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in Ouagadougou, Burkina Faso

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Feasibility of Reducing Land Surface Temperature by Greening in Ouagadougou, Burkina Faso

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Abstract

In hot, semi-arid zones, cities are experiencing longer and more intense warm spells. Although the literature offers strategies to mitigate this threat, studies verifying their feasibility are limited. In this study, we aim to ascertain the feasibility of reducing land surface temperature (LST) through greening. We combine LST analysis with a feasibility assessment of cooling measures and consider physical and ownership dimensions alongside environmental and social factors, with Ouagadougou (Burkina Faso) serving as a case study. The average LST during the hottest period (April–May) was calculated from ECOSTRESS and Landsat remotely sensed data, and multiple regression models were used to analyse the relationship between LST and land cover/land use across the city's districts and sectors. Our assessment incorporates greening scenarios, SWOT analyses, and equity assessments, and our results indicate that barren land is the primary determinant of diurnal LST. Planting 0.45 million trees could reduce LST by up to 2.4 °C in peripheral sectors if large roads, utilities, and vacant lands are targeted. This may reduce disparities in tree cover between sectors but could widen the gap between districts. Recommendations include a more hierarchical street network, enhancing utility provision, and reducing barren land in the peripheral sectors.

Keywords: ECOSTRESS; Landsat; environmental equity; greening; participatory SWOT; urban planning; warm spells

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1. Introduction

Over the past 25 years, the urban population in hot, semi-arid zones has grown by 85%, now exceeding 200 million [1]. In these areas, temperatures frequently rise above 40 °C, increasing the risk of heat-related morbidity and mortality [2–4]. Projections indicate that, under various warming scenarios, West Africa will have the highest number of vulnerable individuals, specifically those under 5 and over 64 years of age, exposed to urban heatwaves by 2100 [5].

Land surface temperature (LST), measured using satellite or drone sensors, is crucial for assessing the spatial distribution of heat across different areas and capturing surface temperature at individual pixels. In contrast, air temperature (AT), recorded at weather stations or via mobile sensors, is available at significantly fewer locations, generally at airports or along roads [6].

Within the hot, semi-arid zone [7], research on LST has focused on understanding urban heat islands (UHIs) and how they are influenced by built-up, vegetated, and cultivated lands, as well as water bodies [8–46]. This body of knowledge is based on seminal studies conducted in other climatic zones on UHIs [47], on the automated mapping of built-up areas [48], on landscape classification for the study of temperatures [49], and on land cover classes that determine the rural–urban gradient [50]. However, only 61% of the studies recommend specific cooling interventions (Table A1). Greening is the most frequently recommended measure (35%) and is based on research conducted in the early 2000s in Guangzhou and Indianapolis [51,52]. Light-coloured building materials, whose potential has been studied since the early 1990s, account for 26% of recommended measures [53]. Proposals for green roofs are less common (22%), perhaps because this measure has only been studied more recently [54]. Other recommended strategies, such as water bodies and low-density developments, are mentioned in only 17 and 13% of studies, respectively. However, these studies rarely assess the feasibility of cooling measures, particularly in relation to spatial constraints, land ownership, and the equitable distribution of greening.

The tree canopy is regarded as an ecosystem service that regulates temperature in many climatic zones [55,56]. The impact of greening on LST is well documented through experiments [57,58] and empirical studies on urban forests [19,59], tree-lined roads [60], planting around buildings [61], living walls, and green roofs [62]. Since these interventions are inherently physical and require space for implementation, urban areas often face limitations in accommodating such green spaces owing to the extent of available land and ownership at the desired locations [63]. Informal settlements and the latest generation of housing estates feature a grid of narrow streets and limited utilities, which do not allow for widespread tree planting, while private plots lack space for planting and resources for maintenance, particularly for irrigation. Policies that overlook these factors risk failing to set realistic targets, possibly leading to non-implementation or, even worse, exacerbating inequalities in access to green spaces between the Poor and others [64,65].

In this study, we address the feasibility of urban greening by posing three research questions: How much space is available for greening? To what extent can greening reduce the LST, and what obstacles or opportunities might it encounter? If implemented, would greening be equitably distributed across all neighbourhoods? Our objective is to evaluate the physical, ownership, environmental, and social feasibility dimensions of greening strategies.

Our research is novel for two reasons: first, it combines LST analysis with a feasibility assessment of cooling measures; second, it examines the often-neglected physical and ownership dimensions of feasibility. The focus is on public properties, as greening these areas is likely more equitable than in private spaces, where space constraints or limited maintenance resources, such as irrigation, are common [40]. We hypothesise that targeting roads and utilities for greening, assuming their wide distribution, could result in a more evenly distributed greening effort.

Our study was conducted in Ouagadougou, the capital of Burkina Faso. In this article, we present the first findings of a research project on Sahelian cities similar in size and warm spells, which include, in addition to Ouagadougou, Niamey (Niger) and N'Djamena (Chad). Administratively, Ouagadougou is organised into a central municipality subdivided into 12 districts and 55 sectors, with a jurisdiction of 533 km^2, of which 160 km^2 remains undeveloped, and five outer municipalities (Figures 1 and A1).

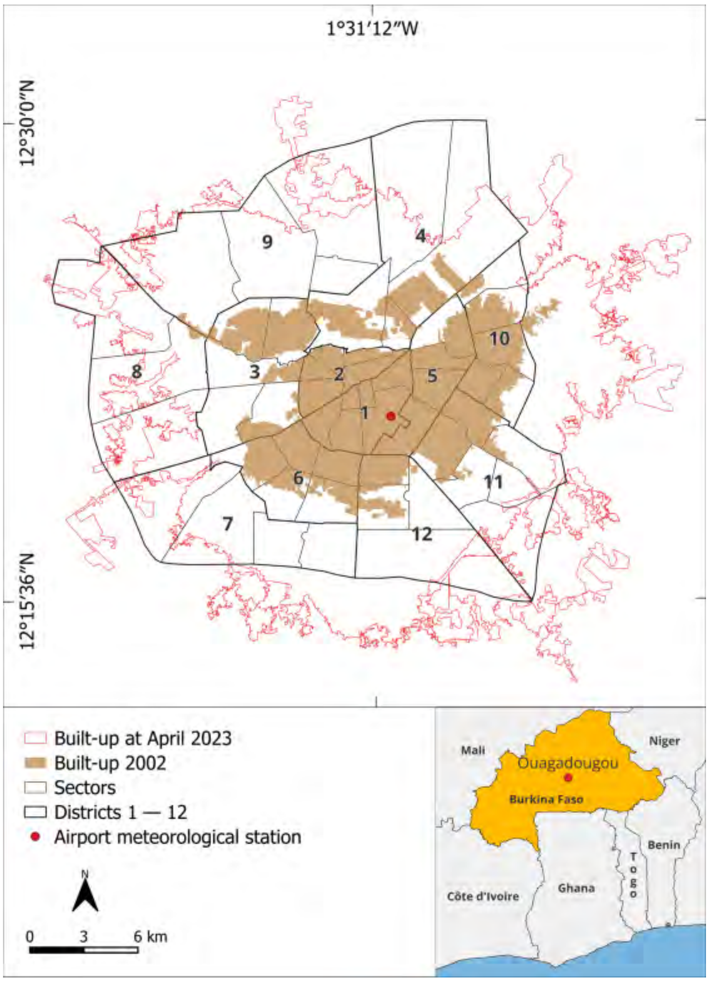

Figure 1. Built-up area in April 2002 and April 2023, and the administrative jurisdictions of Ouagadougou.

The core of the city has 2.4 million inhabitants, while the outer municipalities have 0.6 million. Over the past 15 years, this conurbation, known as Greater Ouagadougou, has doubled its population and tripled its built-up area [66,67]. Notably, 27% of this expansion occurred in informal settlements, which could pose significant challenges to the implementation of equitable greening policies.

In our study, we analysed warm spells using daily AT data recorded at the airport. Subsequently, the average daytime LST for the warmest months of 2021–2025 was examined using data from the ECOSTRESS sensor aboard the International Space Station and from Landsat satellites. The land use/land cover metrics that influence daytime LST were identified using multiple regression analysis. A barren land threshold was used to identify priority areas for greening. Physical and ownership feasibility of greening were considered. Additionally, the environmental feasibility of greening was established using a SWOT analysis. Finally, the social feasibility of greening was considered by analysing the share of green cover per sector and disparities in tree canopy per capita.

The subsequent sections (i) outline the methodology, (ii) present the results that were achieved, (iii) discuss these results in relation to the three research questions concerning urban areas in the BSh climate zone and set out the implications and limitations of our work, and (iv) conclude by highlighting the novelty of our study and the broader significance of the findings.

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2. Materials and Methods

In this study, we use the term “vacant lands” to refer to all undeveloped or abandoned lots and land where no structure exists [68]. The term “barren lands” denotes soils devoid of vegetation as of April–May 2023, encompassing undeveloped lots, areas not yet subdivided into plots, and unpaved roads. The district serves as the administrative entity of reference, holding the status of a municipality and retaining all responsibilities ascribed by law to this administrative level, including those related to greening initiatives [69]. Sectors function as sub-entities of districts but lack administrative roles (Figure A1). The warm spell duration index (WSDI) is defined as a sequence of at least 6 days in which the maximum temperature exceeds the 90th percentile.

Our study primarily focuses on the physical and ownership dimensions of feasibility, essential for measures requiring spatial implementation. We examine available areas, their sizes, their capacity to accommodate the specified greening, and whether they are publicly or privately owned. Additionally, we incorporate environmental and social dimensions, which have previously been utilised alongside economic, technical, and institutional aspects in other climate adaptation analyses [70,71]. The environmental dimension evaluates the LST reduction provided by greening, the obstacles to be overcome, and the opportunities that arise in its implementation. The social dimension assesses the equitable distribution of greening measures across sectors and districts, including those with informal settlements, and the propensity of inhabitants and their organisations to plant and maintain vegetation.

The study was conducted during the peak heat period identified through a trend analysis of warm spells. Daily maximum AT was recorded at Ouagadougou airport from 1980 to 2022. A preliminary completeness check of the dataset confirmed its integrity with a positive result (0.12% of missing data). The WSDI calculation was performed using Rcimdex, adhering to the recommendations of the World Meteorological Organization and the Expert Team for Climate Change Detection and Indices [72].

