DEVELOP Technical Report

Central Park Ecological Conservation II

Assessing Drought and Vegetation Health Conditions in New York City's Central Park with Earth Observation Data

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Abstract:
With over 42 million visitors annually, New York City's Central Park serves as a vital refuge from city life. Yet as climate change accelerates, the park faces increasing challenges from extreme heat and droughts. This study explores how NASA Earth observations can detect drought-induced vegetation stress during a long-term drought in 2002 and a short-term drought in fall 2024. We used Landsat 5 TM, Landsat 7 ETM+, Harmonized Landsat Sentinel-2, and ECOSTRESS environmental indices to assess vegetation stress across lawns, ballfields, and woodlands. Four indices were calculated to measure vegetation health, moisture, and evapotranspiration: Normalized Difference Vegetation Index (NDVI), Red Edge Normalized Difference Vegetation Index (ReNDVI), Moisture Stress Index (MSI), and Evaporative Stress Index (ESI). Percent change for a given index was calculated between drought year and historical baseline values. In the 2002 drought, woodlands were most stable while lawns and ballfields showed the largest declines in vegetative health indicators. By summer 2003, most park areas returned to or exceeded baseline conditions. In 2024, widespread negative percent change occurred in terms of foliar greenness and moistness, except in patches of the Sheep Meadow and Great Lawn. ReNDVI was particularly sensitive in the Ramble and North Woods, with time series showing senescence two weeks earlier than normal. By spring and summer of 2025, lawns and ballfields rebounded, though patches of the Ramble, Mall, Conservatory Water, and West Pinetum still lagged in terms of showing normal values. Limitations included sparse baseline data and confounding effects of fall senescence and management practices. Overall, this study demonstrates the feasibility of using NASA Earth observations to detect drought stress in Central Park, informing irrigation and vegetation management.

Key Terms: Central Park, remote sensing, drought monitoring, vegetation health, Landsat, Normalized Difference Vegetation Index, Moisture Stress Index, red edge

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1. Introduction

2.1. Background Information

The City of New York established Central Park in 1858, and since then, its 843 acres have served as the heart of Manhattan and remains a vital green space for New York City (Central Park Conservancy, 2025a). As part of the city's social infrastructure, Central Park contributes to ecological vitality while also providing social value. High quality public open spaces form the foundation for a strong sense of community (Francis et al., 2012). The park supports a range of social events for its 42 million visitors each year, from informal meetups to large community celebrations, the park serves as a critical place for social connection (Central Park Conservancy, 2025a; Oldenburg, 1989).

These benefits of Central Park are being confronted by growing climate challenges (e.g., drought) that threaten the park's green spaces. Healthy green infrastructure improves air and water quality, reduces carbon dioxide levels, and supports habitat for diverse species (Bounds et al., 2014). Central Park plays a key role in reducing urban heat island effects, in which dense cities become significantly warmer than surrounding areas due to built-up infrastructure and limited vegetation (Central Park Conservancy, 2025b). Urban heat stress significantly reduces the cooling effects of green spaces, decreasing cooling by 15% in tree-dominated areas and 25% in grass-dominated areas (Allen et al., 2021). In 2002 and 2024, New York City experienced severe drought conditions. The 2002 drought was particularly severe affecting much of the Northeast, with a NYC Drought Watch in place from December 2001 to January 2003 (New York City Department of Environmental Protection, 2025). In contrast, the National Weather Service described the 2024 event as a flash drought, defined by an unusually fast intensification of drought conditions and identified through sharp increases in evaporative stress; the event also included the city's driest October on record (Christian et al., 2019; National Weather Service, 2025). The differing nature of these two drought events suggests that their impacts and indicator ratings may vary. In contrast, 2023 saw one of the city's wettest Septembers on record, signaling increased climate volatility (National Weather Service, 2025). Instable environmental conditions can undermine natural processes needed to sustain Central Park's vegetation and landscape. It also can jeopardize the park's ecological integrity and the quality of experience for the millions who rely on it for respite, recreation, and relief from city life (Central Park Conservancy, 2025b).

1.2. Partner Concerns and Objectives

The Central Park Conservancy is a private, nonprofit organization entrusted with the daily care, maintenance, and restoration of Central Park. The Conservancy's mission centers on serving past, present, and future park users by honoring historical landscapes, preserving ecological health, and innovating for long-term sustainability and accessibility. The Conservancy connects the legacy and vision of original landscape architects Frederick Law Olmsted and Calvert Vaux to the newly constructed Davis Center, applying systemic management to advance the park's enduring mission (Central Park Conservancy, 2025a). The Sheep Meadow, Hecksher Ballfields, Ramble, Great Lawn, North Meadow, East Meadow, and North Woods are among the park's most frequently visited regions. These areas of interest include a variety of vegetated land cover types that provide essential ecosystem services within the city, prompting the Conservancy to actively prioritize these named locations for conservation and monitoring (Central Park Conservancy, 2025b).

Figure 1. Map of Central Park, New York, New York.

The Conservancy maintains a skilled on-site team that manages the park year-round, keeping the landscape in excellent condition when possible. However, rising climate variability and extreme weather events, such as the 2024 flash drought, threaten the resilience and function of these highly valued public spaces. To improve resource management, the Conservancy partnered with NASA DEVELOP to integrate synoptic remote sensing into their decision-making. The project aimed to enhance existing field-based strategies by providing remote sensing-based drought stress analyses and a park-wide drought risk map from 1986 to 2025. These tools were developed to support irrigation planning and drought response in high-use and ecologically sensitive areas.

1.3. Previous Term
This project followed the Summer 2024 DEVELOP team's work assessing tree health and vulnerability to Dutch elm disease (DED) in Central Park. The team for the first term used Landsat-based Normalized Difference Vegetation Index (NDVI) time series and in situ tree health records to examine phenology and identify zones with elevated disease risk, focusing on American elm populations that are being threatened by Dutch elm disease. Our team built upon their work by assessing drought stress on vegetation using remote sensing indices from Landsat, Sentinel-2, and ECOSTRESS data that estimate relative levels of vegetation greenness, moisture, and evapotranspiration on a per pixel basis.

1.4. Scientific Basis
In contrast to traditional field-based methods, satellite data enables consistent and comprehensive monitoring of drought conditions and vegetation health across urban and natural environments (Cârlan et al., 2020;

Leisenheimer et al., 2024). Previous studies of urban tree and grass drought have utilized Landsat 8 and 9 data to derive indices like NDVI to monitor vegetation greenness response during drought years (Miller et al., 2022). Red-edge information from satellites such as Red-edge Normalized Difference Vegetation Index (ReNDVI) has been shown to be especially useful at early detection of stress in woodland ecosystems (Eitel et al., 2011). In rapidly developing drought conditions, vegetation stress can also manifest through declines in canopy moisture before structural changes occur, making moisture-sensitive indices like the Moisture Stress Index (MSI) critical for early detection (Rock et al, 1986; Zhu et al., 2024). Additionally, in flash droughts, scientists have utilized the satellite-based Evaporative Stress Index (ESI) as a tool for monitoring rapid drought intensification, given its sensitivity to changes in evapotranspiration and atmospheric demand before other drought indicators show changes due to drought (Christian et al., 2019).

