Матеріали XXV Міжнародної науково-практичної конференції
«Екологія. Людина. Суспільство»
пам'яті д-ра Дмитра СТЕФАНИШИНА
(12 червня 2025 р., м. Київ, Україна)

Proceedings of the XXV International Science Conference
«Ecology. Human. Society»
dedicated to the memory of Dr. Dmytro STEFANYSHYN
(June 12 2025, Kyiv, Ukraine)

ISSN (Online) 2710-3315
https://doi.org/10.20535/EHS2710-3315.2025.331043

SENSITIVITY OF URBAN LANDSCAPE GREENNESS TO SPATIAL RESOLUTION OF THE POPULAR REMOTE SENSING PRODUCTS

Iryna DRONOVA
University of California Berkeley
130 Mulford Hall #3114, Berkeley, CA 94720-3114, USA
e-mail: idronova@berkeley.edu

Abstract

Rapid expansion of remote sensing applications in urban landscapes has increased the opportunities for cost-effective inference of vegetation cover proxies using spectral indices of greenness. However, as these studies and data synthesis efforts advance, an important question arises about the statistical comparability and robustness of greenness indicators across different remote sensing sources. This study tested whether and to what extent the statistical distribution of a popular spectral greenness indicator (Normalized Difference Vegetation Index, or NDVI) changes among popular image products when the latter are acquired over the same study area very closely in time. Using the city of Sacramento, California, USA as a test case study, NDVI metrics were extracted from four remote sensing products at 1m, 10m, 30m, and 500m spatial resolution at nearly the same observation time in June 2022. Comparison of statistical distributions of NDVI indicated that central values tend to progressively increase with coarser pixel sizes, making the city appear on average "greener" at moderate to coarser resolutions than at higher resolutions. In contrast, metrics of dispersion such as standard deviation, and the occurrence of extreme high and low index values decreased with coarser spatial resolution. Aggregation of high-resolution products to coarser pixel scales of other products did not produce equivalent statistical distributions. Together, results indicate that the magnitude and variation of remote sensing-derived greenness indicators in cities must be interpreted relative to both the source sensor product and its spatial resolution. Future work should investigate this scale sensitivity more in-depth expanding to a larger sample of cities in different bioclimatic regions and develop generalizable guidance on navigating across different scales of widely used remote sensing datasets.

Key words: *remote sensing; urban landscapes; spectral greenness; spectral vegetation indices; spatial resolution.*

Remote sensing-based indicators of vegetation greenness have gained huge popularity in urban studies. With the growing availability of open-access satellite image datasets and efficient computational tools, such indices can be now computed from a wide variety of products in different geographic contexts. Not surprisingly, their applications have expanded from basic mapping and inventory to the assessments of urban vegetation effects on human health (e.g., [1– 3]), important ecological functions [4–6], urban planning and socio-economic issues [7,8], and even extensive synthetic reviews and meta-analyses which pool the data from diverse sources (e.g., [2,3]). These efforts raise an important question of the statistical comparability and robustness of greenness indicators across different remote sensing sources.

Despite the increasing accessibility of data, this question remains somewhat under-investigated. In part this is because popular indicators of greenness are often computed as "normalized difference" indices where the difference between two relevant electromagnetic signals is divided by their sum [9]. This produces a unitless outcome constrained to the [-1; 1] range which can be compared more easily between locations and time frames than the original absolute image brightness or reflectance. However, it is not well understood to what extent such normalized greenness varies with image spatial resolution (aka image grain size, the ground dimension of the smallest resolvable pixel). Historically, most readily available products have had moderate to coarse pixel sizes (often 30-1000 m) which in patchy urban landscapes would be frequently "mixed", containing both vegetated and not vegetated surfaces [9]. More recently, higher- resolution commercial and open-access imaging products have started to enhance urban green space monitoring and mapping accuracy [9]; however, due to their limited historical availability, long-term change analyses still tend to rely on the coarser datasets [6]. Yet, explicit multi-sensor comparisons among these versatile data sources are relatively few [5,10,11].

