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Relationship of urban heat with building density and green spaces - a remote sensing-based study across Vietnam's metropolitan areas

Andreas Braun[*], **Elizabeth Carolyn Duffy, Gebhard Warth, Volker Hochschild**

Department of Geosciences, University of Tübingen, Rümelinstraße 19-23,
Tübingen, 72070, Germany

[*]Email: *an.braun@uni-tuebingen.de*

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Abstract. Urban heat island effects are an increasing challenge for metropolitan areas, especially in regions where climate change increases the frequency of extreme temperatures. The consequences for human health are understood and must be addressed by urban planning. Although many studies currently exist regarding relationships of adaptation measures and urban heat amongst individual single cities, there is little general understanding of how urban development impacts temperature on a large scale. In this study we analyze the correlation between urban heat and two indicators of urban morphology: the green spaces and the density of buildings. We hypothesize that the relation between building density, urban green space and urban surface temperature can be quantified using openly available techniques of Earth observation. To grant an objective and consistent analysis over the entire country of Viet Nam, we use information from different high-resolution imaging satellites. The computation of Pearson correlations across 58 Vietnamese districts confirms the hypothesis, indicating a negative impact of urban green space (-0.217), a positive impact of building density (+0.392) and an even stronger relationship with both indicators combined (+0.435). The findings are discussed with data of three research projects involving the cities of Ho Chi Minh, Da Nang, and Hue, and interpreted regarding regional differences and implications for urban planning. As one key finding, building blocks with open architecture show statistically lower temperatures than blocks of compact structure. These differences apply for buildings of all sizes, but they are more distinct for blocks with small buildings.

Keywords: local climate, remote sensing, urban heat island, urban planning.

Classification numbers: 3.4.5, 3.6.2., 4.7.1.

1. BACKGROUND AND RESEARCH QUESTION

Urbanization is one of the main challenges of the 21st century. It is not only linked to socio-economic problems, such as poverty, segregation, or the insufficient provision of basic services, but also requires protection of human health, which is threatened by polluted air or drinking water and heat [1]. Studies have found that particularly urban populations are suffering from the negative consequences of climate change due to increased sensitivity and limited capacities to respond to environmental changes, most notably impacting low-income groups and countries [2] and coastal cities in Southeast Asia [3]. As summer temperatures are globally rising, urban heat islands are phenomena that progressively draws the attention of both spatial planners and public health experts, due to associated peaks in mortality rates, not only compared to rural areas, but also again disproportionally impacting vulnerable social groups [4]. Urban heat islands are characterized by a large difference of air temperature between the built-up area and its surroundings. The main reason for this lies not only in surfaces such as pavements and asphalt, but also glass and metals, which have radiative properties that lead to a higher storage capacity and emission of energy when exposed to solar radiation. Although the general physical and meteorological conditions of urban bodies are well understood [5 - 7], there is still disagreement about the contributions of different factors to the emergence of urban heat, especially in their spatial dimension. While the share of impervious surfaces is accepted as a key influential factor throughout most studies, few claim the importance of other factors, such as atmospheric exchange between the city and the lower atmosphere [8], the presence of urban green spaces [9], or city architecture and morphology [10].

These factors are mostly analyzed within studies on particular cities which provide insights at a large detail, but don’t allow drawing conclusions at the national or global level. For instance, there are studies on urban heat in Ha Noi [11 - 14], Ho Chi Minh City [15 - 17], Da Nang [18, 19], and Can Tho [20], which assess the importance of various aspects, but there are no general indications or comparative studies for Vietnamese cities. We want to close this gap and provide a general analysis on the correlation between building morphology, green spaces and urban heat in Viet Nam based on consistent data and spatial indicators.

2. MATERIALS AND METHODS

In this chapter, we will outline the source data which is used in this study, how we processed it, and what kind of results were generated. A description and interpretation of results will then follow in chapter 3. As urban heat is a spatial phenomenon, we used satellite information as main input for this study. To grant a transparent and consistent processing of data, we used the Google Earth Engine (GEE [21]), a cloud computing environment for large-scale analysis of spatial data with a focus on Earth observation. The described datasets are directly hosted inside the GEE and briefly introduced in the following sections.

2.1. Building density

As the first variable contributing to urban heat, building density was calculated based on the Global Human Settlement Layer (GHSL) provided by the Joint Research Centre (JRC) of the European Commission. It is a dataset of global coverage indicating the presence and development of built-up areas since 1975 at a spatial resolution of 30 meters (GHS_BUILT). It was derived from multi-temporal imagery of the Landsat mission and provides a balanced accuracy of 0.86. Especially in the latest release, errors of omission which were a problem in Asian regions could be reduced by integrating additional radar imagery of the Sentinel-1 mission [22].

An example for the metropolitan area of Ho Chi Minh City is given in Figure 1 (left). This example depicts how built-up areas have evolved over the past decades. For this study, the most recent extent, representing urban areas of the year 2015, was used, recoded as a binary raster with 1 representing built-up areas and 0 representing open areas. The fine spatial resolution of around 30 meters not only shows the outlines of the cities, but also allows to describe inner urban areas which are still unbuilt. As a proxy measure for the building density, we computed a spatial average over a radius of 150 meters, ranging between 1 (completely built-up) and near zero (rarely built-up). As we only want to observe the variations of surface temperatures in urbanized areas, we used a second dataset of the GHSL which describes different forms of settlements (rural, low density, high density) at a spatial resolution of 1 kilometer (GHS_SMOD). We used it to limit our study to the high-density urban areas as shown for the building density in Figure 1 (right).