2. Methodology

2.1. Data Acquisition

2.1.1 Satellite Data

To study vegetation response to drought from 1986 to 2025, we utilized satellite data (Table 1) to derive remote sensing indices for vegetation health, moisture, and evapotranspiration. Using the Google Earth Engine (GEE) Catalog, we acquired Collection 2 Level 2 surface reflectance data from Landsat 5 TM and Landsat 7 ETM+ to evaluate the 2002 drought. The GEE Catalog also provided a consistent source of surface reflectance data from the Harmonized Landsat Sentinel-2 (HLS) project to study 2024 drought in comparison to park conditions from previous years. HLS provides a combined data source from Landsat 8 Operational Land Imager (OLI) and Sentinel-2 Multi-Spectral Instrument data with a revisit every 2 to 3 days (Ju et al., 2024). Lastly, we acquired ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) Tiled Evaporative Stress Index PT-JPL Instantaneous L4 Global 70 m V002 from NASA Earthdata Search to better understand evapotranspiration dynamics during the 2024 drought (Cawse-Nicholson & Anderson, 2021; Hook & Fisher, 2024).

2.1.2 In situ Data

To study the abiotic conditions of drought, we examined daily meteorological data from the Central Park weather station. We acquired weather station data from the Global Historical Climatology Network-Daily (GHCN) database via Applied Climate Information System (SC-ACIS). This included historical daily climate records from 2000 to 2025, and normal precipitation and temperature records calculated from 1991 to 2020. We obtained zonal shapefiles delineating the seven areas of interest (AOIs) across the park from the Central Park Conservancy, accompanied by metadata on management zones and shape area.

Table 1
Remote Sensing Data Products

Satellite Sensor	Product	Spatial Resolution	Temporal Resolution
Landsat 5 TM	Spectral Radiance	30 meters	16 Days
Landsat 7 ETM+	Spectral Radiance	30 meters	16 Days
Harmonized Landsat Sentinel-2 (HLS)	Harmonized Surface Reflectance	30 meters	2-5 Days
ISS ECOSTRESS	Tiled Evaporative Stress Index	70 meters	Daily

2.2 Data Processing

2.2.1 Satellite Data

We processed data by first filtering satellite images with minimal cloud cover. For park-wide spatial analyses, we filtered satellite images to select those with less than 10% cloud cover across Central Park. In our temporal analysis of the seven AOIs selected by the Central Park Conservancy, we filtered satellite imagery across the corresponding AOI to maximize the number of usable images. Images were retained only if less than 10% of AOI pixels were flagged as cloud- contaminated. Additionally, we applied pixel-level bit masking to each image's Quality Assurance (QA) band to remove residual cloud, snow, and cloud shadow pixels.

To prepare Landsat and HLS surface reflectance data for analysis, we scaled surface reflectance digital numbers (DN) to reflectance using NASA-recommended scale factors for both Landsat and HLS data. This conversion was necessary for calculating accurate values for vegetation health and moisture indices, which we processed using the GEE Python API. Using surface reflectance data, we calculated the NDVI and ReNDVI to evaluate vegetation density and greenness (Kriegler et al., 1969; Eitel et al., 2011) as well as the MSI to estimate water content (Rock et al., 1986; Hunt et al., 1989) in vegetation canopy (Equations 1, 2, and 3). Index equations with specific band information can be found in the appendix (Table A1).

$$NDVI = \frac{NIR - Red}{NIR + Red} \quad (1)$$

$$ReNDVI = \frac{NIR - Red\,Edge}{NIR + Red\,Edge} \quad (2)$$

$$MSI = \frac{SWIR\,1}{NIR} \quad (3)$$

For the 2002 drought, we processed Landsat imagery from June to August of 2002 to study drought impact on vegetation during the peak of the growing season. To compare with years before and after this drought, we repeated the same processing steps for Landsat imagery from June to August 2001 and June to August 2003. We contextualized this data with a historical baseline of Landsat imagery from June to August of 1986 to 2000.

To study the 2024 drought, we applied the same processing steps to the HLS imagery for the peak drought months of October to November 2024, October to November 2023 (pre-drought), and May to July 2025 (post-drought). To compare these images with a historical baseline, we processed HLS imagery from 2016 to 2022, which constitutes the operational period of HLS leading up to the 2023 most immediate pre-drought year to 2024. After processing, we exported park-wide median temporal composites of NDVI, ReNDVI and MSI for the above time ranges.

We did not need to apply additional processing to the ECOSTRESS Level 4 Tiled Evaporative Stress Index (ESI), as this product is distributed as an analysis-ready Cloud-Optimized GeoTIFF. NASA processes this product by downscaling evapotranspiration estimates to 70-meter resolution, gridding the data to a global WGS 84 grid, and including cloud and water masks as quality flags. As a result, the ESI data is already formatted for immediate analysis in ArcGIS Pro.

2.2.2 In Situ Data

To process the weather data, we replaced trivial values with 0" for precipitation, then calculated the total days without rainfall between each rainfall event; we investigated the daily normal maximum and minimum temperature as the daily expected temperature range. Beside daily values, we calculated accumulative precipitation and average temperature over time, and counted the days without precipitation between each rainfall. The processed weather data supported the general understanding of the initial drought stage and the analysis of ESI maps

2.3 Data Analysis

2.3.1 Percent Change Analysis of Drought Response

Utilizing the processed median composites of NDVI, ReNDVI, and MSI, we calculated per-pixel percent change maps (Equation 4).

$$Percent\ Change\ of\ Index\ =\ \frac{Index_{Current} - Index_{Baseline}}{Index_{Baseline}} \times 100\ (4)$$

The $Index_{Current}$ values represent per-pixel mean NDVI values of a specified period whereas the $Index_{Baseline}$ values are the median NDVI values across its corresponding historical baseline period. All analyses from 2001 to 2003 have a historical baseline period of June to August from 1986 to 2000. For analyses concerning the 2024 drought, the historical baseline period is October 15 to November 15 from 2016 to 2022. Since this study was conducted in summer of 2025, we could not create a percent change map of fall 2025 as a post-drought comparison. With the most recently available HLS data, we created percent change maps from May to July of 2024 and 2025 to see how vegetation fared in the growing season before and after the fall 2024 drought. Thus, the historical baseline period for these pre- and post-drought comparisons is May to July from 2016 to 2022.

The percent change analysis provided a standardized and easy-to-understand framework to compare vegetation response across different indices and drought years. After exporting these NDVI, ReNDVI and MSI percent change maps as GeoTIFFs from the GEE Python API, we imported them into ArcGIS Pro for further analysis. We referenced the histogram to apply manual intervals over seven percent change classifications. For each drought year, we set the following upper bounds of each change map class using a seven-class density slicing approach, resulting in classes with: <-30%, –15%, –5%, 5%, 15%, 30%, >30% change. These values were selected to balance interpretability and sensitivity in order to examine both subtle and severe vegetation shifts. The classification thresholds remained consistent across NDVI, ReNDVI, and MSI for the two drought events to ensure uniformity.

We overlaid each percent change map with AOI boundaries to better visualize percent change trends among different areas of the park. We then compared these results to a landscape management map provided by the Central Park Conservancy. This comparison contextualized changes in vegetation health and moisture stress with the usage of each AOI, which included non-irrigated woodlands in addition to irrigated ballfields and lawns.

2.3.2 Temporal Analysis of ReNDVI for 2024 Drought

Since ReNDVI has been cited in literature to be useful for early detection of stress, we generated time series analyses of ReNDVI to see how each AOI responds to the 2024 drought on a week-to-week basis (Eitel et al., 2011). One type of time series graph demonstrated ReNDVI values of each AOI alongside each other for comparison. Then, for the North Meadow Ballfields, Great Lawn, Sheep Meadow, and the North Woods, we plotted the drought-specific ReNDVI values along with the historic median values to identify potential drought-induced stress. We represented historic median values as shaded interquartile ranges (25th to 75th percentile) to showcase where the middle 50% of historic ReNDVI values fell during a given week.

