The Hidden Cost of Cloud Computing: Using Remote Sensing Principles and Applications to Analyze Industrial Growth and Land Surface Temperature Changes in Loudoun County, VA

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Introduction

Remote sensing has become an essential tool for monitoring urban expansion and its thermal impact on local environments. Landsat 8 Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) provide multispectral and thermal data, enabling analysis of land-cover changes and land-surface temperature (LST) variations over time. The Normalized Difference Built-up Index (NDBI), derived from Landsat 8's near-infrared (Band 5: 0.85-0.88 µm) and shortwave-infrared (Band 6: 1.57-1.65 µm) bands, has proven effective in identifying urban development patterns. It correlates strongly with increases in land surface temperature (Guha et al., 2018). While thermal Band 10 (10.60-11.19 µm) allows for precise LST calculations using established retrieval algorithms such as the mono-window method and radiative transfer equation-based approaches (Wang et al., 2015; Yu et al., 2014). Multi-year analyses using these indices have successfully documented the relationship between built-up expansion and temperature changes across various urbanized regions, with studies showing temperature differences of 3-4°C between developed and undeveloped areas (Bayraktar & Turalioglu, 2024; Guha et al., 2018).

Objective

This study will compare land-cover and LST changes between 2014 and 2024 for Loudoun County, Virginia, and for a single data center site within the county. NDBI will be used to identify and delineate areas that have been transformed from undeveloped or agricultural land to developed urban land for human populations and industrial use. After quantifying land-cover changes, LST for the entire county and the data center's geographic location will be determined to assess whether an urban heat island (UHI) formed. This direct spatiotemporal comparison correlates urbanization with global warming (Liu et al., 2025) and links Loudoun County's data center facility proliferation explicitly to accelerating temperature increases.

Hypothesis

Data center construction and increases in the human population between 2014 and 2024 will result in measurable increases in LST in and around Loudoun County. What was once agricultural land, vegetation, or bare soil has been transformed into industrial sites and/or suburban communities over the past 10 years. Within this timespan, the urbanized environment and LST multispectral measurements are expected to increase significantly. This hypothesis is based on findings from urban heat island studies showing that the transformation from vegetation to permeable surfaces generates substantial thermal emissions. Documented temperature differences of 3.15-3.31°C between built-up and non-built areas in urban environments (Guha et al., 2018), and correlation analyses demonstrating significant relationships between NDBI and LST over multi-year periods (Bayraktar & Turalioglu, 2024).

Site Background and Description

Outside of Washington D.C. and over the past 5 to 10 years, Northern Virginia has become the epicenter of America's data center boom. Technology companies like Google are building massive warehouse-like buildings, sometimes called "server farms," to house thousands of computers that power the internet, from social media to cloud storage, but more specifically to power the computing needs required by artificial intelligence technology advances such as Gemini, ChatGPT, Claude, and CoPilot. Northern Virginia is the largest data center market in the world, accounting for 13% of all reported data center operational capacity globally and 25% of capacity in the Americas (JLARD, 2024). Loudoun County is home to the world's largest concentration of data centers, collectively known as "Data Center Alley." As of 2025, Eastern Loudoun has the highest concentration of data centers in the world, with approximately 200 built and 117 under development, and there has not been a single day in 15 years when a data center was not under construction in Loudoun County, which has more data centers than the next six U.S. markets combined (Turner, M., 2025). Between 2014 and 2024, the region experienced unprecedented data center expansion driven by demand for artificial intelligence and bitcoin computing infrastructure. Major facilities constructed during this time include the Yondr Group's 96 MW Loudoun County campus in 2024, which transformed previously agricultural or undeveloped land into high-density computing facilities that operate continuously and generate substantial heat through cooling systems and power infrastructure.

