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Environmental Impact of Stadiums and Urban Greening in the FIFA World Cup 2022 in Qatar

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Abstract

This study examines the environmental impact of the FIFA World Cup 2022 on urban areas in Qatar, focusing on landscape transformation, urban greening, and mitigation of land surface temperature (LST). This study employs remote sensing data from Landsat and Google Earth to analyze vegetation dynamics and LST variations in Qatar before and after the 2022 FIFA World Cup. NDVI and LST metrics were derived using advanced processing techniques and spatial analysis, focusing on seven stadiums. Multi-ring buffers with 30-meter intervals enabled the assessment of cooling effects and vegetation changes around the stadiums, providing insights into the environmental impact of mega-event preparations. The findings highlight significant improvements in urban greening, with increased vegetation cover and cooling effects around the stadiums. These effects are most notable in areas with integrated green spaces, such as Education City Stadium and Khalifa International Stadium, where cooling distances extend to 200 meters. However, standalone stadiums like Lusail and 974 Stadium demonstrate localized but impactful cooling effects driven by innovative architectural designs and materials. The study underscores the dual benefits of mega-event infrastructure. Enhancing urban aesthetics and mitigating the urban heat island (UHI) effect. Policy recommendations include integrating green infrastructure, adopting sustainability standards for stadium designs, and aligning mega-event preparations with long-term urban development goals. These insights provide a model for arid regions, particularly Saudi Arabia, preparing to host future events like the FIFA World Cup in 2034. The study advocates for strategies that ensure sustainability in large-scale urban developments by balancing urban growth with environmental preservation.

1. Introduction

Sustainability has become a cornerstone in planning and executing mega-sport events, reflecting the growing global commitment to environmental responsibility and resource efficiency (Bellotto, 2024; Talavera et al., 2019). These events, often characterized by substantial construction, transportation demands, and energy consumption, leave considerable environmental footprints (Zhang et al., 2022). Consequently, host nations are increasingly adopting sustainable practices to minimize ecological impacts while delivering world-class experiences (Husain et al., 2024). From integrating green building standards in infrastructure development to utilizing renewable energy sources, sustainability initiatives have become essential to the success and credibility of such events (Buscarini et al., 2021; Ferranti et al., 2020; Kellison & Hong, 2015). These efforts reduce environmental impacts and set benchmarks for innovation in large-scale projects, inspiring future events to emulate these practices. Moreover, beyond mitigating environmental damage, embedding sustainability in mega-sport events fosters broader social and economic benefits. Sustainable practices, such as developing public transportation systems and creating green spaces, enhance urban livability and contribute to long-term development goals (Azzali, 2020; Cerezo-Esteve et al., 2022). Aligning these events with global sustainability frameworks, like the Sustainable Development Goals (SDGs), positions host countries as leaders in climate action and sustainable growth (Buscarini et al., 2021; Zhou et al., 2024).

Preparations for events like the FIFA World Cup often involve extensive infrastructure upgrades, including modernizing transportation networks, constructing state-of-the-art stadiums, and revitalizing urban spaces (Poynter & Viehoff, 2016; Rabadi et al., 2015; Zaidan & Abulibdeh, 2018). These projects enhance functionality and connectivity and reshape host cities' physical and social fabric. Designed with legacy in mind, these investments extend benefits far beyond the event itself, fostering long-term economic growth and sustainable urban development (Kassens-Noor, 2013; Preuss & Plambeck, 2021; Sánchez & Broudehoux, 2013). However, hosting mega-sport events can also exacerbate environmental challenges, particularly through land surface temperature (LST) changes in urban areas (Abulibdeh et al., 2024). The construction of large-scale infrastructure, such as stadiums and transportation networks, often replaces natural landscapes with heat-absorbing materials like concrete and asphalt (Kellison & Casper, 2017; Lee, 2021; Li & Cheng, 2024). This large-scale construction intensifies the urban heat island (UHI) effect, where cities experience elevated temperatures compared to surrounding rural areas (Abulibdeh, 2021). Reduced vegetation and evapotranspiration further amplify this effect (Imran et al., 2021; Yang et al., 2021). These changes show the importance of strategic land use planning to mitigate climate impacts and enhance urban resilience.

Urban land use and land cover (LULC) changes play a crucial role in influencing regional temperature variations. For instance, deforestation and urbanization reduce surface reflectivity (albedo) and increase heat retention, impacting local and regional climates (Varamesh et al., 2022)(Vujovic et al., 2021). Moreover, during mega-sport events, the influx of visitors and intensified human activity elevate energy consumption and emissions, further contributing to LST increases (Zhang & Wu, 2022). Addressing these challenges requires proactive measures, such as using reflective building materials, energy-efficient cooling systems, and urban greening projects (Tina Pourpakdelfekr & Oboudi, 2022; Zhou et al., 2024). These initiatives counteract heat absorption and improve air quality, urban aesthetics, and thermal comfort.

The Qatar World Cup offers a ground-breaking example of integrating sustainability into mega-event planning. As part of its commitment to environmental stewardship, Qatar aligned its strategies with FIFA's carbon neutrality goals, incorporating innovative approaches to infrastructure design, transportation, and energy use (Al-Qahtani, 2017; Özel, 2024). Guided by five core pillars—Environmental, Social, Human, Governance, and Economic—Qatar emphasized green building techniques, waste management, water conservation, inclusivity, and long-term economic benefits (Mohamed et al., 2022; Zhou et al., 2024). Notably, the event aligned with 11 SDGs, with a particular focus on SDG 11, which advocates for inclusive, resilient, and sustainable cities. Investments in eco-friendly stadiums, public transportation, and urban greening underscore Qatar’s dual goals of hosting a successful event and promoting long-term urban resilience.

This study contributes to the knowledge base by analyzing the interplay between mega-event infrastructure, urban greening, and LST mitigation in an arid urban context. Focusing on Qatar’s preparation for the 2022 FIFA World Cup, it highlights how event-driven development can transform urban landscapes while addressing environmental challenges. The study provides empirical evidence of

cooling effects and enhanced urban greenness using advanced remote sensing techniques, offering actionable insights for integrating sustainability into urban planning. Nevertheless, the novelty of this research stems from its focus on the specific environmental impacts of hosting the FIFA World Cup in a rapidly urbanizing and arid region. Unlike traditional studies that often emphasize economic or social legacies, this study uniquely examines infrastructure projects' thermal and ecological implications on urban microclimates. Its use of innovative metrics, such as cooling distance and correlation coefficients between Normalized Difference Vegetation Index (NDVI) and LST, establishes new methodologies for assessing the environmental benefits of mega-events. Additionally, the study bridges the gap between urban planning and environmental science by proposing actionable policy recommendations, making it highly relevant for future mega-event hosts in similar climates, such as Saudi Arabia, for the 2034 FIFA World Cup.

The findings hold significant implications for future mega-event hosts, particularly in arid regions. Strategic planning to mitigate LST effects—through reflective materials, efficient cooling systems, and urban greening—can ensure that mega-events align with global sustainability frameworks. By learning from Qatar’s experience, future hosts can balance the demands of global events with the need for climate resilience, positioning themselves as leaders in sustainable urban development.

2. Material and Methods

2.1 Study Area

The State of Qatar, located in the eastern Arabian Peninsula (see Fig. 1), has undergone significant transformation over the past few decades, culminating in its successful hosting of the 2022 FIFA World Cup (Zaidan & Abulibdeh, 2018). This global event positioned Qatar as a focal point for international attention, highlighting its rapid urban development and economic prowess. Spanning a modest geographical area of 11,437 square kilometers, Qatar is characterized by its arid climate and limited natural water and arable land resources (Abdullah et al., 2024). Despite these constraints, the country has leveraged its vast hydrocarbon reserves to drive economic growth and fund infrastructural advancements, including water desalination and energy subsidies for its citizens (Jawarneh & Abulibdeh, 2024). Hosting the FIFA World Cup was a catalyst for this transformation, pushing Qatar to invest billions of dollars into modernizing its infrastructure and enhancing its global reputation (Zhou et al., 2024).

The capital city of Doha, located on the eastern coast, served as the hub for World Cup activities, reflecting its role as the economic, cultural, and administrative center of Qatar (Abulibdeh, 2024). Over the last three decades, Doha has experienced remarkable urban expansion and population growth, fueled by the influx of expatriate workers drawn to Qatar's booming economy. This urban primacy city has become a junction for regional transportation routes, further bolstered by investments in public transport systems, such as the Doha Metro, expanded bus networks, and improved taxi services (Abulibdeh, 2023). These developments were particularly spurred by the demands of hosting the World

Cup, as Qatar sought to accommodate the expected influx of visitors and enhance mobility within the city.

However, the rapid urbanization and population growth have also posed environmental challenges, particularly concerning water and energy sustainability. With limited renewable water resources, the increased demand from a growing population and infrastructure development has necessitated reliance on desalination, raising questions about long-term sustainability (Naeem et al., 2024). Beyond the immediate impact of the World Cup, Qatar has aligned its infrastructural developments with the long-term goals of Qatar National Vision 2030, which emphasizes economic, social, human, and environmental sustainability (Talavera et al., 2019). The extensive investments made for the World Cup, including a new airport, ports, roads, and real estate projects, are part of a broader strategy to diversify the economy and position Qatar as a modern, sustainable nation (Abulibdeh et al., 2024). This vision ensures that the legacy of the World Cup extends beyond the event itself, contributing to the country's ongoing transformation and its ambitions to be a global leader in sustainable urban development.

2.2 Data and Method

Remote sensing data from the Landsat series and Google Earth were utilized to analyze vegetation and LST changes across various scales as shown in Fig. 2. Initially, NDVI and LST were derived from Landsat Level 2 reflectance and surface temperature products, providing a comprehensive overview of vegetation dynamics and LST variations within the study area. Subsequently, the analysis focused on stadiums constructed for the FIFA World Cup 2022 in Doha and Al Wakrah cities. Multi-ring buffers with 30-meter intervals were generated around the stadiums, enabling a detailed spatial analysis. These buffers, combined with advanced spatial analysis techniques, facilitated a quantitative assessment and discussion of the cooling effects of the stadiums on urban heat islands.

2.2.1 NDVI and LST inversion

This study leverages Landsat satellite data to analyze changes in vegetation and LST over time. The Landsat data of the study area corresponds to Path/Row numbers 163/043. The analysis utilizes images from the Landsat Level 2 Collection 2 dataset, first released in 2020 by the USGS for Landsat 8 data. Subsequently, Landsat 5 data were updated to align with the latest processing standards. This dataset offers radiometrically calibrated and atmospherically corrected surface reflectance products and surface temperature (ST) products. The ST products in Level 2 Collection 2 employ an enhanced single-channel algorithm incorporating the Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Emissivity Dataset (ASTER GED) to adjust land surface emissivity. Atmospheric corrections are conducted using the Goddard Earth Observing System, Version 5 (GEOS-5) Forward Processing for Instrument Teams (FP-IT), and a Modtran-based transfer model (Malakar et al., 2018).

Evaluation studies comparing land surface temperature products derived from various methods with in-situ data have demonstrated the superior performance of Landsat Level 2 Collection 2 ST products in urban areas and bare land settings (Wang et al., 2023). Additionally, the dataset's improved atmospheric

and radiometric calibration ensures consistency across data from different Landsat missions, enhancing its reliability for long-term analysis (Malakar et al., 2018). This study utilizes cloud-free Landsat images acquired in March to analyze vegetation changes and LST variations in the Doha area. Due to malfunction issues with the Enhanced Thematic Mapper Plus (ETM+) onboard Landsat 7, there is a data gap between 2003 and 2014. Six images were selected, corresponding to the following dates: March 13, 2000; March 14, 2003; March 20, 2014; March 12, 2017; March 4, 2020; and March 29, 2023, as shown in Table 1. The NDVI and LST were derived from these images to quantify land surface greenness and temperature, respectively, enabling a detailed assessment of temporal and spatial changes in vegetation and thermal conditions. The NDVI can be calculated as follows (Sukkar et al., 2024):

$$\mathrm{NDVI} = \frac{NIR - RED}{NIR + RED}$$

1

The NIR and RED bands are Band 4 and Band 3 for Landsat 5 and Landsat 7, and Band 5 and Band 4 for Landsat 8. All Landsat data were downloaded from USGS Earthexplorer (https://earthexplorer.usgs.gov/).