2.3.3 Evaporative Stress Analysis of 2024 Drought

To analyze these vegetation health trends alongside evapotranspiration dynamics, we compared these HLS index-based percent change maps with ESI maps generated for four dates (October 12, 19, 23, 27) just prior to the designation of the 2024 flash drought. Within ArcGIS, we imported the ESI GeoTIFFS and for each date reclassified across specific change intervals into seven classes between 0-1 (typical value range of ESI). We referenced the ESI maps alongside the average temperature and days-since-rainfall for the corresponding day.

3. Results

3.1 Analysis of Results

3.1.1 Percent Change Analysis of 2002 Drought

We began analysis by assessing spectral index-based maps for the 2002 drought, which developed over late 2001 and peaked during the summer of 2002. Meteorological records showed that air temperatures began exceeding 1991-2020 Normals by late fall 2001 and remained elevated into 2002. Precipitation also declined below expected values during this period. The anomaly window, defined by persistent departures from climatological norms, began roughly 60 days prior to the formal Drought Watch designation in December 2001 (Figure A1).

To assess vegetation and moisture response during peak drought conditions, NDVI and MSI percent change were analyzed from June through August 2002, relative to a 1986-2000 median baseline (Figure 2). Across Central Park, NDVI values declined primarily in high-use lawn areas, including Sheep Meadow, East Meadow, and mixed results in North Meadow Ballfields. These same areas also showed elevated MSI values compared to the baseline, indicating increased moisture stress. MSI change was generally more apparent than NDVI change. The Great Lawn was a notable exception for the lawn locations, showing increases of over 30% in both NDVI and MSI compared to baseline, reflecting high vegetation greenness and moisture content changes. Wooded regions such as the North Woods and the Ramble displayed relatively stable values across both indices, with most percent changes remaining between ±5%. These areas showed limited deviation from baseline conditions during this period.

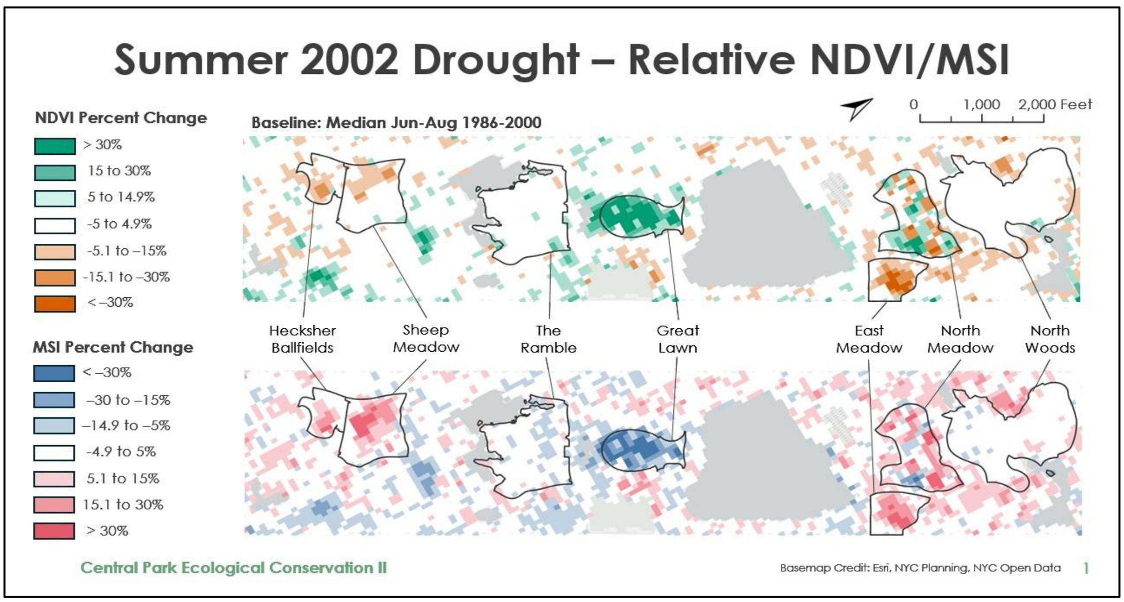

Figure 2. Percent Change Maps of NDVI and MSI for 2002 Drought Comparing Data from June-August 2002 to June-August 1986-2000.

Additional NDVI and MSI percent change maps from summer 2003 provide spatial context for conditions after the peak drought summer (Figure A5). Compared to the 1986-2000 baseline, NDVI values were generally higher indicating more densely vegetated conditions across much of the park. The Great Lawn maintained a 30% increase in NDVI, consistent with patterns observed during the peak drought year. Wooded landscapes such as the Ramble and North Woods continued to remain within ±5% of baseline values. Hecksher Ballfields, which had appeared below the baseline during the drought, displayed increased NDVI by 2003. In contrast, other open spaces such as East Meadow and North Meadow Ballfields continued to exhibit lower NDVI values, indicating reduced greenness compared to baseline. MSI values in 2003 also showed reduced moisture stress in many areas, though some lawn and ballfield regions exhibited residual positive MSI change (i.e., more moisture stress). This was most notable in Sheep Meadow, where increased moisture stress remained evident despite comparatively little NDVI change.

3.1.2 Percent Change Analysis of 2024 Drought

In the weeks preceding the fall 2024 drought, Central Park experienced a historically dry October, receiving only 0.01 inches of rain across the entire month (Figure A2). Abnormally higher temperatures also affected the park during this dry spell. Multiple days in October and November 2024 where the maximum daily temperature exceeded its historical maximum by 10 degrees.

During this hotter and drier fall, there was a relative 5.1% to 15% decline in NDVI and ReNDVI across most areas of Central Park (Figure 3) compared to their historic values for a given index. Certain patches of the lawns and ballfields remained relatively stable, with the inner Sheep Meadow showing the least relative change in NDVI and even an increase in ReNDVI by 5% to 14.9%. On the other hand, Ramble and North Woods showed more vegetation greenness decline, with more than half of Ramble and North Woods experiencing a 30% decline or more in ReNDVI. Through the lens of moisture stress, the majority of Central Park saw an increase in MSI values of 30% or more during this fall, particularly in the Ramble, North Woods, and North Meadow Ballfields (Figure 4). Similar to the ReNDVI results, inner Sheep Meadow and Great Lawn demonstrated the least percent change in MSI, with some patches showing decreases in MSI by 5% to 14.9%.