Data timing is an important challenge for such comparisons. To robustly measure the sensitivity of greenness to image product scale, observations from different instruments should be ideally taken as close in time as possible. Otherwise, their differences may be confounded by seasonal phenological shifts in vegetation or by other landscape changes between the acquisition dates. In practice, however, gaps and misalignment in satellite revisit times as well as cloud cover interference can limit the availability of data for such investigations.

To address this challenge and research need, this study tested whether and to what extent the statistical distribution of a popular spectral vegetation index changes among popular image products when the latter are acquired over the same study area very closely in time. It was hypothesized that changes in spatial resolution would most strongly affect extreme values of the statistical distribution (e.g., minimum and maximum) and dispersion measures (i.e., standard deviation), because smaller pixels are more likely to encounter 100% coverage of very green landscape covers (e.g., urban forest canopy). It was also expected that aggregating high- resolution imagery of a given sensor to coarser resolutions of temporally matching products of other sensors should produce very similar statistical distributions due to high similarity of the state of the landscape and the same seasonality conditions.

To test these predictions, the study focused on the city of Sacramento, California, USA, for which several imaging products were acquired in very close temporal proximity in June 2022 (Table 1). Three of these products are satellite datasets available in open research access as fully atmospherically corrected surface reflectance products: MODIS (Moderate Resolution Imaging Spectroradiometer) Terra with 500 m pixel size, Landsat-9 with 30 m pixel size, Sentinel-2 with 10 m pixel size of the relevant electromagnetic bands. The fourth product was an orthorectified aerial image from the USA-specific publicly accessible product. The latter product was available from the U.S. Department of Agriculture's National Agriculture Imagery Program (NAIP) which collects high resolution (0.6-1 m) imagery once per 2-3 years in each U.S. mainland state during the summer growing season time frame.

Urban vegetation greenness was represented using a popular Normalized Difference Vegetation Index (NDVI), computed as the normalized difference between near-infrared and red electromagnetic wavebands available in all four imaging sensors. Each remote sensing product on its respective day (Table 1) was clipped to the urban boundary of the study area and converted to a single raster NDVI image. Statistical distributions and descriptive summary statistic metrics were then computed for each clipped NDVI image and compared among four products. To further test whether the observed differences were only due to varying pixel size, images of the two finest-grain products (NAIP and

Sentinel-2) were separately aggregated to spatial resolutions of other coarser products (Table 1). Then, relative histogram frequencies and summary statistics of the aggregated images were compared to those of the sensor products at their native spatial resolutions (e.g., NAIP aggregated to 10 m was compared with Sentinel-2 at its native 10 m resolution, NAIP aggregated to 30 m was compared with Landsat at 30m, and so on).

Table 1. Remote sensing datasets used in this study

Sensor	Product	Pixel size, meters	Image date	Red band (micrometres)	Near-infrared band (micrometres)
MODIS Terra	Surface reflectance	500	June 21, 2022	0.62-0.67	0.841-0.876
Landsat-9	Surface reflectance	30	June 20, 2022	0.64-0.67	0.85-0.88
Sentinel-2	Surface reflectance	10	June 21, 2022	0.64-0.68	0.77-0.88
NAIP	Brightness (DN)	1	June 21, 2022	~0.60-0.70	~0.77-0.99

Statistical distributions of NDVI showed pronounced differences between the four image products, despite the similar timing of their acquisitions. Central values (mean and median) of the distributions showed a tendency to increase with greater (coarser-resolution) pixel size (Figure 1, Table 2). Given that the minimum threshold of NDVI for green vegetation is often around 0.3, mean NDVI for Landsat and MODIS were closer to this threshold than the other two products. These results disagree with the expectation that central values of the NDVI distributions should stay similar among different products and instead suggest that the city is more likely to appear on average "greener" when using a coarser-resolution image product than with a higher-resolution product taken on the same date.

