meter quadrats.

During our investigations, voucher herbarium specimens were collected. We also mapped and photographed native and introduced ephemerals and herbs (some of them rare or endangered). Though historically less valued than the trees and shrubs in St. Petersburg's parks, these plants have both botanical and historical significance and are also very important components of park ecosystems.

A compiled floristic list of plants, and an analysis of this list, is shown in Table 1. The scientific names of species and families are presented according to the latest nomenclatural checklist of vascular plants of Russia and adjacent countries (Czerepanov, 1995).

Categories and Abbreviations

We organized the higher vascular plants that occurred in the parks into the following four groups according to origin (see "ORIG" column of Table 1):

1. Native species (**N**).
2. Adventive (nonnative) species that spontaneously appeared in, or were unintentionally introduced into, parks (**A**).
3. "Garden escapees" or deliberately introduced species (**G**) that were planted in flower beds, lawns, and plant collections and that had naturalized in new urban habitats. These plants have different stages of naturalization.
4. Exotic, nonnaturalized woody species (**E**).

We analyzed the flora according to the following parameters:

1. Ecological group (see "ECO" column of Table 1): **1**-forest, **2**-forest-meadow (edge), **3**-weedy-forest, **4**-meadow, **5**-weedy, **6**-open and disturbed, and **7**-aquatic.
2. Anthropotolerance (see "ANTHRO" column of Table 1):
   a. Urbanophil plants (**UPHIL**)—species that prefer human-disturbed or human-altered habitats.
   b. Urbanoneutral plants (**UN**) —species that can grow in undisturbed natural habitats as well as in human-disturbed habitats,
   c. Urbanophob plants (**UPHO**) —species that avoid human-altered urban habitats.
3. Origin of introduced plants, **A**, **G**, or **E** (see the "ORIG" column of Table 1): **Am**-North America; **Sib**-Siberia; **Eu**-Europe; **FE**-Far East; **ES**-Eurasia; **SF**-Siberia and Far East; and **FEA**-Far East and North America.

Results

Floristic Investigation

The flora in the 18 parks consisted of 646 species of vascular plants belonging to 307 genera and 98 families. This comprised 576 species of wild-growing

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[*] Except where noted, measurements throughout this paper are in metric notation; conversions to U.S. equivalents can be obtained at http://www.onlineconversion.com/length.htm.

plants (515 native, 25 nonnative, and 36 "garden escapees") and 70 species of nonnaturalized exotic woody plants. The genus richest in species was *Carex* (33 species). Among the exotic woody plants, North American species were the most represented (20 species), and these included *Thuja occidentalis*, *Picea pungens*, *Pinus strobus*, *Populus balsamifera*, *Quercus rubra*, and *Ribes aureum*. We found 19 European woody species (including *Larix decidua*, *Salix alba*, *Salix fragilis*, and *Philadelphus coronarius*) and 10 Siberian and Far Eastern species (including *Larix sibirica*, *Pinus sibirica*, *Caragana arborescens*, *Berberis thunbergii*, *Cotoneaster lucidus*, and *Acer ginnala*).

The number of species declined in parks from the outskirts to the center of St. Petersburg. The most species-rich parks were suburban historic parks such as Oranienbaum (400 species); Pavlovsky Park (398); Zverinets, in Gatchina (369); Nizhny (lower) Park, in Peterhof (362); Alexandrovsky Park, in Tsarskoye Selo (361); Shuvalovsky Park (341); and Konstantinovsky Park, in Strelna (340). We recorded the lowest number of species in parks at the city center: the Summer Garden (163), Tavrichesky Garden (149), and Mikhailovsky Garden (147). The flora of gardens in the center of St. Petersburg was comprised mainly of urbanophil and urbanoneutral species belonging to the weedy and meadow ecological groups.

The parks of the V.L. Komarov Botanical Institute and the St. Petersburg State Forest Technical Academy were extremely interesting from a botanical standpoint as likely sources of naturalization and dispersal for garden escapees and nonnative species. They contained the highest number of such species (35 and 16, respectively). Among the most widespread of nonnative plants were *Galinsoga ciliata*, *Tripleurospermun perforatum* (*Matricaria perforata*), *Juncus tenuis*, *Gagea granulosa*, and *Alliaria petiolata*. Detailed floristic analyses of both parks can be found in Ignatieva (1994a) and Konechnaya & Ignatieva (1996).

We recorded rare herbaceous species in almost all the suburban historical parks. *Poa chaixii* was recorded in Gatchina, Pavlovsk, Peterhof, and Oranienbaum parks. *Luzula luzuloides* was found in almost all parks except the central ones (Summer, Tavrichesky, and Mikhailovsky gardens), Shuvalovsky Park, and the park of the botanical institute. The combination of *Poa chaixii*, *Luzula luzuloides*, and *Poa nemoralis* could be used as an excellent groundcover model or "plant signature" (Robinson, 1993) for shady woodlands. Plant signatures could help solve the problem of creating a decorative, sustainable, shade-tolerant groundcover in old St. Petersburg parks and gardens.

German and Scandinavian botanists believe that *Poa chaixii* and *Luzula luzuloides* appeared in European parks via lawn-seed mixtures during the late 18th and early 19th centuries—a period of busy development for landscape parks in Europe (Nordhagen, 1954; Nath, 1990). Landscape parks were characterized by vast open and shaded lawns. For the shaded lawns in Germany, for example, mixtures of *Poa nemoralis* and *Festuca rubra* were widely used. But these mixtures were also contaminated with *Poa chaixii* and *Luzula luzuloides*. After several years of coexistence, all these plants formed an excellent mixture for shady park locations. European botanists are also sure that grasses such as *Trisetum flavescens* and *Arrenatherum elatius* (also found in almost all historical parks of St. Petersburg) appeared in parks accidentally through lawn mixtures. There is a theory that all these plants were brought from central and southern Europe (Nordhagen, 1954; Nath, 1990).

Some rare herbaceous species were found only in particular parks. For example, *Colchicum autumnale*, *Phyteuma orbiculare*, *Valeriana dioica*, and *Carex paniculata* were found only in Zverinets (Gatchina); *Phyteuma nigrum* was found only in Oranienbaum; and *Phyteuma spicatum* was found only in Zverinets and Oranienbaum parks. Saint Petersburg botanist A. Haare (1978) has speculated that some of the rare park species such as *Primula elatior*, *Phyteuma spicatum*, *Phyteuma orbiculare*, and *Colchicum autumnale* are natural relict species of aboriginal meadows that somehow survived within the parks.

We created distribution maps for rare herbaceous species (and spring ephemerals) found in St. Petersburg's historical parks. Figure 3 shows the distribution of rare and spring species in Alexandria Park. We recommend the use of such maps for the protection of rare species during restoration.

In all suburban historical parks, the spring flora was represented by a wide spectrum of early-spring (vernal) native species such as *Ficaria verna*, *Gagea lutea*, *Gagea minima*, *Anemonoides nemorosa*, *Anemonoides ranunculoides*, and *Corydalis solida*. In the gardens at the center of St. Petersburg, profuse blooming of *Gagea lutea*, *Gagea minima*, and *Facaria verna* (greater than 70% groundcover) was observed only in the plant communities of the Summer Garden (Ignatieva, 1999). *Hepatica nobilis* was found only in Gatchina and in Pavlovsky Park, and *Viola odorata* and *Primula elatior* was found only in Dvortsovy Park and Zverinets in Gatchina. We strongly recommend protecting vernal species as high-quality groundcovers.

Our ecological and phytocoenological analyses (Ivanova & Ivanova, 1992; Rubtsova, 1996; Skosireva, 1993) of park floras showed large percentages of wetland and aquatic plants in most of St. Petersburg's suburban parks (Shuvalovsky park in St. Petersburg, and Alexandria and Nizhny parks in Peterhof, for example). The presence of these plants indicates that disturbances, such as the use of heavy machinery during construction work or poor management practices, have disrupted the parks' drainage systems. In the city-center parks, species such as *Plantago major*, *Trifolium repens*, and *Poa annua* were dominant, reflecting the influence of disturbances of a different kind, such as trampling, mowing, fertilizing, and construction.

As a result of our floristic investigations, we identified ten indicator plant groups. These groups can be used in future analysis and monitoring of environmental conditions in the historical parks. They reflect the ecological origin of the plants in the parks, the immigration history of the plants, and the management history of the parks.

1. Nemoral plants characterizing groundcover in natural broadleaf forests: *Convallaria majalis*, *Fragaria moschata*, *Anemonoides nemorosa*, *Anemonoides ranunculoides*, *Corydalis solida*, *Gagea lutea*, and *Gagea minima*.
2. Boreal (northern) plants characterizing typical taiga forests: *Trientalis europea*.
3. A meadow group characterizing natural meadows: *Agrostis tenuis*, *Anthoxanthum odoratum*, *Alopecurus pratensis*, *Alchemilla monticola*, *Achillea millefolium*, *Campanula patula*, and *Vicia cracca*.
4. Nonnative plants that arrived with lawn grass seed mixtures: *Trisetum flavescens*, *Arrhenatherum elatius*, *Luzula luzuloides*, *Poa chaixii*, *Phyteuma nigrum*, *Phyteuma spicatum*, and *Pimpinella major*.
5. Garden escapees: *Scilla siberica* and *Gagea granulosa*.
6. A group characterizing anthropogenic disturbance: *Plantago major*, *Trifolium repens*, *Poa annua*, *Potentilla anserina*, and *Ranunculus repens*.
7. A group characterizing fertile and well-drained soils: *Aegopodium podagraria*, *Anthriscus sylvestris*, and *Dactylis glomerata*.

8. A group characterizing wet and poorly drained soils in woodlands, edges, and lawns: *Filipendula ulmaria*, *Lysimachia vulgaris*, *Calamagrostis phragmitoides*, *Carex vesicaria*, *Carex nigra*, *Juncus conglomeratus*, *Viola palustris*, and *Deschampsia caespitosa*.
9. A weedy group: *Capsella bursa-pastoris*, *Chenopodium album*, *Artemisia vulgaris*, and *Arctium tomentosum*.
10. A group of aquatic plants: *Glyceria maxima*, *Carex acuta*, *Potamogeton natans*, and *Alisma plantago-aquatica*.

Vegetation Investigation

Before St. Petersburg was built, the natural landscape consisted of bogs, thickets of alder (*Alnus incana*) and willow (for example, *Salix phylicifolia* and *Salix caprea*), and wet conifer-deciduous forests dominated by *Picea abies*, *Pinus sylvestris*, *Betula pendula*, *Betula pubescens*, *Populus trem*ula, and *Alnus glutinosa*. Peter the Great initiated an experiment to change the natural landscapes and make them into traditional European formal parks dominated by deciduous trees such as oak (*Quercus*), linden (*Tilia*), and maple (*Acer*). Only parts of some later-constructed (19th-century) landscape parks were based on native vegetation. These included parts of Pavlovsky Park (White Birch, Old and New Sylvia, Great Star, and Red Ponds sections), Sylvia and Zverinets parks in Gatchina, Shuvalovsky Park, Verkny (upper) Park in Oranienbaum, and Konstantinovsky Park in Strelna.

We found that the present-day plant communities for 10 of the 18 historical parks sampled were dominated by European park species (*Acer platanoides*, *Tilia cordata*, *Quercus robur*, *Ulmus laevis*, *Ulmus glabra*, and *Fraxinus excelsior*, for example). Plant associations for the 10 parks were identified as follows.

Alexandria Park in Peterhof (see case study below)

Alexandrovsky Park in Tsarskoye Selo:

1. *Ulmus laevis—Filipendula ulmaria—Aegopodium podagraria*
2. *Acer platanoides—Dactylis glomerata—Aegopodium podagraria*
3. *Quercus robur—Tilia cordata—Aegopodium podagraria—Dactylis glomerata*
4.

Dvortsovy Park in Gatchina:

Quercus robur—Tilia cordata—Acer platanoides—Aegopodium podagraria—Dactylis glomerata—Filipendula ulmaria—Cirsium heterophyllum

Ekaterininsky Park in Tsarskoye Selo:

Acer platanoides—Tilia cordata—Quercus robur—Aegopodium podagraria—Dactylis glomerata

Konstantinovsky Park in Strelna:

1. *Ulmus laevis—Filipendula ulmaria*
2. *Acer platanoides—Aegopodium podagraria*
3.

Letny Sad/Summer Garden (see case study below)

Mikhailovsky Garden:

Tilia cordata—Acer platanoides—Ulmus glabra—Poa annua—Plantago major—Taraxacum officinale

Nizhny (lower) Park in Peterhof:

1. *Acer platanoides—Deschampsia caespitosa*
2. *Tilia cordata—Acer platanoides—Aegopodium podagraria*
3. *Betula pubescens—Anthriscus sylvestris—Aegopodium podagraria*

4. *Quercus robur—Ranunculus cassubicus—Filipendula ulmaria*
5. *Tilia cordata—Alnus glutinosa—Equisetum pratensis*
6.

Tavrichesky Garden:

Ulmus glabra—Quercus robur—Tilia cordata—Acer platanoides—Poa annua—Plantago major—Polygonum aveculare— Stellaria media

Verkhny (upper) Park in Oranienbaum:

1. *Tilia cordata—Luzula luzuloides*
2. *Tilia cordata— Stellaria nemorum—Dactylis glomerata*
3. *Tilia cordata—Calamagrostis sylvaica—Filipendula ulmaria*
4. *Quercus robur—Tilia cordata—Calamagrostis arundinacea—Phyteuma nigra—Phyteuma spicatum—Luzula luzuloides—Trisetum flavescens*

We found that all meadow plant communities in the historical parks were artificially maintained. Without regular planned management, these meadow communities would be replaced by woody pioneer plant species such as *Alnus incana*, *Betula pendula*, *Salix phylicifolia*, *Salix caprea*, and *Salix myrsinifolia*.

We found that ephemeral plants such as *Gagea lutea*, *Gagea minima*, and *Ficaria verna*, along with *Aegopodium podagraria* and a group of weedy and meadow-forest species (*Taraxacum officinale*, *Poa annua*, and *Plantago major*), dominated the groundcover of the Summer Garden (Gorlanova, 1991; Ignatieva, 1994b). The mesophytic meadow grasses traditionally planted in this park, such as *Poa pratensis*, *Festuca pratensis*, and *Lolium perenne*, have never managed to persist due to the shady conditions there. The success of the ephemerals and *Aegopodium podagraria* indicates a process of stabilization of the park's ecosystem, which is very important for extending the life of the old trees and should be nurtured. Aesthetic problems with *Aegopodium podagraria* can be addressed using special trimming techniques prior to establishment to increase the plant's decorative qualities.