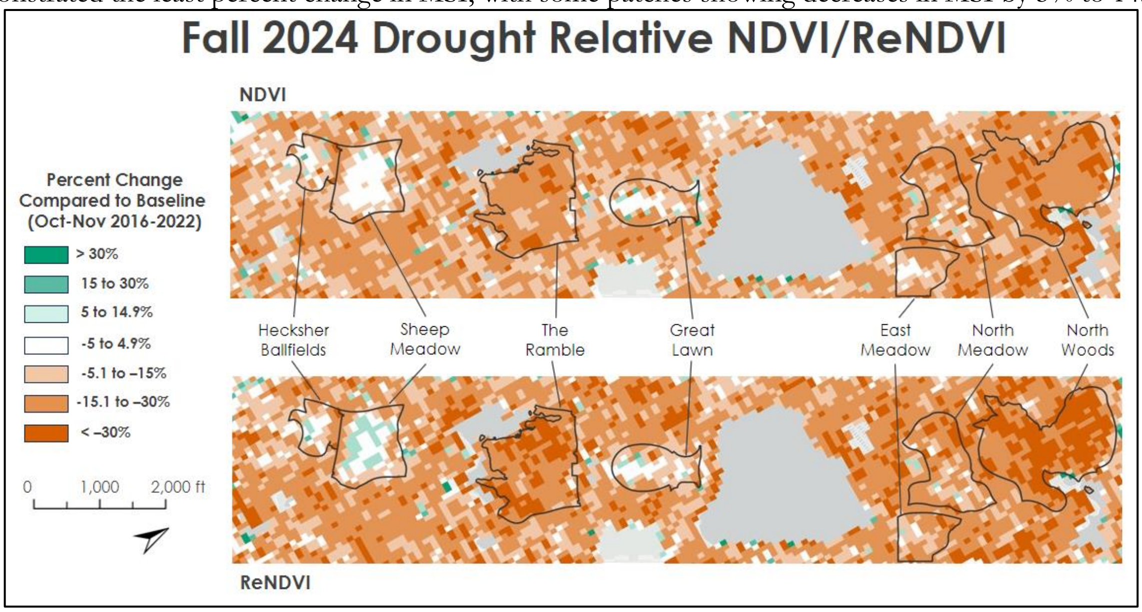

Figure 3. Percent Change Maps of NDVI and ReNDVI for Fall 2024 Drought, Comparing Oct-Nov 2024 to Oct-Nov 2016-2022.

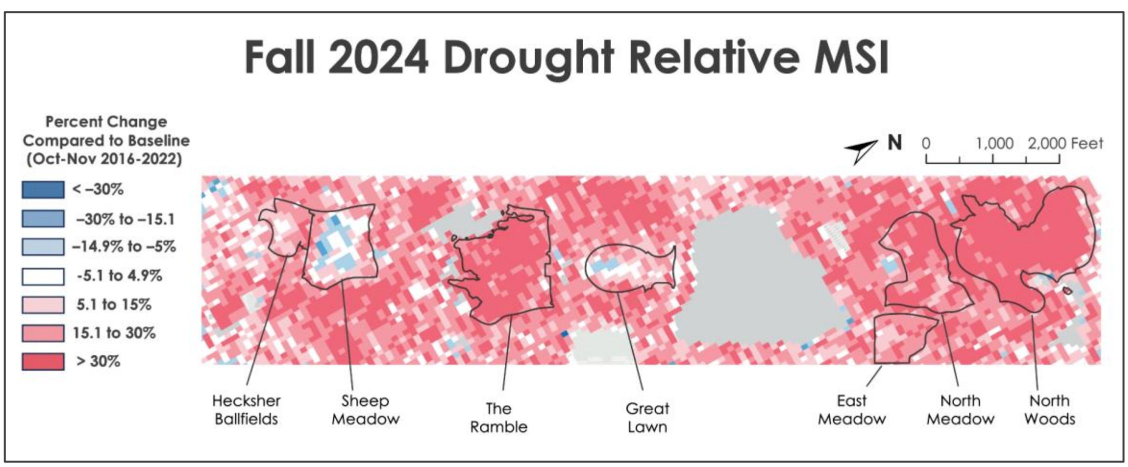

Figure 4. Percent Change Map of MSI for Fall 2024 Drought, Comparing Oct-Nov 2024 to Oct-Nov 2016-2022.

3.1.3 Temporal Analysis of ReNDVI for 2024 Drought

Following how different areas of the park changed each week, Sheep Meadow was the most stable, with only a 0.1 decrease in ReNDVI throughout the fall (Figure 5). During the first two weeks of October, the Great Lawn's ReNDVI dropped to below 0.5 while the East Meadow reached its lowest ReNDVI value (0.41) of the fall in late October. Compared to the lawns and meadows in the fall, Heckscher and North Meadow Ballfields held a lower ReNDVI value range of 0.5 to 0.3, with the largest declines occurring during the second and third week of October. However, across all AOIs in the fall, the wooded Ramble and North Woods experienced the largest declines in ReNDVI. In September, ReNDVI values of the Ramble and North Woods were above 0.6 and had dropped to 0.25 by late November. Compared to its historic median interquartile range of ReNDVI, North Woods ReNDVI typically does not drop below 0.4 until early November (Figure 6). However, ReNDVI values in 2024 dropped below 0.4 approximately two weeks earlier in mid-October.

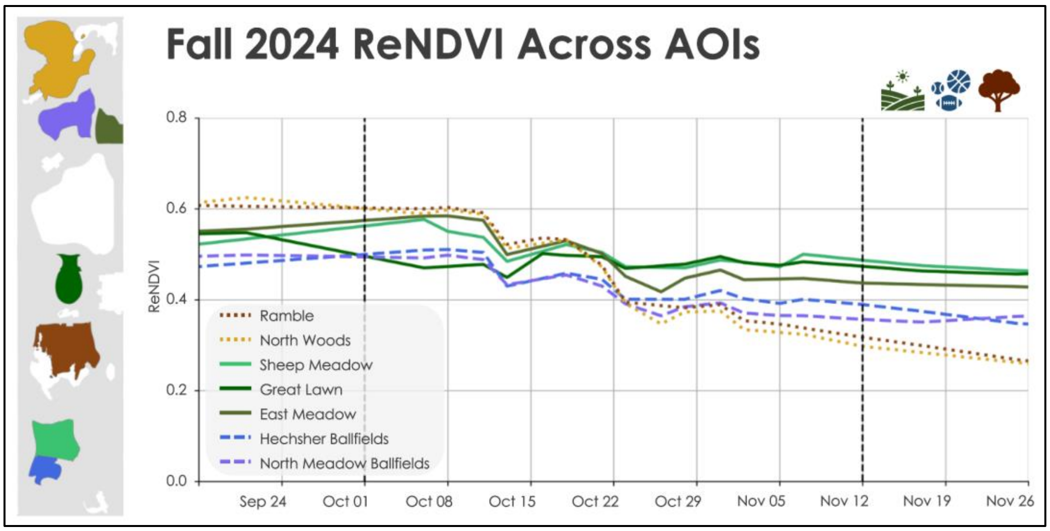

Figure 5. Time Series Graph of Median ReNDVI values within AOIs from Fall 2024.

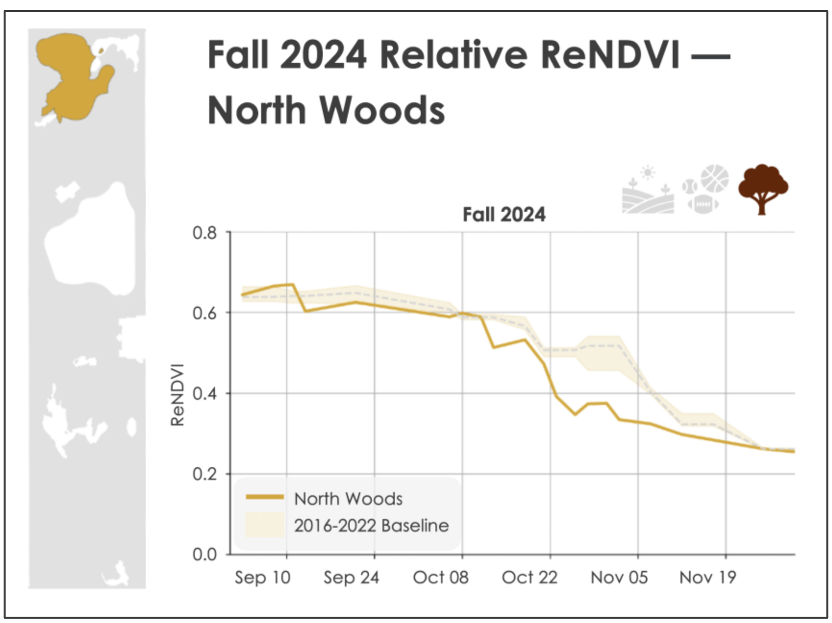

Figure 6. Time Series Graph of North Woods Comparing Fall 2024 Median ReNDVI values to Interquartile Range of Historic (2016-2022) Median ReNDVI values.

