# Multi-temporal Green Roof Vegetation Assessment Using Sentinel-2: A Pilot Study

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**Abstract**

The City of Toronto has reported having over 1,000 green roofs (GRs) since implementing its green roof bylaw, but their conditions are not systematically monitored and require a remote, cost-effective method. Satellite remote sensing has proven useful in studies of urban green spaces to evaluate vegetation health and conditions, but it has not yet been explored for long-term GR vegetation monitoring. The study aims to assess open-source Sentinel-2 images from Google Earth Engine to monitor vegetation density and water-stress conditions in four selected GR modules. Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI), and Normalized Difference Moisture Index (NDMI) are used to measure vegetation health and water stress from the summer months of 2018 to 2025 (April - September). These multi-temporal indices highlight the seasonal and intra-seasonal dynamics of vegetation, showing potential loss and gain over the period. Vegetation gain was observed in the GRs until 2021 with a gradual increase in NDVI and EVI, followed by a steady trend afterward. Occasional lower NDVI and EVI values have been observed due to potential moisture content deficit, as indicated by low NDMI.

## 1. Introduction

### 1.1 Background

Green roofs (GRs) are one of the most implemented Green Stormwater Infrastructures (GSIs) across the world that help reduce urban runoff, mitigate heat island effects, relieve pollution, increase carbon sequestration, and promote biodiversity. Due to higher reflectivity and resistance to increasing temperatures, GR vegetation also provides a cooling advantage through evapotranspiration (Sánchez-Cordero et al., 2025). The benefits make GRs important GSI assets. As the number of GRs grows, they are increasingly discussed in infrastructure asset management planning (AMP), requiring systematic collection of information on their state and condition to ensure their intended level of service.

GRs are dispersed and primarily small-scale GSI assets on private properties. Regular inspections are recommended and can be helpful for identifying GRs that need service or replacement to address plant damage, water stress, or other maintenance issues. Individual GR inspections could also be supplemented with efficient and non-invasive monitoring procedures, potentially alerting the owners and regulators to maintenance needs. Most GSI monitoring studies focus on mapping or identifying changes in large, vegetated areas, and there is a lack of approaches for monitoring the condition of smaller, built-up surface mixed urban GSIs. Since issues like invasive growth and unhealthy plants can severely affect GSI performance from clogging filter media, inlets, or outlets, vegetation health has been identified as a practical indicator for an early warning of GSI failure (Bahrami et al., 2024).

Remote sensing can help with GSI performance monitoring and maintenance decision-making for optimal planning (Seidu et al., 2025). It is demonstrated as a useful approach for GR vegetation monitoring and stress detection, a few years after installation (Moroni et al., 2019). Studies demonstrate that close-range remote sensing can provide high-quality information (Lee et al., 2024a, 2024b), but it is labour-intensive and difficult to scale. Recent research employed airborne remote sensing to monitor GSIs, such as very high-resolution ortho-imagery (Liao et al., 2025) and drone remote sensing (Dupasquier and McDonald, 2025). However, while such imagery provides finer spatial resolution and vegetation-state details, it is usually captured once per year, and historical images may not be widely available for all urban areas, thereby limiting a comprehensive and continuous assessment of GR conditions within seasons and across many spatially dispersed units. The process of such scanning of GRs also requires significant logistical support, scanning permits, and expertise with significant processing effort.

The broader aim of this study is to address the monitoring challenge as the GSI AMP evolves and enable comprehensive, intra- and inter-annual monitoring using satellite-based remote sensing. Contemporary satellites such as Landsat 8-9 (30 m), Sentinel-2 (10 m), Planet (3-5 m), and WorldView-3 (31 cm) offer high temporal and varying spatial resolutions with global coverage. The research presented here develops and tests an approach for evaluating the condition of GRs by monitoring changes in plant density and water stress using open-source Sentinel-2 images. Despite having a lower spatial resolution of 10 m compared to previous efforts that involved high-resolution images, Sentinel-2 provides a greater temporal frequency (5 days) over an annual assessment, global coverage, an additional band for shortwave infrared (20m) for potential moisture condition monitoring, and it is freely available. This study presents a scalable and economically feasible option for frequent GR monitoring.