Along with the significant increase in data centers, Loudoun County has experienced a population boom, transforming from rural farmland into one of America's most affluent and fastest-growing communities. The county's population surged by 22.37%, adding over 81,050 people in just 10 years (World Population Review, 2025). This rapid demographic growth has driven extensive residential and commercial development, adding pressure on land use and contributing to broader environmental changes observed in satellite imagery. The combination of data center expansion and residential growth has fundamentally altered the landscape, replacing forests and farmland with buildings, roads, and infrastructure that contribute to rising land surface temperatures and the formation of urban heat islands across the region.

Description of Data and Methodology

Launched in 2013, Landsat 8 is equipped with two key instruments: the Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS). These sensors collect data across 11 spectral bands: OLI captures eight multispectral bands at 30-meter resolution, and TIRS records two thermal bands (Bands 10 and 11) at 100-meter resolution, resampled to 30 meters for consistency. Operating at an altitude of 705 km, Landsat 8 achieves global coverage every 16 days, providing the temporal and spatial resolution needed to monitor land-use change and thermal dynamics.

The following data acquisition and analytical methodology were applied to examine both Loudoun County at large and the Yondr Group's data center location specifically. Landsat 8 imagery with less than 15% cloud cover from July 2014 and August 2024 was acquired from the USGS Global Visualization Viewer (GloVis) to analyze urbanization patterns over this ten-year period. The Normalized Difference Built-up Index (NDBI) was employed to distinguish built-up areas from vegetation and bare soil using the near-infrared band (Band 5: 0.85-0.88 μm) and shortwave infrared band (Band 6: 1.57-1.65 μm). This index is calculated as NDBI = (SWIR - NIR) / (SWIR + NIR), or for Landsat 8 specifically: NDBI = (Band 6 - Band 5) / (Band 6 + Band 5). Following

NDBI quantification, Band 10 was used to calculate land surface temperature (LST) using the atmospheric window algorithm, which has been shown to accurately retrieve LST when ground emissivity, atmospheric transmittance, and effective mean atmospheric temperature are properly determined (Wang et al., 2015).

To estimate thermal readings for Loudoun County, high, medium, and low thermal points were manually selected from the Google Earth Engine data visualization to represent the range of land surface temperatures across the study area. This approach was adopted due to technical limitations in calculating the county-wide average LST, allowing for a representative assessment of temperature variability by identifying distinct thermal zones within the imagery. Geographic information systems used for spatial analysis included ArcGIS Pro and Google Earth Engine, with thermal analysis conducted in Google Earth Engine and open-source code developed to quantify and visualize LST estimates (Ermida, 2020), while ArcGIS Pro was used to calculate NDBI and visualize the spatial distribution of urban versus vegetative areas.

Analysis and Results

Loudoun County NDBI

Between 2014 and 2024, Loudoun County experienced significant urbanization as measured by the Normalized Difference Built-up Index (NDBI). Analysis of spectral data revealed a near-infrared (NIR) median decrease from 22,920.000 in 2014 to 2,126.3286 in 2024, while the shortwave infrared (SWIR) median increased from 13,279.8704 to 14,237.6030 over the same period. These spectral shifts resulted in an NDBI change of +1.01, with values moving from -0.2663 in 2014, indicating dense vegetation cover, to +0.7401 in 2024, signifying extreme urban development. This transition represents a dramatic landscape conversion from natural vegetative areas to heavily built-up infrastructure characterized by impervious surfaces, buildings, roads, and paved areas.

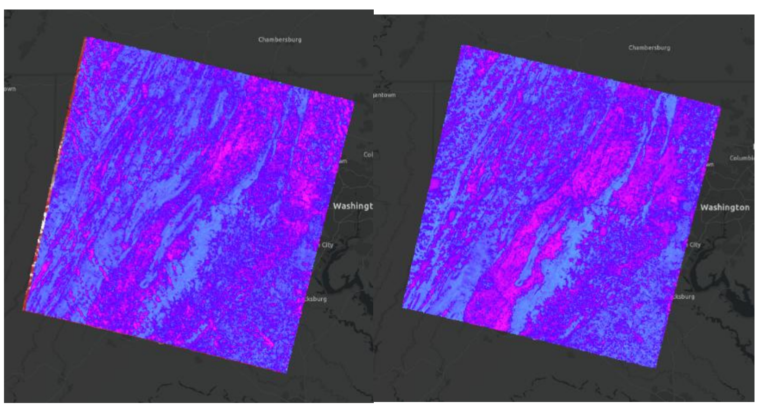

Figure 1. Loudoun County urban growth comparison 2014 (left) vs 2024 (right)