Table 1
Date of the images

Gallery	Observation Date
Landsat 5	2000/03/13
Landsat 7	2003/03/14
Landsat 8	2014/03/20, 2017/03/12, 2020/03/04, 2023/03/19
Google Earth Image	2004/08/16, 2005/11/04, 2014/10/21, 2017/10/09, 2020/03/07, 2023/04/29

2.2.2 Landscape from Google Earth

In addition to Landsat data, historical imagery from Google Earth is incorporated into the analysis to provide visual context for LULC changes over time. Google Earth offers access to a comprehensive collection of high-resolution satellite and aerial imagery spanning several decades. These images provide a more detailed, ground-level perspective of changes that may not be fully captured by Landsat data. For the study area, high-resolution images from the years 2004, 2005, 2014, 2017, 2020, and 2023 were utilized, offering valuable insights into the construction processes of all seven stadiums built for the 2022 FIFA World Cup.

2.2.3 Cooling Effect Assessment

Various indicators can be employed to quantify the cooling effect of parks or open green spaces on their surrounding environments. The cooling effect refers to the phenomenon where urban green spaces

exhibit lower temperatures than adjacent built-up areas. It can be quantitatively assessed using the "Cooling Distance" and “Cooling Effect Intensity” indicators (see Fig. 2), which measure the spatial extent to which the cooling effect is perceptible and the intensity of temperature reduction within the affected area, respectively. These indicators provide a comprehensive understanding of the cooling phenomenon and its spatial and thermal impacts. These indicators are widely applied in urban planning studies.

The cooling distance of stadiums is determined by analyzing the relationship between external ambient LST and the distance from the stadiums' centers. To facilitate this analysis, multi-ring buffers with equal intervals are created around the stadiums, extending to a total distance of 300 meters from their edges. Each ring buffer has a width of 30 meters, aligning with the spatial resolution of Landsat data. The relationship between temperature differences within and outside the buffer zones and distance is modeled using a cubic polynomial. The Cooling Distance is defined as the distance from the first turning point of the cubic polynomial curve to the stadium center. Similarly, the cooling effect intensity is quantified as the difference between the 0-meter distance LST on the curve and the LST value at the cooling distance. A 30-meter interval is selected as the sampling step when identifying the turning point, ensuring consistency with the data scale.

2.2.4 Stadiums classifications

The seven stadiums were classified into three categories based on the landscape of each stadium and its surrounding neighborhood, as shown in Table 2. The classification considers the extent and type of vegetation and whether the stadium is part of a larger complex. This categorization highlights the World Cup stadiums' diverse urban and environmental contexts, reflecting varying approaches to integrating sports infrastructure within Qatar's landscape. The first category is standalone stadiums with little vegetation nearby. This category includes isolated stadiums with minimal greenery in their immediate surroundings. The Lusail Iconic Stadium and 974 Stadium fall under this classification. These stadiums are characterized by the absence of extensive vegetation in their neighborhoods, emphasizing their standalone design within urban or arid settings.

The second class is the stadiums with vegetation nearby. This category represents stadiums surrounded by notable green areas or landscaping efforts. The Education City Stadium, Al Thumama Stadium, and Al Janoub Stadium belong to this category. These stadiums benefit from nearby vegetation, which contributes to mitigating the urban heat island effect and enhancing the visual appeal of their locations. The third class is stadiums that are part of a large complex. This category includes stadiums integrated within larger complexes, often accompanied by extensive vegetation and additional infrastructure. The Ahmed bin Ali Stadium and Khalifa International Stadium fall under this classification. These stadiums are part of multi-functional complexes that include parks, sports facilities, and other amenities, providing a more comprehensive urban design and environmental strategy.

Table 2
Stadiums classification according to the landscape

NO.	Description	Stadiums
1	Standalone Stadium, little vegetation in the adjacent neighborhood	Lusail Iconic Stadium Stadium 974
2	Stadium with vegetation nearby	Education City Stadium Al Thumama Stadium Al Janoub Stadium
3	Stadium is a part of a large complex	Ahmed bin Ali Stadium Khalifa International Stadium

3. Results

3.1 Changes in vegetation cover

The spatial distribution of the NDVI values in Doha and Al Wakrah cities in Qatar is shown in Fig. 3. Between 2000 and 2023, the figure demonstrates that the majority of the area is dominated by low NDVI values, corresponding to built-up and barren regions with minimal vegetation. In 2000 and 2003, the vegetation coverage appeared sparse, with limited pockets of higher NDVI values, likely concentrated around landscaped or irrigated areas. By 2014, the spatial extent of vegetation begins to show slight growth in specific locations, coinciding with urban expansion and associated greening projects. By 2023, notable increases in vegetation are observed in certain areas, particularly in urban zones where landscaping efforts, such as parks or green belts, might have been implemented. As the World Cup 2022 construction begins, the vegetation area grows from less than 3% in 2014 to around 8.5% of the study area in 2023. However, the majority of the region still reflects low NDVI values, indicating that urban infrastructure dominates over natural or artificial greenery. The temporal analysis provided by the figure highlights the dual influence of urbanization, which reduces natural vegetation, and efforts to introduce green spaces in rapidly developing cities like Doha and Al Wakrah.

Table 3 provides a detailed breakdown of the distribution of the NDVI values in Doha and Al Wakrah cities across six time periods. The NDVI values are categorized into seven ranges representing the density and health of vegetation. These categories reveal the extent of vegetative cover, with higher NDVI values indicating denser vegetation. The table highlights that the majority of the area is dominated by low NDVI values (0–0.1) throughout all years. In 2000, about 90.17% of the area fell within this category, and this proportion increased to a peak of 96.80% in 2014. However, by 2023, the percentage of the 0–0.1 category decreased slightly to 89.02%, suggesting a marginal increase in areas with higher NDVI values. This trend implies minimal but noticeable improvements in vegetation cover over the years, likely

due to urban greening projects and landscaping efforts. The higher NDVI ranges (e.g., 0.1–0.2 and 0.2–0.3) gradually increase from 2014 onward. For example, the proportion of areas with NDVI between 0.1 and 0.2 rose from 2.21% in 2014 to 6.31% in 2023. Similarly, the 0.2–0.3 range grew from 0.44% in 2014 to 1.62% in 2023. While higher NDVI ranges (> 0.4) remain negligible, these small increases reflect a positive shift toward improved vegetation density, indicating the impact of targeted environmental interventions and landscaping efforts in these rapidly urbanizing cities. The overall analysis highlights the challenges of maintaining vegetation in arid regions while showing progress in localized greening initiatives.

Table 3
NDVI variation in different years

NDVI	2000.03	2003.03	2014.03	2017.03	2020.03	2023.03
< 0	1.90%	3.90%	0.45%	0.57%	1.50%	2.08%
0-0.1	90.17%	94.40%	96.80%	95.99%	90.57%	89.02%
0.1–0.2	5.80%	1.35%	2.21%	2.86%	5.80%	6.31%
0.2–0.3	1.38%	0.28%	0.44%	0.50%	1.38%	1.62%
0.3–0.4	0.53%	0.07%	0.10%	0.08%	0.53%	0.69%
0.4–0.5	0.20%	0.00%	0.00%	0.00%	0.20%	0.26%
> 0.5	0.02%	0.00%	0.00%	0.00%	0.02%	0.02%

3.2 Temporal and spatial dynamics of LST

The spatial distribution of LST from 2000 to 2023 is shown in Fig. 4. The temporal progression demonstrates significant changes in surface temperatures, reflecting the impact of urbanization and development on the region's thermal environment. In 2000 and 2003, the LST maps indicate relatively cooler surface temperatures, signifying LST values below 30°C. This cooler pattern is attributed to the limited urban infrastructure and natural desert landscapes, which tend to retain lower surface temperatures. The spatial variation shows pockets of moderate LST values in urbanized zones, but the heat distribution appears less concentrated. By 2023, a marked increase in surface temperatures is evident, with the majority of the region representing LST values exceeding 38°C. This increase reflects the extensive urban expansion and the rise in impervious surfaces, such as roads and buildings, which absorb and retain heat. The highest temperatures are observed in densely urbanized areas, underscoring the UHI effect. These temporal changes highlight the growing impact of urbanization on LST and emphasize the need for sustainable urban planning strategies, such as increasing green spaces to mitigate the heat island effect.

Figure 5 illustrates the spatial variations in the standard deviation (STD) of LST across the study area using a 900m × 900m grid system. Figure 5a shows the differences in LST STD between 2000 and 2014,

while Fig. 5b represents the differences between 2014 and 2023. Larger STD differences indicate greater variability in LST distribution within a grid, reflecting changes in land use, urbanization, and infrastructure development. Between 2000 and 2014, significant changes in LST variability were concentrated along the coastal areas, where prominent infrastructure projects such as Hamad International Airport, West Bay, and Pearl Island were developed. These large-scale constructions altered the surface properties, increasing heat retention and modifying the thermal environment. Additionally, noticeable changes are observed along the highways stretching from Al Thumama to the Industrial Area, reflecting the impact of road development and urban sprawl on LST distribution. These findings emphasize the transformative effects of rapid urbanization on the region's thermal landscape during this period.

In contrast, the LST STD differences between 2014 and 2023 are less pronounced, indicating a deceleration in urbanization. The relative stability in LST variability during this period suggests that major construction projects have tapered off, leading to a more consistent and balanced landscape. This stabilization reflects the maturity of urban developments within the study area and highlights a shift from rapid expansion to maintenance and refinement of existing urban spaces. The analysis underscores the dynamic relationship between urbanization and thermal variability, demonstrating how human activities shape and stabilize the thermal environment over time.

3.3 Landscape, vegetation, and thermal impacts of World Cup Stadiums

Figure 6 provides a detailed comparison of landscape, vegetation, and LST changes for class 1 stadiums over different time periods. Each subfigure illustrates time-series data, including satellite imagery, NDVI values, and LST distributions. These changes highlight the impact of stadium construction and associated infrastructure development on the local environment. The Ahmed bin Ali Stadium (Fig. 6a) was built on the site of the former Al-Rayyan stadium, which was surrounded by parking lots and bare land with minimal vegetation before 2016. Construction began in 2016 and was completed by December 2020. Post-construction, significant landscaping efforts introduced grasslands and vegetation with NDVI values exceeding 0.5, transforming the area's visual and environmental landscape by 2023. LST results show that impervious surfaces, such as parking lots and roads, retained the highest temperatures before and after construction. However, the stadium created a cooling effect, reducing temperatures by approximately 5°C compared to its surroundings.

Built-in 1976, Khalifa International Stadium (Fig. 6b) is one of Qatar's oldest stadiums. It underwent major renovations starting in 2014. These updates not only modernized the stadium but also altered its surrounding landscape. Large areas of vegetation appeared as part of a newly established complex, contributing to steadily increasing NDVI values through 2023. By 2023, this area featured significant greenness, enhancing its environmental quality. The stadium and adjacent green spaces demonstrated a cooling effect, with noticeable temperature differences compared to the surrounding impervious surfaces.