The daytime LST was studied by analysing satellite images collected during the average hottest period (April—mean AT, 40 °C). Images from April were selected for the period 2021–2025. Due to limited image availability, mainly caused by cloud coverage, May (mean AT, 38.3 °C) images were also included to increase temporal robustness. The satellite images were sourced from the ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS, https://ecostress.jpl.nasa.gov) attached to the International Space Station and from the Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) on Landsat satellites. ECOSTRESS provides atmospherically corrected LST and emissivity values derived from five thermal infrared bands with a spatial resolution of 70 m and an expected thematic accuracy of 1 °K (≈1 °C) [73], while Landsat products provide images with a spatial resolution of 30–100 m, depending on the sensor, and an expected accuracy of approximately 1–2 °K [74,75]. ECOSTRESS images were accessed via AppEEARS (Application for Extracting and Exploring Analysis Ready Samples), while Landsat images were accessed via the U.S. Geological Survey (USGS) EarthExplorer data portal. Both ECOSTRESS and Landsat quality control data provide various quality indicators classifying each pixel result as nominal, abnormal, or defined under other conditions.

Only pixels meeting specific quality control (QC) criteria were considered. Overall, 24 satellite images (14 Landsat and 10 ECOSTRESS scenes) were collected and analysed, allowing the integration of the temporal dimension. Because ECOSTRESS and Landsat have different overpass times, the datasets were not cross-validated as simultaneous pixel-level measurements, but were instead jointly used to analyse broader spatial–temporal patterns of LST at aggregated scales.

The average daytime LST was calculated for each of the 55 sectors. This approach, rather than using local climate zones [49] or multiple ring buffer zones [50], as typically conducted in the LST literature, was considered most suitable for a feasibility study aimed at informing district-level cooling policy decisions. However, to assess the robustness of spatial variability, mean LST was also computed using a regular 500 m × 500 m grid, enabling a comparison of the results across different spatial scales.

2.1. Physical and Ownership Feasibility

Physical feasibility was assessed by identifying the critical land cover classes most closely correlated with LST (e.g., barren land) and those most frequently recommended for reducing LST (e.g., tree cover and water bodies) based on the literature on cities in the BSh zone (Table A1). A supervised classification approach was applied to distinguish between barren land, tree canopies, and water bodies in a PlanetScope multispectral image acquired on 25 April 2023 (Figure 2).

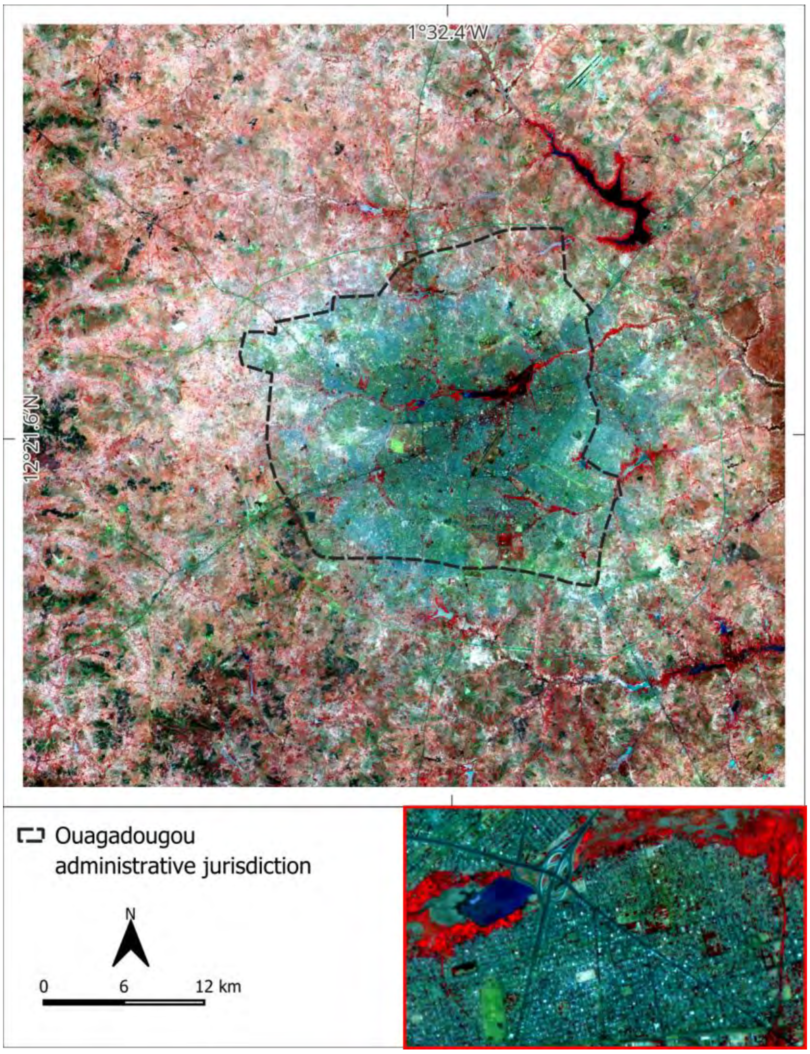

Figure 2. PlanetScope imagery of Ouagadougou (25 April 2023) in false colour composite (4-3-2), and subset of the original scene. The inset (bottom right) shows a full-resolution sample (1:1).

This image featured a 3.7 m ground sampling distance, no cloud cover, and was orthorectified and atmospherically corrected to produce analytic surface reflectance ortho scenes over eight bands (Coastal Blue: 431–452 nm; Blue: 465–515 nm; Green I: 513–549 nm; Green: 547–583 nm; Yellow: 600–620 nm; Red: 650–680 nm; Red Edge: 697–713 nm; NIR: 845–885 nm). Image classification was conducted using the Imagery Classification Wizard tool in ArcGIS, which uses multiple decision trees to categorise each pixel or pixel cluster into specific classes (barren land, tree vegetation, water body). The classification was informed by a preliminary image segmentation phase, with spectral detail set to 18.5 and spatial detail set to 15. The classification was further refined using the random forest algorithm with 150 trees, a maximum tree depth of 30, and 1000 samples per class. Subsequent post-processing involved cleaning small classification errors and generalising data to remove extraneous details, using boundary clean to smooth class boundaries and majority filter to adjust spurious cells based on neighbouring cells. Following this, areas of barren land and tree crowns were quantified using zonal statistics.

Ownership feasibility was investigated by identifying public and private land and their associated use. Firstly, wide roads, paved roads, utilities (educational, sports, health, socio-cultural), and land use classes were identified using the official lists of educational facilities [76], OpenStreetMap [77], and the Google Earth Pro (GEP) "places" layer (health, socio-cultural, and industry). Subsequently, vacant lands, informal settlements, industrial sites, and gardens were identified according to their configuration (Figure 3).

Figure 3. Ouagadougou land use classes in April 2023.

Finally, the area, the lot edge length, and the non-wooded portion of the lot edge of utilities were determined through visual photo interpretation of the April 2023 very-high-resolution imagery available on GEP.

Multiple satellite images were analysed to incorporate a temporal dimension into LST assessment and to reduce dependence on a single acquisition date. This method captures day-to-day variability while allowing the identification of persistent relationships between LST and land cover composition.

To account for daily meteorological variability, a multiple linear regression model with a categorical variable *Day* was applied (Equation (1)). This model enables us to separate temporal fluctuations in LST from the effects of land cover composition. Land cover variables were aggregated to the same spatial units as LST, and the regression coefficients represent sector- or grid-scale relationships between mean LST and land cover composition rather than the local thermal effect of individual pixels or narrow linear interventions. Moreover, the model allows us to test whether the selected compositional factors consistently influence LST despite inter-day variability.

$$LST_i = \beta_0 + \sum_{d=1}^{n-1} \beta_d Day_d + \beta_1 Barren_i + \beta_2 TreeCanopy_i + \beta_3 Roads_i + \varepsilon_i, \quad (1)$$

where

LST_i = mean LST in sector or grid cell i (°C);

Day_d = acquisition date (reference day, 22 April 2023, as intercept);

$Barren,\ TreeCanopy,\ and\ Roads$ = proportion of land cover in sector or grid cell i (0–1);

ε_i = residual error term.

The *Day* variable is included to isolate daily variations in LST due to meteorological conditions. *Barren land*, *tree canopy*, and *road* variables were selected based on their influence on LST in cities in the BSh zone and their relevance for implementing greening interventions (Table A1).

To assess whether the relationship between LST and land cover is consistent across acquisition dates, the baseline regression model is compared with an extended version that includes interaction terms between the *Day* variable and the land cover predictors. To further evaluate whether land cover effects differ across daytime acquisition periods, an additional robustness model was constructed, including a binary acquisition period variable ("morning" vs. "afternoon") and its interactions with land cover predictors, allowing their marginal associations with LST to differ between periods while still controlling for date-specific variability (*Day* variable).

Tree planting along wider roads, at utility edges, in agroforestry, and shrubs along lot fences was identified as a strategy for cooling the LST. It has been established that the wider the streets, the more effective the cooling impact of trees [78], a relationship confirmed in Niamey [40]. Agroforestry has been shown to reduce LST in the BSh zone [79] and is thus proposed for inclusion in Ouagadougou's urban agriculture. The area to be planted was estimated at 100 stems/ha, with each stem providing a canopy coverage of 79 m^2. This density is considered the minimum for the roadside density of 108–192 stems/ha observed in other cities within the BSh zone [80–82]. Greening scenarios were developed to gradually increase the greened area, prioritising districts where barren lands show a strong correlation with LST.

2.2. Environmental Feasibility

The regulation of temperature provided by tree planting was quantified by setting the second quartile of barren land cover of sectors as the threshold for prioritising greening. The vacant lands required to be planted were consequently estimated.

The expected cooling effect of tree planting on vacant lands was assessed using regression coefficients relating LST to land cover composition. For each targeted sector, changes in barren land and tree canopies associated with greening scenarios were estimated, and the corresponding variation in LST was computed using the regression model coefficients.

$$\Delta LST = (\beta\ Barren * \Delta Barren) + (\beta\ TreeCanopy * \Delta TreeCanopy), \quad (2)$$

where

ΔLST = variation in land surface temperature (°C);

$\beta\ Barren$, $\beta\ Tree\ Canopy$ = regression coefficients of the land cover variables;

$\Delta Barren$, $\Delta TreeCanopy$ = Changes in land cover composition (% of sector).