3.1.4 Post-Drought Percent Change Analysis of Spring and Summer of 2025
By spring and summer of 2025, NDVI values for most areas of the park returned to the baseline range of ± 5% while ReNDVI values still lagged by -5% to -15% in the Ramble, Mall, Conservatory Water, West Pinetum, and Conservatory Gardens (Figure A6). Across both indices, south of the Jacqueline Kennedy Onassis Reservoir and a corner of the North Woods had values 30% or lower than historic medians. MSI values also returned closer to its historic medians by spring and summer of 2025, with most areas of the park within ±15% of the baseline range (Figure A7). Similarly to the ReNDVI results for summer 2025, relative MSI values for the Mall, Ramble, Conservatory Water, and West Pinetum locations are still higher than baseline values by 5.1% to 30%.

3.1.5 Evaporative Stress Analysis of 2024 Drought
The ESI maps show a clear progressive increase in evaporative stress across the park from October 12 through October 23, with the highest concentration of high-stress pixels, with mean ESI values of 0.29-0.70, consistently located in the ballfields and lawn areas. By October 27, a noticeable decline in overall evaporative stress is seen park wide, but ballfields and lawn regions continue to exhibit high-stress values (Figure 7), which may be due to the temperature being much lower on October 27 compared to earlier dates.

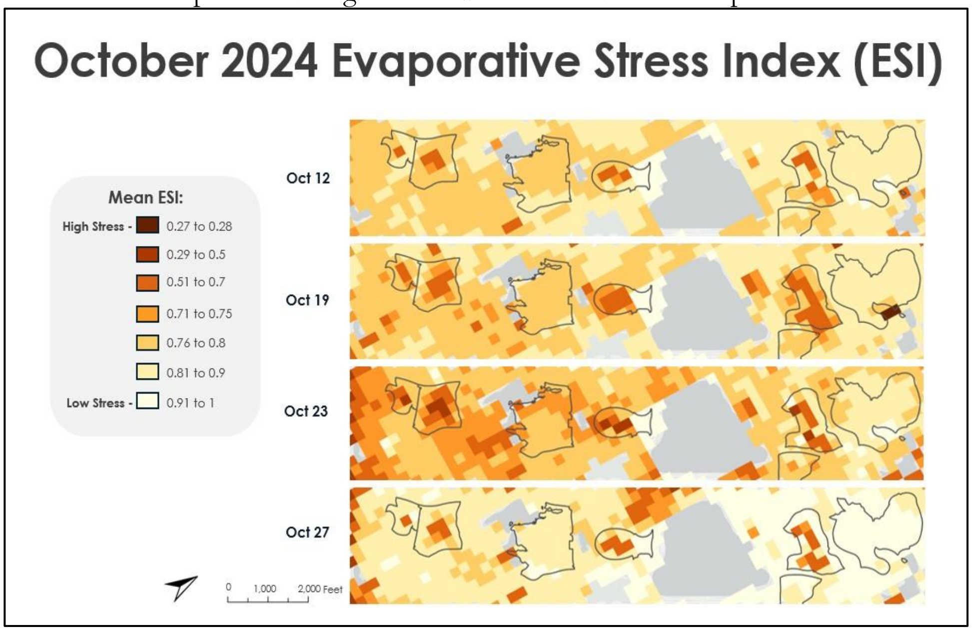

Figure 7. ESI Maps for select October 2024 dates.

3.2 Errors & Uncertainties
The errors and uncertainties of the drought assessment maps from this project in part regard baseline limitations, the impacts of fall senescence and park development, and spectral index specific constraints. First, the historical baseline for each drought is imperfect in terms of cloud free data availability and was also limited by when the data available from each satellite product. The baseline used for the 2002 drought analysis includes droughts occurring in 1989, 1991, and 1995 (New York City Department of Environmental Protection, 2025). Additionally, given the lifespan of HLS, the 2024 change map baseline spanned only 7 years to include ReNDVI data for a consistent comparison across indices. In contrast, most baselines for many climatic studies tend to be of longer duration (e.g., multi-decadal periods).

Second, it cannot be concluded with certainty that the change in vegetation for the fall 2024 drought is exclusively due to drought impacts given other variables like fall senescence and park development. It is likely that drought conditions contributed to an earlier fall senescence, but this expected annual seasonal change could compound vegetation changes seen in our maps and time series. Additionally, park developments in irrigation and construction can present localized vegetation changes that were not produced by drought impacts.

Lastly, for ESI, only four cloud-free ECOSTRESS images were available for October 2024, which limited the ability to do temporal analysis with the ESI data. Frequent cloud cover and limited data availability prevented the retrieval of usable imagery during the official Drought Watch and warning periods starting in November, which restricted our ability to observe evaporative stress during peak drought conditions. It is also difficult to determine whether evaporative stress observed in October had already been present before the onset of meteorological drought conditions, since no usable ESI imagery was available for the early fall. In addition, NASA's ECOSTRESS ESI product is a more highly processed Level 4 modeled dataset that estimates evaporative stress by taking the comparing actual evapotranspiration to reference evapotranspiration, using the DisALEXI-JPL algorithm (Cawse-Nicholson & Anderson, 2021). This method relies on land surface temperature from ECOSTRESS, meteorological data, and vegetation information like albedo and leaf area index to estimate how much water is being used by a given vegetative surface. This may increase the ability to visualize vegetation stress at a higher spatial resolution than other available sources, though it also comes with uncertainty, especially in a mixed land cover area like Central Park. Each 70-meter pixel (~1.21-acre area) can include multiple land cover types so the model's assumption about land cover type may not be accurate. Other errors in temperature data or land cover classification can influence the ET calculation making it harder to determine what is causing the stress.

4. Conclusions

4.1 Interpretation of Results

Analysis of the 2002 drought demonstrated that Landsat-based NDVI and MSI effectively captured spatial variability in vegetation and moisture response across Central Park. Significant increased vegetation and moisture content within the Great Lawn across pre, during, and post-drought conditions can be observed. These trends likely reflect the lawn restoration efforts that were completed in 1997 following the area's degradation during the 'Great Dust Bowl' era of the 1980s, which falls within our baseline period (Central Park Conservancy, 2025b). With this exception, other high-use lawns and ballfields showed potential drought stress across both indices in summer 2002, while wooded landscapes mostly showed resiliency to drought. By the following summer of 2003, areas that experienced potential drought stress in 2002 generally returned to baseline conditions or higher, as shown in areas like Hecksher Ballfields. However, some open spaces like Sheep Meadow indicated possible lingering drought stress, especially according to observed MSI index values. Overall, the spatial analysis suggested that vegetation conditions across Central Park were comparatively healthier in terms of foliar greenness and moistness both prior to and following the 2002 drought event (Figure A3; Figure A4). As outlined in Section 3.2, these trends should be interpreted with the understanding that our baseline for the 2002 drought also includes multiple drought years. Relative to the baseline, the pre, during, and post-drought analysis for 2002 may have influenced values of vegetation greenness and moisture change maps. In turn, this could have led to an underestimation of potential drought stress, contributing to more subdued percent change across the maps and making the drought period appear comparatively neutral despite documented impacts.