The Lusail Iconic Stadium (Fig. 6c), constructed between 2017 and 2021, is the largest stadium built for the 2022 FIFA World Cup Qatar. Before construction, the area exhibited a uniform LST pattern, with the main hotspot being the road crossing the site. Post-construction, the stadium became a prominent cooling spot, forming an elliptical cool area in contrast to the surrounding higher-temperature regions, particularly the parking lots. Vegetation also increased along the roads and within the stadium's vicinity, as shown by the NDVI results, indicating improved infrastructure and landscaping accompanying the stadium's development.

Built using modular steel frames and shipping containers, 974 Stadium (Fig. 6d) is uniquely located near the sea, with a dense urban area nearby. Construction began in 2018 and was completed by 2021. Unlike other stadiums, there were minimal changes in vegetation before and after construction, as indicated by consistent NDVI values. However, the LST patterns shifted significantly. Post-construction, the stadium became a circular cooling spot, with temperatures approximately 3°C lower than its surroundings, emphasizing its role in mitigating local heat despite limited vegetation changes.

Each stadium demonstrates a unique relationship between construction, vegetation, and temperature changes. Ahmed bin Ali and Khalifa International Stadiums exhibit significant increases in vegetation and corresponding cooling effects, highlighting the benefits of landscaping efforts. In contrast, Lusail Iconic Stadium and 974 Stadium emphasize cooling effects driven by structural design rather than vegetation, with noticeable temperature reductions in their immediate vicinities. These findings underscore the importance of integrating sustainable landscaping and infrastructure design in large-scale developments. While vegetation contributes to mitigating UHIs, the structural properties of stadiums, such as reflective surfaces, also play a crucial role. These examples highlight the varying approaches to balancing urban development with environmental sustainability in Qatar's rapidly urbanizing landscape.

Known as the "Diamond in the Desert," the Education City Stadium (Fig. 7a) was constructed between 2016 and 2020. Adjacent to a golf course, the stadium benefits from significant nearby vegetation. From 2017 to 2023, the NDVI results show a notable increase in vegetation density and high-value areas, indicating enhanced greening in this region. Interestingly, the stadium consistently acts as a cooling spot, with LST values approximately 2°C lower than the golf course. This finding contrasts with conventional observations where green spaces typically display lower temperatures than built-up areas. While cooler than surrounding bare land and impervious surfaces, the golf course demonstrates slightly higher LST values than the stadium.

Construction of Al Thumama Stadium (Fig. 7b) began in 2017 and was completed by 2021. Alongside the stadium's development, vegetation and other facilities emerged, significantly increasing NDVI values. The location exhibited cooler temperatures before the stadium was established than nearby urbanized areas. By 2023, the cooling effect intensified, with the stadium showing an LST difference of approximately 3°C compared to its surroundings. However, the spatial extent of the cooling spot decreased. Like the Education City Stadium, the green spaces near Al Thumama Stadium exhibit higher

LST values than the stadium itself. However, they remain cooler than adjacent impervious surfaces such as parking lots and urban infrastructure.

Construction of Al Janoub Stadium (Fig. 7c) began in 2014 and was completed in 2019. Vegetation around the stadium remained relatively stable from 2020 to 2023, as consistent NDVI values show. Meanwhile, the cooling effect of the stadium became more pronounced over time. In 2017, the LST difference between the stadium and its surroundings was minimal. By 2020, this difference increased to approximately 2°C, and by 2023, the stadium demonstrated a cooling effect exceeding 3°C compared to nearby urban surfaces. This improvement highlights the combined influence of architectural design and surrounding greening efforts in mitigating heat.

3.4 Cooling Effects of FIFA World Cup 2022 Stadiums

Figure 8 illustrates the cooling effects of FIFA World Cup 2022 stadiums, classified into three categories based on their landscape and neighborhood characteristics. The analysis uses cooling distance as a quantitative measure to describe how much each stadium influences its surrounding thermal environment. Cooling Distance refers to the distance from the stadium at which the cooling effect diminishes, and its relationship with LST difference is represented for each stadium. Lusail Iconic Stadium and 974 Stadium (Fig. 8a) are characterized by limited vegetation in their surrounding neighborhoods. In the case of Lusail Iconic Stadium, the cooling distance decreased from 180 meters in 2020 to 90 meters in 2023, although the LST difference increased over time. This suggests a stronger but more localized cooling effect. Conversely, for 974 Stadium, the cooling distance and LST difference increased over the years, indicating an intensified cooling effect. These patterns emphasize the unique thermal behavior of standalone stadiums in urban environments with limited greenery.

Figure 8b illustrates class 2 stadium cooling effects. Education City Stadium and Al Janoub Stadium exhibited an increase in cooling distance from 2017 to 2023, reflecting the role of vegetation and landscaping in enhancing the cooling effect. However, Al Thumama Stadium's cooling distance slightly decreased in 2023, although it maintained a consistent cooling distance exceeding 100 meters. The LST differences also showed an upward trend for all three stadiums, indicating stronger cooling impacts over time. The well-fitting curves between buffer distance and LST highlight the stable and effective thermal mitigation provided by this category of stadiums.

Khalifa International Stadium and Ahmed Bin Ali Stadium (Fig. 8c) are situated within larger complexes with extensive vegetation and infrastructure. Unlike the other categories, the cooling effects of these stadiums are less prominent, as evidenced by lower coefficients of determination (R^2) for the fitted curves. This suggests that factors beyond the stadiums, such as the complex’s overall landscape and built environment, significantly influence the LST distribution patterns. While the cooling distance is still observable, it is not as clearly defined or impactful as in the first two categories.

Across all three categories, the results demonstrate that 2022 FIFA World Cup stadiums exert a cooling effect on their surroundings, albeit with variations in intensity and extent. Standalone stadiums (Class 1)

exhibit more localized cooling effects, which vary based on structural and environmental conditions. Stadiums with nearby vegetation (Class 2) show the most consistent and extended cooling effects, underscoring the role of landscaping in urban thermal management. In contrast, stadiums within large complexes (Class 3) display more diffuse and less predictable cooling patterns, likely due to multiple environmental and design factors. These findings highlight the significance of incorporating vegetation and sustainable design principles into urban developments to mitigate heat. Class 2 stadiums demonstrate the positive synergy between green spaces and thermal regulation, providing a blueprint for future stadium designs. Meanwhile, the results from Class 3 stadiums suggest the need for further investigation into how complex urban landscapes interact with thermal dynamics.

The cooling effects of 2022 World Cup stadiums in Qatar highlight the potential of large-scale infrastructure to influence urban thermal environments. The variability across classes underscores the importance of context-specific approaches to stadium design and landscaping, emphasizing a balance between functionality and environmental sustainability. By leveraging insights from this analysis, future developments can prioritize cooling strategies that enhance urban livability.

Figure 9 highlights the cooling effect of various 2022 FIFA World Cup stadiums in Doha, demonstrating their influence on mitigating urban heat through localized thermal regulation. The figure uses cooling distance, represented in 30-meter intervals, to quantify how far the cooling effects extend from each stadium. It also presents cooling intensity in degrees Celsius, illustrating the magnitude of temperature reduction achieved by the stadiums. These metrics underscore the effectiveness of the stadiums in influencing their surrounding thermal environments, driven by structural design, materials, and adjacent greenery.

The analysis reveals distinct patterns across different stadium categories. Standalone stadiums, such as Lusail and 974 Stadium, exhibit substantial but localized cooling effects. On the other hand, class 2 stadiums demonstrate extended cooling distances, emphasizing the synergistic role of green infrastructure. Meanwhile, class 3 stadiums show moderate cooling effects influenced by the compound landscape of built and vegetative elements. This figure underscores the critical role of sustainable design and urban greening in mitigating the urban heat island effect, offering valuable insights for future infrastructure development in arid and urbanized regions.

Table 4 presents the cooling effect intensity ($\Delta T1$) of several FIFA World Cup 2022 stadiums at different years: 2017, 2020, and 2023. The cooling effect intensity is defined as the temperature difference between the fitted temperature at the turning point (TD) and the fitted temperature inside the park (T0). This measurement provides insight into the extent to which each stadium influences its surrounding thermal environment over time. For Lusail Iconic Stadium and 974 Stadium, the cooling effect intensity has increased significantly over time. Lusail Iconic Stadium shows a dramatic rise from 1.67°C in 2020 to 3.61°C in 2023, indicating a growing impact on its thermal surroundings. Similarly, 974 Stadium shows a sharp increase from 0.56°C in 2017 to 3.07°C in 2023, highlighting an intensified cooling effect. These

trends suggest that structural and design elements, rather than surrounding greenery, are playing a crucial role in reducing LST in these cases.

For stadiums surrounded by notable vegetation, such as Education City Stadium, Al Janoub Stadium, and Al Thumama Stadium, the cooling effect intensity consistently increased over time. Education City Stadium experienced a rise from 0.98°C in 2017 to 2.75°C in 2023, while Al Janoub Stadium improved from 1.13°C in 2017 to 2.91°C in 2023. Al Thumama Stadium, although showing a smaller increase, still demonstrated consistent growth from 1.70°C in 2017 to 2.16°C in 2023. These results reflect the significant contributions of surrounding green spaces to the cooling effects, underscoring the role of landscaping in thermal regulation.

The cooling effects for Khalifa International Stadium and Ahmed bin Ali Stadium are less pronounced. Khalifa International Stadium showed a slight decrease in cooling effect intensity, from 0.77°C in 2017 to 0.58°C in 2023, suggesting a minimal impact on its surrounding environment. For Ahmed bin Ali Stadium, data is available only for 2023, with a cooling effect of 1.28°C, which is modest compared to other stadiums. These trends indicate that the combined landscape of the complex influences the overall LST distribution, potentially diluting the individual cooling effect of the stadium itself.

The data illustrates that the cooling effect intensities of the stadiums vary based on their classification and surrounding landscape. Standalone stadiums exhibit the highest increases in cooling effect over time, possibly due to the thermal behavior of their structures. Stadiums with nearby vegetation consistently show moderate to strong cooling effects, benefiting from the synergy between design and landscaping. In contrast, stadiums within large complexes demonstrate weaker cooling effects, reflecting the influence of surrounding infrastructure on thermal patterns. These insights emphasize the importance of incorporating sustainable design and landscaping strategies to optimize the environmental benefits of large-scale urban developments.

Table 4
Cooling Effect Intensity (℃)

	2017	2020	2023
Lusail Iconic Stadium	\	1.67	3.61
Stadium 974	0.56	0.53	3.07
Education City Stadium	0.98	1.23	2.75
Al Janoub Stadium	1.13	1.83	2.91
Al Thumama Stadium	1.70	1.63	2.16
Khalifa International Stadium	0.77	\	0.58
Ahmed bin Ali Stadium	\	\	1.28

T_D - fitted temperature at the turning point.

T_0 – fitted temperature inside the park

Cooling effect intensity: $\Delta T_1 = T_D - T_0$

Table 5 highlights the maximum temperature difference (ΔT2) between FIFA World Cup 2022 stadiums and their surrounding neighborhoods in 2017, 2020, and 2023. This metric reflects the stadiums' cooling impact by comparing the highest neighborhood temperature (Tmax) with the stadium's temperature (Tstadium). The analysis offers insights into how each stadium influences its local thermal environment over time. The standalone stadiums demonstrate significant increases in cooling effects over the years. For Lusail Iconic Stadium, the temperature difference rose from 1.47°C in 2017 to 4.93°C in 2023, reflecting a growing ability to reduce local temperatures. Similarly, 974 Stadium shows an increase from 2.13°C in 2017 to 4.14°C in 2023, emphasizing its consistent and intensified cooling effect. These patterns suggest that these stadiums' structural design and thermal properties significantly mitigate urban heat despite the lack of significant vegetation nearby.