In contrast, standard deviation of NDVI generally decreased with greater pixel size from NAIP to MODIS, despite the simultaneous decrease in the total number of pixels, though it was relatively similar between Landsat and Sentinel-2 (Table 2). The coarsest-grain MODIS data also had the highest minimum and the lowest maximum NDVI values compared to the other three sensors (Table 2). These results agree with the expectation that smaller pixels are more likely to capture cases of extreme positive values such as high-NDVI pixels with 100% green tree or grass cover. Notably, MODIS was the only product here with a positive minimum NDVI value (Table 2).

While more common in water bodies, negative values of NDVI in urban contexts may also occur in pixels with 100% cover of dark urban shadows. At the high solar elevation midday time frames of sun-synchronous satellite observations (e.g., Landsat) such shadows are likely to be relatively narrow, and thus not as likely to produce low negative values in larger pixels.

The statistics of NAIP and Sentinel-2 images aggregated to coarser spatial resolutions in most cases differed from the statistics of the respective datasets at those native resolutions (examples for three statistical metrics are shown in Figure 2). When using a simple average-based aggregation, mean values of the aggregated datasets stayed the same, while mean values at the original resolutions, as discussed earlier, differed to begin with, with higher values observed at coarser pixel sizes (Figures 1 & 2). Among other statistics, NAIP's minimum values remained consistently low even after aggregation; however, for Sentinel-2 aggregation to MODIS resolution produced a positive minimum value though lower than that of MODIS (Figure 2).

Standard deviations of the aggregated images compared differently with native data distributions for NAIP versus Sentinel-2 (Figure 2). For NAIP, even after aggregation standard deviations remained high, exceeding those of Sentinel-2, Landsat and MODIS at their native 10 m, 30 m, and 500 m resolutions, respectively (Figure 2). This evidence suggests that high heterogeneity in the finest-resolution NAIP data did not get fully dampened by the aggregation, even though it progressively decreased with larger pixel size. This could be again due to higher sensitivity to extreme values and broader overall range of values in the original fine-scale NAIP data (Figure 1). In contrast, for Sentinel-2, aggregation led to a somewhat lower standard deviation compared both to Landsat at 30m resolution and MODIS at 500m (Figure 2), suggesting a more excessive than expected homogenization of spectral variation with this artificial aggregation.

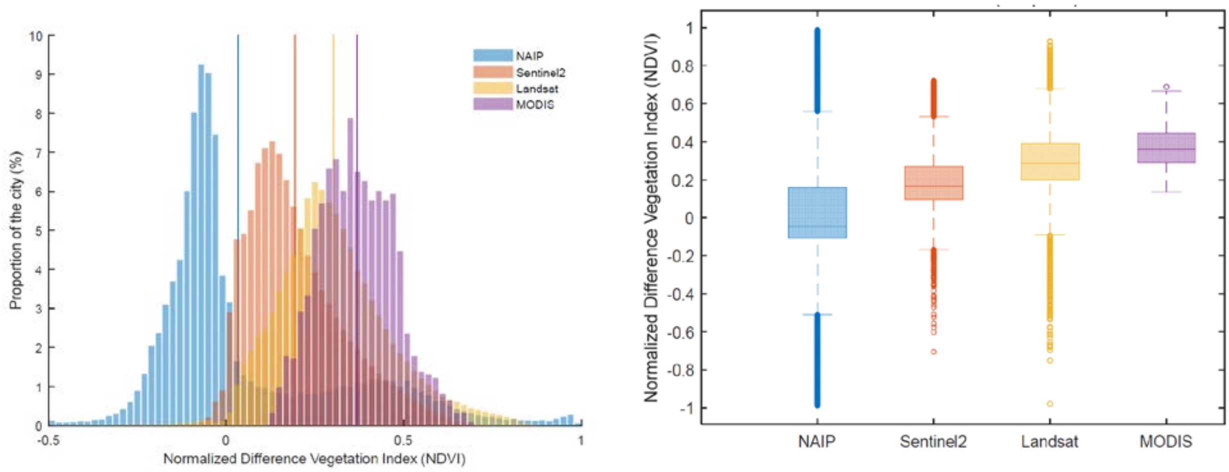

Figure 1. *Statistical distributions of NDVI from the four imaging products. The left panel shows for overlapping histograms with vertical lines indicating mean values in the respective colour of each dataset. The right panel shows the same distributions as boxplots with median values in boxes and outliers indicated as hollow points of the boxplot whiskers*