In some parks (for example, Nizhny Park and Alexandria Park in Peterhof and Dvortsovy Park in Gatchina), we found that plant communities are dominated by oak (*Quercus*) and other broadleaf trees in the tree layer and *Filipendula ulmaria* on the ground. This combination is typical of artificially created park communities in wet St. Petersburg conditions and has no analog in the native vegetation. The abundance of *Filipendula ulmaria* in many suburban parks indicates surplus humidity and dysfunction of the drainage system. Oak and other broadleaf trees need well-drained conditions. In time, native trees tolerant of this particular hydrological regime, such as alders and willows, will most likely replace the broadleaf trees.

Case Studies

Letny Sad: The Summer Garden (11.2 hectares; 27.6 acres)

History: In 1704, Peter the Great invited a group of talented architects and gardeners (D. Tresini, A. Schluter, I. Matveev, J.B. Leblon, I. Zhemtsov, and J. Roosen) to create a summer residence for him in the new Russian capital. Over the next 50 years, the palace, fountain system (about 50 fountains), water organ, carp pond, and amphitheatre (designed by the architect B. Rastrelli) were constructed; the formal garden was planned and planted; and 222 sculptures from Venice and Rome were installed. In 1777, a catastrophic flood destroyed many of the garden's trees, sculptures, and fountains. Since that time, the Summer Garden has been transformed into a public garden.

The Planting Design: Originally the landscape of the Summer Garden was most likely covered by spruce-birch plant communities (*Picea abies—Betula pendula—Betula pubescens*) on wet soils typical of the Neva River delta. The area for the garden was drained, and fertile soils were added. Initially, thousands of lime trees (*Tilia cordata*) and oaks (*Quercus robur*) from Holland and the Novgorod and Pskov regions of Russia were planted. More lime trees and oaks and other broadleaf trees such as ashes (*Fraxinus*), elms (*Ulmus*), and maples (*Acer*) were planted to replace specimens killed during catastrophic floods in 1777, 1824, and 1924, and after World War II.

Current Plant Communities: In a 1989 inventory, the garden was found to contain 2,003 trees and 7,278 shrubs (*Inventory of Summer Garden, 1989*). The majority of trees were 50 to 100 years old. There were quite a few 150- to 200-year-old trees and 50 trees more than 200 years old. Lime trees dominated in all the plantings (more than 50% of all trees). The second most abundant were maple (*Acer platanoides*), followed by elm (*Ulmus laevis* and *Ulmus glabra*), oak (*Quercus robur*), and ash (*Fraxinus excelsior*). According to our floristic investigations (Gorlanova, 1991), the main type of plant community identified was *Tilia cordata—Gagea minima—Gagea lutea—Ficaria verna—Aegopodium pogagraria*. In some bosquets, we found small groupings of *Taraxacum officinale*, *Ranunculus repens*, and *Glechoma hederacea*—typical anthropogenic plants, with wide ecological ranges. Observations of the Summer Garden plant communities by Konechnaya and Ignatieva in June 2001 indicated that *Aegopodium podograria* was spreading successfully too. For example, many bosquets planted with typical lawn grasses (*Poa pratensis*, for example) in the 1990s were almost completely dominated by *Aegopodium*.

Gagea and *Aegopodium* species probably arrived in the garden as seeds in the root balls of trees that were brought from Novgorod and Pskov. These typical nemoral species found ideal conditions under the canopy of the garden's broadleaf trees. Taking into account the natural reproductive capabilities and highly competitive character of *Aegopodium*—a competitor species according to the Grime-Ramensky classifications (Ramensky, 1938)—as well as the absence of other natural competitors, it is not surprising that these plants have become dominant in the Summer Garden.

We found only a few turf plant communities. They were located on the slopes of the Lebyaziya Canal and the carp pond, as well as on the parterre. The turf on the slopes of the canal originated from natural meadow. Because of this, typical meadow plants such as *Trifolium repens*, *Poa pratensis*, *Alopecurus pratensis*, *Trifolium hybridum*, *Galium mollugo*, *Alchemilla* spp., *Campanula rotundifolia*, and *Campanula glomerata* (rare for a central urban park) were found there in abundance.

Flora: There were 163 species of higher vascular plants, 39 species of fungi, 14 species of mosses, and 8 species of lichens (Malisheva, Tikhomirova, Tobias, Ignatieva & Shavrina, 1995) in the Summer Garden. The nitrophylic lichens *Lecanora hagenii* and *Scoliciosporum chlorococcum*—typical indicators of air pollution—were present. However, we also found some lichens that were more characteristic of large suburban parks, such as *Cetraria sepincola*, *Evenia prunastri*, and *Lecanora symmicta*. These were growing in an area of the garden close to the Neva River where the higher winds most likely decreased the level of air pollution.

Alexandria Park in Peterhof (115 hectares; 284 acres)

History: Alexandria Park, an English landscape–style park, was created in the 1820s and '30s for Tsar Nicholas I. During World War II, it was almost completely destroyed. This monument of landscape architecture was virtually reborn after the war.

The Planting Design: Two-thirds of the park is located on coastal lowland between the ledge of a natural terrace and the Gulf of Finland. The remaining third is situated on the upper part of the terrace. Wetland forests of alder (*Alnus*) and willow (*Salix*) species originally covered the site. The park area was drained and 1.5 meters of fertile soil were added to the lower terrace. Thousands of oaks (*Quercus robur*), lime trees (*Tilia cordata* and *Tilia platyphylos*), maples (*Acer platanoides*), birch (*Betula pendula*), European mountain ash (*Sorbus aucuparia*), ash (*Fraxinus excelsior*), and also many exotic trees and shrubs (*Caragana arborescens*, *Syringa vulgaris*, *Philadelphus coronarius*, *Cornus mas*, *Sambucus racemosa*, *Rosa majalis*, *Malus baccata*, and *Hippophae rhamnoides*) were planted. Extensive meadows were grown in the front of the northern facade of the palace (the Cottage) and the Gothic Capella. Flower beds filled with exotic plants added a decorative accent.

Current Plant Communities: The dominant plant associations are *Quercus robur—Filipendula ulmaria; Quercus robur—Filipendula ulmaria—Matteucia struthiopteris*; and *Quercus robur—Matteucia struthiopteris*. There are also small areas of *Quercus robur—Aegopodium podagraria* and *Tilia cordata—Aegopodium podagraria* (Figure 4). The trees are 150 to 170 years old. All the plant communities had artificial origins; without special management and maintenance (especially drainage) they would be replaced by more moisture-tolerant natural species through succession.

The meadow is dominated by grasses (*Alopecurus pratensis*, *Bromopsis inermis*, *Deschampsia caespitosa*, *Poa pratensis*, *Gliceria fluitans*), legumes (*Trifolium repens*, *Vicia cracca*), *Geranium palustre*, *Alchemilla* spp, *Stellaria graminea*, and *Cirsium heterophyllum*. The presence of species such as *Deschampsia caespitosa*, *Juncus effusus*, and *Glyceria fluitans* indicates high humidity. Most of the Alexandria meadows need permanent drainage and annual mowing to prevent the meadow plants being replaced by early successional shrubs such as *Alnus incana*, *Salix salicifolia*, and *Salix myrsinifolia*.

Flora: We found 317 species of higher vascular plants. Meadow plant species were the most abundant, followed by aquatic and riverside species. The high percentage of wetland species, as well as the abundance of species in the *Juncaceae*, suggests a process of waterlogging in the park over the last few decades.

There were six spring ephemeral and hemiephemeral native species: *Anemonoides nemorosa*, *Anemonoides ranunculoides*, *Corydalis solida*, *Ficaria verna*, *Gagea lutea*, and *Gagea minima*. *Anemonoides nemorosa* dominated in almost all the park's oak woodlands. The decorative ephemerals give Alexandria Park tremendous aesthetic appeal during the spring months.

We also found a number of rare species: *Poa chaixii*, *Luzula luzuloides*, *Trisetum flavescens*, *Matteucia struthiopteris*, and *Melandrium dioicum* (Figure 4). *Poa*, *Luzula*, and *Trisetum* probably appeared in Alexandria between 1830 and 1850, in the period when the main trees and lawn were planted.

White Birch Region, Pavlovsky Park (250 hectares; 618 acres)

History: The development of Pavlovsky Park began in 1777 and continued for almost 50 years. At 600 hectares (1,483 acres), Pavlovsky is the largest of St. Petersburg's European landscape parks. Contributing to the design, based on a native forest of spruce (*Picea*), pine (*Pinus*), and birch (*Betula*), were Charles Cameron, who worked here from 1780 to 1786 (Slavyanka, Palace, and Great Star sections), Vincenzo Brenna, from 1796 to 1801 (Great Circles and Old and New Sylvia sections), and Pietro Gonzago, from 1801 to 1828 (White Birch, Parade Ground, and Pond Valley sections).

White Birch covers 250 hectares (618 acres) of the park. The main theme of this area is a celebration of the natural landscapes of northern Russia. There are no ponds, pavilions, or sculptures, only Gonzago's "music for the eyes," a planting style that blends native woodlands with open meadows.

The Planting Design: Gonzago worked with natural woodlands, cutting some areas to create meadows but also leaving groups of trees and single specimens to punctuate the open spaces (Figure 5). Small numbers of broadleaf trees (mainly oak, lime, and maple) were planted as well for special emphasis or accent. The original plant communities of White Birch were dominated by pine (*Pinus sylvestris*, 60%), spruce (*Picea abies*, 30%), and birch (*Betula pendula*, 9%). Gonzago chose birch and pine as his two major theme plants for their contrasting color, form, and texture. Oaks, limes, and maples were his planting "accompaniments."

Damage to Pavlovsky Park during World War II was catastrophic. Almost two-thirds of the trees were cut or damaged, and the drainage system was completely destroyed. All the meadows were left unmanaged and became overgrown by pioneer vegetation. During restoration after the war, a process of intensive natural regeneration of all major forest species (spruce, pine, and birch) occurred.

Current Plant Communities: Today, 65% of the trees in the White Birch region are spruce; pine only makes up 10%, and birch, 23%. Successional replacement of pine by spruce is quite evident and understandable. *Picea abies* plant communities are the climax type for the southern taiga zone.

The following forest associations occur here: *Picea abies—Vaccinium myrtillus—Oxalis acetosella—Maianthemum bifolium* (dominant type); *Picea abies—Oxalis acetosella; Picea abies—Anthyrium filix-femina—Oxalis acetosella; Picea abies—Equesetum pratense—Oxalis acetosella; Pinus sylvestris—Vaccinium myrtillus—Sphagnum* spp.; *Pinus sylvestris—Equisetum pratense—Oxalis acetosella; Pinus sylvestris—Athyrium filix-femina—Aegopodium podagraria; Betula pubescens—Picea abies—Vaccinium myrtillus—Oxalis acetosella; Betula pubescens—Vaccinium myrtillus*; and *Betula pubescens—Calamagrostis arundinacea—Oxalis acetosella*.

Meadow plant communities cover the major part of the White Birch region (120 hectares; 297 acres). All meadows were replanted after World War II. The foundations of these meadows are typical grass species such as *Agrostis tenuis*, *Anthoxanthum odoratum*, *Deschampsia caespitosa*, *Alchemilla* spp, *Luzula multiflora*, *Juncus filiformis*, *Juncus effusus*, *Carex leporina*, *Campanula patula*, *Ranunculus acris*, *Trifolium repens*, *Rumex acetosa*, and *Lathyrus pratensis*. The presence of species such *Deschampsia*, *Luzula*, and *Juncus* indicate naturally wet conditions and inadequate functioning of the drainage network in some places. There are a total of 82 herbaceous species and 4 woody species (*Betula pubescens*, *Salix salicifolia*, *Salix aurita*, and *Alnus incana*). The number of pioneer woody plants is quite low and directly dependent on the frequency of mowing. The average number of species per square meter varies from 11 to 20.

Flora: We found 224 higher vascular plant species in the White Birch region. Among the spring-flowering herbaceous species, *Anemonoides nemorosa* dominated in many forest and edge associations. We also found four protected species (*Lycopodium clavatum*, *Platanthera bifolia*, *Drosera rotundifolia*, and *Nuphar lutea*) and two rare species (*Pimpinella major* and *Actaea spicata*). *Pimpinella major* was probably introduced into Pavlovsky Park via seed mixtures. This particular plant dominates in the many meadow and edge communities of Pavlovsky Park.

Conclusion

Our study suggests that the most significant factor limiting floral diversity in St. Petersburg's historical parks was anthropogenic pressure, including air pollution, trampling, and disturbances such as building construction and maintenance work typical of city environments. Species diversity decreased with proximity to the city center. Large percentages of wetland and water plants in almost all the suburban parks indicated disturbance or management modification of the parks' drainage systems.

We found that ephemeral spring flora was represented by species with important ecological and decorative functions in the parks. We also found that all the suburban parks examined had a few rare species. Some of these (*Poa chaixii*, *Luzula luzuloides*, and probably *Pimpinella major*) could be the oldest of the parks' lawn species, while others (*Primula elatior*, *Phyteuma spicatum*, *Phyteuma orbiculare*, and *Colchicum autumnale*) could be linked to the region's ancient relict meadows. We recommend that planners of future restoration and reconstruction projects in the parks take steps to avoid or minimize damage to these species.

Through our investigations, we identified how a very old problem in the parks—creating a sustainable shade-tolerant groundcover—might be solved. We also identified ten indicator species groups for use in the monitoring of existing ecological conditions in the parks.

Our case studies of three of the St. Petersburg parks provide an example of how floristic and phytocoenological analyses can help identify historical and post restoration pathways of succession in plant communities. This kind of data is crucial to predicting future succession in parks and other habitats so that successful restoration may be carried out and past mistakes avoided.

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Glossary

Anthropogenic: Caused by humans.

Anthropotolerance: The reaction of plants to human influences, and the level of stability of this reaction (see Wittig, Diesing & Gödde, 1985).

Bosquet: A thicket or small grove that has a formal or regular configuration.

Climax: The final stage in a plant succession (see below) in which the vegetation attains equilibrium with the environment and, provided the environment is not disturbed, the plant community becomes more or less self-perpetuating.

Mesophytic: Of or pertaining to plants that grow under average conditions of water supply.

Nemoral: Of or pertaining to a wood or grove.

Phenological phase: A recurring biological event, such as leafing or flowering, usually tied to climatic conditions.

Phytocoenology: The scientific study of plant communities.

Pioneer plant: A plant that occurs early in plant succession (see below). Typical characteristics include rapid growth, the production of copious, small, easily dispersed seed, and the ability to germinate and establish on open sites.

Quadrats: A quadrat is a small, usually rectangular or square plot used for close study of the distribution of plants or animals in an area.

Succession: The sequential change in vegetation and the animals associated with it, either in response to an environmental change or induced by the intrinsic properties of the organisms themselves.

Taiga: A subarctic, evergreen coniferous forest of northern Eurasia located just south of the tundra and dominated by firs and spruces.

