

## URBAN ECOLOGICAL LAND-COVER MAPPING FOR NEW YORK CITY

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*October 16, 2014*

*Please cite report as:*

O'Neil-Dunne, J.P.M., S.W. MacFaden, H.M. Forgione, and J.W.T. Lu. 2014. Urban ecological land-cover mapping for New York City. Final report to the Natural Areas Conservancy. Spatial Informatics Group, University of Vermont, Natural Areas Conservancy, and New York City Department of Parks & Recreation. 22 pp.

## Summary

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An urban ecological land-cover map containing 37 unique classes was created for New York City using object-based imagery analysis (OBIA) techniques in conjunction with multispectral orthoimagery, Light Detection and Ranging (LIDAR) data, and thematic Geographic Information System (GIS) layers. Based on a classification scheme adapted from the United States National Vegetation Classification (NVC), the new map included a mix of ecological and anthropogenic features mapped across four hierarchical levels of detail: 1) basic land cover; 2) land-cover sub-classes; 3) NVC Group; and 4) NVC Association. All ecologically-relevant classes were mapped to the NVC Group level, and a subset of 9 classes were mapped to the NVC Association level. An accuracy assessment conducted on the Level 2 map indicated an overall accuracy of 92%, a high classification rate attributable in part to the efficient mapping of widely-distributed upland forest classes. However, Forested Wetlands and other uncommon wetland features were mapped with much lower accuracy, suffering particularly from high rates of omission. Insufficient reference data were available to conduct a quantitative accuracy assessment for the Level 3 and Level 4 NVC classes, but the quality of these classes likely varied by data input (i.e., high for classes based on expert opinion, lower for classes based on spectral criteria). The current map will serve as baseline documentation for monitoring and protection of New York City's most important ecological features, and subsequent versions could be materially improved by advances in wetlands mapping and additional field-based expert opinion.

## Methods

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The workflow for ecological mapping first focused on development of a classification scheme that would provide the highest possible level of detail while remaining technologically feasible and time efficient, given the available processing methods and input datasets. After collecting or developing all pre-existing remote-sensing datasets and GIS layers, the mapping process used automated feature extraction informed by expert opinion and experimentation to produce a draft ecological map. The draft map was reviewed for accuracy and visual coherence, and obvious modeling errors and other non-systematic inconsistencies were removed with manual editing. An accuracy assessment was then performed on the Level 2 map to help gauge the final product's quality and subsequent applicability to natural resources modeling and assessment.

## Development of Classification Hierarchy

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The United States National Vegetation Classification (NVC) is a hierarchical classification scheme that describes natural vegetation assemblages at a series of scales ranging from broad growth forms such as forests and grasslands (i.e., Formation level) to diagnostic plant species (i.e., Association level) (USNVC 2014). For mapping ecological features in New York City, NVC provided a framework for identifying the vegetation classes that are known to occur in the region and could be reliably mapped with the available source data. The overall goal was to map all relevant ecological features to the Association level, but *a priori* it was clear that many classes would be limited to the Group level, which is a step above Associations (the Alliance level technically occurs between Groups and Associations but has not been fully implemented in the NVC scheme). Groups describe sets of diagnostic species with similar composition and growth forms (e.g., Oak-Pine Forest and Woodland). Working with the Natural Areas Conservancy (NAC) and the New York City Department of Parks & Recreation (NYC DPR), a hybrid

scheme was created that identified all pertinent ecological features to the Group level (Level 3) and a subset of these features to the Association level (Table 1). Anthropogenic features were restricted to Levels 1 and 2. Specifically:

### Level 1

Basic land-cover features were adapted from a high-resolution, 7-class land-use\land-cover (LULC) map previously produced for New York City by MacFaden et al. (2012). This classification included features clearly anthropogenic in origin (*Buildings, Roads\Railroads, Other Paved Surfaces, Bare Soil*) as well as landscape elements that may be either anthropogenic or natural (*Tree Canopy, Grass\Shrubs, Water*). Wetlands were not mapped in the basic classification; emergent and scrub\shrub wetlands were grouped into the *Grass\Shrubs* class while forested wetlands were included in *Tree Canopy*.

### Level 2

Land-cover sub-classes were created by adding sub-divisions to the original 7-class LULC map, producing a 14-class map. For example, *Tree Canopy* representing trees growing with minimal human influence or distant from highly-developed areas was divided into *Upland Forest, Maritime Forest, and Forested Wetland*. Tree canopy in dense urban areas was assigned to a fourth sub-division, *Other Tree Canopy*; this class included trees likely to be isolated stems, street trees, or highly-managed plantings. Similarly, *Grass\Shrubs* encompassing naturally-occurring vegetation was divided into *Upland Grass\Shrubs, Freshwater Wetlands, and Tidal Wetlands* while anthropogenic features were assigned to *Maintained Lawn\Shrubs*. Additional Level 2 classes were created from the original *Water* class: *Freshwater Aquatic Vegetation* and *Saltwater Aquatic Vegetation*. The Level 1 classes representing anthropogenic features were transferred unchanged into the lower tier.

### Level 3

Level 2 classes containing ecological features were further divided into 26 NVC Groups. *Freshwater Wetlands* contained the largest number and diversity of sub-classes, including tidal marshes, wet meadows, marshes, swamps, and disturbed (ruderal) wetlands dominated by invasive species (e.g., *Phragmites*). *Tidal Wetlands* was similarly diverse with multiple salt marsh groups, and *Upland Grass\Shrubs* contained ruderal meadows and coastal grasslands on beaches, sand barrens, and dunes. *Upland Forest* groups represented oak-hickory forests, northern hardwood-conifer complexes pitch pine barrens, plantations, and ruderal forests; *Forested Wetland* accommodated hardwood swamps, acidic swamps, and floodplains; and *Maritime Forest* included coastal scrub forests. The aquatic groups included freshwater plant assemblages and intertidal shore vegetation. *Other Tree Canopy, Maintained Lawn\Shrubs*, and the anthropogenic features from Level 1 were transferred unchanged into the third level.

### Level 4

*Upland Forest, Maritime Forest, and Saltwater Aquatic Vegetation* contained the only NVC Groups that could be identified at the Association level. The *Northeastern & North-Central Oak-Hickory Forest Group* (G158) was sub-divided into hardwood combinations: *Mid-Atlantic Mesic Mixed Hardwood Forest* (CEGL006075); *Coastal Oak-Hickory Forest* (CEGL006336 and CEGL006377); and *Serpentine Forest* (CEGL006438). The *Northern Hardwood-Hemlock-White Pine Forest Group* (G163) was also sub-divided: *Oak-Tulip Forest* (CEGL006125) and *Hemlock-Northern Hardwood Forest* (CEGL006566). A third *Upland Forest* group, *Pitch Pine Barrens* (G161) was not sub-divided but was narrowed to diagnostic species:

**Table 1. Classification hierarchy for New York City Urban Ecological Land-cover Map.**

<i>Level 1</i>	<i>Level 2</i>	<i>Level 3</i>	<i>NVC Group-level Class Name</i>	<i>Level 4</i>	<i>NVC Association-level Class Name</i>
Grass\Shrubs, Bare Soil	Freshwater Wetlands	G110	Atlantic & Gulf Coastal Plain Freshwater Tidal Marsh Group		
		G111	Atlantic & Gulf Coastal Plain Pondshore & Wet Prairie Group		
		G112	Eastern North American Wet Meadow Group		
		G125	Eastern North American Freshwater Marsh Group		
		G167	Northern & Central Shrub Swamp Group		
		G342	Eastern North American Lake Flat & Beach Group		
		G556	Northern & Central Ruderal Wet Meadow & Marsh Group		
	Tidal Wetlands	G120	North American Atlantic Brackish Tidal Marsh Group		
		G121	North American Atlantic High Salt Marsh Group		
		G122	North American Atlantic Low Salt Marsh Group		
	Upland Grass\Shrubs	G123	North American Atlantic Tidal Flat & Panne Group		
		G059	North & Central Ruderal Meadow & Shrubland Group		
		G063	Northern & Central Sand Barrens Group		
		G124	Eastern Coastal Beach Group		
		G493	Northern Atlantic Dune & Coastal Grassland & Shrubland Group		
Tree Canopy	Maintained Lawn\Shrubs				
	Forested Wetland	G038	Coastal Plain Hardwood Swamp Group		
		G040	Silver Maple-Green Ash-Sycamore Floodplain Group		
		G045	Northern & Central Conifer & Hardwood Acidic Swamp Group		
	Upland Forest	G030	Northern & Central Hardwood & Conifer Ruderal Forest Group		
		G032	Northern & Central Conifer & Hardwood Plantation Group		
		G158	Northeastern & North-Central Oak-Hickory Forest Group	G158_C EGL006075	Mid-Atlantic Mesic Mixed Hardwood Forest
				G158_C EGL006336_6377	Coastal Oak-Hickory Forest
				G158_C EGL006438	Serpentine Forest
	Maritime Forest	G161	Pitch Pine Barrens Group	G161_C EGL006372	Post Oak-Blackjack Oak Barrens
		G163	Northern Hardwood-Hemlock-White Pine Forest Group	G163_C EGL006125	Oak-Tulip Forest
				G163_C EGL006566	Hemlock-Northern Hardwood Forest
		G495	North Atlantic Maritime Scrub Forest Group	G495_C EGL006373	Maritime Post Oak Forest
				G495_C EGL006379_6145	Maritime Shrubland and Successional Maritime Forest
Water	Other Tree Canopy				
Buildings	Freshwater Aquatic Vegetation	G114	Eastern North American Freshwater Aquatic Vegetation Group		
		G387	North American North Atlantic Intertidal Shore Group	G387_C EGL006341	Rockweed (Pelham Bay Park rocky shore)
Roads\Railroads	Saltwater Aquatic Vegetation				
Other Paved Surfaces	Building				
Bare Soil	Roads\Railroads				
	Other Paved Surfaces				
	Bare Soil				

Level 1 = Classes derived from 2010 land-cover map for New York City

Level 2 = Land-cover sub-classes

Level 3 = Group-level National Vegetation Classification (NVC) classes

Level 4 = Association-level NVC classes

*Post Oak-Blackjack Oak Barrens* (G161\_C EGL006372). For *Maritime Forest*, the *North Atlantic Maritime Scrub Forest Group* (G495) was sub-divided into *Maritime Post Oak Forest* (CEGL006373) and *Maritime Shrubland and Successional Maritime Forest* (CEGL006379 and CEGL006145). Finally, the *North American North Atlantic Intertidal Shore Group* (G387) was narrowed to *Rockweed* (CEGL006341) occurring near Pelham Bay Park in the northern Bronx.

## Source Datasets

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The best available land cover, LiDAR derivatives, multispectral imagery, and thematic GIS datasets were obtained, processed, or created for use in ecological mapping (Table 2). These included:

### Land Cover

As described in MacFaden et al. (2012), the available 7-class LULC map was created using a combination of 2010 LiDAR acquired in 2010 and high-resolution (0.5 ft) orthoimagery acquired in 2008. Considered current as of 2010, this map included: *Tree Canopy*, *Grass\Shrubs*, *Bare Soil*, *Water*, *Buildings*, *Roads\Railroads*, and *Other Paved Surfaces*. Overall accuracy was 96%.

### LiDAR Derivatives

High-resolution (0.7 m, or 2.3 ft) LiDAR was acquired in 2010, as described in MacFaden et al. (2012). A series of derivatives were created for use in creating the 7-class LULC map, including a digital elevation model (DEM) that indicated the topographical elevations above sea level and a normalized digital surface model (nDSM) that indicated the aboveground height of all natural and anthropogenic features (i.e., both trees and buildings). A layer providing the standard deviation of height values (Z Deviation) was also created; it was useful for characterizing the texture of tree canopy (i.e., smooth, closely-spaced conifers vs. rough, heterogeneous deciduous canopy). For ecological mapping, these LiDAR derivatives were used in manual interpretation of thematic GIS layers (see below) and directly in classification.

### Multispectral Imagery

The most recent multispectral imagery available for New York City was 0.152-m (0.5-ft) resolution orthoimagery acquired in spring 2010. This imagery contained 4 spectral bands (Near Infrared, Red, Green, and Blue) and was acquired across at least several dates, creating a mix of leaf-off and partial leaf-on conditions; Manhattan was mostly leaf-on while the other four boroughs were leaf-off. The presence of the Near Infrared band permitted calculation of the Normalized Difference Vegetation Index (NDVI), which is useful for vegetation discrimination. Visible Brightness (sum of the Red, Green, and Blue bands) and textural indices (i.e., rough vs. smooth surfaces) were also commonly-used modeling variables derived from spectral properties.

### Thematic GIS Layers

Many GIS layers have been created for New York City that directly show important ecological features at various scales and level of precision, including water, wetlands, vernal pools, and soils. Similarly, many other layers exist that delineate elements of the built environment and can be used to help contextualize natural features among the city's natural features, including buildings and roads. All available datasets were obtained from NYC DPR and other New York City or New York State departments and examined for relevance to the NVC classification hierarchy. In addition to these pre-existing GIS layers, new datasets describing pertinent topographical features and approximate range maps for specific NVC groups were created when they would help guide and simplify classification. These layers were developed using manual data editing techniques in ArcGIS (ESRI, Redlands, California, USA), submitted to NAC and NYC DPR for expert review, and modified as necessary. For example, a map delineating the boundary between the coastal plain and the upland zones on the terminal moraine

**Table 2. Input datasets used to derive New York City Urban Ecological Land-cover Map.**

<b>Name</b>	<b>Source</b>	<b>Year</b>	<b>Comment</b>
<b><i>Land Cover</i></b>			
7-class land use/land cover (LULC)	MacFaden et al.	2010	0.152-m (0.5-ft) resolution
<b><i>LiDAR Derivatives</i></b>			
Digital Elevation Model (DEM)	MacFaden et al.	2010	Derived from 0.7-m (2.3-ft) LiDAR
Normalized Digital Surface Model (nDSM)	MacFaden et al.	2010	Derived from 0.7-m (2.3-ft) LiDAR
Standard Deviation of Height Values (Z Deviation)	MacFaden et al.	2010	Derived from 0.7-m (2.3-ft) LiDAR
<b><i>Multispectral Imagery</i></b>			
4-band Orthoimagery	NYC DOITT	2010	0.152-m (0.5-ft) imagery, mostly leaf off
<b><i>Thematic GIS Layers</i></b>			
Buildings	NYC DOITT	2012	Used to create building density map; specific layer: Buildings_1012.shp
Coastal Plain Boundary	In house	N/A	Based on manual interpretation of DEM and expert opinion of NYC DPR and NAC
Political Boundaries – Boroughs	NYC DCP	2004	Specific layer: nybbwi.shp
Range Map – G038 (Coastal Plain Hardwood Swamp Group)	In house	N/A	Based on manual interpretation of coastal plain on western third of Staten Island and expert opinion of NYC DPR and NAC
Range Map – G110 (Atlantic & Gulf Coastal Plain Freshwater Tidal Marsh Group)	In house	N/A	Based on manual interpretation of orthoimagery for freshwater wetlands immediately upstream from tidal marshes identified in Wetlands – Tidal - DPR (2010) layer.
Range Map – G161_C EGL006372 (Post Oak-Blackjack Oak Barrens)	In house	N/A	Based on intersection of a specific soil type (MUYSM = 238) and boundary of Clay Pit Ponds State Park, the only known location of this NVC Association (NYNHP 2013)
Range Map – G163_C EGL006566 (Hemlock-Northern Hardwood Forest)	In house	2010	Based on manual interpretation of orthoimagery in a remnant habitat patch previously described by Rudnický and McDonnell (1989)