Table 2. The main summary statistics of the NDVI data values from the four imaging products

Input	Mean	Median	Maximum	Minimum	Standard deviation	#Pixels
NAIP	0.034	-0.048	0.990	-0.988	0.294	330644501
Sentinel-2	0.194	0.166	0.721	-0.706	0.135	2587940
Landsat-9	0.302	0.286	0.929	-0.979	0.158	289382
MODIS Terra	0.369	0.361	0.689	0.134	0.107	1231

Collectively, these preliminary results demonstrate that statistical distributions of NDVI greenness may show notable differences among popular imaging products, and that these differences cannot be solely attributed to contrasts in spatial resolution. While coarser pixels necessarily suppress some of the underlying landscape heterogeneity, we should remember that the original image products also differ in the sensor instruments, specific wavelength ranges used in NDVI computation (Table 1), specifics of data preprocessing, and some other parameters and procedures. All these differences can also ultimately contribute to the contrast in NDVI values and distributions even when controlling for spatial extent and timing of the image data collection. Such effects should be studied more in-depth in the future.

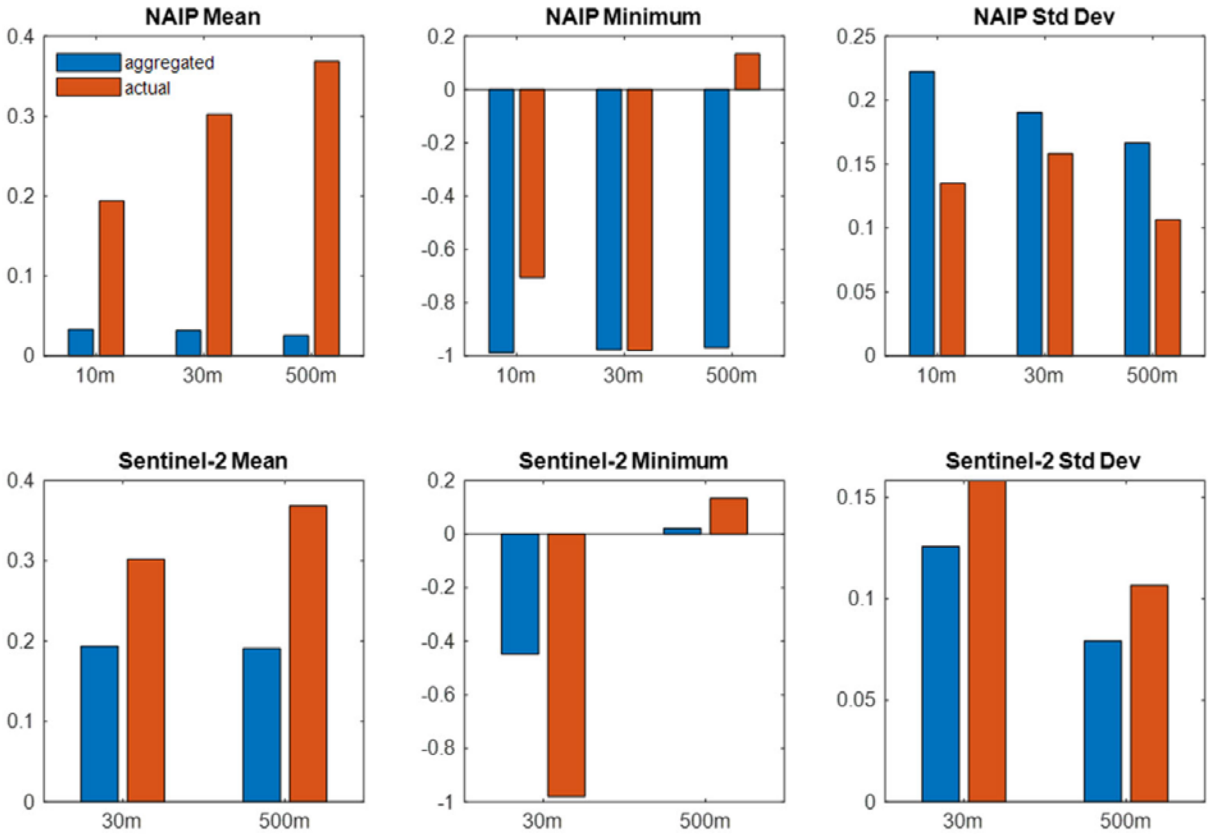

Figure 2. *Example of descriptive statistics (mean, minimum, and standard deviation) compared for the images of NAIP (upper three figures) and Sentinel-2 (lower three figures) aggregated to coarser pixel sizes of other sensors (Sentinel-2, Landsat, and MODIS for NAIP imagery; Landsat and MODIS for Sentinel-2). Blue bars represent statistics of the aggregated images, while red bars indicate the statistics of datasets with the equivalent native pixel size of that magnitude*

From a practical perspective, these findings imply that the magnitude and variation of remote sensing-derived greenness indicators in cities must be interpreted relative to both the source sensor product and its spatial resolution, echoing earlier concerns [1,5]. Meta-analyses, modeling studies, and other efforts working with NDVI data from different sources must proceed with high caution and explicitly account for such product-scale differences by using control variables, stratifying the