Yondr Group Location NDBI

The Yondr Group location in Loudoun County experienced dramatic land-use changes between 2014 and 2024. Analysis of spectral data revealed a near-infrared (NIR) median decrease from 22,920.000 in 2014 to 2,126.3286 in 2024, while the shortwave infrared (SWIR) median increased from 13,279.8704 to 14,237.6030 over the same period. These spectral shifts resulted in a remarkable NDBI change of +1.01, with values moving from -0.2663 in 2014, indicating dense vegetation and forest cover, to +0.7401 in 2024, signifying extreme urban development. This transition represents a complete landscape conversion from natural vegetative cover to heavily built-up infrastructure, characterized by impervious surfaces, buildings, and paved areas associated with data center development. The magnitude of this change exemplifies how the site transformed from a forested landscape into an intensely urbanized environment within just a decade.

Loudoun County Thermal Readings

Between 2014 and 2024, Loudoun County experienced a substantial increase in LST, with the median LST rising from 304.31 Kelvin (88.01°F) to 316.55 Kelvin (110.12°F), an increase of 12.24 Kelvin (22.03°F). This dramatic warming is directly correlated with the county's rapid urbanization during this period. The temperature range also shifted upward, with the maximum LST increasing from 310.18K (98.55°F) to 317.25K (111.38°F) and the minimum rising from 295.33K (71.93°F) to 300.17K (80.63°F). This widespread temperature elevation reflects the replacement of vegetative cover with impervious surfaces such as buildings, roads, and parking lots, which absorb and retain more heat than natural landscapes. The LST increase mirrors the dramatic transformation captured by the NDBI shift from -0.27 (dense vegetation) in 2014 to +0.74 (extreme urban) in 2024, demonstrating the direct thermal consequences of converting the landscape to accommodate a population that grew by 22.4%, adding over 81,000 residents during this decade.

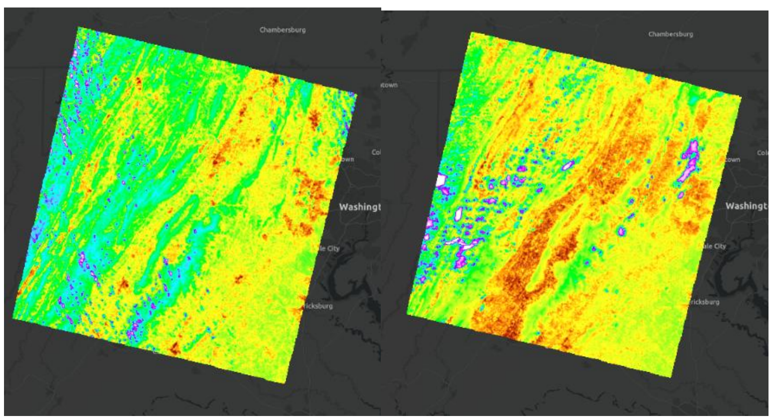

Figure 2. Figure 1. Loudoun County urban heat island formation, a thermal comparison of 2014 (left) vs 2024 (right)

Yondr Group Thermal Readings

The Yondr Group's data center location experienced a dramatic increase in land surface temperature between 2014 and 2024. In August 2014, LST readings measured 303.782K (87°F), reflecting moderately warm surfaces typical of the dense forest and vegetated land cover that existed at the site before development. By August 2024, following the construction of the data center complex, LST readings surged to 313.27K (104°F), representing hot surfaces characteristic of urban infrastructure, impervious surfaces, and the extensive built environment associated with data center operations. This 17°F (9.5K) increase demonstrates how the transformation from natural forest to industrial development has dramatically altered the landscape's thermal properties. The elevated temperatures at the Yondr site are consistent with urban heat island effects, where the replacement of vegetation with buildings, concrete, and other heat-absorbing materials creates localized hotspots that contribute to the broader pattern of warming observed across Loudoun County's rapidly developing data center corridor.