Name	Source	Year	Comment
Range Map – G387_C EGL006341 (Rockweed)	In house	N/A	Based on manual interpretation of rocky shores along Pelham Bay Park and expert opinion of NYC DPR and NAC
Roads	NYC DOITT	2009	Used to create road density map; specific layer: ROADBED.shp
Shoreline	NYC DCP	2010	Used to create distance to shoreline map; specific layer: ShorelinePiers.shp
Soils	USDA NRCS	2005	Reconnaissance Soil Survey of New York City
State Park Boundaries	NYS OPRHP	2005	Specific layer: Parks_State.shp
Vernal Pools	NYC DPR	2011	Specific layer: Vernal_Pools_2011.shp; see Appendix A for more information
Water	NYC DOITT	2009	Specific layer: HYDRO.shp
Wetlands	NYC DPR	2012	Specific layer: New_York_City_All_Wetlands_Master_Eymund_2012v3.shp; see Appendix A for more information
Wetlands – Tidal	NYS DEC	1999	Specific layer: citywide_DPR_Wetland_Tidal_NYSDEC_1999_DRAFT_Shifted.shp; see Appendix A for more information
Wetlands – Tidal – DPR	NYC DPR	2010	Specific layer: Tidal_Wetlands_NRG_Study_2010.shp; see Appendix A for more information

NYC DCP – New York City Department of City Planning

NYC DOITT – New York City Department of Information Technology & Telecommunications

NYC DPR – New York City Department of Parks & Recreation

NYS DEC – New York State Department of Environmental Conservation

NYS OPRHP – New York State Office of Parks, Recreation & Historic Preservation

USDA NRCS – United States Department of Agriculture, Natural Resources Conservation Service

N/A = Not applicable

above it was developed by examining the available DEM and drawing a boundary along the sharp break in elevation values that is observable on the upland edge of the coastal plain.

Expert opinion was especially important for the approximate range maps. The *Coastal Plain Hardwood Swamp Group* (G038) is believed to occur only on the Staten Island coastal plain, so a map demarcating coastal areas on the western third of the island was created from the city-wide coastal plains layer, the DEM, and the orthoimagery. Similarly, likely habitat zones for the *Atlantic and Gulf Coastal Plain Freshwater Tidal Marsh Group* (G110) were delineated upstream from tidal marshes previously mapped by NYC DPR (Wetlands – Tidal – DPR, Table 2), and rocky shores adjacent to Pelham Bay Park were targeted for saltwater aquatic vegetation (Rockweed, G387\_C EGL006341).



Where possible, published data was also used to construct range maps. The only known location of remnant hemlock stands (*Hemlock-Northern Hardwood Forest*, G163\_CEGLO06566) in New York City is in the Thain Family Forest, located on the grounds of the New York Botanical Garden. Occurrence maps showing these stands as of the mid-1980s (Rudnický and McDonnell 1989) were revised manually using the available leaf-off orthoimagery, creating an approximate range map current as of 2010. An approximate range map was also developed from scratch for *Post Oak-Blackjack Oak Barrens* (G161\_CEGLO06372); according to the New York Natural Heritage Program (NYNHP 2013), this vegetation type occurs only on Staten Island in Clay Pit Ponds State Park (NYNHP 2013). Its range map was created by intersecting a specific sandy soil type (Windsor-Windsor, Loamy Substratum-Deerfield Loamy Sands, 0 to 8 Percent Slopes; MUSYM = 238) with the boundary for Clay Pit Ponds State Park, extracted from the available State Park Boundaries layer.

### Automated Feature Extraction

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Object-based image analysis (OBIA) is a processing technique that focuses on groups of pixels that form meaningful objects rather than individual pixels (Benz et al. 2004). It has been used successfully for a wide variety of land-cover mapping projects, including numerous tree-canopy mapping projects (MacFaden et al. 2012, O'Neil-Dunne et al. 2013, O'Neil-Dunne et al. 2014). For New York City ecological mapping, the software program eCognition (Trimble Navigation Limited, Westminster, Colorado, USA) was used for all OBIA modeling; this program relies on user-defined rules to segment and classify source imagery into meaningful objects that represent actual features on the ground. A complete sequence of rules, called a rule set, is essentially an expert system; it approximates the way that humans perceive and differentiate landscape features. Other important eCognition features are its data-fusion capabilities, which permit simultaneous analysis of multispectral imagery, LiDAR derivatives, and thematic GIS layers, and enterprise processing, which enables efficient and rapid modeling of source datasets divided into multiple tiles.

Prior to rule-set development, the available 2010 orthoimagery was divided into 6,162 4,000 x 4,000-pixel (610-m x 610-m, or 2,000-ft x 2,000-ft) tiles with 10% overlap using ERDAS IMAGINE (Intergraph Corporation, Huntsville, Alabama, USA) and then imported into an eCognition workspace. All other needed source datasets were imported during processing of individual tiles. A draft rule set was designed by examining individual tiles and then testing algorithms for segmenting the source imagery and creating the desired output classes. As many tiles as possible were tested with each draft rule set to check processing quality and efficiency across a range of landscape heterogeneity. To evaluate overall progress, the rule set was periodically run on the entire set of tiles, and the output for all tiles was compiled into a cohesive draft map using Mosaic Pro in ERDAS IMAGINE. After evaluating the strengths and weaknesses of each draft map, this iterative process of rule-set development was continued until it became apparent that additional testing would provide only small incremental improvements given the available source datasets. The resolution of the eCognition output was equivalent to the input 2010 orthoimagery (0.152 m, or 0.5 ft).

### Manual Corrections

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No automated process will perfectly capture all land-cover features, and ultimately diminishing returns per labor investment make additional rule-set development inefficient. This is especially true for non-systematic errors that could only be addressed with site-specific rules. It is thus often more efficient to ensure a final increment of quality through manual review and editing rather than further rules testing. Although manual corrections have little or no effect on statistical accuracy (O'Neil-Dunne et al. 2013), they improve the overall coherence and realism of the final map by eliminating tiling glitches and



obvious errors of commission and omission. For this project, the nearly-complete draft map was reviewed in ArcGIS and polygons were drawn around observed errors that could not be easily remedied with new or revised processing rules. To complete a final map, the corrections polygons were imported into eCognition, all tiles were re-processed using rules interpreting the correct class assignments, and the output was mosaicked in ERDAS IMAGINE.

## Accuracy Assessment

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To provide a quantitative analysis of the final map, a per-pixel accuracy assessment was performed on the Level 2 map showing enhanced land cover. Ideally, the assessment would have been performed on the Level 3 map delineating NVC Groups and Associations, but no systematic reference data existed with this level of detail. However, a high-quality Level 2 map would at least demonstrate the applicability of the hierarchical classification scheme, even if the quality of the finest scale remained unquantifiable. For this project, the final, corrected Level 3 map was generalized to Level 2 classes using the Thematic Recode function in ERDAS IMAGINE and then resampled to a 0.914-m (3-ft) resolution using IMAGINE's Resample function. The coarser resolution facilitated subsequent generation of reference points, which was performed in ArcGIS. An initial set of 10,000 reference points randomly located within the city boundary were created using the Create Random Points function. These points were then intersected with Level 2 classes encompassing NVC Groups and Associations and by *Other Tree Canopy* and *Maintained Lawn\Shrubs* within 100 m (328 ft) of NVC classes. This stratified sampling scheme eliminated Level 1 anthropogenic features whose accuracy was previously assessed by MacFaden et al. (2012) but preserved the ability to assess possible confusion between generalized NVC classes and adjacent *Other Tree Canopy* and *Maintained Lawn\Shrubs*. It also reduced the initial reference dataset to a manageable number, preferably around 2,000 points. To populate the reference dataset, the stratified random points were examined relative to the 2010 orthoimagery and other pertinent datasets (e.g., nDSM, thematic GIS layers), and the correct Level 2 label was assigned to each. The accuracy assessment was then performed in ERDAS IMAGINE; user's and producer's accuracies were calculated for each Level 2 class and an overall accuracy and accompanying kappa statistic were also estimated.