Class 2 stadiums also exhibit a steady increase in cooling effects over time. Education City Stadium's maximum temperature difference grew from 1.26°C in 2017 to 3.37°C in 2023, while Al Janoub Stadium's cooling impact rose from 1.39°C to 3.15°C over the same period. Al Thumama Stadium showed a more minor but notable increase, from 1.90°C in 2017 to 2.43°C in 2023. These findings underscore the contribution of surrounding green spaces in enhancing the cooling impact of these stadiums. The cooling effects of class 3 stadiums are more variable. Khalifa International Stadium displayed a decline in maximum temperature difference, from 1.43°C in 2017 to 1.04°C in 2023, suggesting a diminishing cooling impact over time. Ahmed bin Ali Stadium, in contrast, exhibited a moderate increase from 0.92°C in 2017 to 1.93°C in 2023, though its overall cooling effect remains less pronounced compared to other stadiums. These trends indicate that the surrounding infrastructure and landscape of large complexes influence the thermal behavior, potentially offsetting the individual cooling effect of the stadiums.

The data highlights a general increase in cooling effects across all stadiums from 2017 to 2023, with varying intensities based on stadium classification. Class 1 stadiums exhibit the most dramatic improvements, likely due to structural and material properties optimized for thermal regulation. Class 2 stadiums demonstrate moderate but consistent increases, benefiting from green spaces that amplify their cooling effects. Class 3 within large complexes shows less pronounced or inconsistent impacts, likely due to the complex interplay between their surroundings and urban heat dynamics. These results emphasize the importance of considering structural and environmental factors in designing large-scale urban developments. The strong performance of standalone stadiums and those with nearby vegetation suggests that integrating sustainable materials and landscaping can significantly mitigate urban heat. In contrast, the variability observed in stadiums within large complexes highlights the need for further

research to optimize cooling effects in densely developed areas. These findings provide valuable insights for future infrastructure projects that balance functionality and environmental sustainability.

Table 5
Maximum Temperature Difference between the stadiums and their neighborhood (℃)

	2017	2020	2023
Lusail Iconic Stadium	1.47	1.86	4.93
Stadium 974	2.13	2.23	4.14
Education City Stadium	1.26	1.40	3.37
Al Janoub Stadium	1.39	2.09	3.15
Al Thumama Stadium	1.90	1.80	2.43
Khalifa International Stadium	1.43	0.56	1.04
Ahmed bin Ali Stadium	0.92	0.94	1.93
$\Delta T_2 = T_{max} - T_{stadium}$			

3.5 Impact of vegetation on cooling effects around the stadiums

Table 6 illustrates the correlation coefficients between NDVI and LST around FIFA World Cup 2022 stadiums, calculated using 2000 random points within a 3-kilometer radius of each stadium. Negative values in the table indicate an inverse relationship, where higher vegetation cover corresponds to lower LST, reinforcing the role of greenness in mitigating heat. Across the years, the coefficients reveal variations in this relationship, with notable improvements in the cooling effect in 2023, particularly around stadiums like the Khalifa International Stadium and the Education City Stadium.

For standalone stadiums like 974 Stadium, the table shows consistently strong negative correlations, particularly in earlier years, with coefficients exceeding 0.7 in 2000 and 2003. This indicates that the limited but well-distributed vegetation around the stadium has effectively reduced LST. However, the relationship is weaker for other standalone stadiums, such as the Lusail Iconic Stadium, with coefficients declining from 0.318 in 2000 to -0.184 in 2023. This suggests that while some greening efforts were made, the vegetation's impact on LST remains limited due to the stadium's sparse greenery and urban context.

Stadiums with adjacent vegetation, such as the Khalifa International and Education City Stadium, strengthen relationships over time. Khalifa International Stadium, for instance, exhibited a significantly stronger negative correlation in 2023 (-0.521) compared to previous years. This reflects the growing

contribution of adjacent green spaces in alleviating heat around the stadium. Similarly, Education City Stadium's coefficient shifted from positive or weak values in earlier years to -0.547 in 2023, indicating a robust cooling effect from surrounding vegetation. These findings confirm that extensive green spaces can significantly extend cooling distances and reduce urban heat. Overall, the table underscores the importance of integrating vegetation into stadium landscapes to enhance their thermal benefits.

Table 6: Correlation coefficient with NDVI and LST around the stadiums (P<0.1)

Stadium	Year					
	2000	2003	2014	2017	2020	2023
Ahmed bin Ali Stadium	0.29159	-0.03268	0.005288	0.00514	0.073364	-0.17317
Khalifa International Stadium	0.205749	0.055424	-0.37259	-0.10934	-0.31594	-0.521
Al Thumama Stadium	0.253397	0.166069	-0.09387	0.000808	-0.03287	-0.1947
Al Janoub Stadium	-0.03676	-0.15386	0.210822	0.164968	5.31E-05	-0.16709
Stadium 974	0.73243	0.73145	0.69931	0.68364	0.54568	0.482889
Education City Stadium	0.223529	0.121662	-0.04814	-0.18715	-0.27489	-0.5471
Lusail Iconic Stadium	0.317946	0.048521	0.064758	0.073541	0.008664	-0.18436

4. Discussion

This study utilized satellite imagery from multiple sources to examine the 2022 FIFA World Cup's impact on urban areas in Qatar, focusing on urban greenness and LST at various scales. Analyzing temporal data enabled the study to uncover the changes induced by this mega-sports event and provide a comprehensive understanding of its environmental implications. The findings demonstrate that Qatar's World Cup stadiums have a measurable cooling effect, mitigating the UHI phenomenon. This outcome offers valuable insights into urbanization processes in regions with similar climatic and meteorological conditions. These results highlight the potential for incorporating sustainable infrastructure and urban planning strategies to address environmental challenges in arid and hot regions.

Although urban heat islands are inevitable due to rapid urbanization, developing sports facilities associated with major events can significantly mitigate their effects. These facilities enhance the thermal environment and contribute to the overall sustainability and resilience of urban areas. Integrating green spaces, reflective materials, and innovative architectural designs in stadiums exemplifies how large-scale infrastructure can be aligned with environmental objectives. This research underscores the importance of leveraging sports infrastructure for sustainable urban development. Highlighting the environmental benefits of Qatar's World Cup preparations, the study offers a model for future host nations to adopt similar strategies, balancing the demands of urban growth with the need for environmental preservation.

4.1 Impact of the FIFA World Cup 2022 on urban greening

The findings of this study underscore the transformative effect of the 2022 FIFA World Cup on Qatar's urban greening. The significant increase in NDVI values across Doha and Al Wakrah reflects the strategic introduction of landscaping projects, particularly around World Cup stadiums. The results suggest that integrating green infrastructure was a deliberate effort to enhance urban aesthetics, mitigate heat islands, and improve the overall urban environment. Such changes beautified the cities and provided ecological benefits, including better air quality and reduced LST. These achievements demonstrate how mega-events can catalyze long-term environmental improvements when sustainability is prioritized in urban planning. The findings of this study align with and expand upon the results of other studies in the literature that investigate the environmental and urban impacts of mega-sport events. The observed increase in NDVI values and the associated benefits of urban greening in Qatar resonate with the findings of Martínez-Bravo et al. (2019) and Zhou et al. (2024), which emphasize the role of mega-events in driving urban transformation and environmental improvements. These studies also identify landscaping projects and green infrastructure as critical interventions in mitigating the UHI effect and enhancing urban resilience. Similar results have been observed in other contexts, such as the 2008 Beijing Olympics and the 2014 FIFA World Cup in Brazil. For instance, Preuss and Plambeck (2021) reported significant improvements in urban greenery in Beijing, where deliberate investments in green belts and parks around event venues improved air quality and reduced LST. Likewise, Rabadi et al. (2015) noted that Brazil's event-led greening projects contributed to ecological restoration efforts, although they were somewhat limited by inconsistent post-event maintenance.

4.2 Cooling effects of stadiums

The study highlights the cooling effects of stadiums, measured using LST data. Across all three categories of stadiums, the cooling impact was evident, albeit with varying intensities. Standalone stadiums demonstrated the most significant temperature differences due to their reflective designs and localized cooling effects. Conversely, stadiums with adjacent vegetation benefitted from the synergy between architectural elements and green spaces, which amplified their cooling impact. These findings emphasize the importance of structural and environmental factors in mitigating urban heat, offering insights into optimizing future infrastructure projects for environmental benefits.

The synergistic impact of combining green spaces with architectural elements, as observed in this study, aligns with findings from Wang et al. (2022), which demonstrated that stadiums surrounded by vegetation experience enhanced cooling effects due to increased evapotranspiration and reduced surface albedo. Similarly, Imran et al. (2021) highlighted that integrating vegetation into urban infrastructure amplifies cooling effects and improves the thermal comfort of surrounding areas, a conclusion mirrored in the current research's findings on stadiums with adjacent vegetation. Studies on mega-sport events like the 2008 Beijing Olympics and the 2016 Rio Olympics corroborate these findings. Poynter et al. (2015) noted that stadiums with integrated green infrastructure exhibited measurable reductions in urban heat compared to those without such interventions. Additionally, Martínez-Bravo et al. (2019) emphasized the importance of combining architectural innovations with urban greening to

achieve optimal environmental benefits, further validating the importance of structural and environmental synergies highlighted in this study.

4.3 Challenges in maintaining vegetation in arid regions

The study also reveals the challenges of sustaining vegetation in Qatar's arid climate, where barren land and built-up areas dominate the landscape. Although vegetation increased from 3% in 2014 to 8.5% in 2023, most of the area still reflects low NDVI values. This limitation highlights the need for innovative strategies, such as using drought-resistant plants and advanced irrigation systems, to maintain urban greenery. For regions with similar climatic conditions, such as Saudi Arabia, these lessons underscore the necessity of adopting adaptive and sustainable greening techniques in preparation for hosting future mega-events.

The observed increase in vegetation is consistent with the findings of Zhou et al. (2024), who reported similar increases in vegetation in arid regions following large-scale urban projects. However, both studies underscore that such progress is often constrained by the dominance of barren land and built-up areas, which limit the extent of greening efforts. The recommendation to use drought-resistant plants and advanced irrigation systems aligns with the conclusions of Abdullah et al. (2024), who emphasized the importance of species selection and efficient water management in sustaining urban greenery in arid climates. Similarly, Imran et al. (2021) highlighted that employing xeriscaping techniques and integrating treated wastewater for irrigation are effective strategies for maintaining vegetation in regions with limited water resources. These strategies are particularly relevant for Qatar and other arid regions, such as Saudi Arabia, which face similar climatic constraints.

4.4 Role of sustainable stadium design

The materials and vertical structures of the stadiums played a pivotal role in reducing urban heat. High-reflectivity materials and energy-efficient designs, mandated by the 4-star GSAS ratings, significantly minimized heat retention. The façades and roofs of the stadiums were constructed using materials with high light transmission and reflectance properties, such as PTFE, ETFE, and Tensotherm™ tensile membranes from Birdair (Leach et al., 2024; Stockhusen et al., 2024). These materials effectively prevent ambient radiation from passing through and make the stands insusceptible to sunlight, regardless of the incidence angle, resulting in a cooler environment and reduced energy consumption. An on-site study found that roofs made with PTFE could reduce the average temperature difference between outdoor and indoor spaces by up to 7.7°C (Yin et al., 2022). Moreover, the stadiums' open-area locations and structural designs form urban canyons, enhancing shading effects and reducing surface temperatures in their neighborhoods. Urban canyons with low height-to-width ratios and high-reflectance façades provide significantly larger temperature differences compared to those of other structures (Morini et al., 2018; Ornam et al., 2024; Tabatabaei & Fayaz, 2023). This integration of sustainable materials and innovative design principles serves as a model for future large-scale developments, demonstrating how urban infrastructure can effectively contribute to climate adaptation and resilience.