The ESI results for October 2024 show that grass-dominated areas such as ballfields and lawns consistently exhibited higher evaporative stress compared to other areas of interest. The park-wide increase in stress from October 12 to October 23 aligns with the meteorological data which indicated a lack of rainfall and average daily temperatures exceeding the norm for late October. The park-wide reduction in stress seen on October 27 is likely influenced by a significant drop in average daily temperature, approximately 10-15°F cooler than previous days. This highlights how short-term weather changes have the potential to shift ESI values without major precipitation changes. While overall stress declined on October 27 on the ESI map, the continued presence of evaporative stress in ballfields and lawns on the same date suggests these kinds of non-forested areas may act as early indicators of emerging drought conditions.

Concerning the short-term drought in fall of 2024, the exceptionally dry and hot conditions of October and November of 2024 (Figure A2) may have contributed to fall senescence occurring earlier in the season in 2024 compared to normal years. The time series results of North Woods ReNDVI also demonstrated that leaf senescence in the woodlands occurred two weeks earlier than usual in the park. These results align with the widespread declines in relative vegetation greenness, density, and moisture content across the park during the drought. While ReNDVI and MSI percent change maps indicated that the wooded areas may have experienced the most drought-induced stress, Sheep Meadow and Great Lawn appeared to be least affected by drought conditions — likely due to the park's irrigation and vegetation management of open green spaces. By the following spring and summer, most areas of the park appeared to return to their baseline conditions. However, the ReNDVI and MSI results indicated that vegetation stress lingered in some wooded areas, such as the Ramble, Mall, Conservatory Water, and West Pinetum locations.

4.2 Feasibility & Partner Implementation

Our study demonstrated the utility of Earth observations products for assessing drought-induced vegetation stress in Central Park. Using satellite-derived indices, it was feasible to detect changes in vegetation greenness, density, moisture, and evapotranspiration during a long-term drought (in 2002) and a short-term drought (in 2024) for the Central Park in New York City. Our analyses focused on seven AOIs across culturally and ecologically significant lawns, ballfields, and woodlands to help guide the Central Park Conservancy's future vegetation management practices. Since the results utilize satellite data (e.g., Landsat) from the past 40 years, our study provides a temporally comprehensive overview of park vegetation health and enables the Conservancy to assess vegetation management practices since its founding in the 1980s. These findings can support the Conservancy in their partnership with the World Monuments Fund as they work together to adapt Central Park's natural systems to future climate stress. Currently, satellite remote sensing does not play a key role in Conservancy's vegetation management strategies. Thus, our study demonstrates a strong potential for the Conservancy to incorporate satellite-based monitoring into their current irrigation practices and soil moisture monitoring. Our research suggests that Sentinel-2-based ReNDVI may be a useful index for earlier detection of drought impacts in the wooded areas of the park. NDVI and MSI from Landsat data also showed potential for aiding Central Park drought impact assessments, especially for earlier droughts prior to when HLS data is available.

5. Acknowledgements

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6. Glossary

Area of Interest (AOI) – a defined geographic region selected for focused analysis within Central Park

Baseline – a historical reference period used to compare current conditions

ECOSTRESS – a NASA instrument on the International Space Station that measures surface temperature and evapotranspiration, providing data for calculating the Evaporative Stress Index (ESI)

Earth observations – satellites and sensors that collect information about the Earth's physical, chemical, and biological systems over space and time

Evaporative Stress Index (ESI) – a remote sensing index that estimates evapotranspiration anomalies. Low ESI values indicate high evaporative stress

Google Earth Engine (GEE) – a cloud-based geospatial analysis platform used to process and analyze satellite imagery at scale

Harmonized Landsat and Sentinel-2 (HLS) – a NASA data product that combines Landsat 8/9 and Sentinel-2 surface reflectance data to provide frequent earth observations

Landsat – a series of Earth-observing satellites operated by NASA and USGS

Moisture Stress Index (MSI) – a remote sensing metric used to assess and monitor moisture content and stress within vegetation

Normalized Difference Vegetation Index (NDVI) – a remote sensing metric used to assess and monitor vegetation greenness and density

Quality Assurance (QA) – a band used with the Landsat collection to mask clouds

Red Edge NDVI (ReNDVI) – a variation of the traditional NDVI that uses the red edge band to assess vegetation health

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8. Appendix

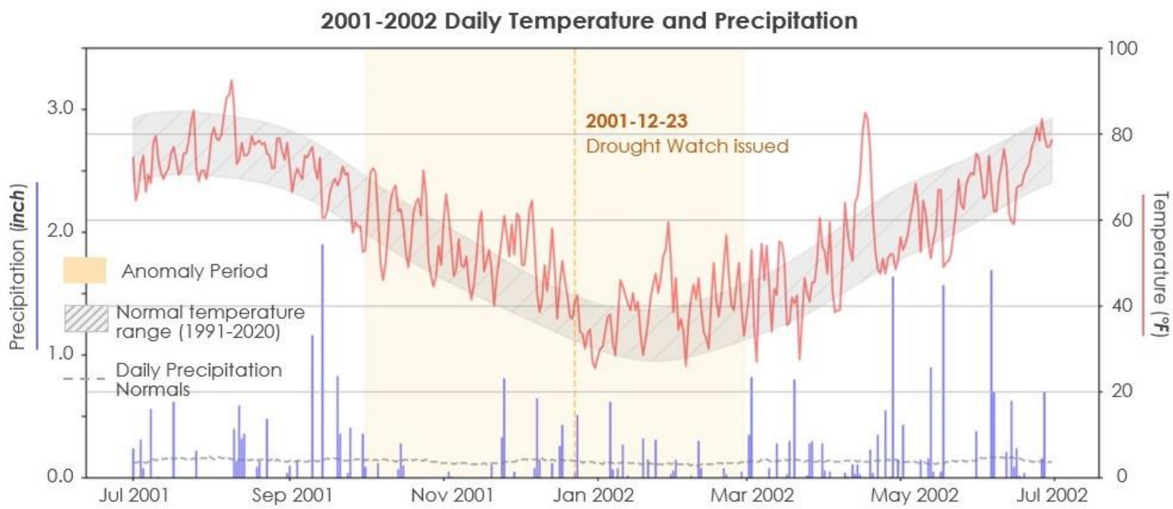

Figure A1. Daily temperature and precipitation from August 2001 to March 2002. The shaded grey band indicates the average minimum to maximum temperature range for a given day from 1991 to 2020.