## Results

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The data-fusion capabilities of eCognition proved essential to ecological mapping for New York City, maximizing the value of individual datasets to specific NVC classes while minimizing their disadvantages. For example, the leaf-off properties of the 2010 orthoimagery proved very useful for mapping conifers but limited its effective for the deciduous NVC types that dominate the city, necessitating a focus on landscape context for these latter classes. Thematic GIS layers also were critical, facilitating finer-scale contextual analysis by narrowing the range of geographic, topographic, and spectral variability. Indeed for some rare and sparsely distributed NVC categories, detailed thematic datasets were the only viable mapping option (e.g., hemlock stands, saltwater aquatic vegetation).

## Automated Feature Extraction

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Initial rule-set development focused on experimentation with machine-learning techniques (e.g., Decision Trees) that identify statistical patterns in source imagery. This early work attempted to find usable classification thresholds in the available leaf-off orthoimagery acquired in 2010. However, the leaf-off imagery lacked adequate detail for discriminating deciduous vegetation encompassed by the *Tree Canopy* and *Grass\Shrubs* Level 1 classes, so this approach was discarded in favor of class-by-class experimentation. A 3-level hierarchy was created that sequentially refined the 7-class LULC map (Level 1) to an enhanced land-cover map showing primary landscape features (Level 2) and then finally to a

detailed urban ecological map showing NVC Groups and Associations (Level 3). Levels 3 and 4 of the *a priori* NVC classification were combined into a single level to simplify modeling and to produce a unified output map with all relevant classes. Specifically:

### Level 1 Processing (Basic Land Cover)

The Level 1 classification was created directly from the 2010 7-class LULC map; the only modification was additional filling of small gaps in contiguous tree canopy.

### Level 2 Processing (Land-cover Sub-classes)

The finer-scale features of Level 2 were developed from Level 1 using available thematic GIS layers and minor contextual analysis:

**Forested Wetlands.** *Tree Canopy* in the Level 1 map that coincided with features in the available thematic dataset for wetlands (Wetlands) was re-assigned to this class. Note that the Wetlands layer is known to have various errors of commission and omission, so the Level 2 assignment was considered a rough approximation only, intended to serve as a starting point for wetlands mapping.

**Maritime Forest.** Level 1 *Tree Canopy* map was assigned to this class when it coincided with sandy soils known to occur in flat coastal areas. In particular, the following MUSYM categories in the available soils layer (Soils) guided selection: Beaches (5); Pavement & Buildings, Wet Substratum-Big Apple-Verrazano Complex, 0 to 8 Percent Slopes (92); Big Apple-Fortress Complex, 0 to 8 Percent Slopes (99); Hooksan-Dune Land Complex, 0 to 25 Percent Slopes (129); Pavement & Buildings-Hooksan-Verrazano Complex, 0 to 8 Percent Slopes (208); Jamaica-Barren Sands, 0 to 3 Percent Slopes (210); Hooksan-Verrazano-Pavement & Buildings Complex, 0 to 8 Percent Slopes (242); and Gravesend and Old Mill Coarse Sands, 0 to 8 Percent Slopes (268). After the initial assignment, small *Maritime Forest* objects near buildings or adjacent to upland trees were reverted to *Tree Canopy*.

**Upland Forest.** All remaining *Tree Canopy* was assigned to this class.

**Freshwater Wetlands.** Level 1 *Grass\Shrubs* that coincided with thematic Wetlands features were assigned to *Freshwater Wetlands*. As with *Forested Wetlands*, these features were considered a rough approximation only.

**Tidal Wetlands.** *Grass\Shrubs* coinciding with thematic tidal wetlands (Tidal\_Wetlands) were assigned to this class. Estuarine and marine wetlands represented in the city-wide wetlands layer were also considered *Tidal Wetlands*.

**Upland Grass\Shrubs.** All remaining *Grass\Shrubs* were assigned to this class.

Although technically part of the Level 2 classification, the *Maintained Lawn\Shrubs* and *Other Tree Canopy* classes were created during Level 3 modeling to maximize context-based evaluation of the preliminary classification.

### Level 3 Processing (NVC Groups and Associations)

The logic used to map individual classes at Level 3 varied greatly by source data:

**Atlantic & Gulf Coastal Plain Freshwater Tidal Marsh Group (G110).** The approximate range map for this group (Range Map – G110, Table 2) was the primary data input, incorporating any *Tidal Wetlands* and adjacent *Freshwater Wetlands* that overlapped with it.

**Atlantic & Gulf Coastal Plain Pondshore & Wet Prairie Group (G111).** Lakes and ponds were first identified by the available hydrology layer (Water, Table 2) and then adjacent *Freshwater Wetlands* were evaluated according to NDVI (low), Visible Brightness (high), and texture (high). Adjacent *Upland Grass\Shrubs* were also evaluated with these spectral and textural criteria to capture transitional zones possessing wetland characteristics.

**Eastern North American Wet Meadow Group (G112).** *Freshwater Wetlands* were evaluated according to NDVI (high), Near Infrared (high), Visible Brightness (low), and vegetation height (high). Adjacent *Upland Grass\Shrubs* were then evaluated with the same criteria to adequately capture transitional zones.

**Eastern North American Freshwater Marsh Group (G125).** The shorter, wetter vegetation of this group was identified by evaluating *Freshwater Wetlands* according to NDVI (high), Near Infrared (low), Visible Brightness (low), and vegetation height (low). As with other wetland groups, adjacent *Upland Grass\Shrubs* were also evaluated with these criteria.

**Northern & Central Shrub Swamp Group (G167).** *Freshwater Wetlands* that overlapped palustrine scrub\shrub features in the available wetlands GIS layer (Wetlands, Table 2) and had a mean vegetation height (as determined by nDSM) greater than 1.22 m (4 ft) were assigned to this group. *Forested Wetlands* were also assigned to this group if they overlapped with scrub\shrub features and had a vegetation height less than 6.1 m (20 ft).

**Eastern North American Lake Flat & Beach Group (G342).** Although this NVC group is listed under *Freshwater Wetlands*, the only known examples in New York City are woodland vernal pools. Accordingly, point locations in the available vernal pools GIS layer were incorporated into Level 2 *Forested Wetlands* and *Upland Forest* and then adjacent objects were added to the original points if the orthoimagery indicated the presence of water (i.e., low Near Infrared values).

**Northern & Central Ruderal Wet Meadow & Marsh Group (G556).** All *Freshwater Wetlands* features not already assigned to other classes were assigned to this group and then adjacent *Upland Grass\Shrubs* were evaluated according to NDVI (low), Visible Brightness (high), and smooth texture. In the available leaf-off imagery, the emergent vegetation (*Phragmites*) that dominates this group tended to be very bright and smooth.

**North American Atlantic Brackish Tidal Marsh Group (G120).** The city's brackish wetlands are also dominated by *Phragmites*. Accordingly, features labeled as *Phragmites* in the DPR tidal wetlands layer (Wetlands – Tidal – DPR, Table 2) that overlapped *Tidal Wetlands* were assigned to this group. Adjacent *Upland Grass\Shrubs* with spectral and textural characteristics indicative of *Phragmites* (low NDVI, high Visible Brightness, and smooth texture) were also included.

**North American Atlantic High Salt Marsh Group (G121).** This group was based primarily on the NYS DEC layer created in 1999 (Wetlands – Tidal, Table 2). *Tidal Wetlands* overlapping features labeled as “High Marsh” or “Graminoid” were assigned to it, as were the *Bare Soil* and *Water* features interspersed with tidal wetlands in some areas.

**North American Atlantic Low Salt Marsh Group (G122).** This second salt marsh group was also based primarily on the NYS DEC layer; *Tidal Wetlands*, *Bare Soil*, and *Water* overlapping with features labeled as “Intertidal Marsh” were incorporated into it.

**North American Atlantic Tidal Flat & Panne Group (G123).** Features initially classified as salt marsh types (G121 or G122) were re-assigned to this group according to multiple spectral, shape, and distance criteria: Visible Brightness (low), roundness (high), texture (rough), and distance to shoreline (high).