4.5 Spatial dynamics of UHI

The study highlights the spatial variability of UHIs in the study area, with the most pronounced changes observed in densely built regions and major infrastructure zones. The shift in LST patterns over time, particularly around stadiums and major highways, reflects the interplay between urbanization and thermal dynamics. The cooling effects of green spaces and stadiums provide a valuable counterbalance to these changes, reducing temperature disparities and improving urban microclimates. These findings underscore the importance of integrating UHI mitigation strategies into urban development plans.

4.6 Implications for future hosts of mega-events

Qatar's urban development and sustainability approach provides a model of innovative practices and strategic planning that future World Cup hosts, particularly Saudi Arabia in 2034, can draw upon. Qatar's experience demonstrates how hosting a mega-event in an arid climate can catalyze transformative urban changes when sustainability is embedded in the planning and execution stages. Through integrating green spaces, reflective materials, and advanced cooling designs, Qatar successfully mitigated urban heat island effects, enhanced the livability of its cities, and created environmentally resilient infrastructure. These efforts illustrate the importance of combining technological innovation with ecological solutions to address the unique challenges of hosting large-scale events in extreme climatic conditions.

As it prepares to host the 2034 FIFA World Cup, Saudi Arabia faces similar environmental and climatic challenges, such as high temperatures, limited water resources, and the predominance of impervious urban surfaces. By adopting strategies like those implemented in Qatar, Saudi Arabia can achieve a balance between meeting the immediate requirements of hosting a global event and ensuring long-term environmental sustainability. Integrating drought-resistant vegetation, efficient irrigation systems, and urban greening initiatives can enhance the aesthetic appeal of urban areas while providing critical cooling and air quality benefits. Similarly, utilizing reflective building materials and energy-efficient designs for stadiums and associated infrastructure can significantly reduce heat retention and energy consumption, creating a more sustainable urban environment.

This study underscores the potential for sports infrastructure to play a dual role in urban transformation: accommodating the functional needs of a mega-event while simultaneously driving sustainable urban growth. Qatar's stadiums, designed with advanced architectural techniques and surrounded by green spaces, demonstrate how infrastructure can be optimized to improve urban microclimates, reduce land surface temperatures, and create spaces that benefit local communities beyond the event's conclusion. These lessons are highly relevant for Saudi Arabia, where integrating climate-conscious designs into urban development plans can help mitigate the environmental impacts of rapid urbanization and extreme heat.

4.7 Broader urban and environmental impacts

Beyond the immediate cooling effects, the study highlights the broader implications of integrating sustainability into mega-sport event planning. From reducing UHIs to enhancing urban biodiversity, the legacy of the 2022 World Cup extends well beyond the event itself. These findings demonstrate how

hosting global events can catalyze long-term urban transformation, benefiting residents and visitors while addressing pressing environmental challenges.

4.8 Contributions to Global Sustainability Goals

Qatar’s alignment with 11 United Nations SDGs, particularly SDG 11 on sustainable cities, highlights the potential for mega-events to contribute to global sustainability frameworks. Prioritizing green infrastructure, sustainable materials, and inclusive urban planning, Qatar has set a benchmark for future hosts. This study reinforces the importance of integrating sustainability into every aspect of event planning, ensuring that mega-events leave a lasting positive impact on their host cities and beyond.

5. Limitations of the study

The primary uncertainties in this study stem from the estimation of Land Surface Emissivity (LSE) during the transformation of brightness temperature to surface temperature. An alternative approach to estimating LSE involves calculations based on the NDVI and Fractional Vegetation Cover (FVC). LSE is derived as a weighted average of vegetation and bare soil emissivity. The method employed in this study, the USGS LST method, integrates a high-precision emissivity dataset with a single-channel algorithm, effectively reducing the uncertainties associated with LSE estimation during LST inversion.

Besides emissivity, local climatic conditions may influence the LST results and the observed temporal changes. According to ERA5 data, the 2m temperature in March has remained stable over the years (Fig. 10), whereas the LST results in this study reveal an increasing trend. This discrepancy highlights the role of atmospheric conditions, which can introduce uncertainties during the atmospheric correction process required for calculating LST. Given the study area's proximity to the Arabian Gulf and desert regions, atmospheric water vapor content variations should be considered a significant source of uncertainty in LST inversion. Additionally, the atmospheric correction process is susceptible to humidity and aerosol content changes, which are more pronounced in areas close to the sea and desert. These variations can amplify uncertainties in derived LST values. However, this study focuses on relative LST differences to evaluate the UHI effect and the mitigation provided by stadiums. As such, absolute uncertainties in LST due to atmospheric corrections have a minimal impact on this analysis's primary objectives and findings.

While the study acknowledges potential uncertainties from emissivity estimation and atmospheric correction, the chosen methodologies ensure that these factors do not significantly compromise the results. The emphasis on relative LST differences enables robust analysis of urban heat dynamics and the cooling effects of stadiums, offering reliable insights into the environmental impacts of urbanization and large-scale infrastructure.

6. Conclusion and policy implications

This study provides a detailed analysis of the environmental impact of the FIFA World Cup 2022 in Qatar, mainly focusing on urban greening and the mitigation of LST. The findings demonstrate that the construction of stadiums and associated infrastructure not only contributed to urban development but also significantly impacted the thermal environment of their surroundings. The increase in NDVI values, particularly near stadiums such as the Khalifa International Stadium and Education City Stadium, highlights the effectiveness of integrating vegetation into urban planning to combat UHI effects. The study emphasizes that such infrastructure can positively influence urban sustainability in arid regions.

The cooling effects of stadiums were evident across all three categories of facilities, standalone stadiums, those with adjacent vegetation, and stadiums within large complexes. Standalone stadiums exhibited localized but intense cooling effects driven by their structural designs. In contrast, stadiums with adjacent vegetation demonstrated consistent and enhanced cooling effects due to the synergy between landscaping and architectural elements. However, stadiums within large complexes showed less prominent cooling effects, indicating that surrounding infrastructure influences their thermal impact. These findings underscore the importance of tailoring cooling strategies to the specific context of urban developments.

Qatar's implementation of sustainability measures, including green infrastructure and innovative architectural designs, sets a benchmark for future mega-events in similar climatic conditions. The cooling distances observed around the stadiums, extending up to 200 meters in some cases, provide quantitative evidence of their positive environmental impact. These insights reinforce mega-events' role in catalyzing urban transformation and addressing environmental challenges.

The research highlights the potential for cities hosting mega-events to leverage infrastructure projects for long-term sustainability gains. Host nations can mitigate UHI effects by prioritizing green infrastructure, efficient cooling systems, and reflective building materials while improving urban livability. As countries like Saudi Arabia prepare to host future events, the lessons from Qatar’s World Cup provide valuable guidance for integrating sustainability into urban development plans.

The successful hosting of the FIFA World Cup 2022 in Qatar provides valuable insights into how large-scale infrastructure projects can be leveraged to address pressing urban and environmental challenges. The event demonstrated the potential for integrating sustainability into urban planning and stadium design, especially in arid regions prone to urban heat island (UHI) effects. The following policy implications outline actionable strategies that future host nations can adopt to balance the demands of urban development with environmental preservation. These recommendations emphasize the importance of green infrastructure, sustainable design standards, long-term urban planning, and regional collaboration to create resilient and climate-conscious cities.

1. Incorporation of green infrastructure in urban planning. Future mega-event hosts should prioritize integrating green infrastructure, such as urban parks, green roofs, and tree-lined boulevards, into their planning processes. The findings from Qatar demonstrate that vegetation significantly enhances the cooling effects of large-scale infrastructure, reducing LST and mitigating UHI effects.

Policymakers should adopt zoning regulations and incentives to ensure the inclusion of sustainable landscaping in urban developments, especially in arid climates.

2. Sustainability standards for stadium design. Policymakers should establish mandatory sustainability standards for the design and construction of stadiums and other major event facilities. These standards should emphasize high-reflectivity materials, energy-efficient cooling systems, and designs that enhance natural ventilation. Qatar's approach, guided by GSAS ratings, demonstrates that such measures can reduce thermal footprints while ensuring energy efficiency. These standards can be adapted to local climatic and environmental conditions to maximize their impact.
3. Long-term urban development strategies. Mega-event preparations should be aligned with broader urban development goals to ensure a lasting legacy beyond the event. Policymakers should use these events to invest in infrastructure that improves urban resilience, such as integrated transportation networks and sustainable housing. Qatar's alignment with the United Nations SDGs, particularly SDG 11 on sustainable cities, offers a model for integrating mega-events into long-term urban strategies.
4. Regional collaboration and knowledge sharing. Countries in arid regions, such as Saudi Arabia, can benefit from regional collaboration to share best practices and innovative solutions for sustainable urban development. Qatar's experience highlights the importance of leveraging advanced technologies and cross-disciplinary expertise to address the challenges of hosting mega-events in extreme climates. Establishing regional forums for knowledge exchange can enhance the capacity of policymakers to implement climate-resilient strategies and foster regional leadership in sustainability.

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Author Contribution

AA: Conceptualization, Methodology, Investigation, Data Curation, Formal Analysis, Writing – Original Draft, Writing – Review & Editing, Visualization, Supervision, Project AdministrationXL: Conceptualization, Methodology, Investigation, Data Curation, Formal Analysis, Writing – Original Draft, Writing – Review & Editing, Visualization, Supervision, Project AdministrationSP: Conceptualization, Investigation, Data Curation, Writing – Original Draft, Writing – Review & EditingSZ: Conceptualization, Investigation, Data Curation, Writing – Original Draft, Writing – Review & EditingZF: Conceptualization, Investigation, Data Curation, Writing – Original Draft, Writing – Review & Editing