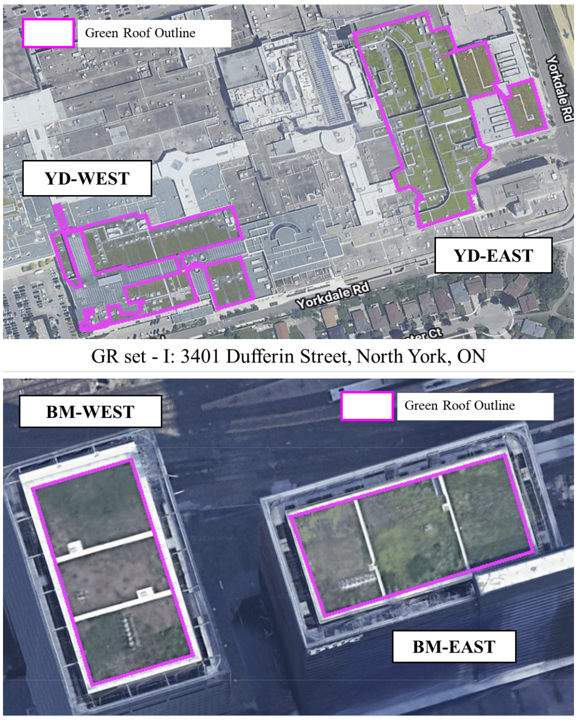
### 1.2 Case Study

The City of Toronto, used as a case study in this paper, enacted the GR Bylaw in 2009. Since then, it is estimated that over 1,000 GRs have been installed, with more permit applications still being reviewed. The Bylaw that was in effect for more than 16 years stipulated that new construction with a gross floor area greater than 2,000 m² requires including GR areas with 20%–60% plant coverage. The most common vegetation type used for GRs is sedum, but sometimes mixed grasses/shrubs or edible crops have also been planted. To ensure adequate function during service life, GRs are intended to have 80% of their vegetation sites in "good" condition (GIO, 2021). The standard GR maintenance procedures for Toronto advise plant watering during drought conditions and inspecting the vegetation coverage (%) once a year as a minimum required frequency (TRCA, 2016). The current maintenance programs lack continuous vegetation performance data and seasonal variation insights. Since GR monitoring is still in its early stages in AMP, it is necessary to investigate how and to what extent satellite imagery can be utilized to help adhere to the maintenance guidelines.

## 2. Methodology

### 2.1 Information on Selected Green Roofs

The case study involves two sets of GR modules: YD-EAST and YD-WEST, at Yorkdale Shopping Center, 3401 Dufferin Street, North York, ON, and BM-EAST and BM-WEST, at 120 Bremner Boulevard, Toronto, ON. The modules were chosen based on their appearance on Google Earth Pro historical images. While the two Yorkdale modules have shown denser, greener plant coverage since installation, the two Bremner modules had bare soil with problematic vegetation patches and evidence of required maintenance (replacement or replantation). The four GR modules cover the following areas: YD-EAST = 17,092 m², YD-WEST = 9,775 m², BM-WEST =1,178 m², and BM-EAST = 1,251 m².




GR set - I: 3401 Dufferin Street, North York, ON

GR set – II: 120 Bremner Boulevard, Toronto, ON

Figure 1. Green Roof Case Study Modules

### 2.2 Data Collection

Each GR module boundary is specified as a polygon in Google Earth Engine (GEE), which is used to filter pixels that are within the GR module. The study used Sentinel-2 Level-2A (L2A) from the Copernicus Collection from 2018 to 2025, spanning April through September, when vegetation actively grows. A cloud filter threshold of 20% was initially applied; however, in some cases, a higher threshold of cloud coverage was tolerated to extract the monthly image, ensuring that no polygons were affected by cloud interference during spatial clipping. The daily minimum and maximum temperatures, as well as total precipitation (mm) from April to September of each year, are gathered from Environment Canada using Toronto Pearson International Airport station data for Yorkdale Shopping Center GRs and Toronto City Center station data for other GRs.