Figure 1.

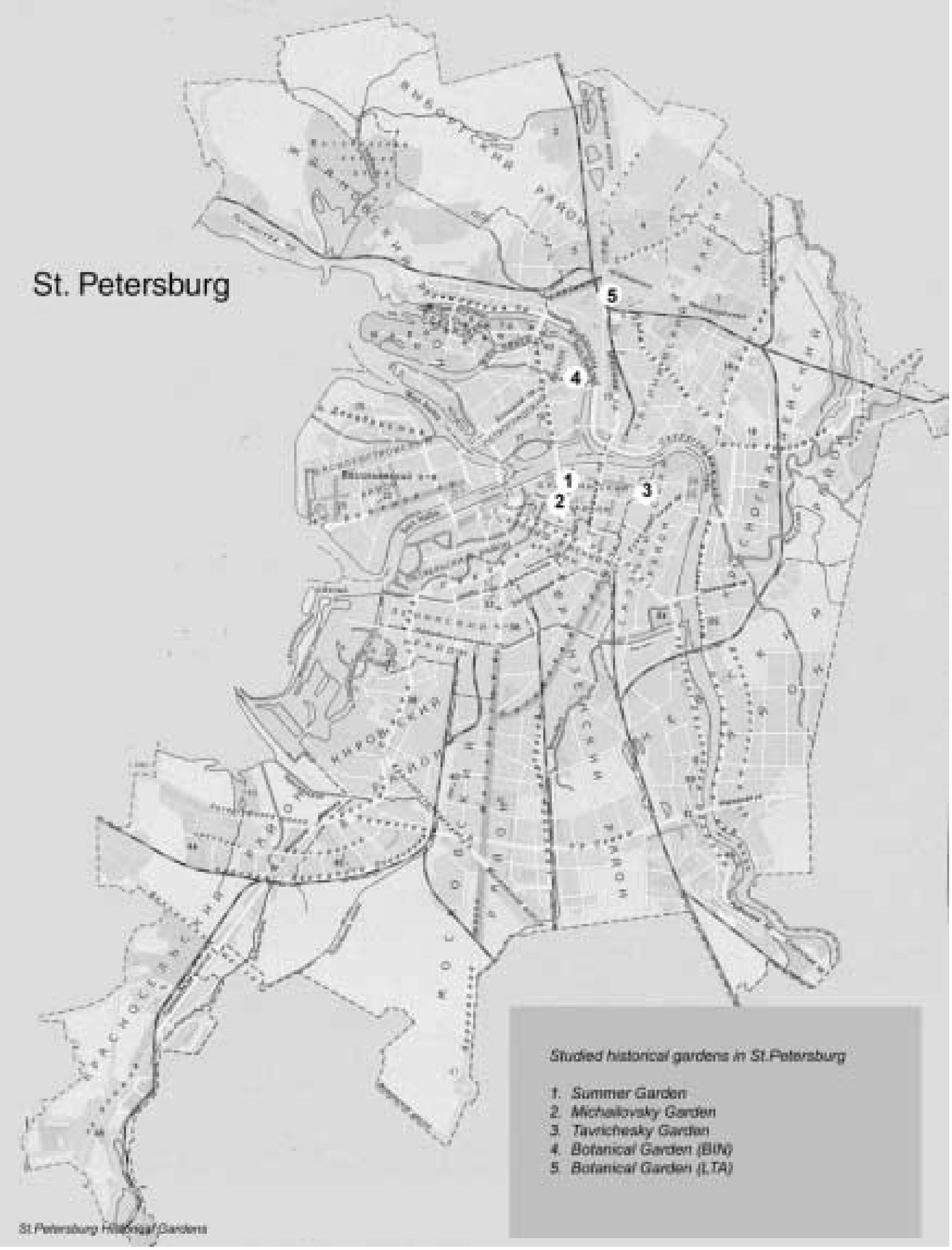


Figure 1. St. Petersburg Historical Gardens in Study

Figure 2.

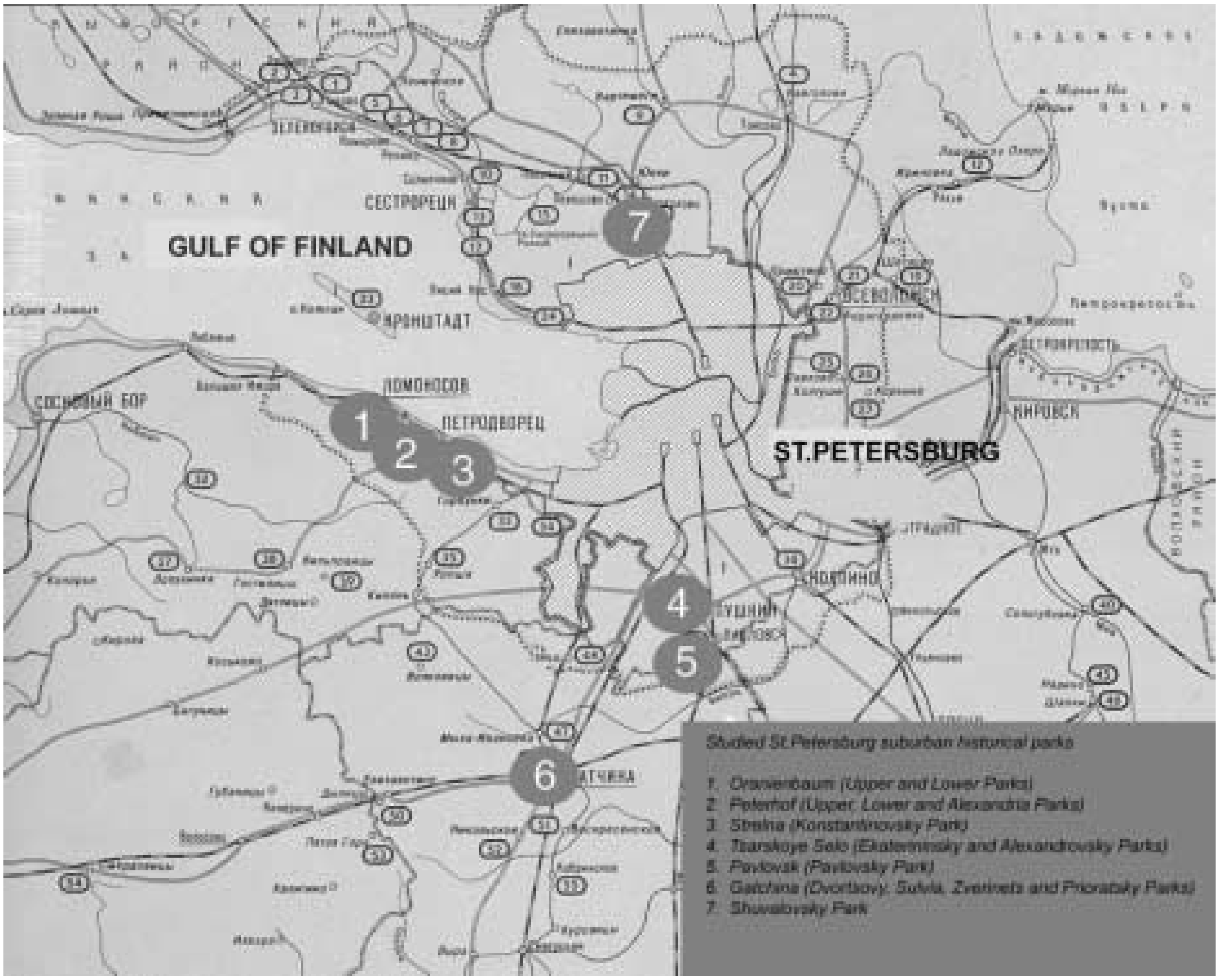
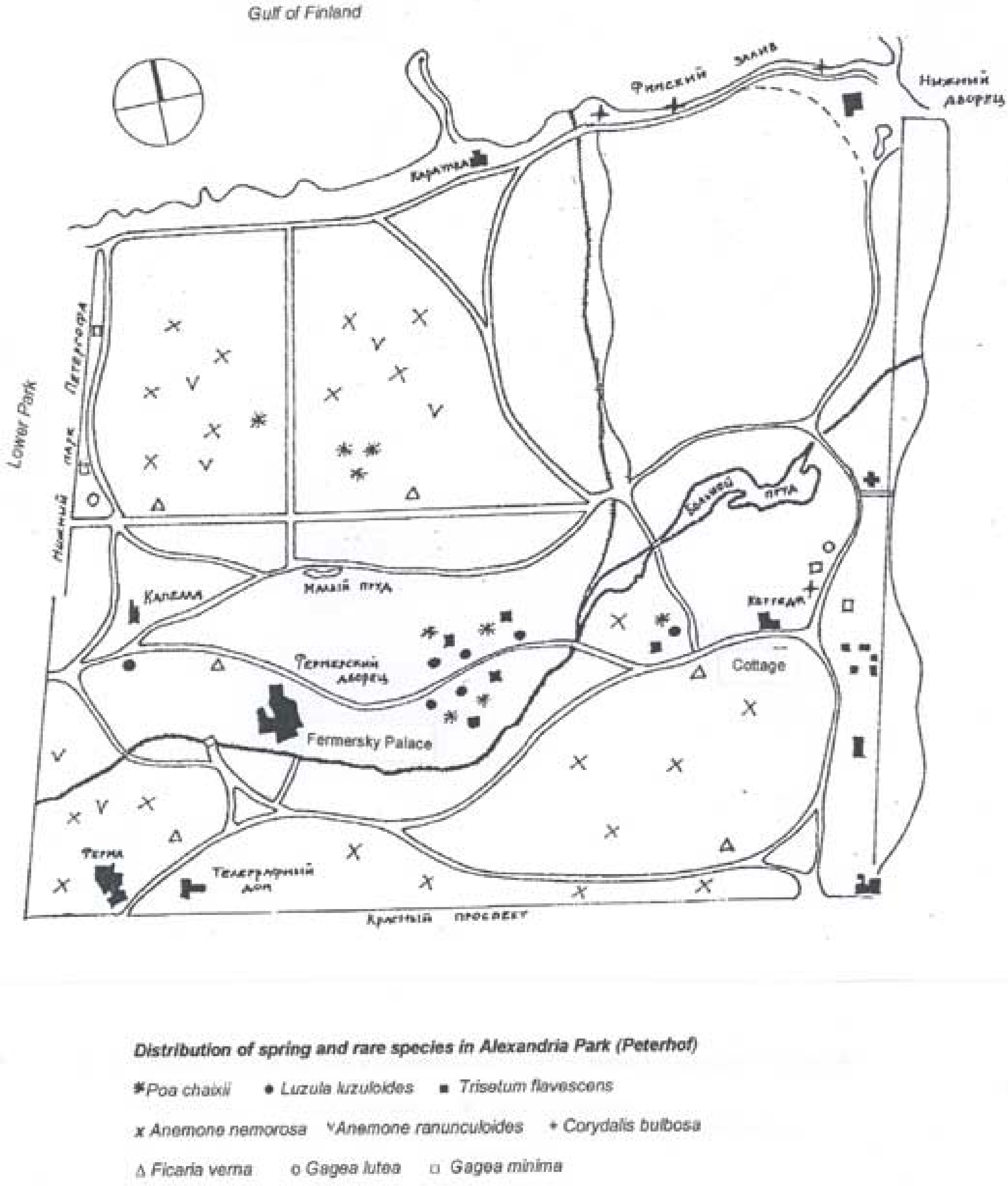


Figure 2. Suburban St. Petersburg Historical Parks in Study

Figure 3



Distribution of spring and rare species in Alexandria Park (Peterhof)

Figure 3. Distribution of Spring and Rare Plants in Alexandria Park (Peterhof)

Figure 4.

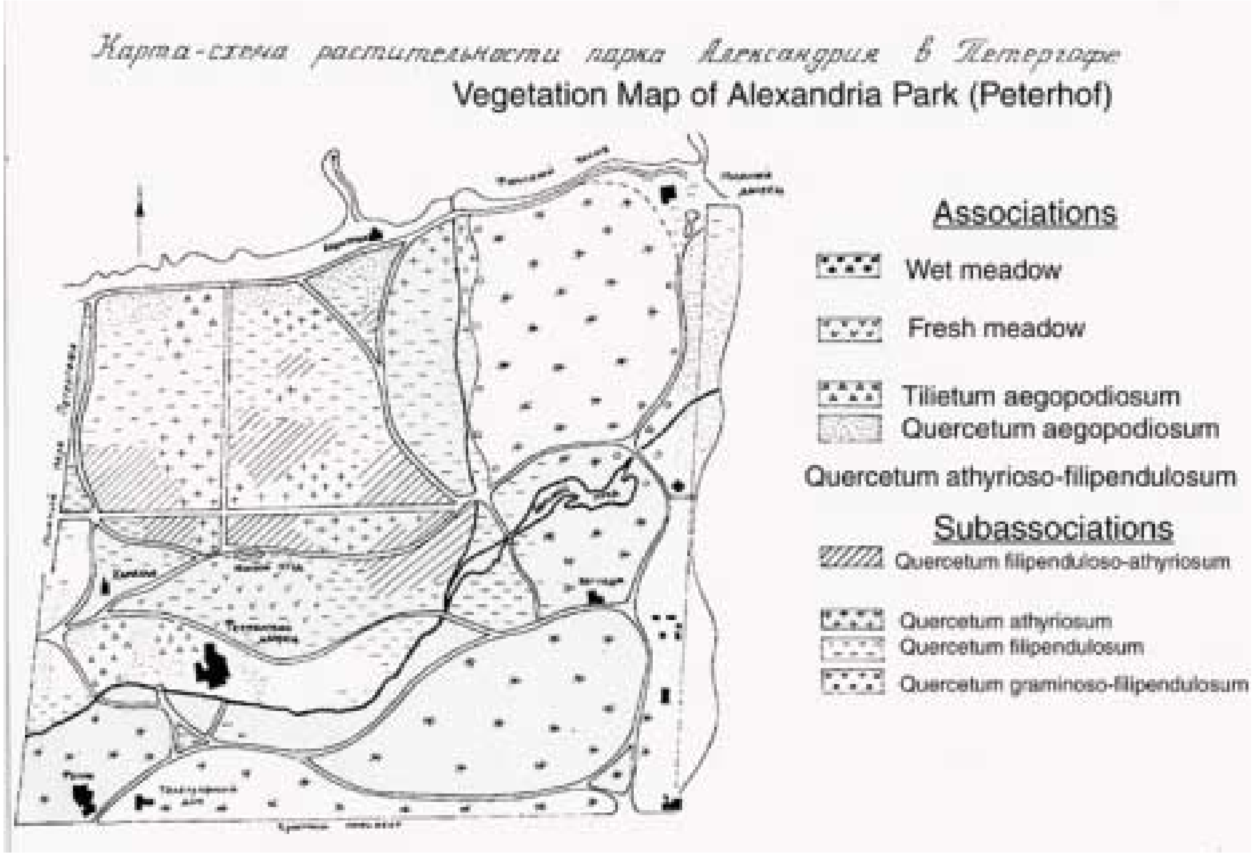


Figure 4. Vegetation Map of Alexandria Park

Figure 5.