The strengths, weaknesses, opportunities, and threats of implementing the four most widespread greening measures in Ouagadougou were then identified through a SWOT analysis conducted with local experts, balanced in gender and profession.

2.3. Social Feasibility

Social feasibility was assessed by considering the percentage of tree cover in the formal and informal sectors, as well as the per capita canopy in each district. Population figures were sourced from the 2019 census. The share of land designated for planting was subtracted from the vacant lands outside the built-up area. The population density was then applied to the remaining area, and the projected number of future residents was calculated. This figure was used to determine the per capita tree cover (Figure 4).

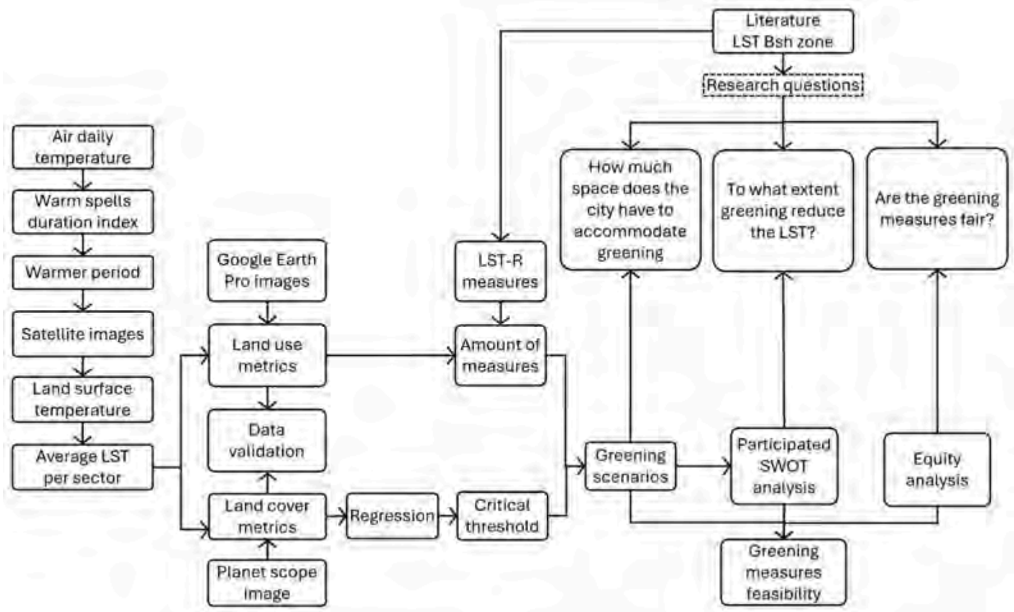

Figure 4. Flowchart of the feasibility study for greening Ouagadougou.

2.4. Land Cover Land Use Validation

The producer accuracy, user accuracy, overall accuracy, and Kappa coefficient were calculated using confusion matrices for both land cover and land use classifications. For land cover, class accuracy was assessed using a confusion matrix based on 693 training samples used for classification and 120 independent validation points interpreted from high-resolution satellite imagery. For land use, accuracy was evaluated using the land use map created according to the rules shown in Figure 3, along with 110 independent validation points interpreted from high-resolution satellite imagery (ArcGIS Living Atlas, World Imagery basemap, accessed in April 2023). The confusion matrices (Tables 1 and 2) show overall accuracies of 0.85 (Kappa = 0.81) for land cover and 0.86 (Kappa = 0.83) for land use, confirming the reliability of the classifications.

Table 1. Confusion matrix and the accuracy assessment for land cover.

Classification	Ground Truth						
	Water	Developed	Barren	Tree Canopy	Shrubland	Total	User Accuracy
Water	8	1	0	0	0	9	0.89
Developed	0	23	1	0	1	25	0.92
Barren	0	2	26	0	1	29	0.90
Tree Canopy	0	0	0	10	0	10	1
Shrubland	0	5	5	0	27	37	0.73
Total	8	31	32	10	29	110	
Producer Accuracy	1	0.74	0.81	1	0.93		0.85
Overall Accuracy = 0.85				Kappa Coefficient = 0.81			

Table 2. Confusion matrix and the accuracy assessment for land use.

Classification	Ground Truth								
	Vacant Land	Informal Settlement	Roads >18 m	Paved Roads	Utilities	Industry	Garden	Total	User Accuracy
Vacant Land	34	2	0	0	0	0	2	38	0.89
Informal Settlement	2	20	0	0	2	0	0	24	0.83
Roads > 18 m	0	0	8	0	0	0	0	8	1
Paved Roads	0	0	4	7	0	0	0	11	0.64
Utilities	0	1	0	0	9	0	0	10	0.90
Industry	0	0	0	0	0	10	0	10	1
Garden	2	0	0	0	0	0	7	9	0.78
Total	38	23	12	7	11	10	9	110	
Producer Accuracy	0.89	0.87	0.67	1	0.82	1	0.78		0.86
Overall Accuracy = 0.86					Kappa Coefficient = 0.83				

3. Results

Over the past 43 years, the AT in Ouagadougou has been characterised by warm spells. Since 2015, these warm spells have become longer (23 days/year) and more frequent than in the preceding 35 years, indicating an increase in heat spikes and highlighting the importance of this study (Figure 5).

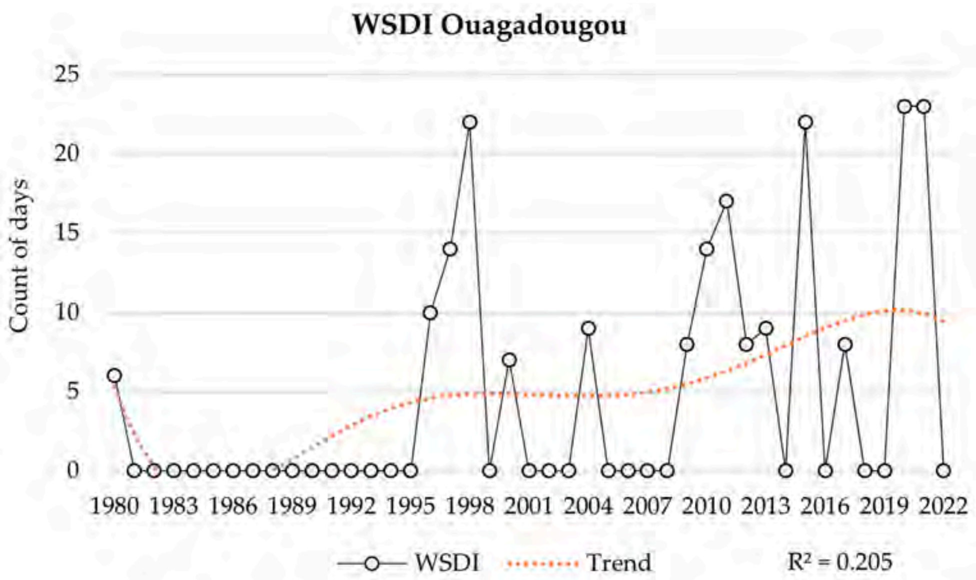

Figure 5. Ouagadougou WSDI and its polynomial trend from 1980 to 2022.

To preliminarily assess temporal stability, the mean LST was calculated at two spatial scales—administrative sectors and 500 m × 500 m grid cells—to have meaningful land cover percentages for each cell. To ensure consistency between ECOSTRESS and Landsat data, all 24 images were aggregated to these common units before mean LST values were computed, reducing the effects of different spatial resolutions. Day-to-day variations in mean LST likely reflect short-term weather variability affecting surface heating independently of land cover. Moreover, mean LST values computed at the two spatial scales remain highly consistent (Figure 6), with differences not exceeding 1 °C on any given day.

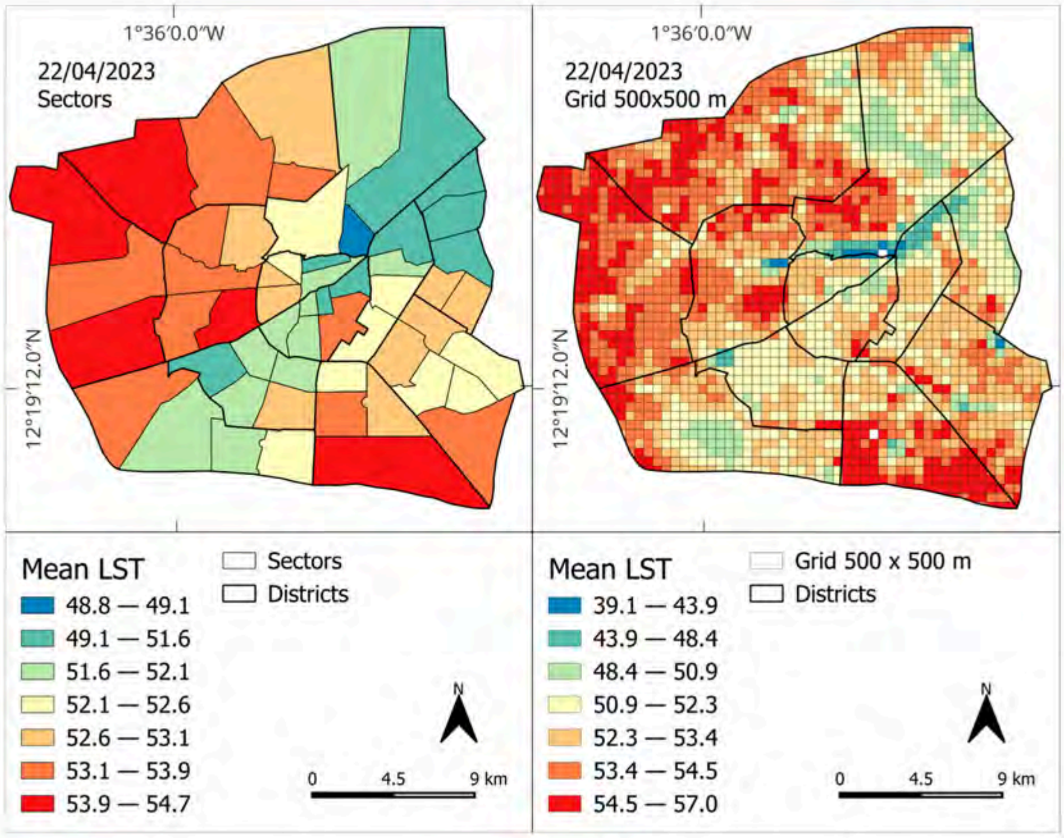

Figure 6. LST for sectors and 500 m × 500 m grid.