GR vegetation is assessed in this study by determining three indices using Sentinel 2 data: vegetation greenness and density by Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI) (Huete et al., 2010), as well as vegetation water content measured by the Normalized Difference Moisture Index (NDMI).

$$NDVI = \frac{B8 - B4}{B8 + B4} \tag{1}$$

$$EVI = 2.5\,\frac{B8 - B4}{B8 + 6B4 - 7.5B2 + 1} \tag{2}$$

$$NDMI = \frac{B8 - B11}{B8 + B11} \tag{3}$$

where B4 = Red (665 nm)
B8 = Near-Infrared (NIR) (842 nm)
B11 = Short-Wave Infrared (SWIR) (1610 nm)

## 3. Result Analysis

The study first assessed vegetation density using NDVI classifications to delineate long-term changes in vegetation coverage across multiple growing seasons. The season and time of year were found to influence the vegetation density and state, hence, the performance of NDVI. Here, the NDVI values are separated into six classes based on the number of pixels falling within the class out of the total pixels as follows: <0, 0-0.2, 0.2-0.4, 0.4-0.6, 0.6-0.8, and 0.8-1. The classification results are presented in Figure 2 in terms of percent distribution. From the expansion spans of classes, it is seen that the Yorkdale GRs experienced no (YD-EAST) to less than 5% (YD-EAST) NDVI < 0, and about 40% NDVI within the range of 0.4-0.6 for YD-EAST, and 0.2-0.4 for YD-WEST. On the contrary, NDVI distribution shows approximately 40% of BM-EAST within 0.2-0.4, and 55% of BM-WEST within 0-0.2, with 15-20% having NDVI < 0. The year 2021 is identified as the good vegetation recovery time with the highest observed NDVI peaks among all GR modules. This may be associated with favourable soil moisture conditions.

Higher NDVI values generally imply healthier and denser vegetation, with NDVI< 0.6-1 commonly found in forest/tree areas or urban parks of continuous canopy, and a lower NDVI range is observed in shrubs (0.19-0.50) (Aryal et al., 2022). A lower NDVI high limit (maximum 0.7) in comparison to forest ecosystems (~1.0) is also confirmed, which reflects the sparsity of urban vegetation as well as the impaired ecological conditions (Skachkova, 2024). These adjustments highlight that thresholds developed for the ground-based agricultural or forest vegetation may not transfer directly to sparse GRs for monitoring. Scattered GR vegetations can remain low, highlighting NDVI's limitations for fragmented modules. Such vegetation often consists of sedum, or low shrubs, and can exhibit lower NDVI even in healthy conditions. Conventional vegetation thresholds (NDVI ≥ 0.2) can also drop in extensive GRs, since sedum and other low-biomass species often exhibit lower NDVI values (Louis-Lucas et al., 2021).