"The Most Beautiful Place" in White Birch Region (Pavlovsky Park). Spruce and Birch native plant communities.

Figure 5. Vegetation in Pavlovsky Park (White Birch region)

Table 1. List of Higher Vascular Plants in Historical Parks and Gardens of St. Petersburg

Table starts on next page.

Table 1. List of Higher Vascular Plants in Historical Parks and Gardens of St. Petersburg

	SPECIES	GATCHINA		GATCH INA		PAVLOVSKY	TSARS	SELO	PETER	HOF		ORANIENBAUM	STRELNA	SHUVALOVSKY	LETNY	MIKH	TAVR	FTA	BOT	ORIG	ECO	ANTHRO
		Dvortsovy	*Sylvia*	*Zverinets*	*Priorat*		*Ekaterin*	*Alexandr*	*Verkhny*	*Nizhny*	*Alexan*											
	ATHYRIACEAE																					
1	*Athyrium filix-femina* (L.) Roth	X	X	X	X	X	X	X	X	?	X	X	X	X	X	X		X	X	N	1	UPHO
2	*Cystopteris fragilis* (L.) Bernh.	X					X	X	X	?									X	N	1	UPHO
3	*Gymnocarpium dryopteris* (L.) Newn.			X		X		X			X	X	X	X				X		N	1	UPHO
	DRYOPTERIDACEAE																					
4	*Dryopteris carthusiana* (Vill.) H.P. Fuchs.	X	X	X	X	X	X	X	X	?	X	X	X	X				X		N	1	UPHO
5	D. expansa (C.Presl) Fraser-Jenkins																					
	& Jermy					X						X		X						N	1	UPHO
6	*D. filix-mas* (L.) Schott				X	X					X	X	X	X						N	1	UPHO
	HYPOLEPIDACEAE																					
7	*Pteridium aquilinum* (L.) Kuhn							X				X		X						N	1	UPHO
	ONOCLEACEAE																					
8	*Matteuccia struthiopteris* (L.) Tod.						X			?	X	X	X	X				X	X	N	1	UPHO
	THELEPTERIDACEAE																					
9	*Phegopteris connectilis* (Michx) Watt			X		X		X		?	X	X		X						N	1	UPHO
	EQUISETACEAE																					
10	*Equisetum arvense* L.	X	X	X	X	X	X	X	X	?	X	X	X	X	X	X	X	X	X	N	6	UPHIL
11	*E. fluviatile* L.	X	X	X	X	X	X	X	X	?	X	X	X	X				X		N	5	UN
12	E. palustris L.	X	X	X	X	X	X	X	X			X		X						N	5	UPHO
13	*E. pratense* L.	X	X	X	X	X	X	X	X	?	X	X	X	X				X	X	N	3	UPHO
14	*E. sylvaticum* L.	X	X	X	X	X	X	X	X	?	X	X	X	X						N	1	UPHO
	LYCOPODIACEAE																					
15	*Lycopodium annotinum* L.			X		X														N	1	UPHO
16	*L. clavatum* L.					X														N	1	UPHO
	CUPRESSACEAE																					
17	*Thuja occidentalis* L.					X	X	X	X	?	X	X	X	X			X	X	X	E:Am		
	PINACEAE																					
18	*Abies sibirica* Ledeb.	X				X	X	X	X	?	X	X	X	X				X	X	E:Sib		
19	*Larix decidua* Mill.														X					E:Eu		
20	*L. sibirica* Ledeb.	X		X	X	X	X	X	X	?	X	X	X	X	X	X	X	X	X	E:Sib		

Table 1. List of Higher Vascular Plants in Historical Parks and Gardens of St. Petersburg

	SPECIES	GATCHINA		GATCH INA		PAVLOVSKY	TSARS SELO		PETER HOF			ORANIENBAUM	STRELNA	SHUVALOVSKY	LETNY	MIKH	TAVR	FTA	BOT	ORIG	ECO	ANTHRO
		Dvortsovy	*Sylvia*	*Zverinets*	*Priorat*		*Ekaterin*	*Alexandr*	*Verkhny*	*Nizhny*	*Alexan*											
21	*Picea abies* (L.) Karst.	X	X	X	X	X	X	X	X	?	X	X	X	X				X		N	1	UPHO
22	*P. pungens* Engelm.						X		X	?		X	X					X	X	E:Am		
23	*Pinus peuce* Grisen.																	X	X	E:Eu		
24	*P. sibirica* Du Tour	X				X				?		X	X	X					X	E:Am		
25	*P. strobus* L.	?									X	X							X	E:Am		
26	*P. sylvestris* L.	X	X	X	X	X	X	X		?	X	X	X	X				X		N	1	UPHO
27	*Pseudotsuga menziesii* (Mirb.) Franco											X							X	E:AM		
	TYPHACEAE																					
28	*Typha latifolia* L.	X	X	X	X	X	X	X	X	?	X	X	X	X				X	X	N	5	UN
	SPARGANIACEAE																					
29	*Sparganium emersum* Rehm.	X		X	X	X	X	X	X	?	X	X	X	X						N	5	UPHO
30	*S. microcarpum* (Neum.) Raunk.																		X	N	5	UPHO
	POTAMOGETONACEAE																					
31	*Potamogeton berchtoldii* Fieb.					X						X								N	5	UPHO
32	*P. crispus* L.					X							X							N	5	UPHO
33	*P. lucens* L.						X	X										X		N	5	UPHO
34	*P. natans* L.	X	X	X	X	X	X	X	X	?	X	X	X	X				X		N	5	UPHI
35	*P. obtusifolius* Mert.								X	?										N	5	UPHO
36	*P. pectinatus* L.			X		X	X		X			X	X	X						N	5	UPHO
37	*P. perfoliatus* L.						X		X			X	X	X						N	5	UPHO
38	*P. trichoides* Cham. & Schlecht			X	X															N	5	UPHO
	JUNCAGINACEAE																					
39	*Triglochin palustris* L.	X	X	X	X	X	X	X						X		X				N	5	UN
	ALISMATACEAE																					
40	*Alisma plantago-aquatica* L.	X	X	X	X	X	X	X	X	?	X	X	X	X				X	X	N	5	UN
41	*Sagittaria sagitifolia* L.					X	X	X	X	?	X	X	X	X					X	N	5	UN
	BUTOMACEAE																					
42	*Butomus umbellatus* L.					X														N	5	UPHO
	HYDROCHARITACEAE																					
43	*Elodea canadensis* Michx.	X	X	X	X	X	X	X	X	?	X	X	X	X			X	X	X	N	5	UN
44	*Hydrocharis morsus-ranae* L.					X		X				X		X						N	5	UPHO

Table 1. List of Higher Vascular Plants in Historical Parks and Gardens of St. Petersburg

	SPECIES	GATCHINA		GATCH	INA	PAVLOV	TSARS	SELO	PETER	HOF		ORANI	STREL	SHUVA	LETNY	MIKH	TAVR	FTA	BOT	ORIG	ECO	ANTHRO
		Dvortsovy	Sylvia	Zverinets	Priorat	SKY	Ekaterin	Alexandr	Verkhny	Nizhny	Alexan	ENBAUM	NA	LOVSKY								
	POACEAE																					
45	*Phalaroides arundinacea* (L.)Rauschert	X		X	X	X	X	X	X	?	X	X	X	X				X	X	N	5	UN
46	*Anthoxanthum odoratum* L.	X	X	X	X	X	X	X	X	?	X	X	X	X	X	X		X	X	N	4	UN
47	*Hierochloe odorata* (L.) Beauv.			X	X	X	X	X			X		X	X						N	4	UPHO
48	*Milium effusum* L.	X	X	X	X	X	X	X		?	X	X	X	X				X	X	N	1	UN
49	*Phleum pratense* L.	X	X	X	X	X	X	X	X	?	X	X	X	X	X	X	X	X	X	N	4	UN
50	*Alopecurus aequalis* Sobol.	X	X	X	X	X	X	X	X	?	X	X	X							N	5	UPHO
51	*A. geniculatus* L.	X	X	X	X	X	X	X	X	?	X	X	X	X		X	X	X	X	N	4	UN
52	*A. pratensis* L.	X	X	X	X	X	X	X	X	?	X	X	X	X	X	X	X	X	X	N	4	UN
53	*Agrostis gigantea* Roth	X		X	X	X	X	X	X	?	X	X	X	X			X	X	X	N	4	UN
54	*A. stolonifera* L.	X	X	X	X	X	X	X	X	?	X	X	X	X	X	X	X	X	X	N	4	UN
55	*A. tenuis* Sibth.	X	X	X	X	X	X	X	X	?	X	X	X	X	X	X	X	X	X	N	4	UN
56	*Calamagrostis arundinacea* (L.) Roth	X	X	X	X	X	X	X	X	?	X	X	X	X						N	1	UPHO
57	*C. canescens* (Web.) Roth	X		X	X	X	X	X		?	X	X	X	X						N	5	UPHO
58	*C. epigeios* (L.) Roth	X	X	X	X	X	X	X	X	?	X	X	X	X				X	X	N	3	UN
59	C. neglecta (Ehrh.) Gaertn., Mey &																					
	E. Scherb.			X		X	X	X		?	X	X	X	X						N	5	UPHO
60	*C. phragmitoides* C. Hartm.	X		X		X		X		?	X	X	X	X						N	5	UPHO
61	*Deschampsia caespitosa* (L.) Beauv.	X	X	X	X	X	X	X	X	?	X	X	X	X	X	X	X	X	X	N	4	UN
62	*Avenella flexuosa* (L.) Drej	X	X	X	X	X		X		?	X	X	X	X				X		N	1	UPHO
	(*Lerchenfeldia flexuosa* (L.) Schur)																					
63	*Trisetum flavescens* (L.) Beauv.	X		X	X	X	X	X			X	X	X							N	4	UPHO
64	*Helictotrichon pubescens* (Huds.) Pilg.	X		X	X	X	X	X				X	X							N	4	UPHO
65	*Arrhenatherum elatius* (L.) J. & C. Presl	X		X	X	X	X	X		?	X	X	X		X				X	N	4	UPHO
66	*Beckmannia eruciformis* (L.) Host			X																N	4	UPHO
67	*Sesleria caerulea* (L.) Ard.			X																N	5	UPHO
68	*Phragmites australis* (Cav.)Trin. ex Steud.	X	X	X	X	X	X	X	X	?	X	X	X	X				X	X	N	5	UN
69	*Molinia caerulea* (L.) Moench.	X		X		X														N	4	UPHO
70	*Melica nutans* L.	X		X	X	X	X	X		X	X	X	X	X				X		N	1	UPHO
71	*Briza media* L.	X		X	X	X	X	X	X	X	X	X	X	X	X					N	4	UPHO
72	*Dactylis glomerata* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	4	UN

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	SPECIES	GATCHINA		GATCH INA		PAVLOV	TSARS	SELO	PETER	HOF		ORANI	STREL	SHUVA	LETNY	MIKH	TAVR	FTA	BOT	ORIG	ECO	ANTHRO
		Dvortsovy	*Sylvia*	*Zverinets*	*Priorat*	SKY	*Ekaterin*	*Alexandr*	*Verkhny*	*Nizhny*	*Alexan*	ENBAUM	NA	LOVSKY								
73	*Cynosurus cristatus* L.		X		X	X							X							N	4	UPHO
74	*Poa annua* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	6	UPHI
75	*P. chaixii* Vill.	X		X		X				X	X	X								G		
76	*P. compressa* L.			X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	N	4	UN
77	*P. nemoralis* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	1	UN
78	*P. palustris* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	4	UN
79	*P. pratensis* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	4	UN
80	P. remota Forsell.	X	X	X	X	X		X				X								N	1	UPHO
81	*P. trivialis* L.	X	X	X	X	X	X	X	X	X	X	X	X	X				X	X	N	4	UN
82	*Glyceria fluitans* (L.) R. Br.	X	X	X	X	X	X	X	X	X	X	X	X	X			X	X		N	5	UN
83	*G. maxima* (C. Hartm.) Holmb.	X		X	X	X	X	X				X	X					X	X	N	5	UPHO
84	*G. notata* Cheval.	X		X				X				X		X						N	5	UPHO
85	*Puccinellia distans* (Jacq.) Parl.						X	X												N	7	UN
86	*Festuca arundinacea* Screb.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	A		
87	*F. gigantea* (L.) Vill	X	X	X	X	X	X	X	X	X	X	X	X	X				X	X	N	1	UN
88	*F. ovina* L.													X						N	4	UPHO
89	*F. pratensis* Huds.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	4	UN
90	*F. rubra* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	4	UN
91	*Lolium perenne* L.	X				X	X	X	X	X	X	X	X	X	X	X	X	X	X	A		
92	*Bromopsis inermis* (Leyss.) Holub	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	4	UN
93	*Nardus stricta* L.			X		X	X	X				X								N	4	UPHO
94	*Brachipodium pinnatum* (L.) Beauv.		X	X	X							X								N	1	UPHO
95	*Elytrigia repens* (L.) Nevski	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	4	UN
96	*Elymus caninus* (L.) L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	1	UN
97	*Leymus arenarius* (L.) Hochst.										X									N	7	UPHO
	CYPERACEAE																					
98	*Eriophorum latifolium* Hoppe		X																	N	5	UPHO
99	*E. polystachion* L.			X																N	5	UPHO
100	*Scirpus lacustris* L.						X	X												N	5	UPHO
101	*S. radicans* Schkuhr					X							X							N	5	UPHO
102	*S. sylvaticus L.*	X	X	X	X	X	X	X	X	X	X	X	X	X				X	X	N	5	UN
103	*Blysmus compressus* (L.) Panz. ex Link	X		X																N	5	UPHO