This indicates that the city's spatial thermal structures are stable across units of analysis. However, the grid scale captures micro-scale variations more effectively (standard deviation ≈ 2.6 °C vs. ≈1.7 °C).

The Landsat image from 22 April 2023 [83] was selected as the reference image for the study. This choice is justified by its quality and by its temporal proximity to the PlanetScope scene used for supervised land cover classification. On this date, the mean daytime LST was 52.5 °C at the sector level and 52.9 °C at the 500 m × 500 m grid scale.

3.1. *Physical and Ownership Feasibility of Greening*

The primary research question addressed how much space in Ouagadougou should be allocated to greening, and who should own it. According to the supervised classification results, as of April 2023, barren lands and tree canopies accounted for slightly more than one third of the municipal area (Table 3, Figure 7).

Table 3. Ouagadougou municipality land cover in April 2023.

Land Cover Classes	Ouagadougou Municipality	
	km^2	%
Barren lands	142	27
Tree canopy	42	8
Water bodies	3	1
Buildings, paved roads	187	64
Municipal jurisdiction	533	100

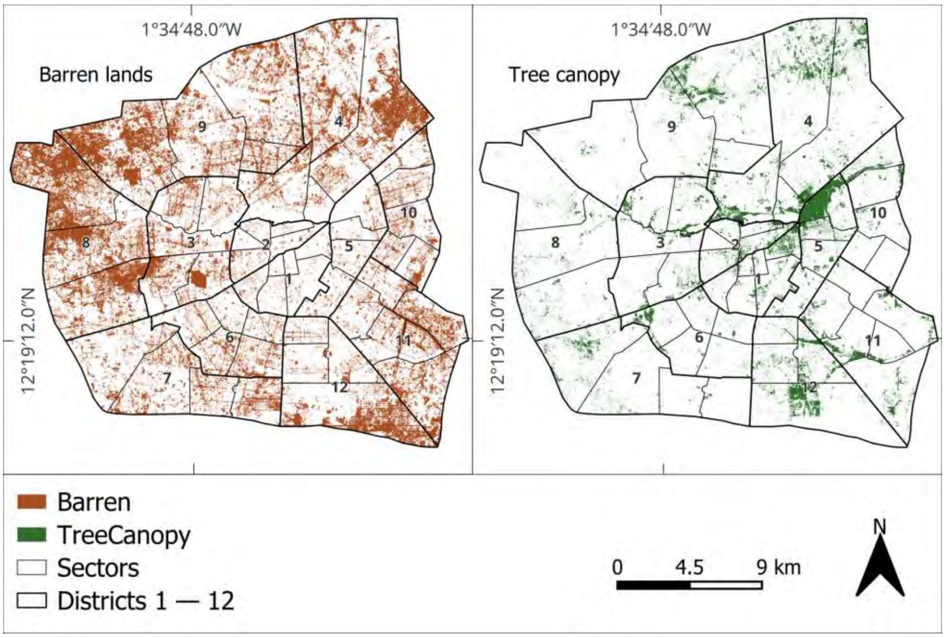

Figure 7. Barren lands and tree canopy in Ouagadougou municipality in April 2023.

In 2023, the land use in Ouagadougou municipality comprised formal settlements (46%), vacant lands (30%), and informal settlements (13%), with the remaining 11% occupied by wide roads, utilities, private schools, industries, gardens, and paved roads (Table 4).

Table 4. Ouagadougou land use in April 2023.

Land Use	km^2	%
Residential with minor roads	246	46
Vacant lands	160	30
Informal settlement	71	13
Roads > 18 m wide	27	5
Utilities + private schools	14	3
Industry	5	1
Gardens	3	1
Paved roads	4	1
Sum	533	100

The described multiple linear regression model, which included *Day* as a categorical variable computed at both the sector and 500 m × 500 m grid scales, revealed a strong, consistent relationship between LST and land cover variables, confirming the robustness of the results. All models are statistically significant ($p < 0.001$) and show high explanatory value (Adjusted R^2 = 0.75–0.86) (Table 5).

Table 5. Multiple linear regression summary at sectors and 500 m × 500 m grid scale.

Model	Observation	Parameters	R^2	Adj. R^2	Std. Error	F-Statistics	*p*-Value
Sectors	1320	27	0.8599	0.8571	1.721	305.2	$<2.2 \times 10^{-16}$
Grid 500 m × 500 m	53,448	27	0.7486	0.7484	2.518	6117	$<2.2 \times 10^{-16}$

At both sector and grid scales, barren land increases LST, while tree canopy reduces LST; both effects are statistically significant. Roads wider than 18 m exhibit weaker, less consistent effects. Nevertheless, the variable is retained because wide roads represent a key public space for urban planning and greening interventions. Given the consistency across scales, the following analysis uses the results from the sectors model, which are more useful for planners and local stakeholders. On average, a 1% increase in barren land is associated with an increase of about 0.03 °C in LST, while a 1% increase in tree canopy produces a cooling effect of approximately 0.06 °C.

To assess the temporal stability of the relationship between LST and land cover variables, interaction terms between the categorical variable *Day* and the land cover variables were added to the multiple linear regression model. The extended model explained approximately 1.7% more variance than the base model (Table 5) without altering the overall structure of the relationships. A second robustness analysis accounted for morning and afternoon acquisitions by interacting the acquisition period with the land cover predictors. This test was constrained by the image distribution, which included 17 morning scenes and seven afternoon scenes, with only three dates including both periods. Afternoon scenes showed a higher LST overall (+2.7 °C), confirming that acquisition time affects the LST. However, this did not materially alter the main relationships: barren land remained positively associated with LST, tree canopy was negatively associated, and roads wider than 18 m retained a weaker and less consistent effect. Temporal variation was mainly observed for barren land, with warming effects stronger in afternoon scenes, whereas the interaction with the tree canopy was not statistically significant. This second interaction model did not improve explanatory performance relative to the base model, probably reflecting the increased number of parameters and partial collinearity between Day and Period. Therefore, to simplify interpretation and highlight the general relationship, the simple model without interaction terms was retained. In this model, the effects of land cover variables are assumed to be constant across days, resulting in parallel slopes with different intercepts that reflect daily meteorological variability (Figure 8).

Further analysis was conducted by setting the second quartile of barren land cover (20%) as the minimum threshold for prioritising intervention to influence LST more significantly. Accordingly, priority is given to reducing barren land in 28 sectors across districts 3, 4, 6, 7, 8, 9, 11, and 12, where barren land cover exceeds 20%. The most effective measure to mitigate barren lands involves increasing tree cover. Strategies such as tree planting along roads over 18 m wide and at the edges of utilities, agroforestry, and covering lot fences with thorny shrubs have been shown to influence LST in the BSh zone [40] (Figure 9).

However, in Ouagadougou, the latter two strategies have limited potential to cover barren lands compared to the first two (Table 4). While wide roads, large utilities, and scattered vacant lands offer opportunities for greening policies, extensive informal settlements, characterised by narrow, non-hierarchical streets, few utilities, and high lot coverage, pose challenges to greening efforts. Industries with large buildings and extensive roof coverage also limit the impact of greening initiatives.

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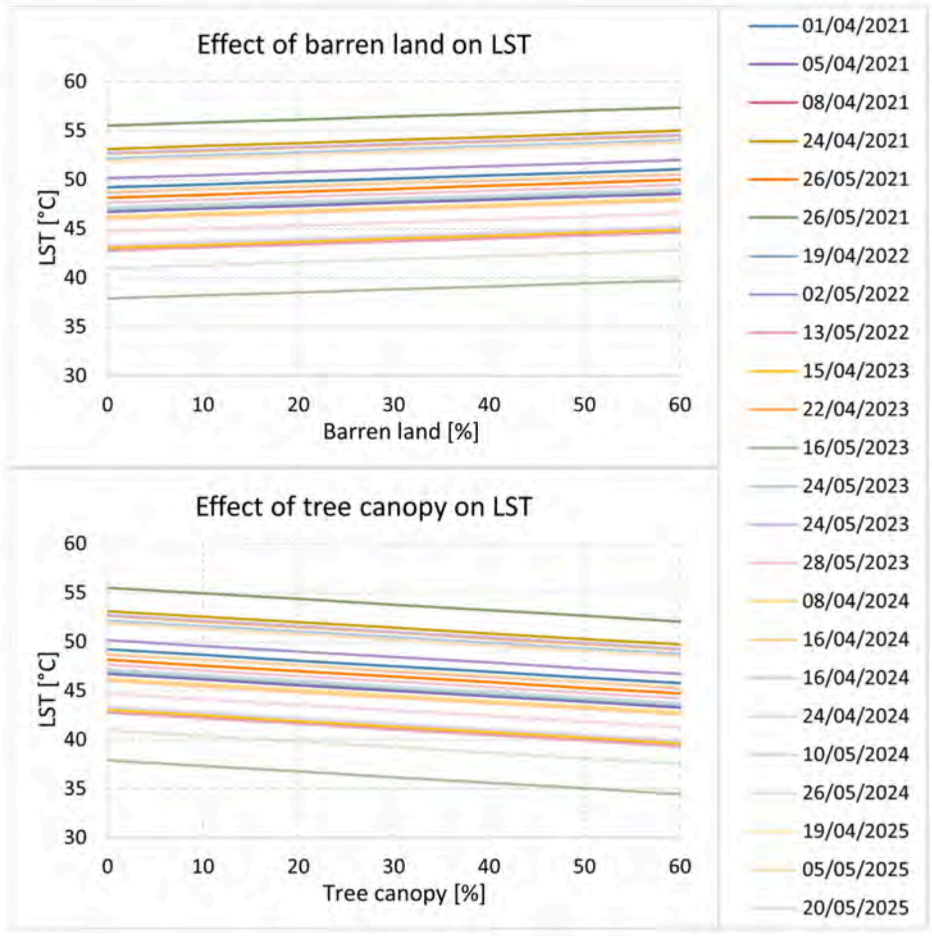

Figure 8. Relationship between LST and barren land (**top**) and tree canopy (**bottom**). Lines represent different acquisition days derived from a regression model with *Day* as a categorical variable; slopes are identical, while intercepts vary among acquisition days, reflecting different meteorological conditions.