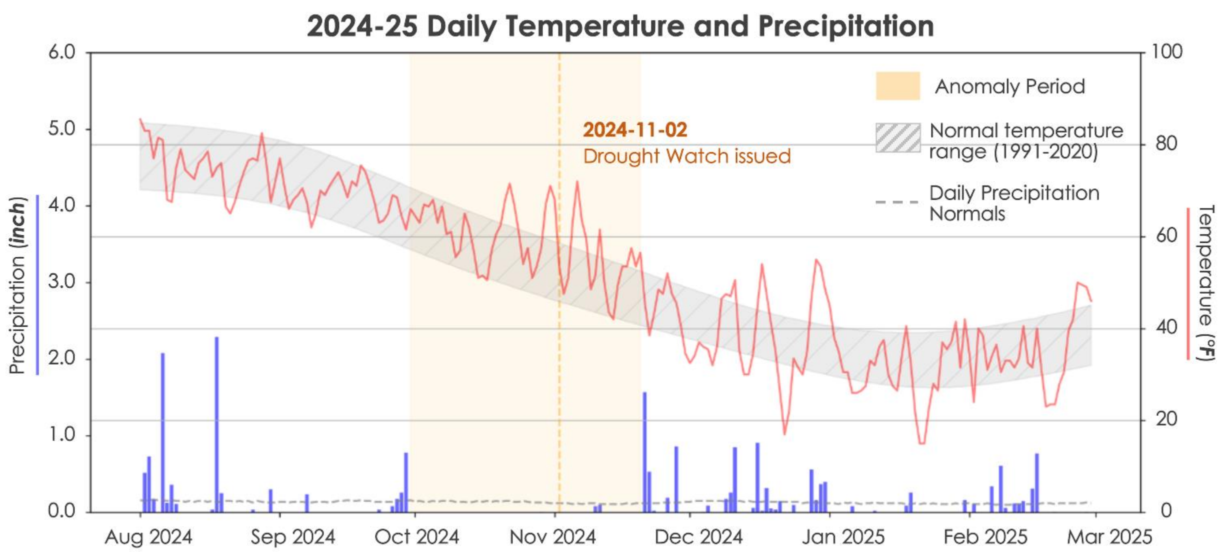

Figure A2. Daily temperature and precipitation from August 2024 to March 2025. The shaded grey band indicates the average minimum to maximum temperature range for a given day from 1991 to 2020.

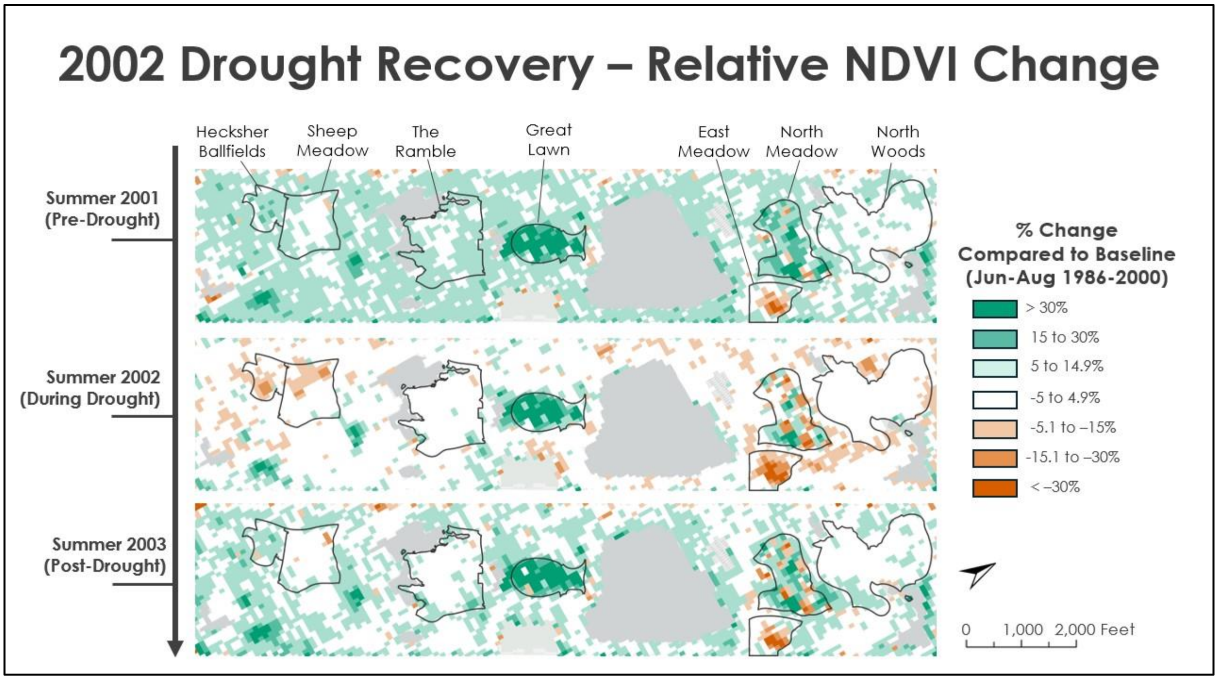

Figure A3. NDVI Percent Change Maps for Sumer 2001 (Pre-Drought), Summer 2002 (During Drought), and Summer 2003 (Post-Drought), Relative to 1986-2000 Baseline.

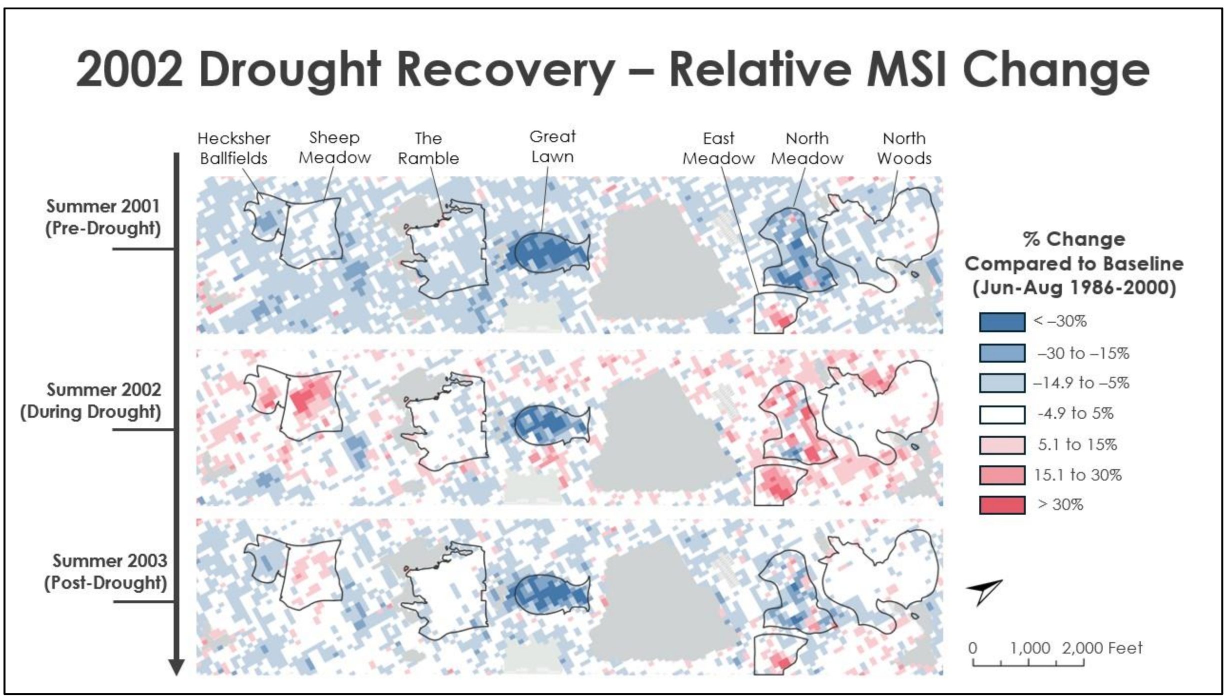

Figure A4. MSI Percent Change Maps for Sumer 2001 (Pre-Drought), Summer 2002 (During Drought), and Summer 2003 (Post-Drought), Relative to 1986-2000 Baseline.