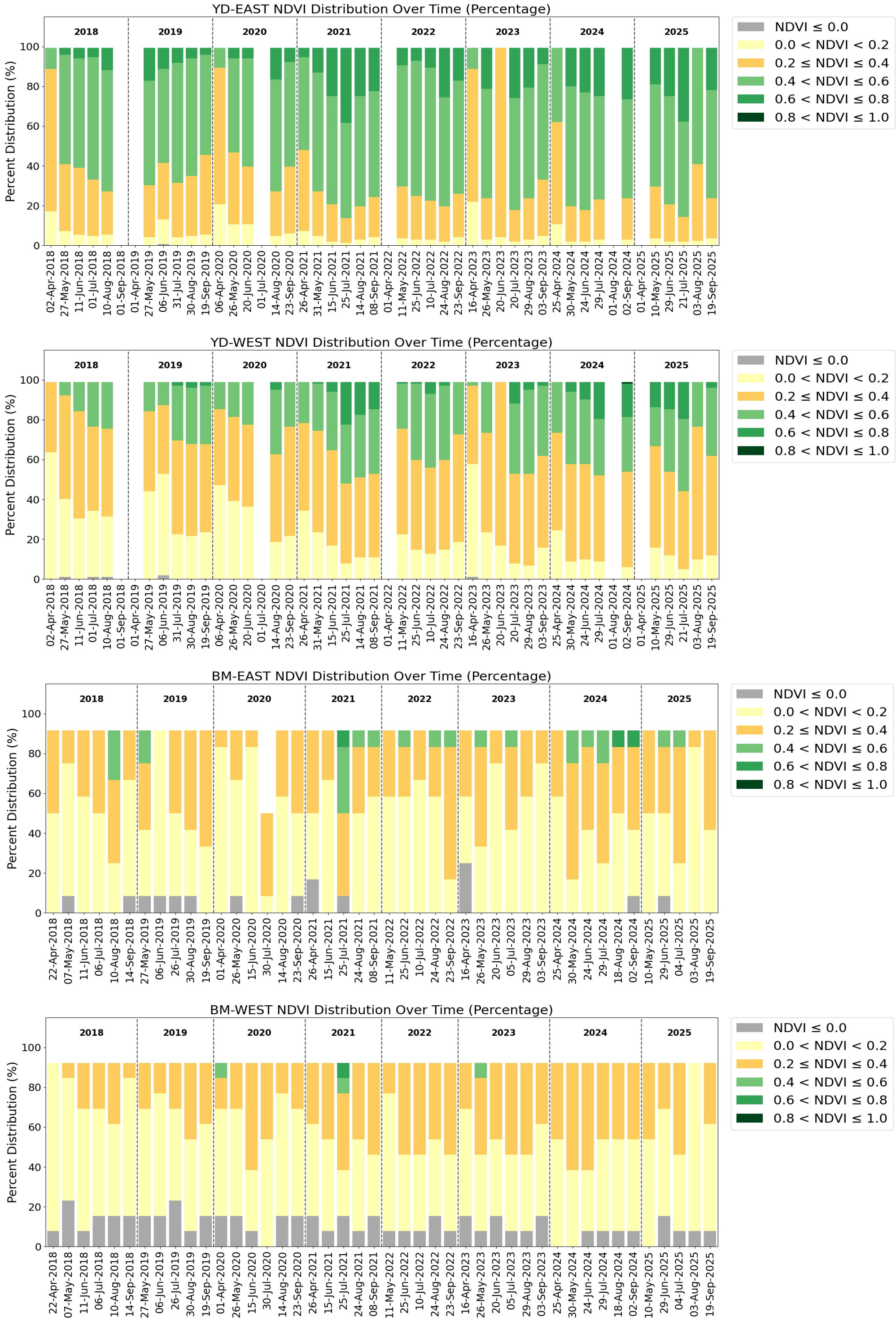



Figure 2. Summer NDVI distribution among GR modules

The study also compared the NDVI, EVI, and NDMI values for all GR modules from 2018 to 2025, focusing on the months from April to September. Figure 3 presents the variation of these indices across the four modules using box-whisker plots with mean and median index values to help track the seasonal growth stages. The pixel-wise values within each GR boundary are used here to present the heterogeneity across them. NDVI indicates the degree of chlorophyll-based vegetation greenness and helps understand canopy coverage in the GR modules. It is observed that the NDVI mean is lowest in April during each year, due to the pre-bloom season in the study area, after which it steadily increases until July and then lessens (senescence) from August till the end of the season. However, when compared among the annual time series, overall historical NDVI mean and median values have depicted a gradual increasing trend from 2018 to 2021 and have become steady until 2025 with occasional inter-season lows. Most GR vegetation is drought-tolerant and can manifest a low shift of NDMI. The higher interquartile range of NDMI in this study indicates the importance of moisture status for NDVI and NDMI peaks in 2021. To better understand vegetation structure without GR growing medium and atmospheric effects, EVI analysis is done, which demonstrates mostly similar trends and spatial patterns like NDVI, but with a lower mean and median range. Both monthly NDVI and EVI are found to reach peaks during June-July compared to other months, except for a sharp seasonal drop on 20th June 2023, when NDMI is observed to be low as well. Otherwise, high NDMI values are observed on days when vegetation density increases. The YD-EAST and YD-WEST modules have exhibited reliable vegetation coverage with consistently higher NDVI and EVI mean and medians. They show the least interquartile change of NDMI, revealing uniform moisture distribution, compared to BM-EAST and BM-WEST, where greater moisture variability is observed. Considering their location and facility types, such performance can be impacted by management practices and local microclimate.