The tree planting potential of public areas is predominantly along roads wider than 18 m, which, when lined with trees on both sides, can generate about 8 km^2 of tree cover. Additionally, planting trees along utility fence lines can increase the tree canopy by an additional 2.3 km^2. Of these, three quarters are schools, contributing 1.2 km^2 of tree cover for private schools and 0.5 km^2 for public schools, with the remaining quarter comprising other utilities (0.6 km^2 of tree cover).

Three progressive scenarios have been developed to achieve the targeted area for tree planting. The first scenario focuses on the edges of utilities (including schools, sports, health, worship, culture, and others) and along roads wider than 18 m, as these locations can accommodate a row of trees on each side without obstructing circulation or informal activities. Implementing this scenario would increase the municipal tree cover from 7.9% to 9.8% by planting 0.1 million trees (Figure 10).

The second scenario extends greening to include vacant lands beyond the built-up area. If the existing greenery proportion in the built-up areas of each sector is applied to these areas (business as usual), municipal tree cover would increase to 11%, requiring the planting of 0.16 million trees. The zoning map designates these areas for future city expansion [84].

Figure 9. Selected greening measures to reduce LST in Ouagadougou: (**a**) tree-lined roads; (**b**) tree planting along utilities; (**c**) agroforestry; (**d**) lot fence greening.

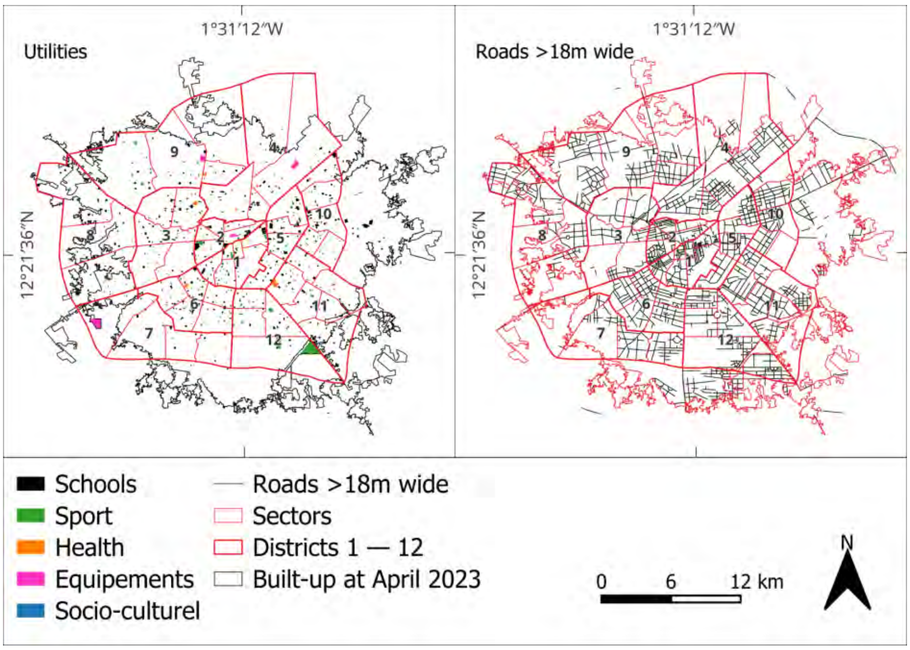

Figure 10. Utilities and roads over 18 m wide designated for tree planting in Ouagadougou in April 2023.

The third scenario aims to reduce barren lands beyond the built-up area to under 20% of each sector's area through tree planting. Depending on the sector, tree cover ranging from 5% to 100% would be applied to these areas. As a result, municipal tree cover could rise to 16.3%, requiring the planting of 0.45 million trees (Table 6, Figure 11).

Table 6. Progression of tree cover according to three scenarios.

Scenario	Target	Tree Cover Progression		Tree Progression (Thousand)
		km^2	%	
Baseline		41.9	7.9	-
1	Roads > 18 m + utility fence	52.1	9.8	103
2	Vacant lands business as usual + scenario 1	58.5	11	166
3	Reduction in barren cover on vacant lands to 20% + scenario 1	86.9	16.3	450

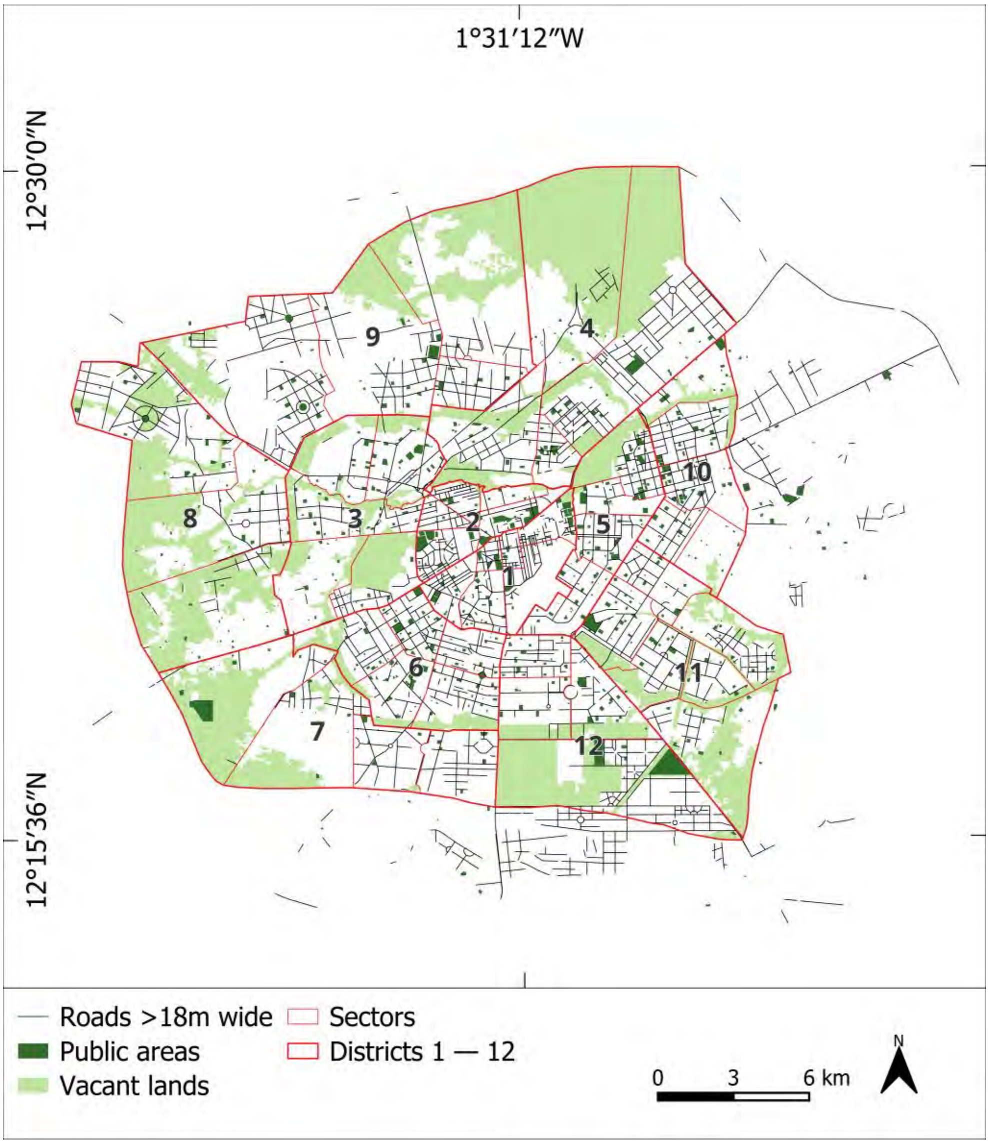

Figure 11. Location of potential greening measures in the Ouagadougou municipality.

3.2. Environmental Feasibility of Greening

The second research question focused on the extent to which greening can reduce LST, and the obstacles and opportunities associated with its implementation. In hot semi-arid climates, shading barren lands and the resulting decrease in surface temperature are primary ecosystem services offered by tree canopies. Twenty-eight sectors contain over 20% barren land (Figure 12), totalling 123 km^2, of which 47 km^2 lies beyond the built-up area. These barren lands can be reduced to under 20% by planting trees on vacant lands beyond the built-up area and along wide roads and utilities within the built-up area. The most significant reduction can be achieved by vegetating vacant lands outside the built-up area from 5% to 100%, depending on the available space in each sector. Thus, the target can be fully met, potentially reducing temperature by 0.02 to 2.4 °C across sectors at tree canopy maturity (Table A2), which is meaningful given that diurnal LST varies by 6 °C between sectors.

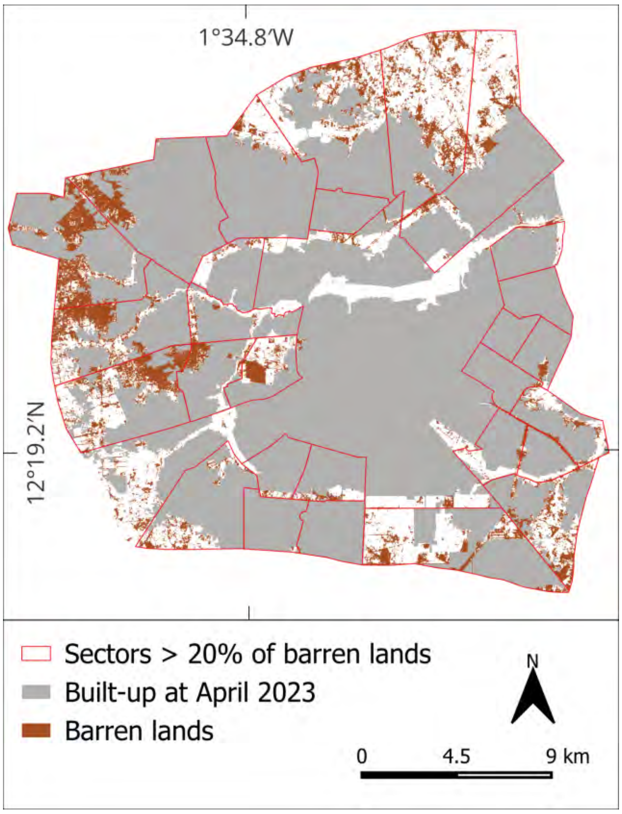

Figure 12. Sectors of Ouagadougou with barren lands covering above 20% as of April 2023.