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Figures

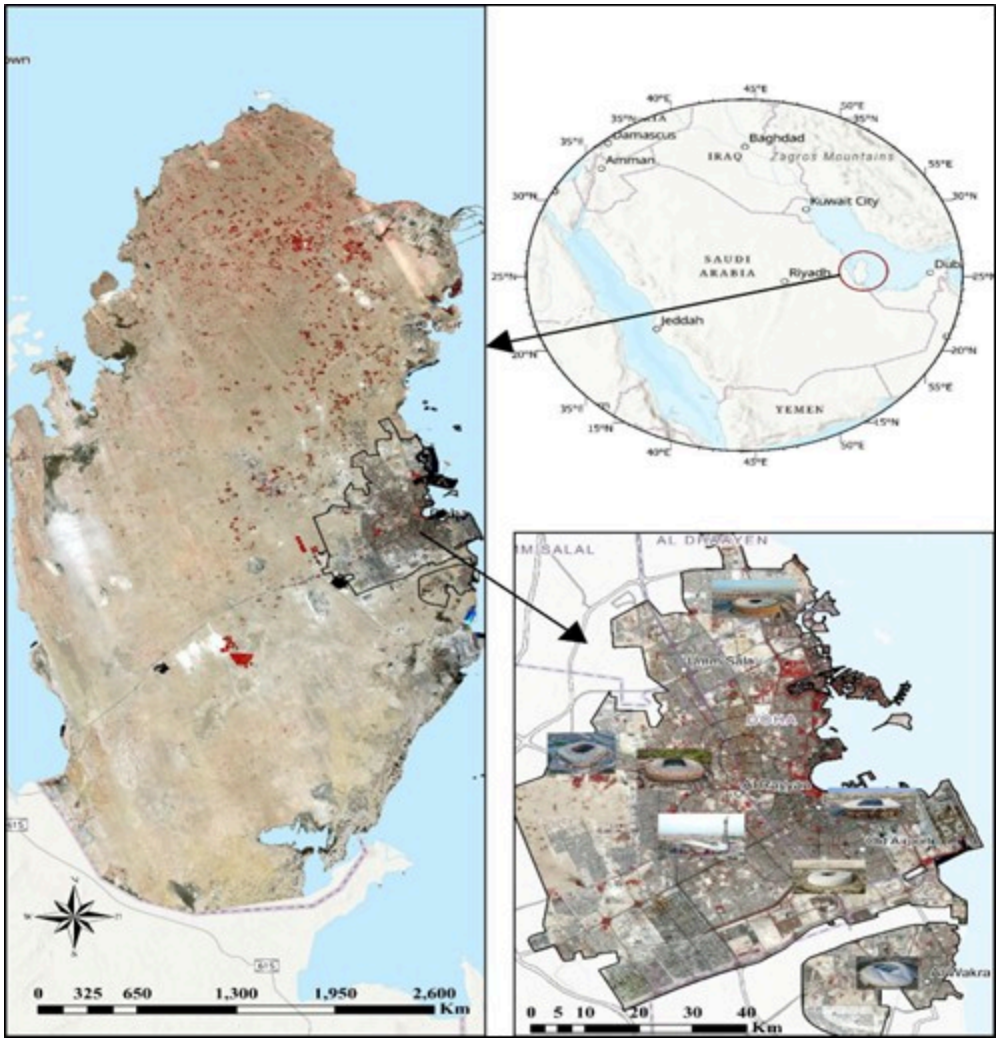


Figure 1

Study Area

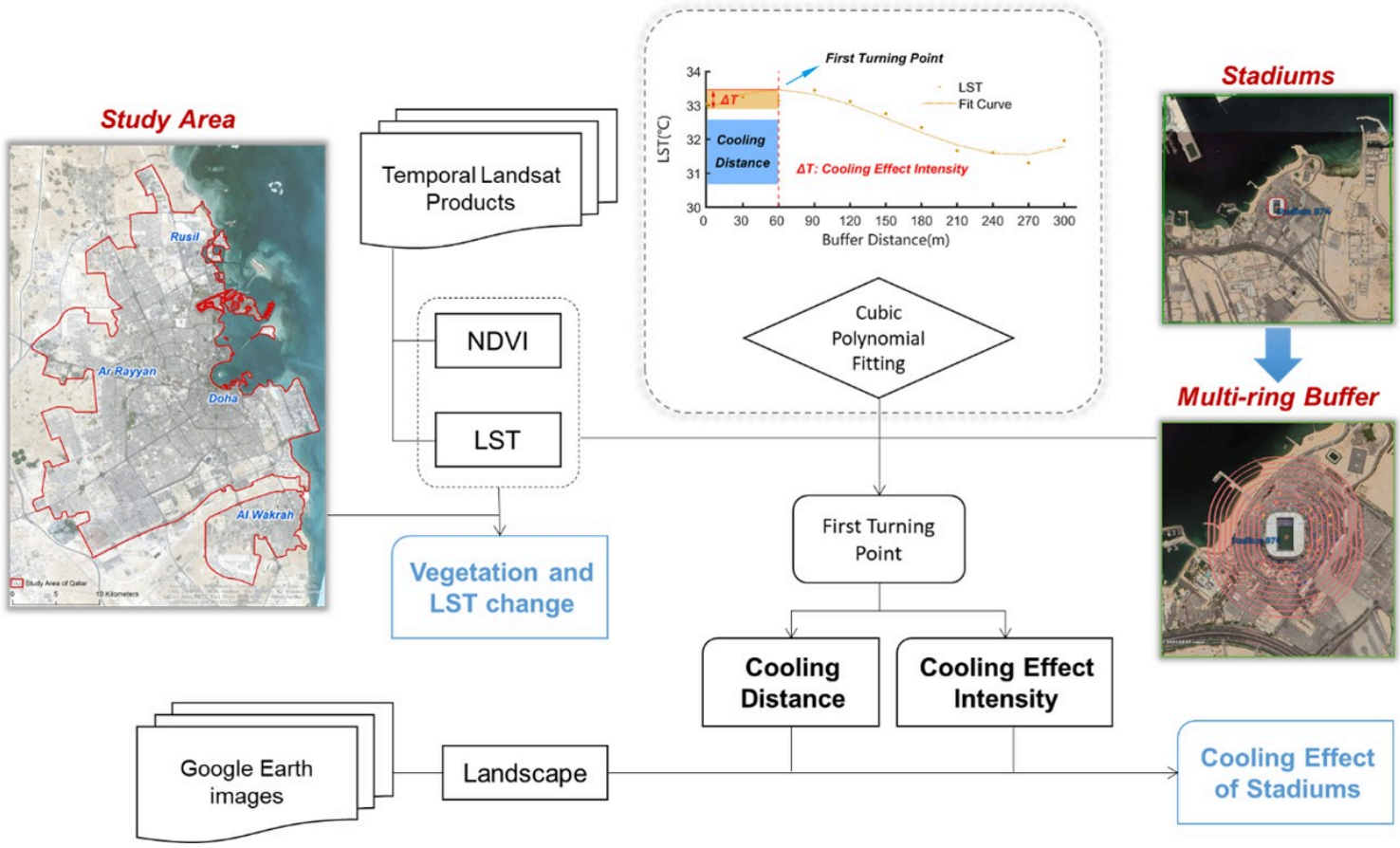


Figure 2

Flowchart of the study

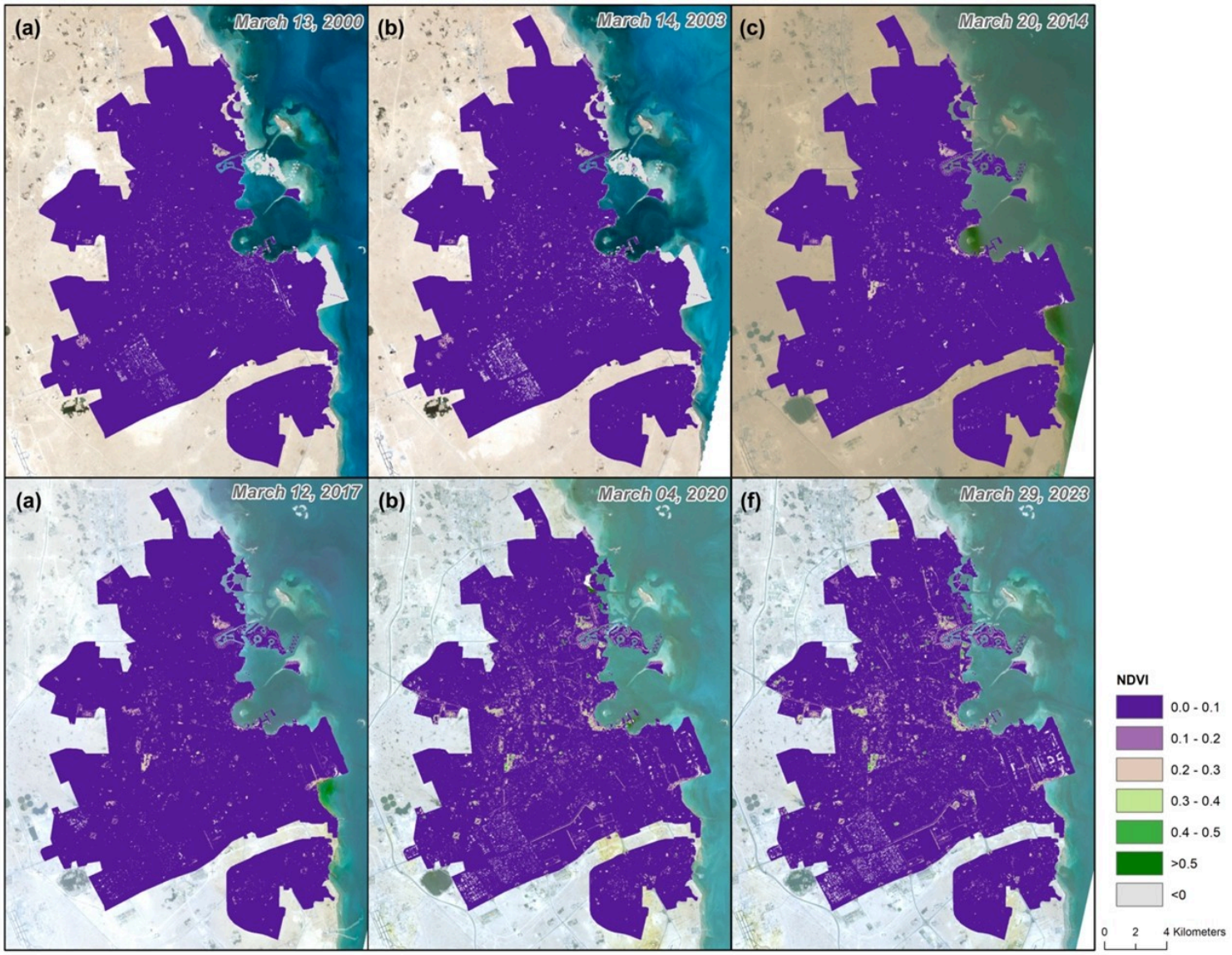


Figure 3

NDVI result of study area

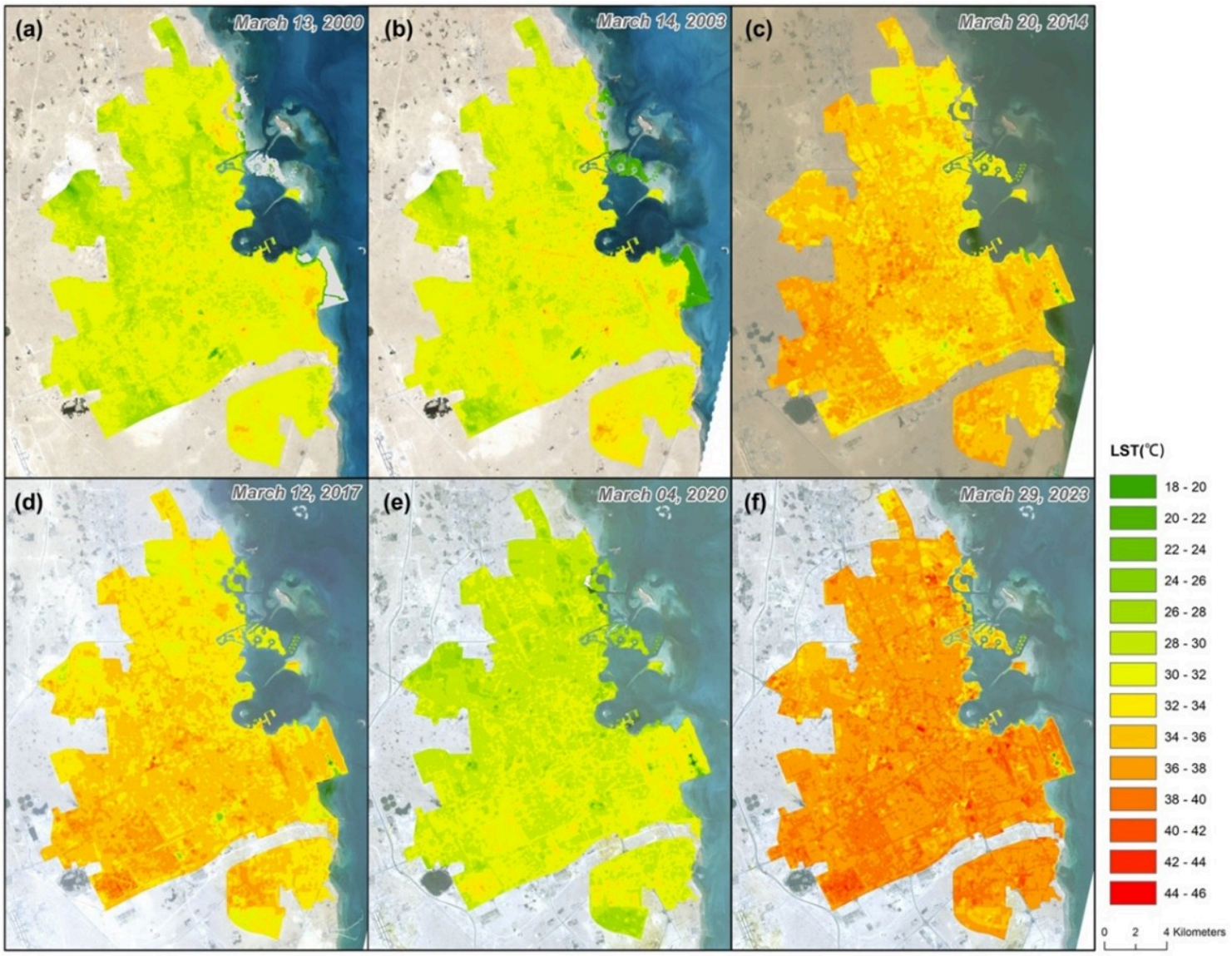


Figure 4

LST results