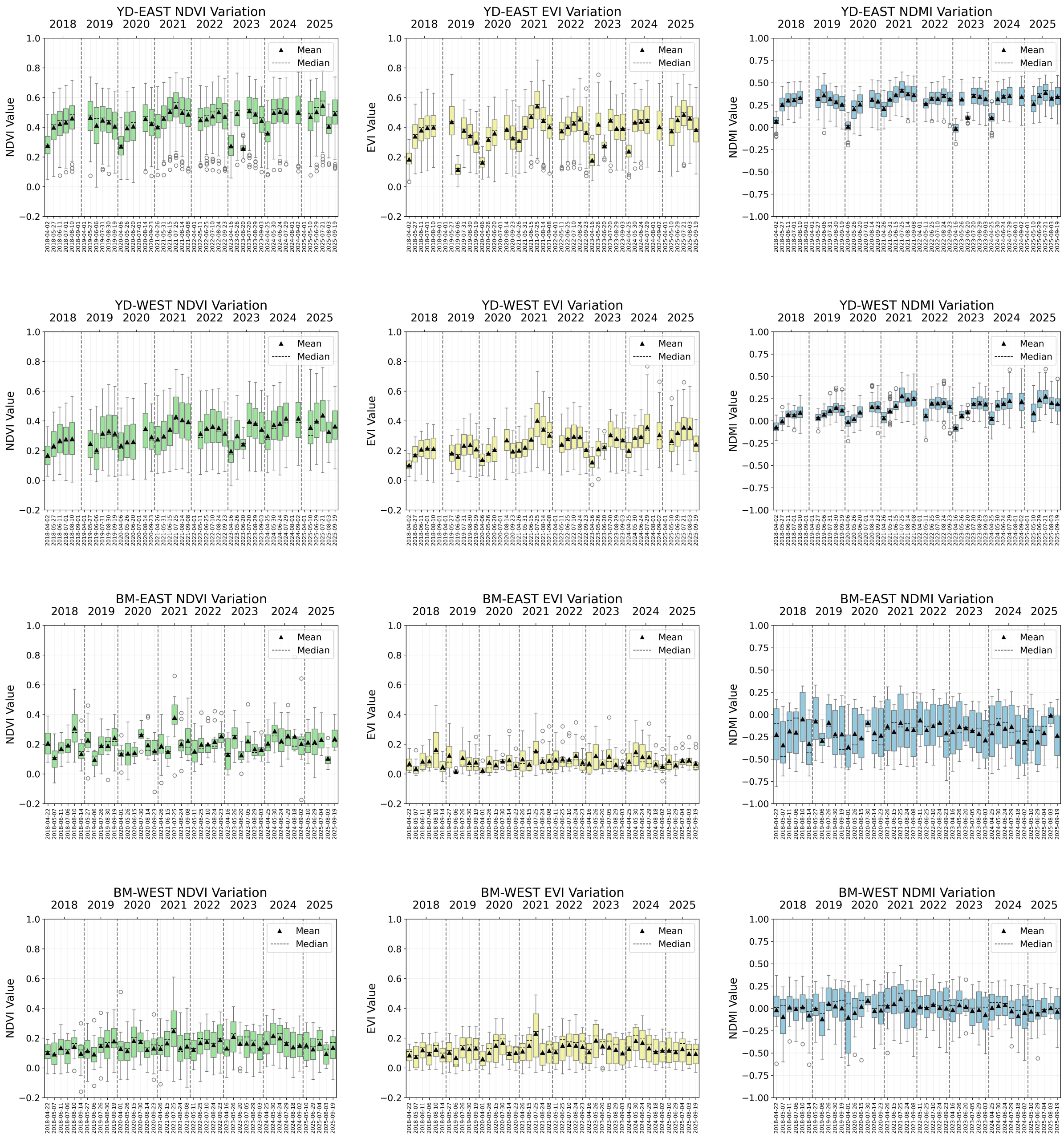



Figure 3. Inter-season and Intra-season variations of NDVI, EVI, and NDMI

The mean NDMI in YD-EAST and YD-WEST range (- 0.15 - 0.3) presents a mid-high vegetation canopy and low water stress condition in the plants. A lower mean NDMI range (- 0.35 – 0.1) is observed in BM-EAST and BM-WEST, interpreted as low and dry vegetation with high water stress conditions in those modules. Higher NDMI reflects well-watered or waterlogged conditions in the soil media, which have not been observed here. BM-EAST resulted in its mean NDMI consistently less than 0, representing a water-stressed condition with low/dry vegetation among the Bremner GR modules. It is also observed that BM-EAST and BM-WEST both received less rainfall compared to Yorkdale GRs. However, this information is derived from ground-based weather stations and may not accurately represent on-site conditions. The Bremner Boulevard GR modules are located in very high-density urban areas on tall buildings, with probably less access to maintenance of the GRs. The potential high temperature exposure and wind damage impact can be the potential drivers of problems correlated with water stress and vegetation development. The differences among roof modules show the impact of such roof-specific external factors on vegetation performance.

GR NDVI and EVI as vegetation density can also be affected by several related factors, including environmental conditions (e.g., rainfall, temperature, solar radiation, and wind speed), design characteristics (e.g., size, substrate depth, drainage, and plant species), and maintenance practices (e.g., irrigation and plant replantation). Since most GRs have a shallow substrate, their seasonal behaviour can differ from the ground-level vegetation. The NDMI insight is particularly relevant for GRs, although vegetation reflectance slightly fluctuates at various growth stages. Lower NDMI from the plant moisture content appears to be a significant indicating factor resulting in low NDVI and EVI. Additionally, NDMI amplitude can also be interpreted to understand the stormwater management and evapotranspiration function of GRs. Based on the long-term shifts in NDVI classification, it can be stipulated that the best vegetation performance is observed on YD-EAST, with YD-WEST reflecting an improving condition. While the BM-EAST vegetation shows high variability, a declining condition is noticed on BM-WEST. Figures 2 and 3 further illustrate that vegetation density in the Bremner Boulevard modules is noticeably sparse and lower than that of the Yorkdale modules, consistent with visual observations from the Google Earth Pro historical collection.