Road planting, utility edge planting, agroforestry, and fence planting are the most common greening measures in Ouagadougou and other Sahelian cities. The SWOT analysis identifies the contributions that planting can offer in Ouagadougou for each of the four greening measures. Besides reducing LST, road planting enhances the city's aesthetics and improves air quality by reducing dust. However, challenges include the exposure of street trees to stray animals, maintenance, and irrigation. Furthermore, street planting may conflict with road-widening programmes if systematic tree planting is not incorporated. Usually, work to lay infrastructure networks along the road cuts down trees without providing compensation. Planting along schools' fences provides shade and offers the younger generation an opportunity for environmental education. Although agroforestry increases biodiversity and soil fertility and acts as a wind barrier, protecting crops, it demands water, reduces cultivable area, and requires farmers' acceptance. Greening lot fences enhances security and beautifies streets, but requires ongoing maintenance, incurs costs, and is only feasible with suitable species. The maintenance of increased tree cover by 108% makes it more susceptible to drought during the initial stages. Over time, planting could also damage underground networks.

Support for these greening measures could come from multilateral programmes such as the United Nations collaborative initiative on reducing Emissions from Deforestation and forest Degradation (REDD), development assistance, and corporate social responsibility initiatives. However, these measures remain vulnerable to climate extremes such as wind, heavy rains, and drought (Figure 13).

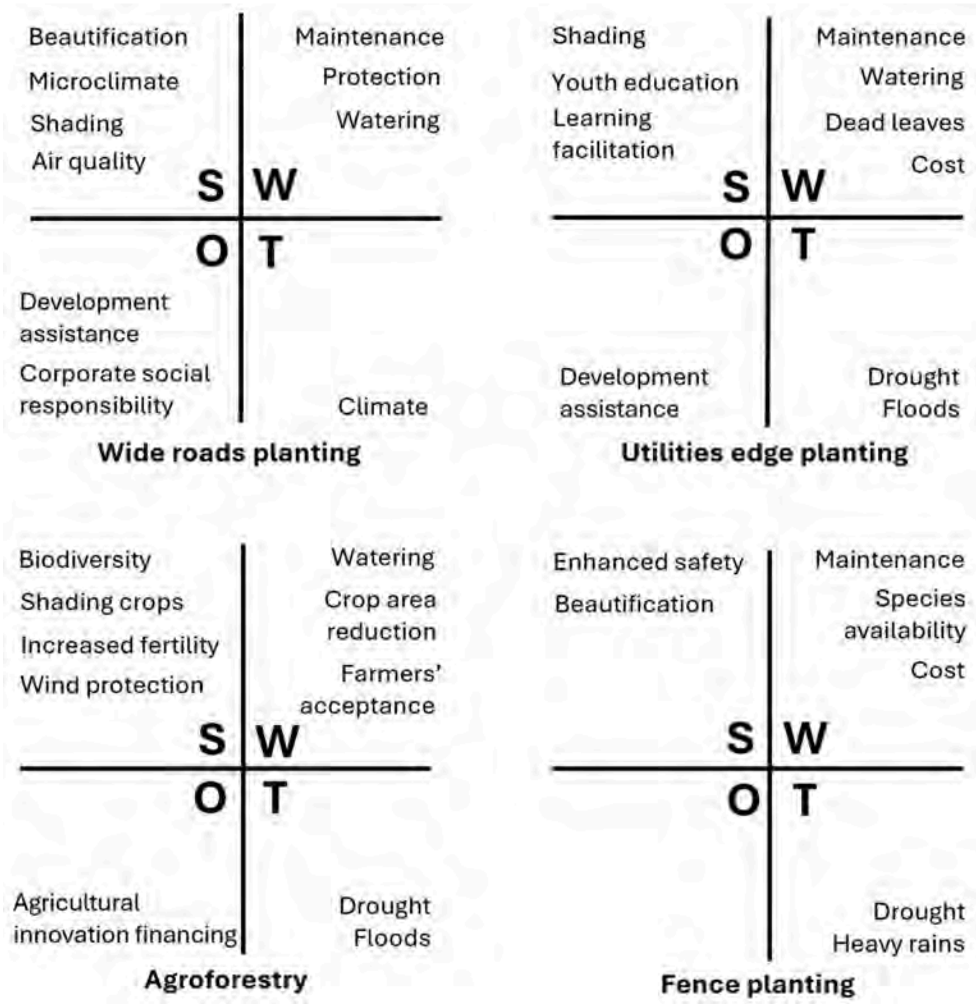

Figure 13. SWOT analysis of four greening measures for Ouagadougou.

3.3. Social Feasibility of Greening

The third research question investigates the equity of greening initiatives. We examined tree cover by sector, with and without informal settlements, and analysed disparities in per capita tree cover across districts and scenarios.

In 2023, Ouagadougou's central and semi-central sectors were surrounded by informal settlements (Figure 14).

Sectors with informal settlements had less tree cover than formal sectors, highlighting a pre-existing spatial inequity in access to greenery (Table 7).

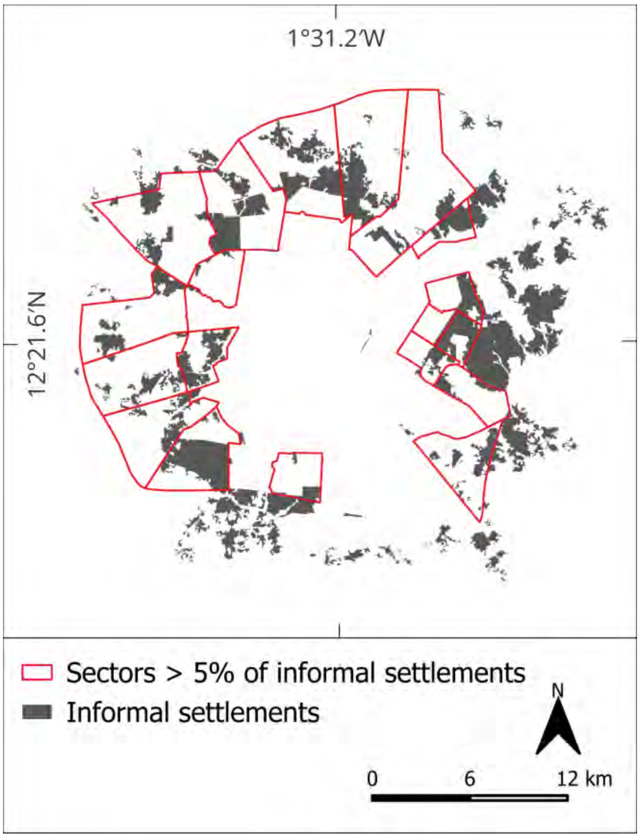

Figure 14. Sectors of Ouagadougou with informal settlements occupying more than 5% of the area in April 2023.

Table 7. Tree cover change in the largely informal and formal sectors of Ouagadougou by scenario.

Sectors	Baseline	Tree Cover Target per Scenario		
		1	2	3
	Tree Cover	Roads > 18 m and Utility Fence	Vacant Lands as Usual + Scenario 1	Barren Cover on Vacant Lands Under 20% + Scenario 1
	%	%	%	%
Largely informal	6	7	8	21
Formal	10	13	15	28

Fair greening aims to increase per capita tree canopy and minimise disparities between districts. In 2023, Ouagadougou had an average tree canopy of 23 m^2 per capita, with a 65 m^2 per capita difference between the district with the lowest and the district with the highest. Given the limited availability of vacant land, wide streets, and utilities to be greened, the large informal settlements in Nioto 2, Polesgo, and Wubiton in District 4, Sanadogo in District 7, and the whole of District 5 would increase the per capita tree canopy only marginally. Under the third scenario, the average per capita tree canopy would increase to 38 m^2, but the disparity between districts would rise to 117 m^2 per capita. Notably, none of the districts with below-average tree canopy per capita would improve their ranking (Table 8).

Table 8. Progression of tree cover per capita by scenario and district of Ouagadougou.

Tree Cover Per-Capita	Baseline	Scenario		
		1	2	3
Min. m^2	6	9	8	7
Max. m^2	71	87	89	124
Average m^2	23	28	25	38
Sub-average districts, n.	8	7	7	8

4. Discussion

Since 2015, warm spells in Ouagadougou have become longer and more frequent. In this study, we have examined the physical, ownership, environmental, and social feasibility dimensions of reducing LST through greening, addressing an area of research that has been largely neglected, particularly in the hot, semi-arid regions of Africa [85]. We aimed to answer three key research questions.

4.1. Physical Feasibility

The first research question addressed the availability of space for greening and its ownership. Our findings confirm barren lands as the metric most significantly influencing LST, as found for other cities in the BSh zone [21,23,37], particularly when they exceed 20% of an urban sector surface area. Most barren land is located on vacant land beyond the built-up area. The most effective strategy for reducing barren land and thereby cooling the environment is through planting. We proposed three scenarios that progressively increase the area and number of elements to be greened. Planting along the edges of utilities, especially schools, offers the least potential, whereas street planting provides a greater contribution. However, planting on municipal vacant lands beyond the built-up area could have the greatest impact, as these areas constitute 30% of the municipal territory and contain 35% of all barren land. Planting these vacant lands could reduce their barren cover from the current 31% to below 10%, potentially lowering the LST in these sectors up to 2.4 °C. However, we cannot compare these results with those of other studies in terms of methodology or values obtained, as considerations of physical feasibility and ownership are not typically included in the literature on LST in the BSh zone and have only recently begun to be explored across different climate zones [63].

4.2. Environmental Feasibility

The second research question addressed the potential of greening to reduce LST in Ouagadougou and its associated implementation constraints and opportunities. Greening is expected to reduce the diurnal LST by up to 2.4 °C in target sectors, compared to a 6 °C range. This effect has long-term potential, as cooling depends on tree survival and water availability in the early years after planting. According to the SWOT analysis, greening beautifies streets and provides shade for recreational areas, while biodiversity is mostly attributed to agroforestry. In Niamey and Maradi (Niger), integrating exotic species such as *Azadirachta indica* or Neem with native species such as *Faidherbia albida* has contributed to the conservation of endangered species, mitigation of air pollution, provision of traditional food and medicine, increased resilience to pests and diseases, and adaptation to climate change impacts [81]. Additionally, such greening efforts could improve air quality around streets (Figure 8), which is particularly crucial in Ouagadougou, where most roads are unpaved. Road traffic increases particulate matter (PM) levels, which are further exacerbated by dust storms during the hot season [84]. Establishing a buffer of shrubs and trees along urban roads has been shown to reduce the horizontal transport of PM generated by road traffic in other semi-arid urban settings [86].