	SPECIES	GATCHINA		GATCH INA		PAVLOV	TSARS	SELO	PETER	HOF		ORANI	STREL	SHUVA	LETNY	MIKH	TAVR	FTA	BOT	ORIG	ECO	ANTHRO
		Dvortsovy	*Sylvia*	*Zverinets*	*Priorat*	SKY	*Ekaterin*	*Alexandr*	*Verkhny*	*Nizhny*	*Alexan*	ENBAUM	NA	LOVSKY								
104	*Eleocharis acicularis* (L.)Roem & Schult.									X			X							N	5	UPHO
105	*E. palustris* (L.) Roem. & Schult.	X	X	X	X	X	X	X		X	X	X	X	X					X	N	5	UPHO
106	*Carex acuta* L.	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X		N	5	UN
107	*C. acutiformis* Ehrh.	X	X	X	X															N	5	UPHO
108	*C. atherodes* Spreng				X															N	5	UPHO
109	*C. brizoides* L.			X				X				X						X		N	1	UPHO
110	*C. brunnescens* (Pers.) Poir.	X	X	X	X	X						X		X						N	5	UN
111	*C. caespitosa* L.	X	X	X	X			X		X		X							X	N	5	UPHO
112	*C. cinerea* Poll.	X	X	X	X	X		X			X	X							X	N	5	UPHO
113	*C. contiqua* Hoppe	X	X	X	X	X	X	X	X	X	X	X	X	X	X			X	X	N	1	UN
114	*C. davalliana* Smith			X																		
115	*C. diandra* Schrank												X							N	5	UPHO
116	*C. digitata* L.	X	X	X	X	X						X	X							N	1	UPHO
117	*C. disticha* Huds.			X		X							X							N	5	UPHO
118	*C. echinata* Murr.	X	X	X	X	X						X								N	5	UPHO
119	*C. ericetorum* Poll.											X								N	5	UPHO
120	*C. elongata* L.			X	X															N	5	UPHO
121	*C. flacca* Schreb.	X	X	X								X								N	5	UPHO
122	*C. flava* L.	X	X	X	X	X						X		X						N	5	UPHO
123	*C. hirta* L.	X	X	X	X	X	X	X		X	X	X	X	X	X				X	N	4	UN
124	*C. leporina* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	3	UN
125	*C. nigra* (L.) Reichard	X	X	X	X	X	X	X	X	X	X	X	X	X				X		N	5	UN
126	*C. ornithopoda* Willd.	X		X																N	3	UPHO
127	*C. pallescens* L.	X	X	X	X	X	X	X		X	X	X	X							N	3	UPHO
128	*C. panicea* L.	X		X		X				X			X							N	5	UPHO
129	*C. paniculata* L.			X																		
130	*C. pilulifera* L.			X																N	3	UPHO
131	*C. praecox* Schreb.	X																	X	N	3	UPHO
132	*C. pseudocyperus* Ehrh.	X	X	X	X	X	X	X			X			X						N	5	UPHO
133	*C. rhizina* Blytt ex Lindbl.	X	X	X	X	X														N	1	UPHO
134	*C. rhynchophysa* C. A. Mey													X						N	5	UPHO
135	*C. rostrata* Stokes	X		X			X	X			X	X	X	X						N	5	UPHO

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	SPECIES	GATCHINA		GATCH	INA	PAVLOV	TSARS	SELO	PETER	HOF		ORANI	STREL	SHUVA	LETNY	MIKH	TAVR	FTA	BOT	ORIG	ECO	ANTHRO
		Dvortsovy	*Sylvia*	*Zverinets*	*Priorat*	SKY	*Ekaterin*	*Alexandr*	*Verkhny*	*Nizhny*	*Alexan*	ENBAUM	NA	LOVSKY								
136	*C. sylvatica* Huds.			X	X							X								N	1	UPHO
137	*C. tomentosa* L.			X																N		UPHO
138	*C. vaginata* Tausch	X	X	X				X				X								N	5	UPHO
139	*C. vesicaria* L.	X		X	X	X	X	X	X	X	X	X	X	X						N	5	UPHO
140	*C. vulpina* L.																	X		N	5	UPHO
	ARACEAE																					
141	*Acorus calamus* L.																		X	N	5	UPHO
142	*Calla palustris* L.	X		X	X	X	X	X				X	X	X						N	5	UPHO
	LEMNACEAE																					
143	*Lemna gibba* L.				X								X							N	5	UPHO
144	L. minor L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	5	UPHO
145	*L. trisulca* L.	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	N	5	UPHO
146	*Spirodela polyrhiza* (L.) Schleid			X									X							N	5	UPHO
	JUNCACEAE																					
147	*Juncus articulatus* L.	X	X	X	X	X	X	X		X	X	X	X	X				X		N	7	UN
148	*J. bufonius* L.	X	X	X	X	X	X	X			X	X	X	X			X	X		N	7	UN
149	*J. compressus* Jacq.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	7	UPHI
150	*J. conglomeratus* L.			X		X	X	X			X	X	X	X				X		N	5	UN
151	*J. effusus* L.	X	X	X	X	X	X	X	X	X	X	X	X	X				X	X	N	5	UN
152	*J. filiformis* L.	X	X	X	X	X	X	X		X	X	X	X	X						N	5	UPHO
153	*J. tenuis* Willd.					X			X	X	X									A		
154	*Luzula campestris* (L.) DC.			X																N	3	UPHO
155	*L. luzuloides* (Lam.) Dandy & Wilmott	X		X		X	X	X		X	X	X	X					X		A		
156	*L. multiflora* (Ehrh.) Lej.	X	X	X	X	X	X	X	X	X	X	X	X	X				X	X	N	4	UN
157	*L. pilosa* (L.) Willd.	X	X	X	X	X	X	X		X	X	X	X	X				X		N	1	UPHO
	MELANTHIACEAE																					
158	*Colchicum autumnale* L.			X																N	4	UPHO
159	*Veratrum lobelianum* Bernh.																		X	N	3	UPHO
	LILIACEAE																					
160	*Gagea granulosa* Turcz.					X									X			X	X	A		
161	*G. lutea* (L.) Ker-Gawl.	X			X	X	X	X	X	X	X	X	X		X	X	X	X	X	N	1	UN

	SPECIES	GATCHINA		GATCH INA		PAVLOV	TSARS	SELO	PETER	HOF		ORANI	STREL	SHUVA	LETNY	MIKH	TAVR	FTA	BOT	ORIG	ECO	ANTHRO
		Dvortsovy	*Sylvia*	*Zverinets*	*Priorat*	SKY	*Ekaterin*	*Alexandr*	*Verkhny*	*Nizhny*	*Alexan*	ENBAUM	NA	LOVSKY								
162	*G. minima* (L.) Ker-Gawl.	X			X	X	X	X	X	X	X	X	X		X	X	X	X	X	N	3	UN
163	*Lilium martagon* L.					X							X							G		
	HYACINTHACEAE																					
164	*Chionodoxa gigantea* Whitt.																		X	E:Eu		
165	*C. luciliae* Boiss.																		X	E:EU		
166	*Scilla siberica* Haw.																	X	X	G		
	ALLIACEAE																					
167	*Allium oleraceum* L.					X							X		X					N	3	UPHO
	CONVALLARIACEAE																					
168	*Maianthemum bifolium* (L.)F.W.Schmidt	X	X	X	X	X	X	X	X	X	X	X	X	X				X		N	1	UPHO
169	*Polygonatum multiflorum* (L.) All.											X	X					X		N	1	UPHO
170	*P. verticillatum* (L.) All.					X														N	1	UPHO
171	*Convallaria majalis* L.	X		X	X	X	X	X		X	X	X	X	X					X	N	1	UPHO
	TRILLIACEAE																					
172	*Paris quadrifolia* L.	X	X	X	X	X	X	X	X	X	X	X	X	X				X		N	1	UPHO
	IRIDACEAE																					
173	*Iris pseudacorus* L.	X	X	X	X	X	X	X		X	X	X	X	X				X	X	N	5	UPHO
	ORCHIDACEAE																					
174	*Cypripedium calceolus* L.			X																N	3	UPHO
175	*Malaxis monophyllos* (L.) Sw.	X																		N	5	UPHO
176	*Listera ovata* (L.) R. Br.	X	X	X		X		X		X		X		X						N	1	UPHO
177	*Epipactis helleborine* (L.) Crantz	X			X															N	3	UPHO
178	*Platanthera bifolia* (L.) Rich.	X		X	X	X		X		X		X		X						N	3	UPHO
179	*P. chlorantha* (Cust.) Reichenb.	X		X		X		X				X						X		N	3	UPHO
180	*Dactylorhiza maculata* (L.) Soo											X								N	3	UPHO
	SALICACEAE																					
181	*Populus alba* L.	X				X				X	X	X						X		E:Eu		
182	*P. balsamifera* L.									X				X		X	X	X		E:Am		
183	*P. x berolinensis* (C. Koch.) Dipp									X				X				X	X	E		
184	P. suaveolens Fish.																		X	E:FE		
185	*P. tremula* L.	X	X	X	X	X	X	X	X	X	X	X	X	X				X	X	N	1	UN

	SPECIES	GATCHINA		GATCH INA		PAVLOV	TSARS SELO		PETER HOF			ORANI	STREL	SHUVA	LETNY	MIKH	TAVR	FTA	BOT	ORIG	ECO	ANTHRO
		Dvortsovy	*Sylvia*	*Zverinets*	*Priorat*	SKY	*Ekaterin*	*Alexandr*	*Verkhny*	*Nizhny*	*Alexan*	ENBAUM	NA	LOVSKY								
186	*Salix alba* L.	X		X	X	X	X	X		X	X	X	X	X		X	X	X	X	E:Eu		
187	*S. aurita* L.	X	X	X	X	X				X										N	5	UPHO
188	*S. caprea* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	1	UN
189	*S. cinerea* L.	X	X	X	X	X	X	X		X	X	X	X	X						N	5	UN
190	*S. fragilis* L.	X	X	X	X	X	X	X		X	X	X	X	X			X	X	X	E:Eu		
191	*S. myrsinifolia* Salisb.	X	X	X	X	X	X	X	X	X	X	X	X	X						N	3	UPHO
192	*S. phylicifolia* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	3	UN
193	*S. pentandra* L.	X		X	X	X	X	X		X	X	X	X	X				X		N	5	UN
194	*S. rosmarinifolia* L.	X		X		X														N	5	UPHO
195	*S. starkeana* Will.			X		X	X	X				X								N	5	UPHO
196	*S. triandra* L.				X	X	X	X		X	X	X	X	X						N	5	UPHO
197	*S. viminalis* L.	X						X												N	5	UPHO
	BETULACEAE																					
198	*Betula pendula* Roth	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	1	UN
199	*B. pubescens* Ehrh.	X	X	X	X	X	X	X		X	X	X	X	X			X	X	X	N	1	UN
200	*Alnus glutinosa* (L.) Gaertn.	X	X	X	X	X	X	X	X	X	X	X	X	X				X	X	N	1	UN
201	*A. incana* (L.) Moench	X	X	X	X	X	X	X	X	X	X	X	X	X			X	X	X	N	1	UN
202	*Corylus avellana* L.	X			X	X	X	X	X	X	X	X	X	X				X		N	1	UPHO
	FAGACEAE																					
203	*Quercus robur* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	1	UN
204	*Q. rubra* L.									X							X	X		E:Am		
	ULMACEAE																					
205	*Ulmus glabra* Huds.	X			X	X	X	X		X	X	X	X	X	X	X	X	X	X	N	1	UN
206	*U. laevis* Pall.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	1	UN
	CANNABACEAE																					
207	*Humulus lupulus* L.																		X	N	1	UPHO
	URTICACEAE																					
208	*Urtica dioica* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	2	UPHI
209	*Urtica urens* L.																X		X	N	6	UPHI
	ARISTOLOCHIACEAE																					
210	*Asarum europaeum* L.	X			X							X								N	1	UPHO

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	SPECIES	**GATCHINA**		**GATCH**	**INA**	**PAVLOV**	**TSARS**	**SELO**	**PETER**	**HOF**		**ORANI**	**STREL**	**SHUVA**	**LETNY**	**MIKH**	**TAVR**	**FTA**	**BOT**	**ORIG**	**ECO**	**ANTHRO**
		Dvortsovy	*Sylvia*	*Zverinets*	*Priorat*	**SKY**	*Ekaterin*	*Alexandr*	*Verkhny*	*Nizhny*	*Alexan*	**ENBAUM**	**NA**	**LOVSKY**								
	POLYGONACEAE																					
211	*Rumex acetocella* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	7	UPHI
212	*R. acetosa* L.	X	X	X	X	X	X	X	X	X	X	X	X	X				X	X	N	4	UN
213	*R. aquaticus* L.	X		X	X	X	X	X		X	X	X	X	X						N	5	UPHO
214	*R. confertus* Willd.			X			X	X		X		X		X				X	X	N	4	UN
215	*R. crispus* L.	X		X	X	X	X	X	X	X	X	X	X	X		X		X	X	N	6	UPHI
216	*R. longifolius* DC.				X	X	X		X	X		X	X		X	X	X			N	6	UPHI
217	*R. obtusifolius* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	2	UN
218	*R. pseudonatronathus* (Borb.)																					
	Borb. ex Murb.												X							N	5	UPHO
219	*Persicaria amphibia* (L.) S. F. Gray	X	X	X	X	X	X	X	X	X	X	X	X	X			X	X	X	N	5	UN
	(*Polygonum amphibium* L.)																					
220	*P. hydropiper* (L.) Spach	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X		N	5	UN
	(*Polygonum hydropiper* L.)																					
221	*P. lapathifolia* (L.) S. F. Gray	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		N	6	UPHI
	(*Polygonum lapathifolium* L.)																					
222	*P. maculata* (Rafin.) A. R. D. Love					X								X						N	6	UPHI
	(*Polygonum persicaria* L.)																					
223	*P. minor* (Huds.) Opiz					X				X			X							N	7	UN
	(*Polygonum minus* Huds.)																					
224	*Polygonum aviculare* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	6	UPHI
225	*Bistorta major* S. F. Gray	X					X	X				X								N	4	UPHO
	(*Polygonum bistorta* L.)																					
226	*B. vivipara* (L.) S. F. Gray	X		X	X	X		X			X	X	X	X						N	4	UPHO
	(*Polygonum viviparum* L.)																					
227	*Fallopia convolvulus* (L.) A. Love	X		X	X	X	X	X		X	X	X	X	X	X			X	X	N	6	UPHI
228	*F. dumetorum (* L.) Holub									X			X							N	5	UN
229	*Reynoutria sachalinensis*																					
	(Fr. Schmidt) Nakai																	X	X	G		
	CHENOPODIACEAE																					
230	*Chenopodium album* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	6	UPHI
231	*C. glaucum* L.				X								X						X	N	6	UPHI