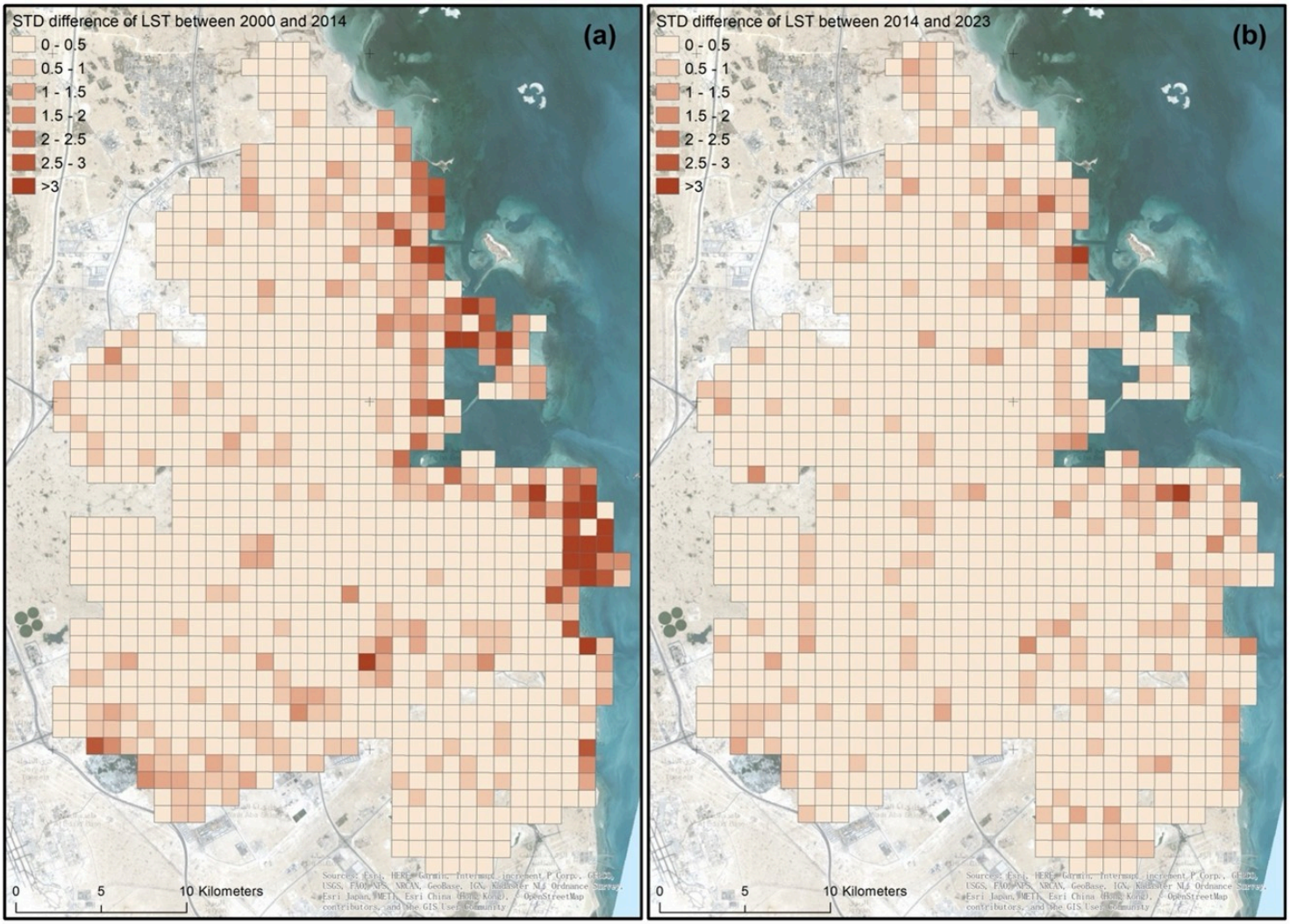


Figure 5

Standard deviation difference of LST, (a) between 2000 and 2014, (b) between 2014 and 2023.

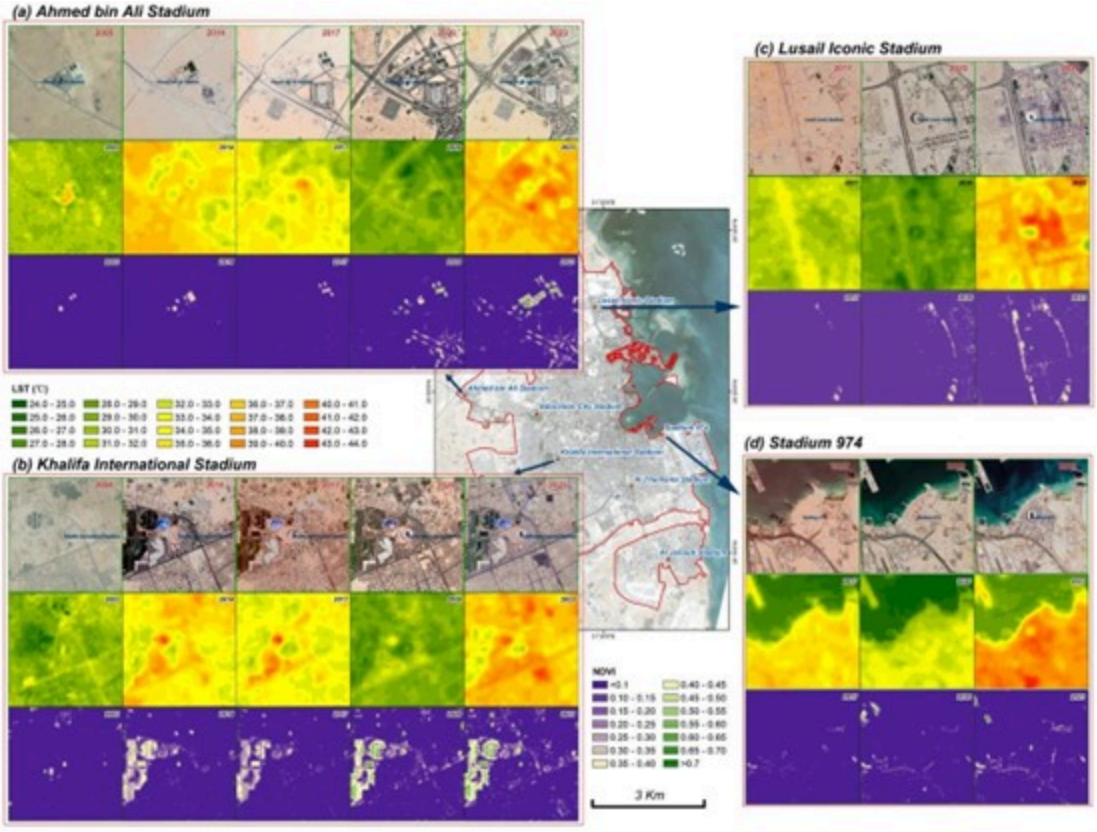


Figure 6

Time series change of landscape, vegetation and LST changes of different stadiums, (a) Ahmed bin Ali Stadium, (b) Khalifa International Stadium, (c) Lusail Iconic Stadium, and (d) Stadium 974.