**North & Central Ruderal Meadow & Shrubland Group (G059).** This group included *all Upland Grass\Shrubs* not assigned to other NVC Groups (G063, G124, and G493) or *Maintained Lawns\Shrubs*.

**Northern & Central Sand Barrens Group (G063).** The available soils layer (Soils, Table 2) was used to make a preliminary classification for this group, selecting *Upland Grass\Shrubs* that overlapped with sandy soils types: Pavement & Buildings-Forest Hills-Montauk Complex, 0 to 8 Percent Slopes (92); Big Apple-Fortress Complex, 0 to 8 Percent Slopes (99); Pavement & Buildings-Chatfield-Greenbelt Complex, 15 to 50 Percent Slopes (208); Jamaica-Barren Sands, 0 to 3 Percent Slopes (210); Windsor-Windsor, Loamy Substratum-Deerfield Loamy Sands, 0 to 8 Percent Slopes (238); Windsor-Verrazano-Pavement & Buildings Complex, 0 to 8 Percent Slopes (240); Gravesend and Old Mill Coarse Sands, 0 to 8 Percent Slopes (268); and Pavement & Buildings-Windsor-Verrazano Complex, 0 to 8 Percent Slopes (304). The initial selection was then refined by evaluating NDVI (high) and texture (smooth) and by adding adjacent *Bare Soil* objects.

**Eastern Coastal Beach Group (G124).** The available wetlands GIS layer (Wetlands, Table 2) was used to create an initial classification for this group, selecting *Upland Grass\Shrubs* and *Bare Soil* that overlapped with features labeled as “Beach\Shoreline.” The initial features were then refined by evaluating adjacent *Bare Soil* according to building density; only *Bare Soil* objects distant from buildings were included. *Maintained Lawn\Shrubs* surrounded by beaches were also incorporated into the group.

**Northern Atlantic Dune & Coastal Grassland & Shrubland Group (G493).** This group was dependent on specific sandy soils that occur in coastal zones: Hooksan-Dune Land Complex, 0 to 25 Percent Slopes (129); and Hooksan-Verrazano-Pavement & Buildings Complex, 0 to 8 Percent Slope (242). *Upland Grass\Shrubs* that overlapped with these soils types were assigned to an initial classification and then refined by adding adjacent *Bare Soil* features.

**Coastal Plain Hardwood Swamp Group (G038).** Hardwood swamps in coastal flats are believed to be limited to the western third of Staten Island, so an approximate range map was used to re-assign previously-mapped *Forested Wetlands* types (see G040 and G045 below) to this group.

**Silver Maple-Green Ash-Sycamore Floodplain Group (G040).** Spectral and textural criteria were used to identify this *Forested Wetlands* group: low NDVI, high Visible Brightness, and rough texture. Shape (e.g., roundness) and size thresholds (< 0.287 acres, or 0.116 ha) were also used to limit individual occurrences to small, symmetrical objects.

**Northern & Central Conifer & Hardwood Acidic Swamp Group (G045).** *Forested Wetlands* with low Near Infrared and Visible Brightness values comprised this group.

**Northern & Central Hardwood & Conifer Ruderal Forest Group (G030).** In leaf-off imagery, ruderal forest generally exhibited NDVI values higher than adjacent deciduous forest, in part because it included conifers (which are easily distinguished in leaf-off imagery) and also because its deciduous component appeared to be leafing out sooner than other trees. Accordingly, this group included *Upland Forest* features with high NDVI and low Visible Brightness.

**Northern & Central Conifer & Hardwood Plantation Group (G032).** Relatively short conifer plantations with smoothly-textured tree canopies were evaluated with a combination of NDVI (very high) and LiDAR-derived Z Deviation (low). Taller pine plantations with rougher-textured canopies were identified by their high NDVI and nDSM values. Initial object size was also important to this group; *Upland Forest* was segmented into smaller objects than those created for ruderal forest (see G030 above) to distinguish closely-spaced conifers from the more numerous deciduous trees that surround them.

**Mid-Atlantic Mesic Mixed Hardwood Forest (G158\_CEGLO06075).** Upland Forest coinciding with coastal plain soils determined this association: Flatbush-Riverhead-Pavement & Buildings Complex, 0 to 8 Percent Slopes (77); Plymouth-Flatbush-Pavement & Buildings Complex, 0 to 8 Percent Slopes (225); and Branford-Pompton Complex, 0 to 8 Percent Slopes (270). These soils are confined to the coastal plain in Queens, Brooklyn, and Staten Island.

**Coastal Oak-Hickory Forest (G158\_CEGLO06336\_6377).** *Upland Forest* overlapping with sandy soil types determined this hardwood forest type: Montauk-Forest Hills Complex, 0 to 8 Percent Slopes (64); Pavement & Buildings-Forest Hills-Montauk Complex, 0 to 8 Percent Slopes (67); Pavement & Buildings-Forest Hills-Canarsie Complex, 8 to 15 Percent Slopes (68); Montauk-Forest Hills Complex, 15 to 35 Percent Slopes (69); Montauk-Forest Hills Complex, 8 to 15 Percent Slopes (165); Montauk-Forest Hills-Pavement 7 Buildings Complex, 8 to 15 Percent Slopes (243); Montauk-Forest Hills-Pavement 7 Buildings Complex, 0 to 8 Percent Slopes (244); Wethersfield-Ludlow-Wilbraham Complex, 0 to 8 Percent Slopes (262); Wethersfield-Ludlow Complex, 8 to 15 Percent Slopes (264); Wethersfield-Ludlow complex, 15 to 50 Percent Slopes (311); and Booton-Haledon Complex, 0 to 8 Percent Slopes (370). These soils generally occur on the terminal moraine that extends through Queens, Brooklyn, and Staten Island.

**Serpentine Forest (G158\_CEGLO06438).** *Upland Forest* was assigned to this class when it coincided with serpentine soils on Staten Island: Wotalf-Todt Hill-Cheshsire Loams, 15 to 50 Percent Slopes (306); Wotalf-Todt Hill-Pavement & Buildings Complex, 8 to 15 Percent Slopes (344); and Pavement & Buildings-Wotalf-Todt Hill Complex, 15 to 50 Percent Slopes (348).

**Post Oak-Blackjack Oak Barrens (G161\_CEGLO06372).** The approximate range map for oak barrens was incorporated directly into the Level 3 map.

**Oak-Tulip Forest (G163\_CEGLO06125).** Sloping soil types in areas above the coastal plain determined this association: Charlton-Greenbelt-Pavement & Buildings Complex, 15 to 50 Percent Slopes (135); Charlton-Sutton Complex, 0 to 8 Percent Slopes (137); Charlton-Sutton Complex, 8 to 15 Percent Slopes (138); Charlton-Sutton Complex, 15 to 50 Percent Slopes (139); Pavement & Buildings-Chatfield-Greenbelt Complex, 15 to 50 Percent Slopes (206); Chatfield-Charlton Complex, 15 to 50 Percent Slopes (207); Chatfield-Greenbelt-Pavement & Buildings Complex, 15 to 50 Percent Slopes (223); Chatfield-Charlton Complex, 0 to 8 Percent Slopes (230); Chatfield-Charlton Complex, 8 to 15 Percent Slopes (231); Leicester-Sutton Complex, 0 to 3 Percent Slopes (232); Charlton-Greenbelt-Pavement & Buildings Complex, 0 to 8 Percent Slopes (235); Riverhead-Flatbush Complex, 8 to 15 Percent Slopes (247);

Riverhead-Pompton Complex, 0 to 8 Percent Slopes (249); and Greenbelt-North Meadow Complex, 0 to 8 Percent Slopes (285). These soils are confined to Manhattan and the Bronx.

**Hemlock-Northern Hardwood Forest (G163\_C EGL006566).** The approximate range map for remnant hemlocks stands was incorporated directly into the Level 3 map; no additional refinements were needed.