	SPECIES	GATCHINA		GATCH	INA	PAVLOV	TSARS	SELO	PETER	HOF		ORANI	STREL	SHUVA	LETNY	MIKH	TAVR	FTA	BOT	ORIG	ECO	ANTHRO
		Dvortsovy	*Sylvia*	*Zverinets*	*Priorat*	SKY	*Ekaterin*	*Alexandr*	*Verkhny*	*Nizhny*	*Alexan*	ENBAUM	NA	LOVSKY								
232	*C. polyspermum* L.											X							X	N	6	UPHI
233	*C. rubrum* L.												X							N	6	UPHI
234	*Atriplex patula* L.	X			X	X	X	X		X	X	X		X		X		X	X	N	6	UPHI
235	*A. prostrata* Boucher ex DC.				X											X	X		X	N	6	UPHI
	PORTULACACEAE																					
236	*Portulaca oleracea* L.																		X	N	6	UPHI
	CARYOPHYLLACEAE																					
237	*Myosoton aquaticum* (L.) Moench											X								N	5	UPHO
238	*Stellaria alsine* Grimm.						X													N	5	UPHO
239	*S. graminea* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	4	UN
240	*S. holostea* L.	X	X	X	X	X	X	X	X	X	X	X	X	X				X		N	1	UPHO
241	*S. media* (L.) Vill.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	6	UPHI
242	*S. nemorum* L.	X	X	X	X	X	X	X	X	X	X	X	X	X				X		N	1	UPHO
243	*S. palustris* Retz.	X		X		X	X	X		X	X	X	X	X						N	5	UPHO
244	*Cerastium arvense* L.									X										N	6	UPHI
245	*C. holosteoides* Fries	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	4	UN
246	*Sagina procumbens* L.	X		X	X	X	X	X	X	X	X	X	X		X		X	X	X	N	7	UN
247	*Moehringia trinervia* (L.) Clairv.	X		X	X	X		X			X	X		X						N	1	UPHO
248	*Spergula arvensis* L.	X		X	X	X	X	X	X	X	X	X	X	X				X	X	N	6	UPHI
249	*Sregularia rubra* (L.) J. & C. Presl.																		X	N	6	UPHI
250	*Oberna behen* (L.) Ikonn.								X	X		X	X						X	N	6	UPHI
	(*Silene vulgaris* (Moench) Garcke)																					
251	*Coccyganthe flos-cuculi* (L.) Fourr.	X	X	X	X	X	X	X	X	X	X	X	X	X				X	X	N	5	UPHO
	(Coronaria flos-cuculi (L.) R. Br.)																					
252	*Melandrium album* (Mill.) Garcke	X					X		X	X		X		X				X		N	6	UPHI
253	*M. dioicum* (L.) Coss & Germ.			X	X	X	X	X	X	X	X	X	X	X				X		N	3	UPHO
254	*Dianthus barbatus* L.					X							X							G		
255	*D. deltoides* L.			X	X	X				X				X					X	N	4	UPHO
256	*Saponaria officinalis* L.											X						X	X	G		
	NYMPHAEACEAE																					
257	*Nymphaea candida* J. Presl													X				X		N	5	UPHO
258	*Nuphar lutea* (L.) Smith	X		X	X	X	X	X		X	X	X	X	X						N	5	UN

	SPECIES	GATCHINA		GATCH	INA	PAVLOV	TSARS	SELO	PETER	HOF		ORANI	STREL	SHUVA	LETNY	MIKH	TAVR	FTA	BOT	ORIG	ECO	ANTHRO
		Dvortsovy	Sylvia	Zverinets	Priorat	SKY	Ekaterin	Alexandr	Verkhny	Nizhny	Alexan	ENBAUM	NA	LOVSKY								
	CERATOPHYLLACEAE																					
259	*Ceratophyllum demersum* L.	X	X	X	X	X	X	X	X	X	X	X	X	X				X	X	N	5	UN
260	*C. pentacanthum* Haynald					X														N	5	UPHO
	RANUNCULACEAE																					
261	*Caltha palustris* L.	X	X	X	X	X	X	X	X	X	X	X	X	X						N	5	UPHO
262	*Trollius europaeus* L.	X		X	X					X		X								N	3	UPHO
263	*Actaea spicata* L.	X			X	X	X	X			X	X	X							N	1	UPHO
264	*Aquilegia vulgaris* L.	X		X		X		X		X								X	X	G		
265	*Aconitum vulparia* Reichenb.					X														G		
266	*Anemonoides nemorosa* (L.) Holub	X	X	X	X	X	X	X	X	X	X	X	X	X	X			X	X	N	1	UPHO
267	*A. ranunculoides* (L.) Holub	X		X	X	X	X	X	X	X	X	X	X	X	X			X	X	N	1	UN
268	*Hepatica nobilis* Mill.	X	X	X	X	X														N	1	UPHO
269	*Ficaria verna* Huds.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	3	UN
270	*Batrachium trichophyllum* (Chaix) Bosch			X	X	X	X				X			X						N	5	UPHO
271	*Ranunculus acris* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	4	UN
272	*R. auricomus* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		N	3	UN
273	*R. cassubicus* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	1	UN
274	*R. fallax* (Wimm. & Grab.) Sloboda	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	1	UN
275	*R. lingua* L.				X															N	5	UPHO
276	*R. monophyllus* Ovcz.			X																N	3	UPHO
277	*R. nemorivagus* Jord.	X																		N	3	UPHO
278	*R. repens* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	4	UN
279	*R. sceleratus* L.	X	X	X	X	X	X	X	X	X	X	X	X	X		X		X		N	5	UN
280	*Thalictrum flavum* L.	X	X	X	X					X	X		X	X						N	4	UPHO
281	*T. lucidum* L.			X	X	X	X	X		X	X	X	X							N	4	UPHO
282	*T. minus* L.					X														N	4	UPHO
	BERBERIDACEAE																					
283	*Berberis vulgaris* L.	X			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	E:Eu		
284	*B. thunbergii* DC.						X		X	X		X			X		X	X		E:FE		
	PAPAVERACEAE																					
285	*Chelidonium majus* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	6	UPHI
286	*Papaver rhoeas* L.																	X	X	G		

	SPECIES	GATCHINA		GATCH	INA	PAVLOV	TSARS	SELO	PETER	HOF		ORANI	STREL	SHUVA	LETNY	MIKH	TAVR	FTA	BOT	ORIG	ECO	ANTHRO
		Dvortsovy	*Sylvia*	*Zverinets*	*Priorat*	SKY	*Ekaterin*	*Alexandr*	*Verkhny*	*Nizhny*	*Alexan*	ENBAUM	NA	LOVSKY								
	FUMARIACEAE																					
287	*Corydalis bracteata* (Steph.) Pers.																		X	G		
288	*C. solida* (L.) Clairv.	X			X	X	X	X	X	X	X	X	X	X				X	X	N	1	UPHO
289	*C. capnoides* (L.) Pers.																		X	G		
290	*C. intermedia* (L.) Merat																		X	N	1	UPHO
291	*C. nobilis* (L.) Pers.																		X	G		
292	*C. ochotensis* Turcz.																		X	G		
293	*Fumaria officinalis* L.	X							X	X				X				X	X	N	6	UPHI
	BRASSICACEAE																			N		
294	*Lepidium ruderale* L.	X				X			X	X		X	X		X	X	X	X	X	N	6	UPHI
295	*Coronopus didymus* (L.) Smith																		X	A		
296	*Thlaspi alpestre* L.			X														X	X	A		
297	*T. arvense* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	6	UPHI
298	*Armoracia rusticana* Gaertn.,Mey & Scherb.				X	X		X	X	X		X	X	X					X	G		
299	*Alliaria petiolata* (Bieb.)Cavara & Grande							X				X	X					X	X	A		
300	*Sisymbrium officinale* (L.) Scop.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	6	UPHI
301	*Sinapis arvensis* L.						X	X			X	X	X					X	X	N	6	UPHI
302	*Brassica oleracea* L.	X		X				X												N	6	UPHI
303	*Raphanus raphanistrum* L.						X	X		X	X	X							X	N	6	UPHI
304	*R. sativus* L.							X												G		
305	*Barbarea vulgaris* R. Br.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		N	6	UPHI
306	*B. stricta* Andrz.												X							N	7	UN
307	*Rorippa amphibia* (L.) Bess			X		X							X							N	5	UPHO
308	*R. palustris* (L.) Bess.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	7	UN
309	*R. sylvestris* (L.) Bess.									X	X							X	X	N	7	UN
310	*Cardamine amara* L.	X	X	X	X	X	X	X	X	X	X	X	X	X				X	X	N	5	UPHO
311	*C. dentata* Schult	X	X	X	X	X	X	X	X	X	X	X	X	X				X	X	N	4	UPHO
312	*C. hirsuta* Schult																		X	N	5	UPHO
313	*C. impatiens* L.				X	X		X		X	X	X	X							N	5	UPHO
314	*Dentaria bulbifera* L.																		X	N	1	UPHO
315	*Capdaminopsis halleri* (L.) Hayek																		X	N		
316	*Capsella bursa-pastoris* (L.) Medik	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	6	UPHI

	SPECIES	GATCHINA		GATCH	INA	PAVLOV	TSARS	SELO	PETER	HOF		ORANI	STREL	SHUVA	LETNY	MIKH	TAVR	FTA	BOT	ORIG	ECO	ANTHRO
		Dvortsovy	*Sylvia*	*Zverinets*	*Priorat*	SKY	*Ekaterin*	*Alexandr*	*Verkhny*	*Nizhny*	*Alexan*	ENBAUM	NA	LOVSKY								
317	*Descurainia sophia* (L.) Webb ex Prantl						X	X												N	6	UPHI
318	*Arabidopsis thaliana* (L.) Heynh.						X	X	X	X		X						X	X	N	7	UN
319	*Turritis glabra* L.					X														N	7	UN
320	*Erysimum cheiranthoides* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	6	UPHI
321	*Berteroa incana* (L.) DC.	X		X	X	X	X	X	X	X	X	X	X	X				X		N	7	UN
322	*Hesperis matronalis* L.																	X		G		
323	*Bunias orientalis* L.	X	X	X	X	X	X	X	X	X	X	X	X	X				X		N	6	UPHI
	DROSERACEAE																					
324	*Drosera rotundifolia* L.					X														N	5	UPHO
	CRASSULACEAE																					
325	*Sedum acre* L.								X											N	7	UPHO
326	*S. hispanicum* L.																		X	G		
327	*Hylotephium maximum* (L.) Holub.																		X	N	7	UPHO
328	*H. triphyllum (* Haw.) Holub					X														N	7	UPHO
	SAXIFRAGACEAE																					
329	*Chrysosplenium alternifolium* L.	X	X	X	X	X	X	X	X	X	X	X	X	X						N	1	UPHO
	HYDRANGEACEAE																					
330	*Philadelphus coronarius* L.	X				X	X	X	X	X	X	X	X	X	X	X	X	X	X	E:Eu		
	GROSSULARIACEAE																					
331	*Grossularia uva-crispa* (L.) Mill.	X		X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	G		
332	*Ribes alpinum* L.	X		X	X	X		X	X		X	X		X	X	X				N	3	UN
333	*R. aureum* Pursh							X	X											E:Am		
334	*R. nigrum* L.	X	X	X	X	X	X	X	X	X	X	X	X	X						N	1	UPHO
335	*R. rubrum* L.	X	X	X					X	X										E		
	ROSACEAE																					
336	*Aruncus dioicus* (Walt.) Fern.											X								E:Am		
337	*Physocarpus opulifolius* (L.) Maxim.	X				X	X	X	X			X		X	X		X	X	X	E:Am		
338	*Spiraea x billardii* Dipp.	X				X	X	X												E:Am		
339	*S. chamaedrifolia* L.	X			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	E:ES		
340	*S. media* Franz Schmidt	X				X							X			X	X			E:Eu		
341	*S. salicifolia* L.	X				X	X	X	X	X	X	X	X	X		X	X	X	X	E:SF		
342	*Sorbaria sorbifolia* (L.) A. Br.	X			X	X	X	X	X	X	X	X	X	X				X	X	E:SF		

	SPECIES	GATCHINA		GATCH	INA	PAVLOV	TSARS	SELO	PETER	HOF		ORANI	STREL	SHUVA	LETNY	MIKH	TAVR	FTA	BOT	ORIG	ECO	ANTHRO
		Dvortsovy	*Sylvia*	*Zverinets*	*Priorat*	SKY	*Ekaterin*	*Alexandr*	*Verkhny*	*Nizhny*	*Alexan*	ENBAUM	NA	LOVSKY								
343	*Cotoneaster lucidus* Schlecht	X				X	X	X	X	X	X	X	X	X	X	X	X	X	X	E:Sib		
344	*Pyrus communis* L.								X	X		X		X						E		
345	*Malus domestica* Borkh.	X			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	E		
346	*Sorbus aucuparia* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	1	UN
347	*Aronia melanocarpa* (Michaux) Elliott								X											E:Am		
348	*Amelanchier spicata* (Lam.) C. Koch	X				X	X	X	X	X	X	X	X	X	X					E:Am		
349	*Prunus domestica* L.			X																E		
350	*Crataegus laevigata* (Poir.) DC								X											E		
351	*C. monogyna* Jacq.				X										X					E:Eu		
352	*C. sanguinea* Pall						X		X	X		X			X	X	X			E:ES		
353	*C. submollis* Sarg.						X													E:Am		
354	*Rubus idaeus* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X			X		N	1	UN
355	*R. saxatilis* L.	X	X	X	X	X	X	X	X	X	X	X	X	X						N	3	UPHO
356	*Fragaria moschata* (Duch.) Weston	X	X	X	X	X	X	X		X	X	X	X	X						N	3	UPHO
357	*F. vesca* L.	X	X	X	X	X	X	X	X	X	X	X	X	X					X	N	3	UPHO
358	*Pentaphylloides fruticosa* (L.) O. Schwartz	X				X	X					X						X		E:FEA		
359	*Comarum palustre* L.	X	X	X	X	X	X	X	X	X	X	X	X	X						N	5	UPHO
360	*Potentilla anserina* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	6	UPHI
361	*P. goldbachii* Rups.					X														N	3	UPHO
362	*P. argentea* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X			X	X	N	4	UN
363	P. erecta (L.) Raeusch.	X	X	X	X	X	X	X	X	X	X	X	X	X					X	N	4	UPHO
364	*P. intermedia* L.					X	X	X	X	X										N	3	UN
365	*P. norvegica* L.											X		X				X	X	N	7	UN
366	*Geum aleppicum* Jacq.					X				X				X						N	3	UN
367	*G. x intermedium* Ehrh.																	X		N	3	UPHO
368	*G. macrophyllum* Willd.													X					X	A		
369	*G. rivale* L.	X	X	X	X	X	X	X	X	X	X	X	X	X				X	X	N	5	UPHO
370	*G. urbanum* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	6	UPHI
371	*Filipendula ulmaria* (L.) Maxim.	X	X	X	X	X	X	X	X	X	X	X	X	X	X			X	X	N	5	UN
372	*Alchemilla vulgaris* s.l.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	4	UN
373	*Rosa acicularis* Lindl.	X			X	X	X	X		X	X	X								N	3	UN
374	*R. majalis* Herrm.	X			X	X	X	X		X	X	X	X	X						N	3	UPHO

Table 1. List of Higher Vascular Plants in Historical Parks and Gardens of St. Petersburg