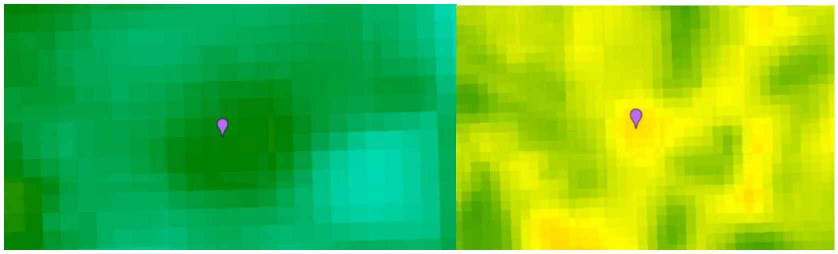

Figure 3. Yondr Group Data Center location, thermal reading for 2014 (left) and 2024 (right)

Limitations

This study has several significant limitations that must be acknowledged. The reliance on single-month snapshots from July 2014 and August 2024 may not fully represent annual temperature patterns or account for seasonal variability, and using imagery from different months could introduce inconsistencies in LST comparisons. The requirement for less than 15% cloud cover may have limited the availability of imagery, potentially excluding more representative data. While Landsat 8's 30-meter resolution is suitable for landscape-level analysis, it may not capture fine-scale thermal variations within the data center complex, which is why individual buildings were not visualized. Resampling TIRS thermal bands from 100-meter to 30-meter resolution introduces interpolation that may reduce measurement accuracy. The manual selection of high, medium, and low thermal points from Google Earth Engine visualizations, rather than computing an actual statistical average, introduces subjectivity and sampling bias that may not accurately represent thermal conditions across Loudoun County.

Additional methodological constraints include the NDBI potentially misclassifying certain land-cover types, such as bare soil or rock outcrops, as urban surfaces. The atmospheric window algorithm's accuracy depends on proper determination of ground emissivity, atmospheric transmittance, and effective mean atmospheric temperature (Wang et al., 2015), and uncertainties in these parameters could propagate errors into LST estimates. The study does not account for temporal variations in atmospheric or weather conditions between 2014 and 2024 that could affect LST retrievals. The ten-year gap provides only two temporal snapshots, limiting the ability to understand the trajectory of change. The study does not control for interannual climate variability, meaning that differences in weather patterns between 2014 and 2024 could partially explain the observed LST increases, independent of land-use change. Furthermore, the analysis does not incorporate ground-truth or validation data to verify remotely sensed temperature measurements.

Conclusion

This study reveals the dramatic environmental transformation of Loudoun County, Virginia, between 2014 and 2024, as measured through satellite-derived LST and NDBI. County-wide median LST increased from 88.01°F to 110.12°F, a 22°F rise, while NDBI values shifted from -0.27 (dense vegetation) to +0.74 (extreme urban development), representing a +1.01 change across the full land cover spectrum. The Yondr Group data center location exemplifies this transformation, experiencing a 17°F temperature increase and an identical NDBI shift from dense forest to intense urbanization. With 199 data centers now operating and 177 more in development, this site illustrates the broader environmental shift across "Data Center Alley." While data centers are not the sole driver, as Loudoun's population grew 22.4%, adding over 81,000 residents, the satellite record confirms that what was once green and cool is now built-up and hot. The challenge facing Loudoun County is balancing economic opportunity with environmental sustainability and quality of life. Despite limitations including single-month snapshots and 30-meter resolution constraints, the findings demonstrate how rapid transformation from rural county to global technology hub has fundamentally altered the local environment. As demand for AI, cloud computing, and digital infrastructure accelerates, these thermal impacts will intensify, necessitating multi-temporal analysis, ground-based validation, and sustainable development policies to mitigate urban heat island effects in one of America's fastest-growing counties.

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