**Maritime Post Oak Forest (G495\_C EGL006373).** Specific Staten Island soils types determined this association: Windsor-Windsor, Loamy Substratum-Deerfield Loamy Sands, 0 to 8 Percent Slopes (238); Windsor-Verrazano-Pavement & Buildings Complex, 0 to 8 Percent Slopes (240); and Pavement & Buildings-Windsor-Verrazano Complex, 0 to 8 Percent Slopes (304). Because these soils types also include *Northern & Central Hardwood & Conifer Ruderal Forest Group* (G030) and *Northern & Central Conifer & Hardwood Plantation Group* (G032), this association was developed from *Upland Forest* after all other forest groups had been classified (i.e., it was not included in Level 2 *Maritime Forest*).

**Maritime Shrubland and Successional Maritime Forest (G495\_C EGL006379\_6145).** *Maritime Forest* from Level 2, established from a set of sandy soils, was refined by expanding it into adjacent *Upland Forest* objects.

**Eastern North American Freshwater Aquatic Vegetation Group (G114).** Lakes and ponds were identified from the available hydrology layer and then refined by selecting only features in the coastal plain.

**Rockweed (Pelham Bay Park rocky shore) (G387\_C EGL006341).** *Water* coinciding with the approximate range map for rocky shore habitat near Pelham Bay Park (Range Map – G387\_C EGL006341, Table 2) was assigned to this association.

**Maintained Lawn\Shrubs.** *Upland Grass\Shrubs* at Level 2 were assigned to this class when grass or shrub features were likely anthropogenic in origin, using both spectral and contextual criteria. For example, well-manicured lawns tended to have high NDVI values and homogenous textures in the available orthoimagery, simplifying classification of these obvious features. However, less-managed lawns and shrubs did not have the same spectral clarity, necessitating evaluation of landscape context. Features near buildings, roads, parking lots, and other developed features were thus assumed to be directly maintained or heavily influenced by adjacent land uses.

**Other Tree Canopy.** *Upland Forest* groups were assigned to this class when trees occurred in small clumps in a matrix of developed features; although all trees make valuable contributions to urban environments (e.g., runoff control, air-pollution mitigation, wildlife habitat), many are highly-managed plantings or non-native species that are not easily categorized in the NVC hierarchy. Also, species-specific identification was impractical with the available source datasets. *Upland Forest* objects adjacent to *Buildings* and *Maintained Lawn\Shrubs* and smaller than 0.232 ha (0.574 acres) were assigned to *Other Tree Canopy*, regardless of the length of the common border; objects smaller than 1.16 ha (2.87 acres) were assigned if the common border with developed features was at least 50% of each object's total length. High road and building densities were also used to re-assign objects smaller than 1.16 ha (2.87 acres) imbedded in more complex patterns of buildings, pavement, and other impervious surfaces.



**Water.** All remaining features classified in the Level 1 map and not re-assigned to aquatic vegetation classes were maintained in the final map without further modification, meaning that saltwater and freshwater were not distinguished.

**Buildings.** Level 1 features were transferred to the final map without modification.

**Roads\Railroads.** Level 1 features were transferred to the final map without modification.

**Other Paved Surfaces.** Level 1 features were transferred to the final map without modification.

**Bare Soil.** Most Level 1 features were transferred to the final map without modification. In some instances, this land-cover type was consolidated into adjacent *Upland Grass\Shrubs* and *Tidal Wetlands* groups.

## Manual Corrections

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More than 4,000 manual corrections were identified and incorporated into the preliminary Level 3 map, including a set of corrections suggested by NAC and NYC DPR. These corrections improved the map's visual quality and coherence by eliminating errors between adjacent processing tiles, which can occur when using classification thresholds based on spectral criteria (i.e., a rule based on NDVI or other spectral properties may produce different results in adjacent tiles when values are close to specific thresholds). Density criteria can also be problematic when using relatively small processing tiles. For example, *Maintained Lawn\Shrubs* were sometimes misclassified as *North & Central Ruderal Meadow & Shrubland Group* (G059) in open areas with few structures and roads such as industrial sites located near shorelines. Another common correction was *Other Tree Canopy* along railroad rights-of-way; small *Northern & Central Hardwood & Conifer Ruderal Forest Group* (G030) objects were often converted to this subjective category but subsequent manual review suggested that these features occupy a unique ecological niche (i.e., isolated, relatively undisturbed forest cover).

## Accuracy Assessment

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A set of 2,079 reference points was established for the Level 2 categories encompassing NVC classes and adjacent *Other Tree Canopy* and *Maintained Lawn\Shrubs*. The overall classification accuracy of these points was 92% (kappa statistic = 0.9012), indicating a strong correspondence to actual landscape features (Table 3). Because of their subjective quality, the accuracies of the *Other Tree Canopy* and *Maintained Lawn\Shrubs* classes were predictably high, and the large proportion of these points in the reference dataset no doubt contributed the high overall accuracy. Overall accuracy was also influenced by the classes based wholly or in part on high-quality thematic GIS layers, including *Upland Forest*, *Maritime Forest*, *Tidal Wetlands*, and *Aquatic Vegetation*. The least effective classes were *Forested Wetlands* and *Freshwater Wetlands*. For *Forested Wetlands*, the producer's accuracy of 28% indicated many errors of omission as actual wetlands were erroneously classified as *Upland Forest*. However, the user's accuracy of 83% indicated that most features classified as *Forested Wetlands* were mapped correctly (i.e., low rates of commission). This dynamic was reversed for *Freshwater Wetlands*; its user's accuracy of 63% indicated a high rate of confusion with the *Upland Grass\Shrubs* and *Tidal Wetlands* classes but the producer's accuracy of 78% indicated a lower rate of omission. The classification was thus better at capturing *Freshwater Wetlands* where they actually existed but tended to overestimate their presence elsewhere.



**Table 3. Per-pixel accuracy assessment for Level 2 Urban Ecological Land-cover Map based on 2,079 stratified random reference point.**

Classified	Reference Data										User's Accuracy
	Other Tree Canopy	Maintained Lawn\Shrubs	Freshwater Wetlands	Tidal Wetlands	Upland Grass\Shrubs	Aquatic Vegetation	Forested Wetlands	Upland Forest	Maritime Forest	Total	
Other Tree Canopy	314	2					1			317	99.1
Maintained Lawn\Shrubs	1	500	5	1	20					527	94.9
Freshwater Wetlands		6	53	8	15			2		84	63.1
Tidal Wetlands		3	1	181	4					189	95.8
Upland Grass\Shrubs	1	29	9	1	220			3	2	265	83
Aquatic Vegetation						11				11	100
Forested Wetlands	1						15	2		18	83.3
Upland Forest		2			1		35	553		591	93.6
Maritime Forest					3		2	2	70	77	90.9
<b>Total</b>	317	542	68	191	263	11	53	562	72	2079	
<b>Producer's Accuracy</b>	99.1	92.3	77.9	94.8	83.7	100	28.3	98.4	97.2		

Overall Classification Accuracy = 92.03%

Overall Kappa Statistic = 0.9012

## Discussion

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The final urban ecological land-cover map provides a high-resolution snapshot of New York City's primary vegetation classes, including topographically-diverse uplands (Figure 1); tidal estuaries and marshes (Figure 2); sandy coastal zones (Figure 3); and ecotones between the coastal plain and the adjacent glacially-influenced landscape (Figure 4). It captures a level of complexity not previously available in local and regional ecological maps, applying the sophistication of the NVC to the City's considerable physical diversity, both natural and anthropogenic. Yet, it is also a coherent, interpretable representation of actual land-cover objects, features that are important to the city's environmental and cultural fabric in a continuously-evolving world.

The new map will be an important resource in the study, long-term monitoring, and conservation of ecological features in New York City. It will serve as a starting point for change detection, permitting evaluation of the extent and intensity of land-cover changes in both contiguous habitat patches and the transitional zones between natural features and the built environment. This type of analysis will be most effective if the map is updated periodically, permitting direct comparison of temporally-distinct ecological maps, but it will also be informative in less formal assessments such as overlays with new orthoimagery or field-based data collections. The baseline documentation provided by this map will thus help monitor environmental changes from specific, identifiable anthropogenic actions as well as more diffuse, globally-significant trends such as climate change. Other significant uses include conservation planning, land protection, and site selection for field studies of ecosystem pattern and function.