	SPECIES	GATCHINA		GATCH	INA	PAVLOV	TSARS	SELO	PETER	HOF		ORANI	STREL	SHUVA	LETNY	MIKH	TAVR	FTA	BOT	ORIG	ECO	ANTHRO
		Dvortsovy	*Sylvia*	*Zverinets*	*Priorat*	SKY	*Ekaterin*	*Alexandr*	*Verkhny*	*Nizhny*	*Alexan*	ENBAUM	NA	LOVSKY								
375	*R. rugosa* Thunb.	X			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	E:FE		
376	*Cerasus vulgaris* Mill								X	X		X		X						E		
377	*Padus avium* Mill.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	1	UN
378	*P. maackii* (Rupr.) Kom.							X										X		E:FE		
379	*P. virginiana* (L.) Mill.								X											E:Am		
	FABACEAE																					
380	*Lupinus polyphyllus* Lindl.								X									X		G		
381	*Medicago lupulina* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X			X	X	N	4	UN
382	*M. sativa* L.								X	X								X		G		
383	*Melilotus albus* Medik.	X		X	X	X	X	X	X	X	X	X	X	X	X			X	X	N	6	UPHI
384	*M. officinalis* (L.) Pall.	X			X		X	X	X	X	X	X	X	X				X		N	6	UPHI
385	*Chrysaspis spadicea* (L.) Greene			X		X				X										N	4	UPHO
	(*Trifolium spadiceum* L.)																					
386	*Amoria hybrida* (L.) C. Presl	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	4	UN
	(*Trifolium hybridum* L.)																					
387	*A. repens* (L.) C. Presl (Trifolium repens L	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	4	UN
388	*Trifolium medium* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	4	UN
389	*T. pratense* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	4	UN
390	*Lotus corniculatus* L.	X		X	X	X			X	X		X	X							N	4	UN
391	*Caragana arborescens* Lam.	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	E:SF		
392	*C. frutex* (L.) C. Koch					X	X	X	X	X	X	X	X		X	X				E:ES		
393	*Vicia cracca* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	4	UN
394	*V. sepium* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	4	UN
395	*V. sylvatica* L.											X								N	1	UPHO
396	*Lathyrus palustris* L.			X															X	N	5	UPHO
397	*L. pratensis* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	4	UN
398	*L. vernus* (L.) Bernh.	X	X	X	X	X		X		X		X								N	1	UPHO
	GERANIACEAE																					
399	*Geranium palustre* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X			X	X	N	5	UN
400	*G. phaeum* L.																		X	G		
401	*G. pratense* L.			X	X		X	X	X	X	X	X	X	X					X	N	4	UPHO
402	*G sibiricum* L.																		X	G	5	UPHI

	SPECIES	GATCHINA		GATCH INA		PAVLOV SKY	TSARS SELO		PETER HOF			ORANI ENBAUM	STREL NA	SHUVA LOVSKY	LETNY	MIKH	TAVR	FTA	BOT	ORIG	ECO	ANTHRO
		Dvortsovy	*Sylvia*	*Zverinets*	*Priorat*		*Ekaterin*	*Alexandr*	*Verkhny*	*Nizhny*	*Alexan*											
403	*G. sylvaticum* L.	X	X	X	X	X	X	X		X	X	X	X	X					X	N	3	UPHO
	OXALIDACEAE																					
404	*Oxalis acetosella* L.	X	X	X	X	X	X	X	X	X	X	X	X	X		X		X	X	N	1	UPHO
405	*Xanthoxalis fontana* (Bunge) Holub														X			X	X	A		
	POLYGALACEAE																					
406	*Polygala amarella* Crantz			X																N	3	UPHO
407	*P. comosa* Schkuhr			X																N	3	UPHO
408	*P. vulgaris* L.			X			X	X		X	X	X	X							N	3	UPHO
	EUPHORBIACEAE																					
409	*Mercurialis perennis* L.	X	X	X	X															N	1	UPHO
410	*Euphorbia dulcis* L.					X														A		
411	*E. helioscopia* L.																	X	X	N	6	UPHI
412	*E. peplus* L.																		X	N		
413	*E. virgata* Waldst & Kit.					X			X					X						N	6	UPHI
	CALLITRICHACEAE																					
414	*Callitriche palustris* L.	X	X	X	X	X	X	X		X	X	X	X	X		X		X		N	5	UN
	CELASTRACEAE																					
415	*Euonymus europaea* L.														X					E:Eu		
	ACERACEAE																					
416	*Acer ginnala* Maxim.							X		X				X	X			X		E:FE		
417	*A. negundo* L.						X					X		X		X	X	X		E:Am		
418	*A. platanoides* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	1	UN
419	*A. saccharinum* L.						X													E:Am		
420	*A. tataricum* L.						X	X	X	X						X				E:ES		
	HIPPOCASTANACEAE																					
421	*Aesculus hippocastanum* L.	X					X		X	X		X			X	X	X	X		E:Eu		
	BALSAMINACEAE																					
422	*Impatiens noli-tangere* L.	X	X	X	X	X	X	X		X	X	X	X	X				X		N	5	UPHO
423	*I. parviflora* DC.	X			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	A		
	RHAMNACEAE																					
424	*Frangula alnus* Mill.	X	X	X	X	X	X	X		X	X	X	X	X				X		N	1	UN
425	*Rhamnus cathartica* L.	X					X					X	X		X	X	X	X		N	1	UN

	SPECIES	GATCHINA		GATCH INA		PAVLOV	TSARS	SELO	PETER	HOF		ORANI	STREL	SHUVA	LETNY	MIKH	TAVR	FTA	BOT	ORIG	ECO	ANTHRO
		Dvortsovy	*Sylvia*	*Zverinets*	*Priorat*	SKY	*Ekaterin*	*Alexandr*	*Verkhny*	*Nizhny*	*Alexan*	ENBAUM	NA	LOVSKY								
	VITACEAE																					
426	*Parthenocissus quinquefolia* (L.) Planch.						X	X	X	X	X	X	X	X				X	X	E:Am		
	TILIACEAE																					
427	*Tilia cordata* Mill.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	1	UN
428	*T. europaea* L.						X	X	X	X		X								E:Eu		
429	*T. platyphyllos* Scop.						X	X	X	X		X			X					E:Eu		
430	*T. x vulgaris* Hayne						X		X											E:Eu		
	MALVACEAE																					
431	*Malva pusilla* Smith																		X	N	6	UPHI
	HYPERICACEAE																					
432	*Hypericum maculatum* Crantz	X	X	X	X	X	X	X	X	X	X	X	X	X	X			X	X	N	4	UN
	VIOLACEAE																					
433	*Viola arvensis* Murr.	X		X	X	X	X	X	X	X	X	X	X	X				X		N	6	UPHI
434	*V. canina* L.	X	X	X	X	X	X	X	X	X	X	X	X	X				X		N	3	UPHO
435	*V. collina* Bess.			X	X															N	3	UPHO
436	*V. epipsila* Ledeb.	X	X	X	X	X	X	X	X	X	X	X	X	X						N	5	UPHO
437	*V. mirabilis* L.	X		X	X	X														N	1	UPHO
438	*V. odorata* L.	X																		A		
439	*V. palustris* L.	X	X	X	X	X	X	X	X	X	X	X	X	X				X		N	5	UPHO
440	*V. riviniana* Reichenb.	X		X	X	X	X	X		X	X	X	X					X	X	N	3	UPHO
441	*V. tricolor* L.																		X	N	6	UPHI
	ELAEAGNACEAE																					
442	*Elaeagnus argentea* Pursh							X		X										E:AM		
	LYTHRACEAE																					
443	*Lythrum salicaria* L.	X	X	X	X	X	X	X		X	X	X	X	X					X	N	5	UPHO
	ONAGRACEAE																					
444	*Epilobium ciliatum* Rafin.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	6	UPHI
445	*E. hirsutum* L.	X	X	X	X	X	X	X	X	X	X	X	X	X				X	X	N	5	UN
446	*E. montanum* L.	X	X	X	X	X						X		X	X			X	X	N	3	UN
447	*E. palustre* L.	X	X	X	X	X	X	X		X	X	X	X	X						N	5	UPHO
448	*Chamaenerion angustifolium* (L.) Scop.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	7	UN

Table 1. List of Higher Vascular Plants in Historical Parks and Gardens of St. Petersburg

	SPECIES	GATCHINA		GATCH INA		PAVLOV	TSARS SELO		PETER HOF			ORANI	STREL	SHUVA	LETNY	MIKH	TAVR	FTA	BOT	ORIG	ECO	ANTHRO
		Dvortsovy	*Sylvia*	*Zverinets*	*Priorat*	SKY	*Ekaterin*	*Alexandr*	*Verkhny*	*Nizhny*	*Alexan*	ENBAUM	NA	LOVSKY								
	HALORAGACEAE																					
449	*Myriophyllum sibiricum* Kom.						X			X	X			X						N	5	UPHO
	HIPPURIDACEAE																					
450	*Hippuris vulgaris* L.	X		X			X													N	5	UPHO
	APIACEAE																					
451	*Chaerophyllum aureum* L.					X													X	E:Eu		
452	*C. bulbosum* L.																		X	G		
453	*C. hirsutum* L.																		X	G		
454	*Anthriscus sylvestris* (L.) Hoffm.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	1	UN
455	*Cicuta virosa* L.	X	X	X	X	X	X	X	X	X	X	X	X	X						N	5	UPHO
456	*Carum carvi* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	4	UN
457	*Pimpinella major* (L.) Huds.			X		X	X													N	3	UPHO
458	*P. saxifraga* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X			X		N	3	UN
459	*Aegopodium podagraria* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	1	UN
460	*Angelica archangelica* L.					X							X						X	N	5	UPHO
461	*A. sylvestris* L.	X	X	X	X	X	X	X	X	X	X	X	X	X				X		N	3	UN
462	*Thyselinum palustre* (L.) Rafin																					
	(*Peucedanum palustre* (L.) Moench)	X	X	X	X	X	X	X	X	X	X	X	X	X						N	5	UPHO
463	*Pastinaca sativa* L.									X										G		
464	*Heracleum sibiricum* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	4	UN
465	*H. sosnowskyi* Manden.													X				X	X	G		
466	*H. sphondylium* L.	X				X														N	1	UPHO
467	*Aetusa cynapium* L.																		X	G		
468	*Astrantia major* L.					X													X	G		
	CORNACEAE																					
469	*Swida sericea* (L.) Holub (*Swida*																					
	stolonifera (Michx.) Rydb.)	X		X	X	X	X	X		X	X	X	X	X		X	X	X	X	E:Am		
	PYROLACEAE																					
470	*Pyrola minor* L.			X								X								N	1	UPHO
471	*P. rotundifolia* L.	X	X	X	X	X	X	X		X	X	X		X						N	1	UPHO
472	*Moneses uniflora* (L.) A. Gray			X																N	1	UPHO
473	*Orthilia secunda* (L.) House	X	X	X	X	X		X			X	X		X						N	1	UPHO

Table 1. List of Higher Vascular Plants in Historical Parks and Gardens of St. Petersburg

	SPECIES	GATCHINA		GATCH	INA	PAVLOV	TSARS	SELO	PETER	HOF		ORANI	STREL	SHUVA	LETNY	MIKH	TAVR	FTA	BOT	ORIG	ECO	ANTHRO
		Dvortsovy	*Sylvia*	*Zverinets*	*Priorat*	SKY	*Ekaterin*	*Alexandr*	*Verkhny*	*Nizhny*	*Alexan*	ENBAUM	NA	LOVSKY								
	ERICACEAE																					
474	*Ledum palustre* L.					X														N	5	UPHO
475	*Calluna vulgaris* (L.) Hull					X						X								N	1	UPHO
476	*Vaccinium myrtillus* L.	X	X	X	X	X		X		X	X	X		X				X		N	1	UPHO
477	*V. uliginosum* L.	X	X	X	X	X						X								N	5	UPHO
478	*V. vitis-idaea* L.	X	X	X	X	X		X		X	X	X		X						N	1	UPHO
	PRIMULACEAE																					
479	*Primula elatior* (L.) Hill	X		X															X	N	3	UPHO
480	*P. veris* L.	X	X	X	X		X					X						X	X	N	3	UPHO
481	*Lysimachia nummularia* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X			X	X	N	4	UN
482	*L. punctata* L.					X														E:Eu		
483	*L. vulgaris* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	5	UN
484	*Naumburgia thyrsiflora* (L.) Reichenb.	X	X	X	X	X	X	X		X	X	X	X	X					X	N	5	UPHO
485	*Trientalis europaea* L.	X	X	X	X	X	X	X		X	X	X	X	X				X		N	1	UPHO
	OLEACEAE																					
486	*Fraxinus excelsior* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	1	UN
487	*F. pennsylvanica* Marsh.												X							E:Am		
488	*Syringa amurensis* Rupr.							X												E:FE		
489	*S. josikaea* Jacq. fil.	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	E:Eu		
490	*S. vulgaris* L.	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	E:Eu		
	MENYANTHACEAE																					
491	*Menyanthes trifoliata* L.		X	X								X								N	5	UPHO
	APOCYNACEAE																					
492	*Vinca minor* L.					X														G		
	CONVOLVULACEAE																					
493	*Convolvulus arvensis* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	6	UPHI
494	*Calystegia sepium* (L.) R. Br.	X	X	X	X	X		X	X	X	X	X	X	X				X	X	N	5	UN
	BORAGINACEAE																					
495	Symphytum *officinale* L.	X				X	X	X	X	X	X	X	X	X				X	X	N	5	UN
496	*Pulmonaria obscura* Dumort	X			X	X				X		X							X	N	1	UPHO
497	*Myosotis arvensis* (L.) Hill	X					X	X	X	X	X	X	X	X	X	X		X	X	N	6	UPHI
498	*M. caespitosa* K. F. Schultz	X		X			X	X		X				X						N	5	UPHO