However, greening measures exhibit several weaknesses, with the most frequently reported challenge in the SWOT analysis being water scarcity. Maintaining a tree park, which would increase by 108% compared with the existing one, is challenging without an adequate water supply. In Dodoma, for instance, tree survival depends heavily on irrigation [87], while, in Santiago, it depends on the specific water requirements of each species and the maintenance provided by municipal services [88]. Increasing tree vegetation inevitably requires water availability, particularly in the early stages of planting. Therefore, the greening policy should proceed in parallel with the development of blue infrastructure, potentially based on local rainwater-harvesting and recycling strategies [89]. Additional concerns include the protection of trees and potential conflicts with road widening programmes that do not integrate tree vegetation [90], which could impede greening efforts. There are opportunities for tree planting outside the municipality of Ouagadougou, such as a development assistance-funded urban forestation programme currently underway in eight major cities in the BSh climate zone in Africa [91]. In recent years, external threats from droughts, which have intensified in both duration and severity, have also impacted greening (Figure 5).

4.3. Social Feasibility

The third research question addresses the equitable distribution of greening across Ouagadougou's sectors and districts. Presently, sectors with informal settlements have significantly fewer trees than formal ones, highlighting disparities in greening that reflect findings in the Global South [64] and in other cities in the BSh zone where climate injustice has been examined [92]. This gap can be bridged by greening wide roads, schools, and sports utilities [93]. However, a substantial benefit could only be achieved by targeting sectors with more than 20% barren land, which are predominantly located beyond the built-up area. The potential for greening roads exceeds that of utilities, especially schools.

Equity also presents another dimension that is not widely assessed in the literature. Greening is primarily the responsibility of districts. In 2023, the disparity between the district with the most tree canopy per capita and the least was significant. Progress in tree planting across different scenarios is likely to widen this gap, owing to the varying availability of suitable greening spaces across districts. Informal settlements and many new formal subdivisions feature roads that are considerably narrow for tree planting. The potential advantage of greening public properties over private ones, where space or funding for irrigation is limited [40], is negated by the scarcity of wide roads and utilities. Therefore, the hypothesis that planting along roads and utility fences in Ouagadougou would facilitate a more equitable reduction in LST is not supported.

Further analyses could benefit from investigating land cover metrics at higher spatial resolution or from using more recent remote sensing thermal data to enhance the assessment of the relationship between land cover and LST. This would also help to mitigate the inherent uncertainty of the input data, including both LULC and LST, which may introduce noise into the analysis.

The complexity of this study, given the limited availability of accessible geodatabases (e.g., road networks, asphalt networks, buildings), introduces several limitations and necessitates approximations.

Differences in sensor overpass times remain a source of uncertainty, particularly given the unbalanced distribution of morning and afternoon acquisitions and the limited number of dates for which both acquisition periods were available. This may partly confound time-of-day effects with day-specific meteorological conditions. Although the main relationships proved robust across the different alternatives, the model is better suited for comparing sector-scale greening scenarios than for precise inferences about hourly microclimatic responses. Consequently, the estimated coefficients should be interpreted as average aggregate associations rather than constant physical effects across different daytime thermal regimes.

To the best of our knowledge, utilities were reconstructed, but many lots in peripheral areas remain unfenced, leading to an underestimation of the land available for planting. We excluded the creation of urban parks from our analysis because, in semi-arid climate zones, there is no consensus on the ideal size for such elements [94]; in other climate zones, recommended sizes range from 0.6 to 14 hectares [95]. Additionally, we did not explore the potential of different tree species, whose cooling capacities through transpiration and shading can vary significantly [96].

Moreover, we used the built-up area configuration as a proxy for the poverty of its inhabitants, given the absence of income and socioeconomic status information at the district or sector scale, which could have refined our identification of disparities. While the scope of our analysis was confined to the municipality's jurisdiction, approximately one quarter of Grand Ouagadougou's built-up area extends beyond this boundary. We did not examine these areas as they are not yet divided into sectors, which would have conflicted with our approach of analysing data at the minimum administrative unit level.

The theoretical implications of these results concern the city's spatial structure. Although the initial layout of roads has a lasting impact over time [97], land subdivision and the road network are predominantly determined by private developers. These developers acquire land from private owners in exchange for a payment in kind (plots) that is two to three times higher than what the State would offer in the event of expropriation. Subsequently, the road network and the provision of utility plots are often disregarded in the pursuit of maximum profit [98]. Consequently, the recent expansion of Ouagadougou is characterised by a poorly hierarchical street grid with narrow streets and limited utilities, which accounts for the low greening potential of public areas. Cities should consider the remaining vacant lands as the last available resource for cooling the microclimate by greening.

The operational implications of this study pertain to future land development and greening policy. In Ouagadougou, the land pooling/readjustment technique [99], the inclusion of wide roads, utilities, a minimum vegetation rate in new subdivisions, and lot sizes that are sufficient to accommodate private vegetation [100] should be considered to eliminate the need for costly future regularisation and partial resettlement [101].

The wider relevance of this study concerns urban greening policies, which should be based on a feasibility assessment of greening that establishes, sector by sector, the amount of tree vegetation that can reduce LST and the amount required in new developments. Greening policies should be complemented with measures for access to irrigation water, without which greening in semi-arid areas would not survive.

This study advances our understanding of LST reduction by identifying available space, who it belongs to, and the extent to which it would contribute to a fair cooling policy.

A final recommendation is directed to the Ouagadougou districts to incorporate the aforementioned points into the establishment of development standards and general requirements for vacant lands beyond the built-up area.

5. Conclusions

The literature on reducing the LST in semi-arid cities rarely considers the feasibility of the proposed measures. In this study, we addressed the physical, ownership, environmental, and social feasibility dimensions of greening Ouagadougou, Burkina Faso's capital. The

LST during periods of maximum AT is statistically influenced by the proportion of barren land, which accounts for 27% of the urban area. Per capita tree canopy was distributed unequally across sectors. While tree vegetation could be implemented along public spaces, such as the widest roads and at the edges of utilities, large roads and utilities are unevenly distributed across the municipal jurisdiction. If these elements are tree-lined, they have only a marginal impact on LST. Planting should be extended to public and private barren lands beyond the built-up area to reduce disparities in tree canopy rates, per capita tree canopy between sectors, and potentially heat-related morbidity and mortality.

The novelty of this study lies primarily in its holistic approach, which considered LST, its determinants, cooling measures, and their feasibility. Moreover, this study is innovative in that it considers the physical and ownership dimensions that have previously been neglected but are crucial for effectively implementing cooling measures.

The wider relevance of this work lies in showing the importance of a feasibility assessment of greening. It shows the extent of planted areas, ownership, and cooling potential sector by sector, along with their limitations. The case of Ouagadougou shows that efforts to address the scarcity of the tree canopy and its uneven distribution among neighbourhoods are hampered by the inequitable allocation of suitable spaces. The root of the problem lies in the management of restless physical expansion.

The broader implications of this study concern the planning of interstitial vacant lands with a network of streets wide enough to be planted, sufficient utilities, and a tree cover rate in new subdivisions as defined by the feasibility assessment. These implications are particularly relevant at a time when several multilateral programmes are supporting urban forestation in the Global South, especially in Africa.

Our methodology is replicable in any city if remote sensing and spatial analyses are integrated with AT studies, assessments of available planting areas are conducted, and extensive consultations with local stakeholders are held. To effectively influence cooling policies, it is insufficient to provide recommendations to decision-makers and planners alone. Studies should explore physical and ownership feasibility, be developed by multidisciplinary teams, and involve planners from the outset.

Author Contributions: Conceptualisation, F.G.T. and M.T.; Methodology, E.B., E.C., F.G.T. and M.T.; Data acquisition, E.B., E.C., Y.E.F.C. and M.T.; Data curation, E.B. and E.C.; Investigation, E.C., F.G.T., Y.E.F.C. and M.T.; Visualisation, E.C. and M.T.; Writing—original draft, E.C. and M.T.; Writing—review, E.B., E.C., F.G.T. and M.T.; Funding acquisition, M.T.; Supervision, M.T. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: Data that support the results of this study are freely available at https://data.mendeley.com/datasets/75nvstkb3m/2 (accessed on 18 February 2026).

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A. Ouagadougou Sectors, Districts, and Land Use