Although a quantitative accuracy assessment could not be performed on the Level 3 map, it is possible to speculate on the quality of the individual NVC Groups and Associations. Classes developed directly from approximate range maps and expert opinion are likely to be quite accurate, including *Hemlock-Northern Hardwood Forest* (G163\_C EGL006566), *Post Oak-Blackjack Oak Barrens* (G161\_C EGL006372), and *Rockweed* (G387\_C EGL006341). Classes developed with significant contributions from detailed thematic GIS datasets should also have high accuracy, including various *Tidal Wetland* groups and *Eastern Coastal Beach Group* (G124). Lower but still good accuracies are likely for the other *Upland Forest* classes, which were derived from landscape position and soils; the even distribution assumed by these modeling criteria probably over-generalized actual occurrences along transitional zones and other heterogeneous areas. For example, *Serpentine Forest* (G158\_C EGL006438) was modeled as even, contiguous blocks in parts of Staten Island containing serpentine soils, but a more complex mosaic of vegetation types is likely in these areas. *Maintained Lawn/Shrubs* and *Other Tree Canopy* were included in the Level 2 assessment and demonstrated very high accuracies, but the criteria used to create them were highly subjective and may have captured significant ecological features worthy of distinct classification.

*Forested Wetlands* and *Freshwater Wetlands* were the weakest part of the Level 2 accuracy assessment, suggesting that the Level 3 classes would have even lower accuracies; these features occur in complex, often interconnected patterns that would be difficult to distinguish without high rates of confusion. In this project, existing wetlands GIS layers were used to mark the general location of known wetlands and then spectral and contextual criteria were used to sequentially evaluate these objects and adjacent

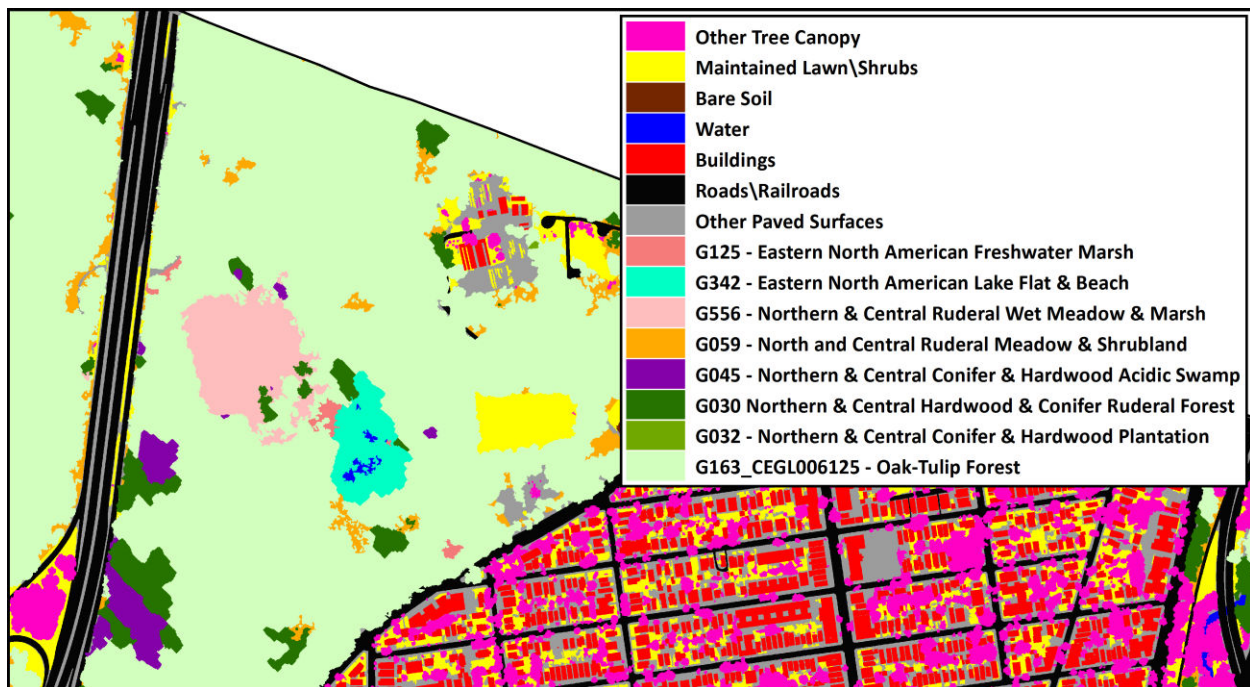


Figure 1. Final urban ecological land-cover map for New York City showing *Upland Forest* and *Freshwater Wetlands* NVC groups in Van Cortlandt Park, Bronx.

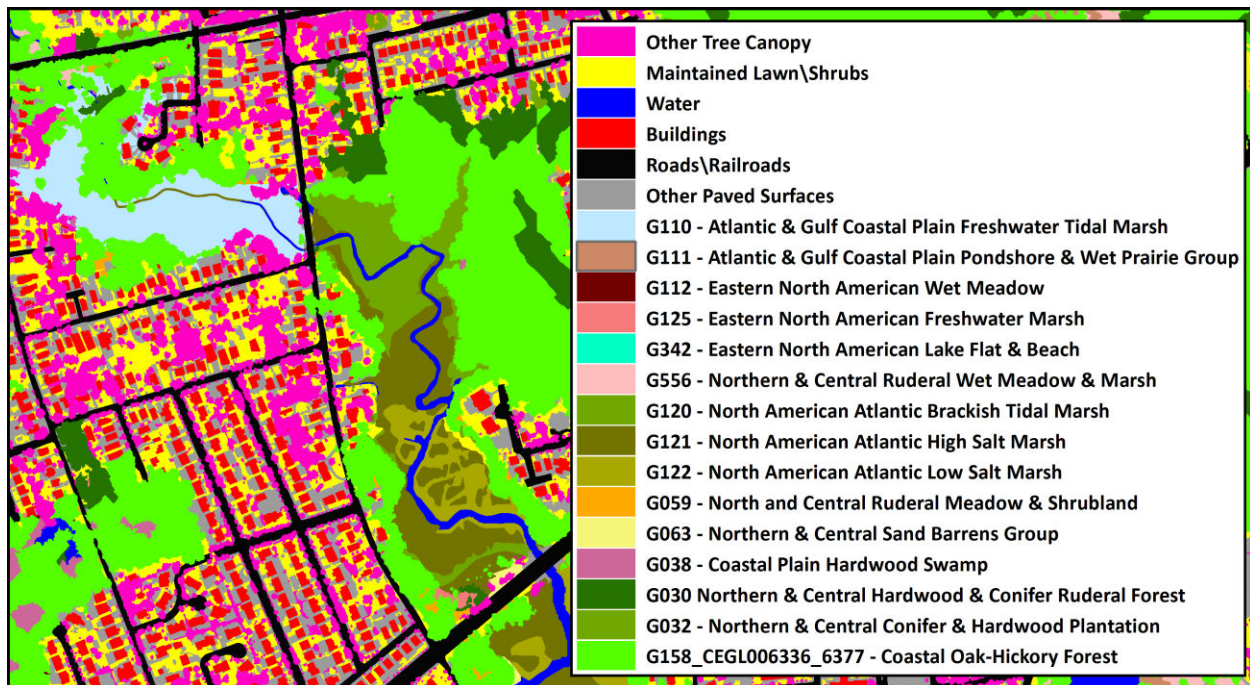


Figure 2. Final urban ecological land-cover map for New York City showing *Tidal Wetlands* and adjacent *Upland Forest* on southwestern Staten Island.