analyses, and/or testing for the source-related group effects. As there is clearly a need for broader, more general guidance, future work should also measure urban NDVI scale- sensitivity across cities with different amount and configuration of green space and different bioclimatic contexts with different vegetation types. Such efforts may ultimately enable a generalizable framework would allow to more easily translate and calibrate the data among the relevant scales and products and reduce the abovementioned inference uncertainty.

References

[1] Jimenez RB, Lane KJ, Hutyra LR, Fabian MP. Spatial resolution of Normalized Difference Vegetation Index and greenness exposure misclassification in an urban cohort. J Expo Sci Environ Epidemiol 2022;32:213–22. https://doi.org/10.1038/s41370-022-00409-w

[2] Liu Y, Kwan M-P, Wong MS, Yu C. Current methods for evaluating people's exposure to green space: A scoping review. Soc Sci Med 2023;338:116303. https://doi.org/10.1016/j.socscimed.2023.116303

[3] Rojas-Rueda D, Nieuwenhuijsen MJ, Gascon M, Perez-Leon D, Mudu P. Green spaces and mortality: a systematic review and meta-analysis of cohort studies. Lancet Planet Health 2019;3:e469–77. https://doi.org/10.1016/S2542-5196(19)30215-3

[4] Zipper SC, Schatz J, Singh A, Kucharik CJ, Townsend PA, Loheide SP. Urban heat island impacts on plant phenology: intra-urban variability and response to land cover. Environ Res Lett 2016;11:054023. https://doi.org/10.1088/1748-9326/11/5/054023

[5] Tian J, Zhu X, Wu J, Shen M, Chen J. Coarse-Resolution Satellite Images Overestimate Urbanization Effects on Vegetation Spring Phenology. Remote Sens 2020;12:117. https://doi.org/10.3390/rs12010117

[6] De S, Das A, Mazumder TN. A systematic literature review of remote sensing approaches in urban green space research: Towards achieving sustainable development goals. Urban Clim 2025;59:102332. https://doi.org/10.1016/j.uclim.2025.102332

[7] Wellmann T, Lausch A, Andersson E, Knapp S, Cortinovis C, Jache J, et al. Remote sensing in urban planning: Contributions towards ecologically sound policies? Landsc Urban Plan 2020;204:103921.https://doi.org/10.1016/j.landurbplan.2020.103921