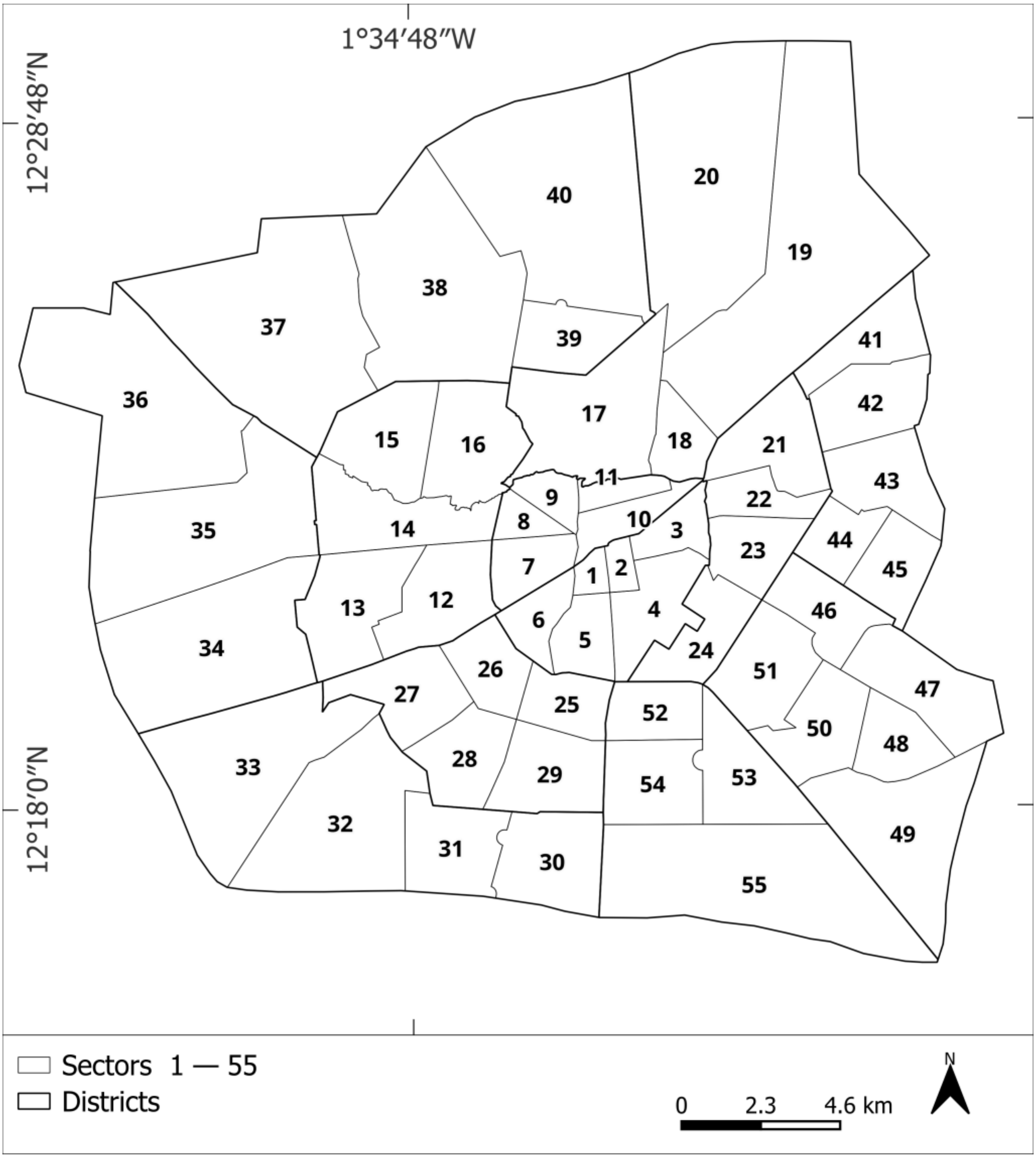

Figure A1. Sectors and districts of Ouagadougou.

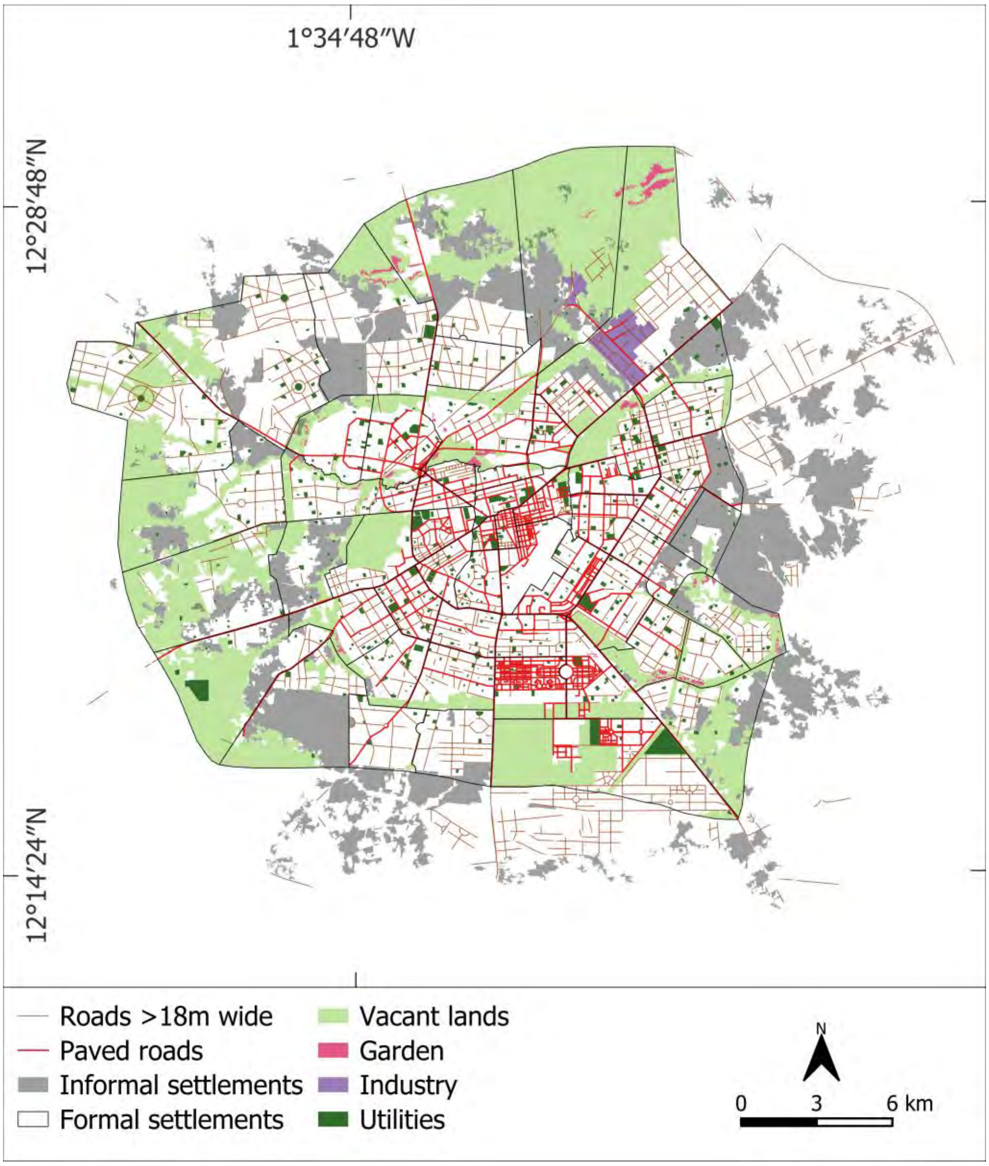

Figure A2. Land use in Ouagadougou in April 2023.

Appendix B. Literature Overview

Table A1. Literature overview of cooling measures in urban hot semi-arid zones.

City Country ISO2	Land Cover		Land Cover Classes Most Correlated with LST	Cooling Measures	Reference
	Tree Canopy	Barren Lands			
	%	%			
Agra IN	-	-	B, BL, V	G, Lp, R, TRds, W	[8]
Ahmedabad IN	0	1	C	-	[9]
Ahmedabad IN	-	-	V	-	[10]
Ahmedabad IN	-	-	BL	-	[11]
Asmara ER	-	-	-	-	[12]
Bathinda IN	-	-	B	G, R, W	[13]
Beer Sheva IL	-	-	-	-	[14]
Beer Sheva IL	-	-	V	-	[15]
Ben Guerir MA	-	-	BL, S	-	[16]
Bulawayo ZW	-	-	AL, BL	-	[17]

Table A1. *Cont.*

City Country ISO2	Land Cover		Land Cover Classes Most Correlated with LST	Cooling Measures	Reference
	Tree Canopy	Barren Lands			
	%	%			
Delhi IN	-	-	BRP	Bld, Lp	[18]
Delhi IN	15	5	-	Ga, P, Rf, TRds,	[19]
Delhi IN	5	4	BL	A, CM, G, Gb, W	[20]
Erbil IQ	18	12	BL	T	[21]
Erbil IQ	-	-	AL	BS, LP	[22]
Faridabad IN	13	2	B	-	[23]
Gandhinagar IN	-	-	BL, I	-	[11]
Gurugram IN	5	-	B	CP, Bld, R, T, W	[24]
Haryana IN	1	4	BL	G	[25]
Herat AF	31	13	B	G	[26]
Hisar IN	27		B	Gb, Rf, Uf	[27]
Hyderabad IN	14	24	V	-	[28]
Jaipur IN	7	-	-	G, W	[29]
Jaipur IN	-	-	B, V	-	[30]
Jaipur IN	-	-	-	-	[31]
Jaipur IN	-	-	B	-	[32]
Jhansi IN	16	29	BL	P, T, Wm	[33]
Kano NG	13	54	B	CM, G	[34]
Kano NG	-	-	-	Epe	[35]
Lahore PK	26	-	Co, In	G, P, R	[36]
Marrakech MO	20	61	BL		[37]
Mekelle ET	34	68	B, BL	CM, G	[38]
Mogadishu SO	-	-	-	-	[39]
Niamey NE	1	40	BL, T	G, TRds	[40]
Noida IN	25	-	B, BL	G, LP, P, R	[41]
Oran DZ	13	-	-	CM, G, R	[42]
Petrolina BR	-	-	-	G	[43]
Queretaro MX	-	-	-	G, Ga, P, VL	[44]
Sari IR	-	-	-	G, Gb, R, TRds, W	[45]
Sokoto NG	20	-	-	CP, G, Bld	[46]

A—sustainable agriculture, AL—agricultural land, B—built-up, BL—bare land, Bld—building low density, BRP—bare rock or paved, BS—bare soil development, C—crops, CM—construction materials with low albedo, Co—commerce, CP—cool pavements, Epe—energy production efficiency, G—greening, Ga—gardening, Gb—green belt, I—impervious surfaces, In—industry, Lp—low plants, LP—light paints, P—park preservation, R—cool/green roof, Rf—roof farming, S—sand, T—trees, TRds—tree-lined roads, Uf—urban forest, V—vegetation, VL—vacant lots development, W—water bodies, Wm—water misting.

Appendix C. Expected Cooling Effect

Table A2. Expected cooling effect (°C) of tree planting of vacant lands in 28 sectors of Ouagadougou.

Sector	Cooling (°C) According to the Percentage of Vacant Lands Tree Planting									
	5	30	40	45	55	60	70	75	85	100
12				−0.8						
13						−0.7				
14		−0.2								
15										−0.4
19										−0.8
20			−0.7							
28										−0.2
29										−0.6
30										−0.0
31										−0.1
32	−0.0									
34								−1.7		

Table A2. *Cont.*

Sector	Cooling (°C) According to the Percentage of Vacant Lands Tree Planting									
	5	**30**	**40**	**45**	**55**	**60**	**70**	**75**	**85**	**100**
35									−1.70	
36										−2.4
37										−0.9
38										−0.3
39										−0.0
40			−0.4							
42										−0.1
43 (*)										
44 (*)										
45					−0.3					
46					−0.1					
47										−1.2
48										−0.8
49							−1.3			
50				−0.2						
55										−1.2

* The sector is devoid of barren land within vacant lands.

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