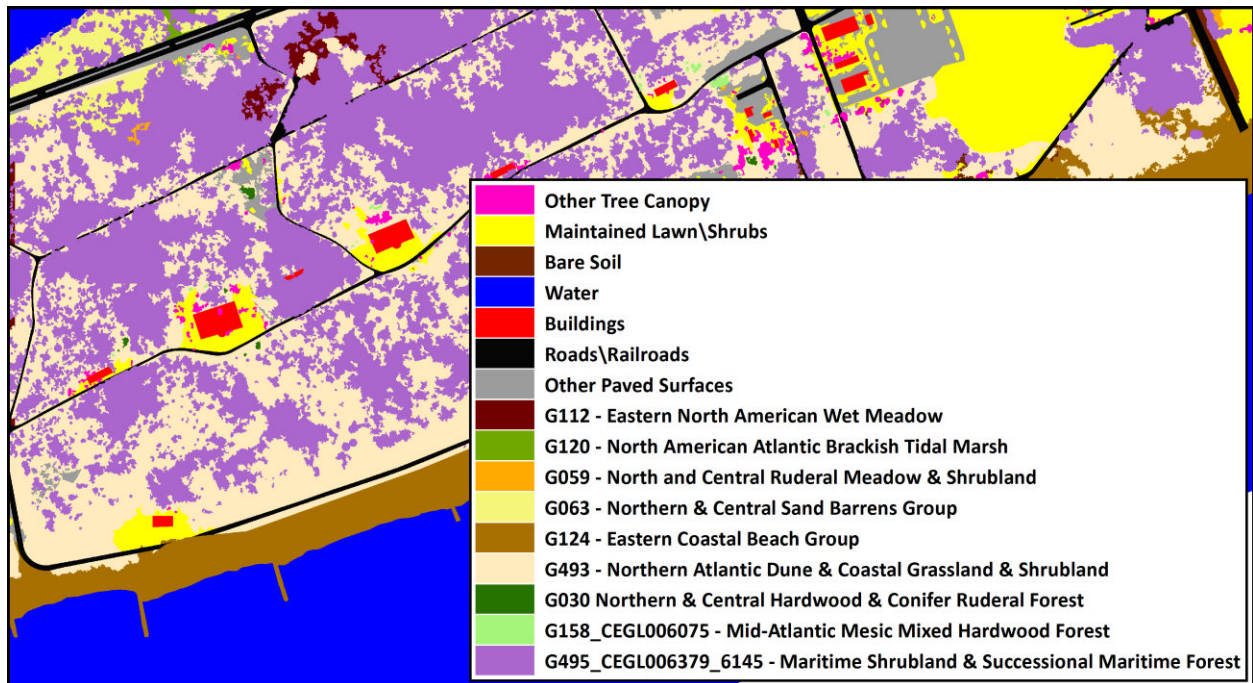


Figure 3. Final urban ecological land-cover map for New York City showing *Maritime Forest* and associated coastal NVC groups on Rockaway Point, Queens.

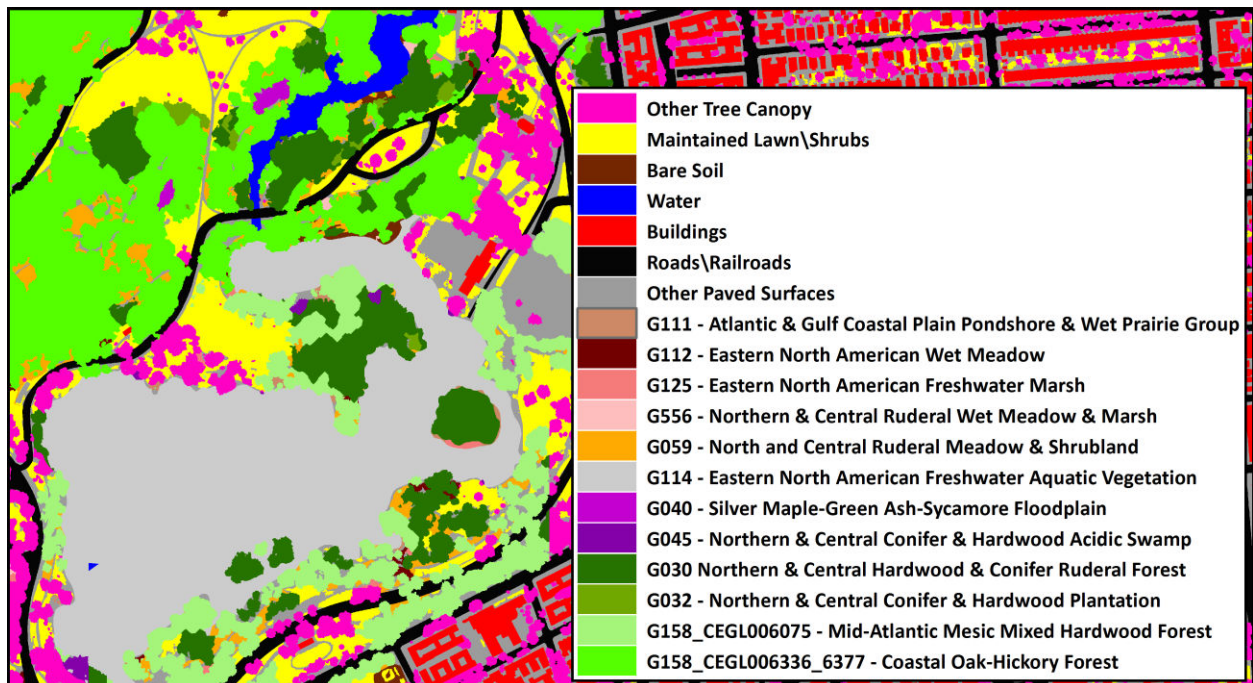


Figure 4. Final urban ecological land-cover map for New York City showing the transition in *Upland Forest* types along the coastal plain boundary in Prospect Park, Brooklyn.

ones. Spectral classification of wetland features has long been a challenging process, especially mapping of forested wetlands that are difficult to distinguish from upland forest canopy. Although low Near Infrared values in leaf-off imagery can be indicative of water, shadows created by trees often had similar spectral properties in the available orthoimagery, confusing discrimination of *Forested Wetlands* types. Wetlands should thus be viewed with caution in the urban ecological map; *Forested Wetlands* are likely under-represented while *Freshwater Wetlands* are overestimated.

Future work on the ecological map should focus on improving these wetlands-related errors. Recent advances in eCognition-based modeling of wetlands (Rampi et al. 2014) hold considerable promise for refining the *Forested Wetlands* and *Freshwater Wetlands* classes in New York City; this approach focuses on use of a LiDAR-derived compound topographic index (CTI) that combines slope and flow potential. It would improve initial classification of wetlands relative to other land-cover types, and it would also help refine classification of individual NVC Groups and Associations. An additional application of the CTI approach would be identification of woodland vernal pools, which could supplement the existing database of known vernal pools in the city. Other refinements could include improved delineation of *Upland Forest* types to better represent finer-scale patterns. For this effort, more detailed, field-based descriptions of the NVC classes would facilitate rule-set development and accuracy assessment.

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## Appendix A – Additional Information on Expert-derived GIS Layers Used in Ecological Land-cover Mapping

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1. Vernal Pools (Vernal\_Pools\_2011.shp). NYC DPR developed this point layer from field surveys of known vernal pools.
2. Wetlands (New\_York\_City\_All\_Wetlands\_Master\_Eymund\_2012v3.shp). NYC DPR compiled this layer by merging wetlands from multiple separate data sources, including the 2004 National Wetlands Inventory (NWI), a 2004 hydrography layer from NYC DOITT, and a 2007 wetlands layer from NYS DEC.
3. Wetlands – Tidal (citywide\_DPR\_Wetland\_tidal\_NYSDEC\_1999\_DRAFT\_Shifted.shp). This layer was originally created by NYS DEC and then modified by NYC DPR to improve locational accuracy.
4. Wetlands – Tidal – DPR (Tidal\_Wetlands\_NRG\_Study\_2010.shp). NYC DPR created this layer from field surveys of *Spartina* and *Phragmites* tidal marshes.