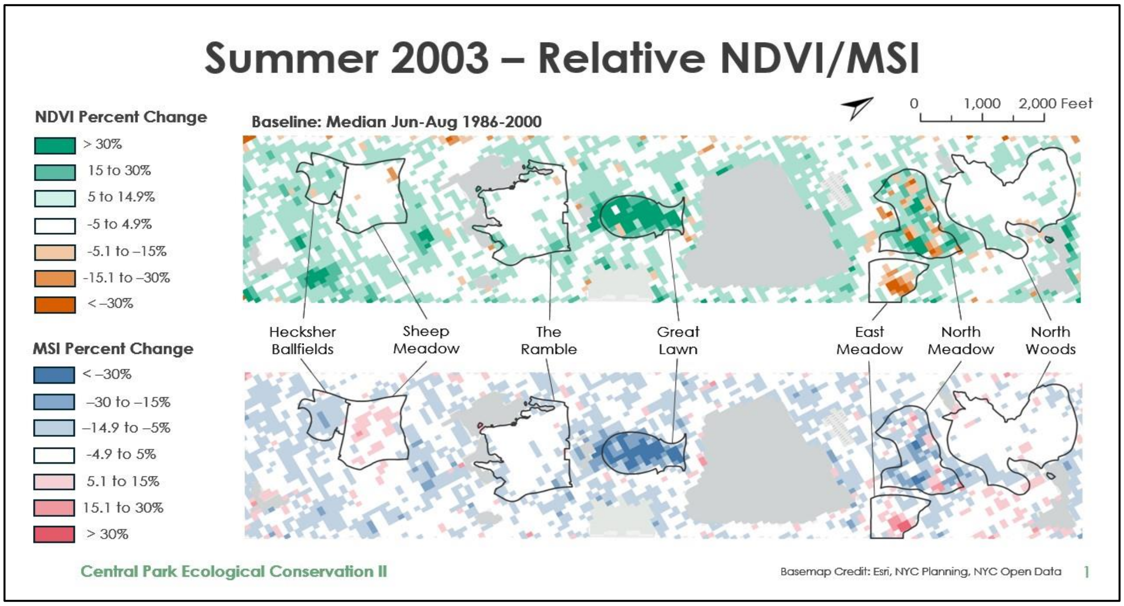

Figure A5. Percent Change Maps of NDVI and MSI Post 2022-Drought Maps Comparing Data for June-August 2003 to June-August 1986-2000.

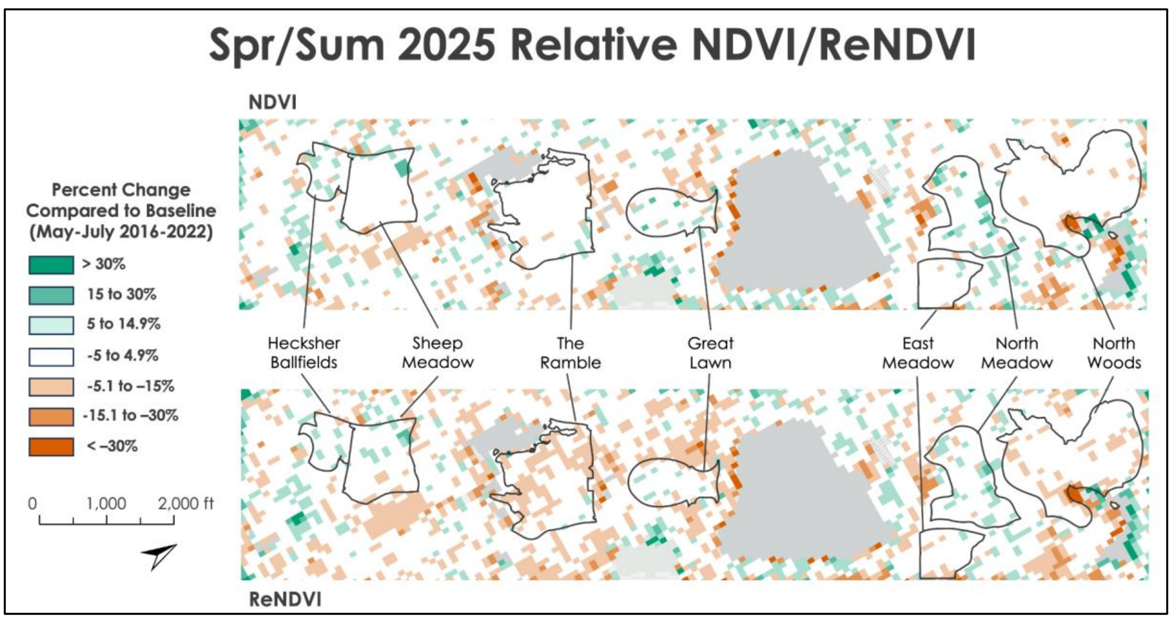

Figure A6. Percent Change Maps of NDVI and ReNDVI for Post 2024 Drought, Comparing May-July 2025 to May-July 2016-2022.

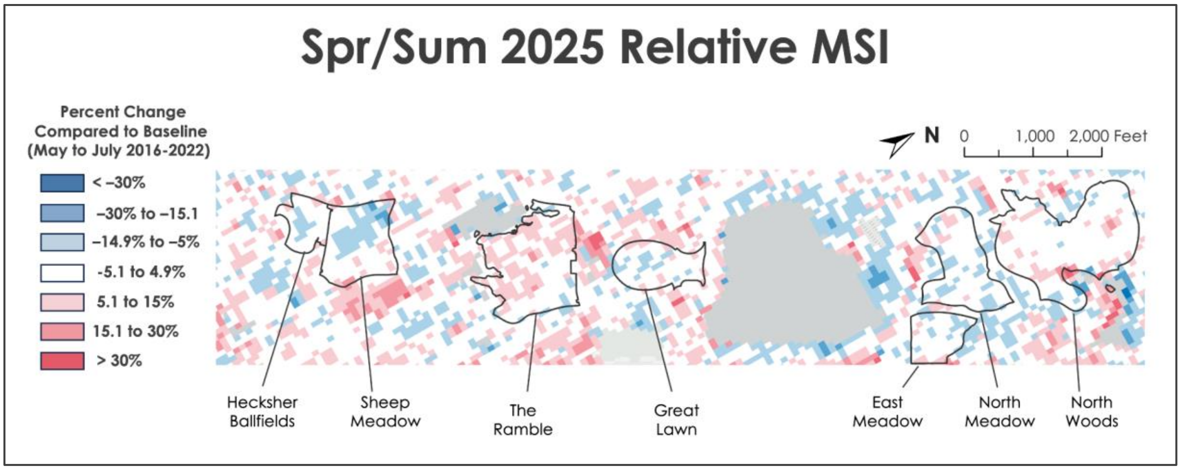

Figure A7. Percent Change Map MSI for Post Drought 2025, Comparing May-July 2024 to May-July 2016-2022.

Table A1. Satellite Sensors and Band Formulas Used for Vegetation and Moisture Indices

	Landsat 5 & 7	Harmonized Landsat Sentinel-2
NDVI	$\frac{Band\,4\ -\ Band\,3}{Band\,3\ +\ Band\,3}$	$\frac{Band\,8\ -\ Band\,4}{Band\,8\ +\ Band\,4}$
ReNDVI	N/A	$\frac{Band\,8\ -\ Band\,5}{Band\,8\ +\ Band\,5}$
MSI	$\frac{Band\,5}{Band\,4}$	$\frac{Band\,11}{Band\,8}$