[8] González-Marín A, Garrido-Cumbrera M. Assessing urban vegetation inequalities: Methodological insights and evidence. Ecol Inform 2025;86:102987. https://doi.org/10.1016/j.ecoinf.2024.102987

[9] Shahtahmassebi AR, Li C, Fan Y, Wu Y, Lin Y, Gan M, et al. Remote sensing of urban green spaces: A review. Urban For Urban Green 2021;57:126946. https://doi.org/10.1016/j.ufug.2020.126946

[10] Nouri H, Nagler P, Chavoshi Borujeni S, Barreto Munez A, Alaghmand S, Noori B, et al. Effect of spatial resolution of satellite images on estimating the greenness and evapotranspiration of urban green spaces. Hydrol Process 2020;34:3183–99. https://doi.org/10.1002/hyp.13790

[11] Li W, Ouyang Z, Zhou W, Chen Q. Effects of spatial resolution of remotely sensed data on estimating urban impervious surfaces. J Environ Sci 2011;23:1375–83. https://doi.org/10.1016/S1001-0742(10)60541-4

ЧУТЛИВІСТЬ ЗЕЛЕНОСТІ МІСЬКОГО ЛАНДШАФТУ ДО ПРОСТОРОВОЇ РОЗДІЛЬНОЇ ЗДАТНОСТІ ПОПУЛЯРНИХ ПРОДУКТІВ ДИСТАНЦІЙНОГО ЗОНДУВАННЯ

Ірина ДРОНОВА
Університет Каліфорнії, Берклі
130 Mulford Hall #3114, Berkeley, CA 94720-3114, США
https://orcid.org/0000-0003-3339-3704

Анотація

Зростання застосувань дистанційного зондування Землі (ДЗЗ) в міських ландшафтах відкрило нові можливості обчислення показників рослинного покриву за допомогою спектральних індексів зеленості. Однак, подальший розвиток таких досліджень ставить важливе питання щодо статистичної порівнюваності та надійності індикаторів зеленості між різними джерелами дистанційного зондування. У цьому дослідженні перевірено, наскільки змінюється статистичний розподіл популярного спектрального індикатора зеленості (нормалізований диференційний вегетаційний індекс, NDVI) серед знімків ДЗЗ з декількох популярних джерел у випадку, коли такі знімки отримані майже одночасно. На прикладі міста Сакраменто, Каліфорнія, США були отримані NDVI-метрики з чотирьох з супутникових і авіаційних продуктів ДЗЗ з просторовою роздільною здатністю 1 м, 10 м, 30 м та 500 м у майже однаковий час спостереження в червні 2022 року. Порівняння статистичних розподілів NDVI показало, що центральні значення мають тенденцію до поступового зростання зі збільшенням розміру пікселя, через що місто виглядає в середньому «зеленішим» на середніх і грубих роздільних здатностях, ніж на високих. Натомість показники дисперсії (стандартне відхилення), а також наявність високих і низьких екстремальних значень індексу зменшилися зі збільшенням просторової роздільної здатності. Агрегація високороздільних продуктів до грубішої роздільної здантості інших продуктів не призвела до еквівалентних статистичних розподілів. Таким чином, результати демонструють, що величину та варіацію індикаторів зеленості, отриманих за допомогою дистанційного зондування в містах, слід інтерпретувати з урахуванням як джерела сенсорного продукту, так і його просторової роздільної здатності. Майбутні дослідження повинні детальніше дослідити цю чутливість і розширити вибірку міст у різних біокліматичних регіонах. Це допоможе розробити узагальнені рекомендації щодо використання на калібрування даних ДЗЗ з різних джерел для майбутніх застосувань міських індикаторів рослинності.

Ключові слова: дистанційне зондування Землі; міські ландшафти; спектральна зеленість; спектральні індекси рослинності; просторова роздільна здатність.