	SPECIES	GATCHINA		GATCH	INA	PAVLOVSKY	TSARS	SELO	PETER	HOF		ORANIENBAUM	STRELNA	SHUVALOVSKY	LETNY	MIKH	TAVR	FTA	BOT	ORIG	ECO	ANTHRO
		Dvortsovy	*Sylvia*	*Zverinets*	*Priorat*		*Ekaterin*	*Alexandr*	*Verkhny*	*Nizhny*	*Alexan*											
499	*M. micrantha* Pall. ex Lehm.																		X	N	5	UPHO
500	*M. palustris* (L.) L.	X	X	X	X	X	X	X	X	X	X	X	X	X				X	X	N	2	UN
501	*M. sparsiflora* Pohl								X	X				X					X	N	1	UPHO
502	*M. sylvatica* Ehrh. ex Hoffm.	X	X	X		X						X							X	A		
	LAMIACEAE																					
503	*Ajuga reptans* L.	X		X			X	X	X	X	X	X							X	N	3	UPHO
504	*Scutellaria galericulata* L.	X	X	X	X	X		X	X	X	X	X	X	X						N	5	UPHO
505	*Nepeta cataria* L.																		X	A		
506	*Glechoma hederacea* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	3	UN
507	*Prunella vulgaris* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	4	UN
508	*Galeopsis bifida* Boenn.	X	X						X	X									X	N	6	UPHI
509	*G. speciosa* Mill						X			X								X		N	6	UPHI
510	*G. tetrahit* L.	X	X	X	X	X	X	X	X	X	X	X	X	X						N	6	UPHI
511	*Lamium album* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	6	UPHI
512	*L. purpureum* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	6	UPHI
513	*Galeobdolon luteum* L.	X	X	X	X	X						X		X						N	1	UPHO
514	*Stachys officinalis* (L.) Trev. (*Betonica officinalis* L.)											X								N	3	UPHO
515	*S. palustris* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	N	5	UPHI
516	*S. sylvatica* L.				X									X						N	1	UPHO
517	*Clinopodium vulgare* L.				X															N	3	UPHO
518	*Thymus serpyllum* L.					X														N	3	UPHO
519	*Lycopus europaeus* L.	X	X	X	X	X	X	X	X	X	X	X	X	X			X	X	X	N	5	UN
520	*Mentha arvensis* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	5	UN
	SOLANACEAE																					
521	*Solanum dulcamara* L.	X	X	X	X	X	X	X	X	X	X	X	X	X				X	X	N	5	UPHO
522	*S. nigrum* L.																	X		N	6	UPHI
	SCHROPHULARIACEAE																					
523	*Verbascum nigrum* L.												X						X	N	4	UN
524	*V. thapsus* L.																		X	N	7	UN
525	*Linaria vulgaris* L.	X	X	X	X	X	X	X	X	X	X	X	X	X			X	X	X	N	6	UPHI
526	*Chaenorhinum minus* (L.) Lange												X						X	N	6	UPHI

	SPECIES	GATCHINA		GATCH	INA	PAVLOV	TSARS	SELO	PETER	HOF		ORANI	STREL	SHUVA	LETNY	MIKH	TAVR	FTA	BOT	ORIG	ECO	ANTHRO
		Dvortsovy	*Sylvia*	*Zverinets*	*Priorat*	SKY	*Ekaterin*	*Alexandr*	*Verkhny*	*Nizhny*	*Alexan*	ENBAUM	NA	LOVSKY								
527	*Scrophularia nodosa* L.	X	X	X	X	X	X	X		X	X	X	X	X				X	X	N	1	UN
528	*Veronica agrestis* L.											X							X	N	6	UPHI
529	*V. anagalis-aquatica* L.			X						X			X							N	5	UPHO
530	*V. arvensis* L.																	X		N	6	UPHI
531	*V. beccabunga* L.	X			X					X		X		X						N	5	UPHO
532	*V. chamaedrys* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	3	UN
533	*V. filiformis* Smith																	X	X	A		
534	*V. longifolia* L.			X			X	X		X		X	X	X						N	5	UN
535	*V. officinalis* L.	X	X	X	X	X		X		X	X	X		X						N	1	UPHO
536	*V. opaca* Fries						X												X	N	6	UPHI
537	*V. peregrina* L.																		X	A		
538	*V. persica* Poir.						X													A		
539	*V. serpyllifolia* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X			X	X	N	4	UN
540	*Melampyrum nemorosum* L.	X	X	X	X	X	X	X		X	X	X	X	X						N	3	UPHO
541	*M. pratense* L.	X	X	X	X	X						X		X						N	1	UPHO
542	*Euphrasia parviflora* Schag.	X	X	X	X	X						X								N	4	UPHO
543	*Odontites vulgaris* Moench	X	X	X	X	X	X	X	X	X	X	X	X	X				X		N	4	UPHO
544	*Rhinanthus minor* L.			X		X					X			X						N	4	UPHO
545	*R. vernalis* (N.Zing.) Schischk & Serg.				X	X	X					X		X						N	4	UPHO
546	*Pedicularis palustris* L.					X														N	5	UPHO
547	*Lathraea squamaria* L.																		X	N	1	UPHO
	OROBANCHACEAE																					
548	*Orobanche pallidiflora* Wimm. & Grab.				X															N	5	UPHO
	LENTIBULARIACEAE																					
549	*Utricularia vulgaris* L.													X					X	N	5	UPHO
	PLANTAGINACEAE																					
550	*Plantado lanceolata* L.				X	X			X	X	X	X								N	4	UPHO
551	*P. major* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	6	UPHI
552	*P. media* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	N	4	UN
	RUBIACEAE																					
553	*Galium album* Mill.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	4	UN
554	*G. boreale* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X					N	1	UPHO

	SPECIES	GATCHINA		GATCH INA		PAVLOV SKY	TSARS SELO		PETER HOF			ORANI ENBAUM	STREL NA	SHUVA LOVSKY	LETNY	MIKH	TAVR	FTA	BOT	ORIG	ECO	ANTHRO
		Dvortsovy	*Sylvia*	*Zverinets*	*Priorat*		*Ekaterin*	*Alexandr*	*Verkhny*	*Nizhny*	*Alexan*											
555	*G. palustre* L.	X	X	X	X	X	X	X	X	X	X	X	X	X					X	N	5	UPHO
556	*G. uliginosum* L.	X	X	X	X	X	X	X		X	X	X	X	X				X	X	N	5	UPHO
557	*G. verum* L.		X	X		X	X	X	X	X			X						X	N	4	UPHO
	SAMBUCACEAE																					
558	*Sambucus racemosa* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	2	UN
	VIBURNACEAE																					
559	*Viburnum lantana* L.						X	X	X	X	X	X			X					E:Eu		
560	*V. opulus* L.	X	X	X	X	X	X	X	X	X	X	X	X	X			X	X	X	N	1	UN
	CAPRIFOLIACEAE																					
561	*Symphoricarpos rivularis* Suksdorf	X			X	X	X	X	X	X	X	X			X	X	X	X	X	E:Am		
562	*Lonicera caprifolium* L.								X											E:Eu		
563	*L. tatarica* L.	X				X	X	X	X	X	X	X	X	X	X	X	X	X	X	E:ES		
564	*L. xylosteum* L.	X	X	X	X	X	X	X	X	X	X	X	X	X				X		N	1	UPHO
	VALERIANACEAE																					
565	*Valeriana dioica* L.			X																N	1	UPHO
566	*Valeriana officinalis* L.	X	X		X		X	X				X	X						X	N	5	UPHO
	DIPSACACEAE																					
567	*Knautia arvensis* (L.) Coult.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	N	3	UN
568	*Succisa pratensis* Moench	X	X	X	X	X		X						X						N	3	UPHO
	CUCURBITACEAE																					
569	*Echinocystis lobata* (Michx.) Torr. & Gray																		X	E:Am		
	CAMPANULACEAE																					
570	*Campanula glomerata* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X			N	4	UN
571	*C. latifolia* L.					X												X		N	1	UPHO
572	*C. patula* L.	X	X	X	X	X	X	X	X	X	X	X	X	X					X	N	4	UPHO
573	*C. persicifolia* L.	X																	X	N	3	UPHO
574	*C. rapunculoides* L.	X				X		X	X	X	X	X	X	X	X			X	X	N	6	UPHI
575	*C. rotundifolia* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X				X	N	3	UN
576	*C. trachelium* L.					X		X		X		X	X							N	1	UPHO
577	*Phyteuma orbiculare* L.			X																N	3	UPHO
578	*P. nigrum* F. W. Schmidt											X								N	1	UPHO
579	*P. spicatum* L.			X								X								N	1	UPHO

	SPECIES	GATCHINA		GATCH INA		PAVLOV	TSARS SELO		PETER HOF			ORANI	STREL	SHUVA	LETNY	MIKH	TAVR	FTA	BOT	ORIG	ECO	ANTHRO
		Dvortsovy	*Sylvia*	*Zverinets*	*Priorat*	SKY	*Ekaterin*	*Alexandr*	*Verkhny*	*Nizhny*	*Alexan*	ENBAUM	NA	LOVSKY								
	ASTERRACEAE																					
580	*Solidago canadensis* L.																		X	G		
581	*S. virgaurea* L.	X	X	X	X	X	X	X	X	X	X	X	X	X				X	X	N	3	UN
582	*Bellis perennis* L.	X		X		X	X	X	X	X		X								G		
583	*Aster x salignus* Willd.	X			X			X		X		X								G		
584	*Phalacroloma annuum* (L.) Dumort																					
	(*Erigeron annuus* (L.) Pers.)																		X	A		
585	*Conyza canadensis* (L.) Cronq.																					
	(*Erigeron canadensis* L.)	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		A		
586	*Gnaphalium uliginosum* L.	X	X	X	X	X	X	X	X	X	X	X	X	X			X	X	X	N	7	UPHI
587	*Omalotheca sylvatica* (L.) Sch.Bip & F.																					
	Schultz (*Gnaphalium sylvaticum* L.)			X	X	X				X			X							N	4	UPHO
588	*Inula helenium* L.																		X	G		
589	*Bidens cernua* L.				X	X	X	X				X		X						N	5	UN
590	*B. tripartita* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	5	UN
591	*Galinsoga ciliata* (Rafin.) Blake														X			X		A		
592	*G. parviflora* Cav.																X			A		
593	*Achillea millefolium* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	4	UN
594	*Ptarmica vulgaris* Hill	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X		N	4	UN
	(Achillea ptarmica L.)																					
595	*Leucanthemum vulgare* Lam.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	4	UN
596	*Matricaria recutita* L.																		X	A		
597	*Lepidotheca suaveolens* (Pursh)Nutt.																					
	(*Matricaria matricarioides* (Less.) Porter)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	6	UPHI
598	*Tripleurospermum perforatum* (Merat) M.																					
	(*T. inodorum* (L.) Sch. Bip.)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	A		
599	*Tanacetum vulgare* L.	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X		N	6	UPHI
600	*Artemisia vulgaris* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	6	UPHI
601	*A. campestris* L.								X				X					X		N	6	UPHI
602	*Tussilago farfara* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	6	UPHI
603	*Petasites hybridus* (L.) Gaertn., Mey &																					
	Scherb.					X	X	X		X	X	X	X							A		

	SPECIES	GATCHINA		GATCH INA		PAVLOV	TSARS SELO		PETER HOF			ORANI	STREL	SHUVA	LETNY	MIKH	TAVR	FTA	BOT	ORIG	ECO	ANTHRO
		Dvortsovy	*Sylvia*	*Zverinets*	*Priorat*	SKY	*Ekaterin*	*Alexandr*	*Verkhny*	*Nizhny*	*Alexan*	ENBAUM	NA	LOVSKY								
604	*Senecio aguaticus* Hill			X																N	5	UPHO
605	*S. sylvaticus* L.											X							X	N	3	UPHO
606	*S. viscosus* L.									X		X	X							N	6	UPHO
607	*S. vulgaris* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	6	UPHI
608	*Arctium tomentosum* Mill.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	6	UPHI
609	*Carduus crispus* L.	X	X	X	X	X	X	X	X	X	X	X	X	X				X	X	N	6	UPHI
610	*Cirsium arvense* (L.) Scop.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	6	UPHI
611	*C. canum* (L.) All.																		X	G		
612	*C. heterophyllum* (l.) Hill.	X	X	X	X	X	X	X	X	X	X	X	X	X				X		N	3	UN
613	*C. palustre* (L.) Scop.		X	X	X	X		X		X	X	X	X	X						N	5	UPHO
614	*C. oleraceum* (L.) Scop	X	X	X	X	X	X	X	X	X	X	X	X	X						N	1	UPHO
615	*C. rivulare* (Jacq.) All.			X																N	5	UPHO
616	*Centaurea jacea* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	4	UN
617	*C. phrigia* L.	X	X	X	X	X	X	X			X	X	X	X						N	3	UPHO
618	*C. scabiosa* L.	X		X																N	3	UPHO
619	*Cichorium intybus* L.																		X	N	6	UPHI
620	*Lapsana communis* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	2	UN
621	*L. intermedia* Bieb.					X														N	1	UPHO
622	*Leontodon autumnalis* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	4	UN
623	*L. hispidus* L.	X		X	X	X						X								N	4	UPHO
624	*Picris hieracioides* L.				X			X												N	3	UPHO
625	*Tragopogon pratensis* L.			X	X	X	X	X	X	X	X	X	X							N	4	UPHO
626	*Taraxacum officinale* Wigg.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	6	UPHI
627	*T. hollandicum* Soest			X																N	4	UPHI
628	*Sonchus arvensis* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	6	UPHI
629	*S. asper* (L.) Hill																		X	N	6	UPHI
630	*S. oleraceus* L.								X	X									X	N	6	UPHI
631	*Cicerbita macrophylla* (Willd.) Wallr.																		X	G		
632	*Lactuca sibirica* (L.) Maxim.									X										N	3	UPHO
633	*Crepis mollis* (Jacq.) Aschers.			X								X								N	3	UPHO
634	*C. paludosa* (L.) Moench	X	X	X	X	X	X	X	X	X	X	X	X	X				X		N	5	UN
635	*C. praemorsa (* L.) Tausch				X															N	3	UPHO

Table 1. List of Higher Vascular Plants in Historical Parks and Gardens of St. Petersburg

	SPECIES	GATCHINA		GATCH INA		PAVLOV	TSARS	SELO	PETER	HOF		ORANI	STREL	SHUVA	LETNY	MIKH	TAVR	FTA	BOT	ORIG	ECO	ANTHRO
		Dvortsovy	*Sylvia*	*Zverinets*	*Priorat*	SKY	*Ekaterin*	*Alexandr*	*Verkhny*	*Nizhny*	*Alexan*	ENBAUM	NA	LOVSKY								
636	*C. tectorum* L.							X												N	7	UN
637	*Hieracium aurantiacum* L.																		X	G		
638	*H. caespitosum* Dumort.																		X	N	3	UPHO
639	*H. dubium* L.																		X	N	3	UPHO
640	*H. hypoglaucum* (Litv. & Zahn) Juxip																					
	(*H. prenanthoides* auct.)			X																N	3	UPHO
641	*H. lactucella* Wallr.													X						N	3	UPHO
642	*H. murorum* s.l.	X	X	X	X	X	X	X	X	X	X	X	X	X						N	3	UN
643	*H. pilosella* L.			X															X	N	3	UPHO
644	*H. rossicum* Schljak.				X															N	3	UPHO
645	*H. umbellatum* L.	X	X	X	X	X	X	X	X	X	X	X	X	X	X			X		N	3	UN
646	*H. vulgatum* s.l.	X		X	X	X				X		X								N	3	UPHO