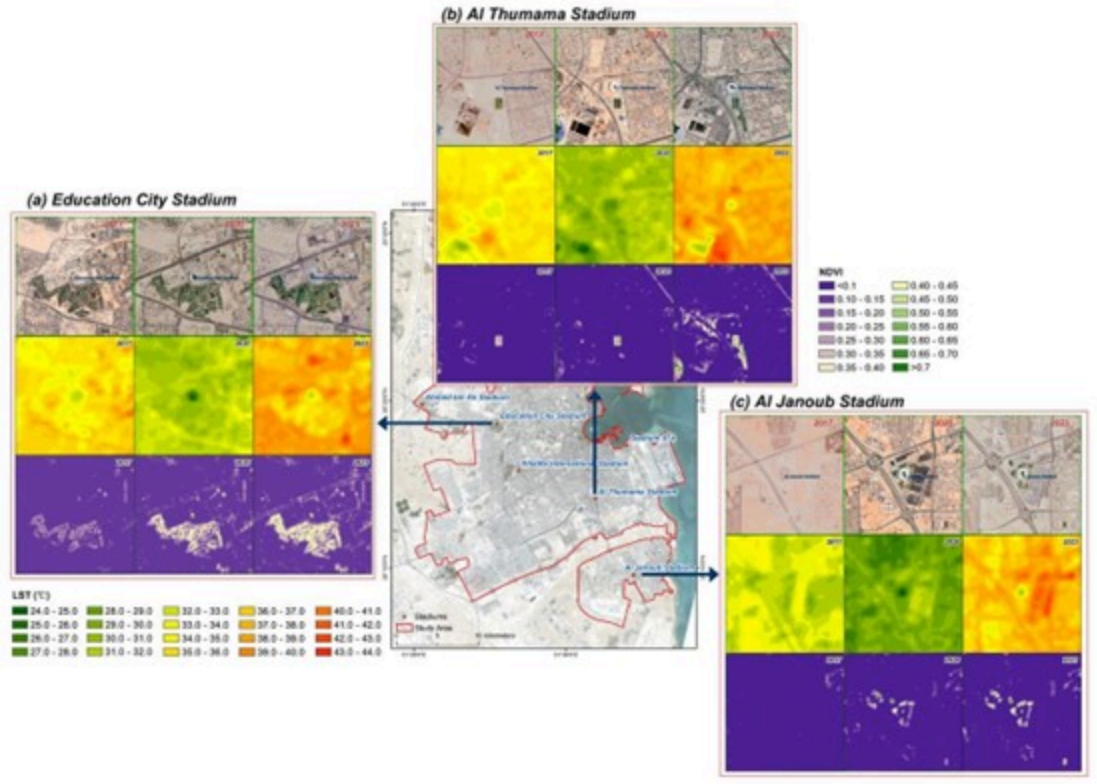
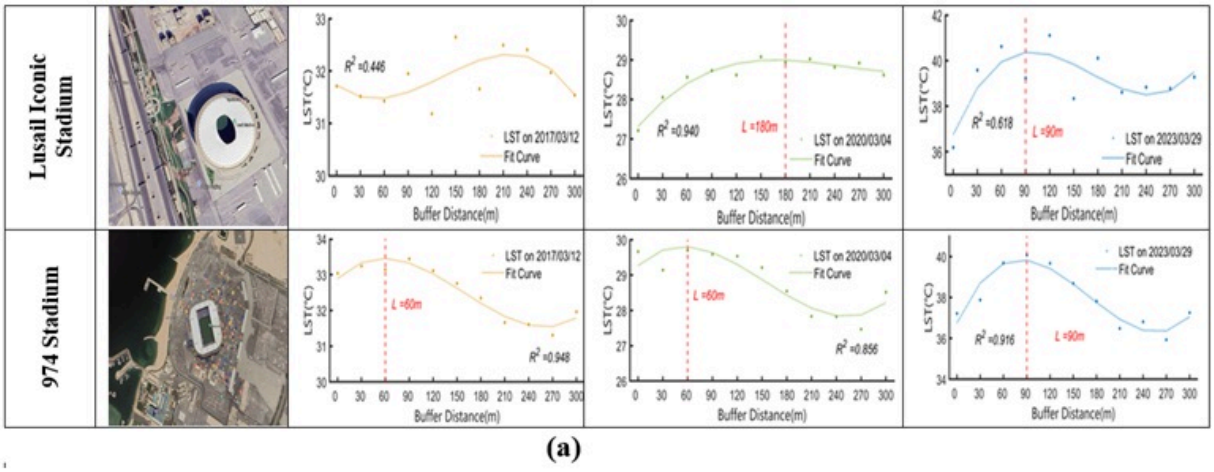
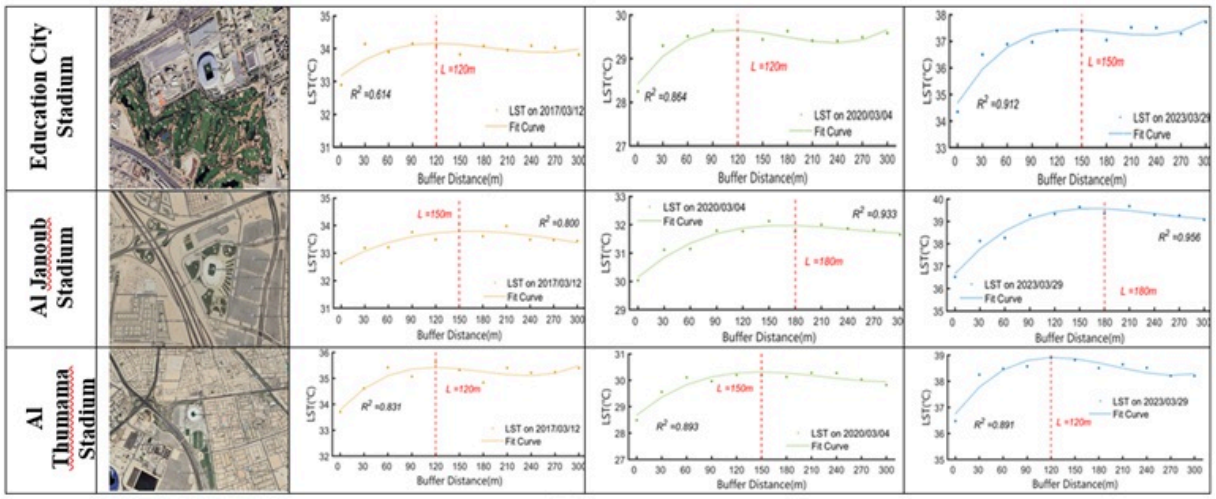


Figure 7

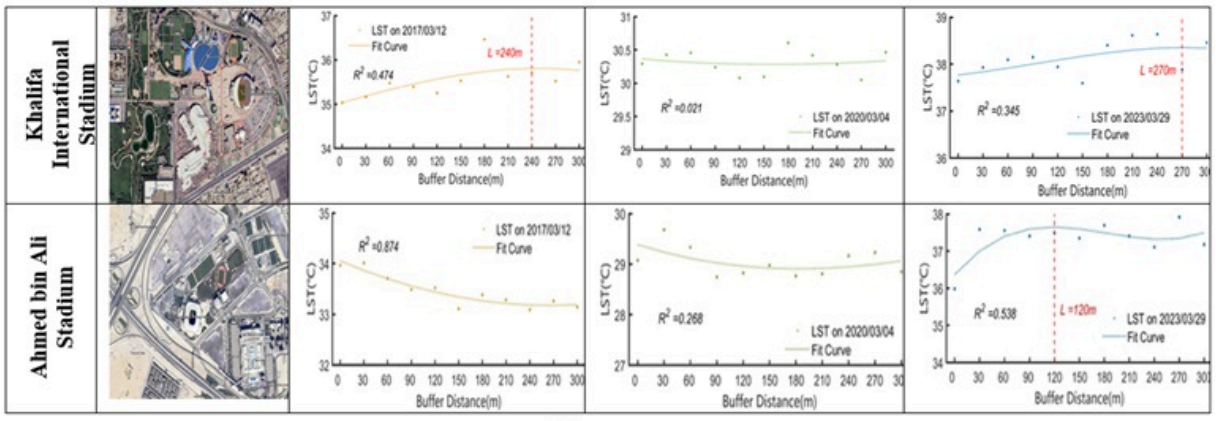
Time series change of landscape, vegetation and LST changes of different stadiums, (a) Education City Stadium, (b) Al Thumama Stadium, (c) Al Janoub Stadium.



(a)



(b)



(c)

Figure 8

Cooling distance of the stadiums (a) class 1, (b) class 2, (c) class 3

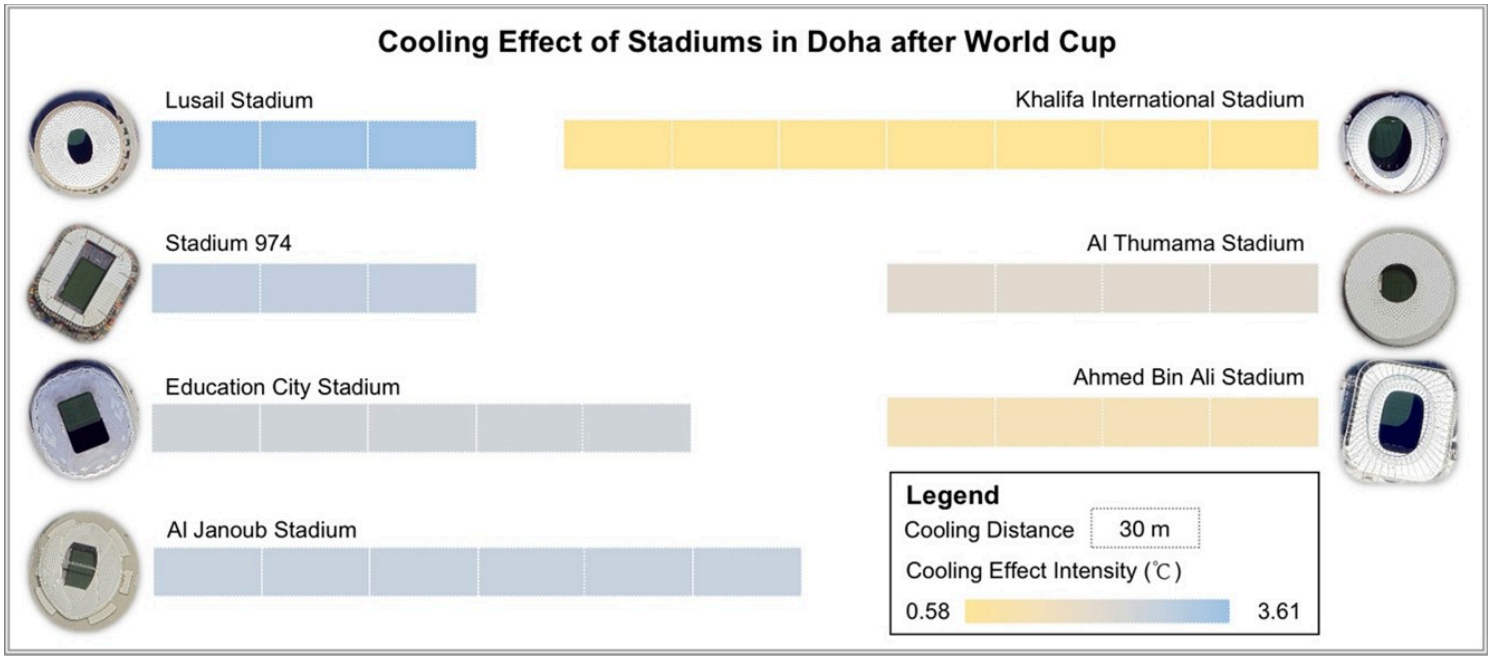


Figure 9

Cooling effect intensity of the stadiums

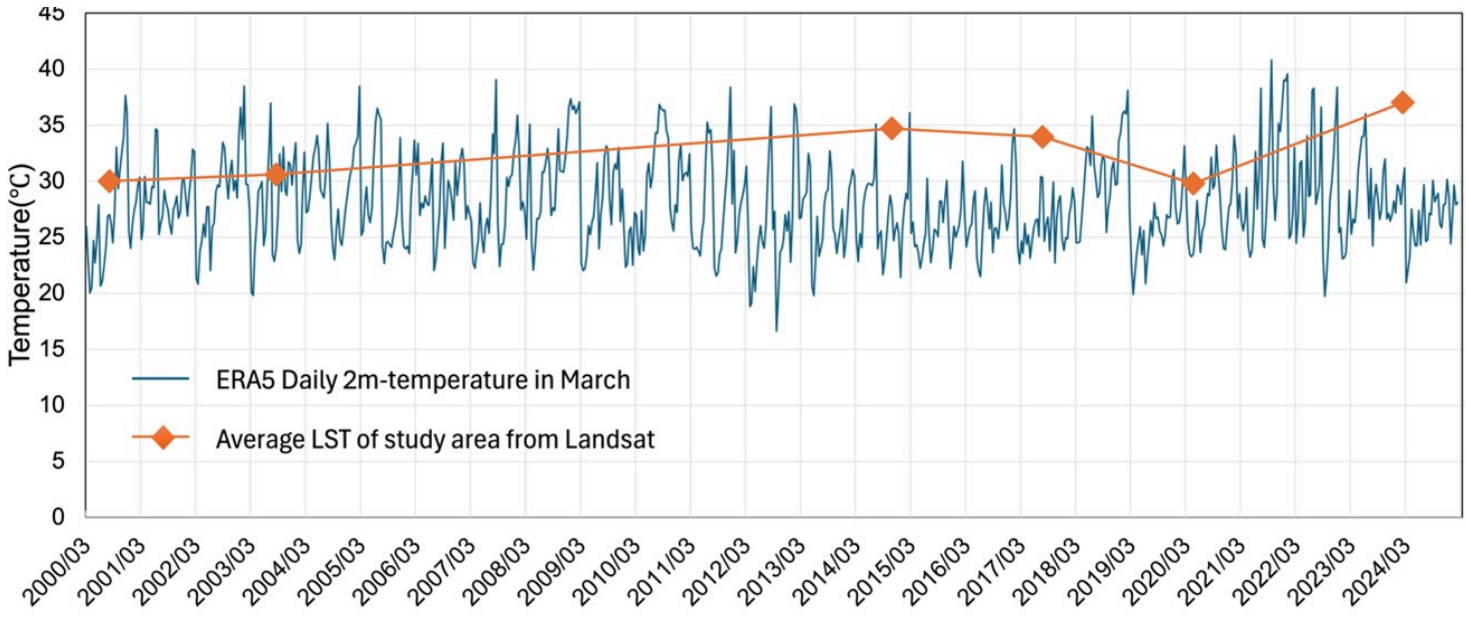


Figure 10

ERA5 2m-Temperature in March and LST Results from This Study