## 4. Conclusion

The assessment shows that a valid estimate of vegetation health can be depicted across urban GRs using Sentinel-2 images as a preliminary inspection tool in long-term GR monitoring. Such long-term monitoring helps demonstrate immediate vulnerability and recovery (regreening) phases within seasons. The results show the effectiveness of NDVI, EVI, and NDMI in assessing plant coverage and moisture content across seasons. High NDVI means lower surface temperature due to increased emissivity, shade, and evapotranspiration (Budzik et al., 2025). NDVI can have sensitivity to soil background and saturates in dense vegetation (Agustiyara et al., 2025), so EVI provides improved performance with higher reflectivity or dense canopy cover by incorporating atmospheric resistance and blue-band correction. Both support maintaining moisture availability measured by NDMI and providing cooling during high temperatures. During the dry periods, NDMI insights could be used for early water stress detection in the GR plants for irrigation needs and to identify dehydrated zones, wherever applicable.

The present study has several limitations. The built-up regions at and inside the GR boundary can have mixed-pixel effects and shadow impact captured by Sentinel 2 pixels. Due to cloud cover, there are some temporal and pixel gaps in the observed period. Although Sentinel-2 imagery is found useful for distinguishing seasonal and interannual changes in this study, its usage at the small-scale GRs (<100 m$^2$) is likely limited. The case study did not include information on soil-media depth, vegetation species diversity, on-site irrigation activities, and ground-truthing of the relevant indices in the GR modules. The study recommends further evaluation by combining plant phenological information (canopy height, density, etc.), other vegetation indices, and relevant field assessment for validation of the vegetation index threshold for species mostly used for GRs. Research is currently ongoing to increase the assessment precision for finer-scale variations using greater-resolution PlanetScope imagery and details of meteorological data.

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