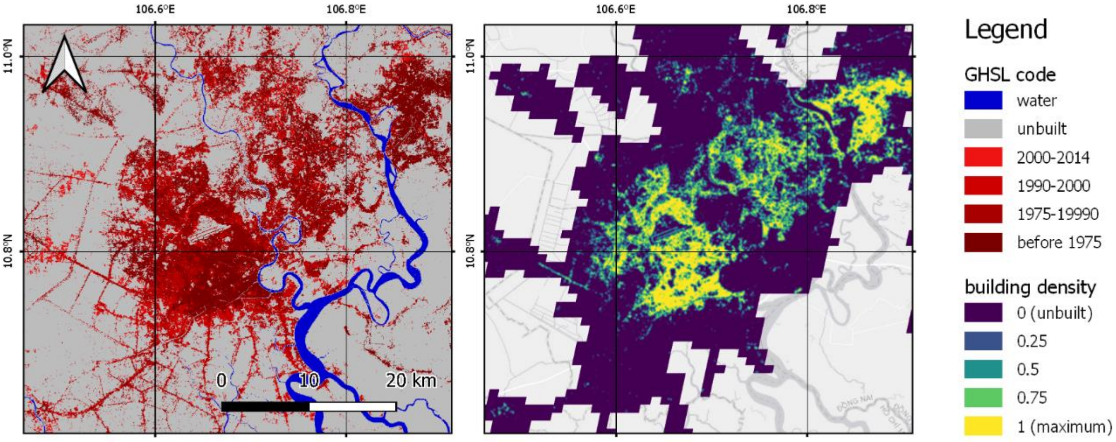

Figure 1. GHSL for Ho Chi Minh City (left) and building density in the highly urbanized areas (right).

2.2. Urban vegetation

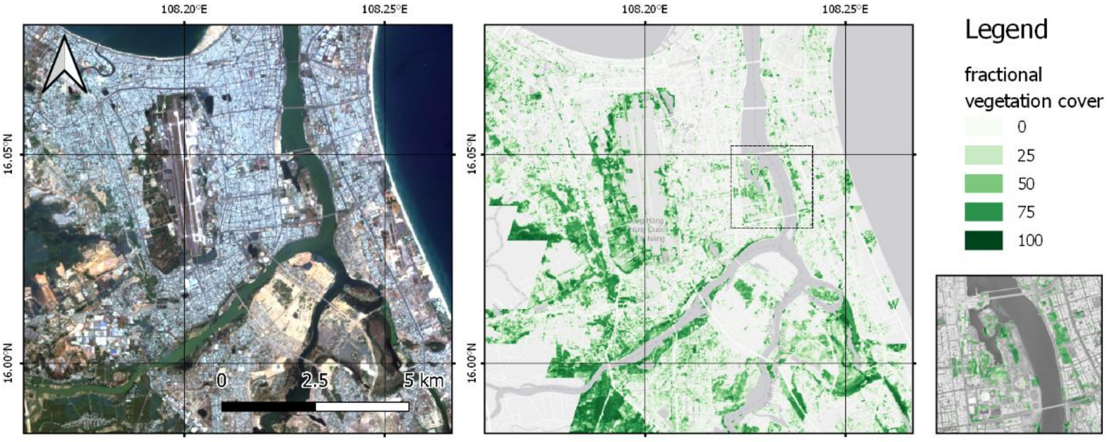

Figure 2. Sentinel-2 image of Da Nang (left) and vegetation cover in the highly urbanized areas (right).

As the second variable, the distribution of urban green spaces is derived from satellite data of the Sentinel-2 mission, a multi-spectral satellite operating at 13 wavelengths at a spatial resolution between 10 and 60 meters. As this resolution does not allow the precise delineation of urban green spaces, we used a spectral unmixing method which predicts the fraction of defined land cover classes within each pixel [23]. This method has been successfully applied to Sentinel-2 data in other studies to produce a reliable estimation of the green cover fraction within cities in China [24, 25] and Europe [26, 27]. A median reducer [28] was used to create a cloudless image of Viet Nam for the year 2016. An example for the city of Da Nang is shown in Figure 2.

2.3. Urban heat

Surface temperatures were derived from the thermal sensor of the Landsat 8 mission at a spatial resolution of 60 meters [29]. All available imageries of July were combined using a median reducer [28] for the year 2016, because this month reportedly shows the highest temperatures throughout the entire country [30]. However, we identified a latitudinal gradient with systematically higher temperatures in the North compared to the South. To grant for a consistent data analysis, we removed this trend by creating a linear regression between the July temperatures of the urbanized areas and their latitude (Figure 4). The observed trend shows a clear positive correlation which was then removed from the temperature data so that values of all cities (building density, urban green and temperature) become comparable in the upcoming analysis.

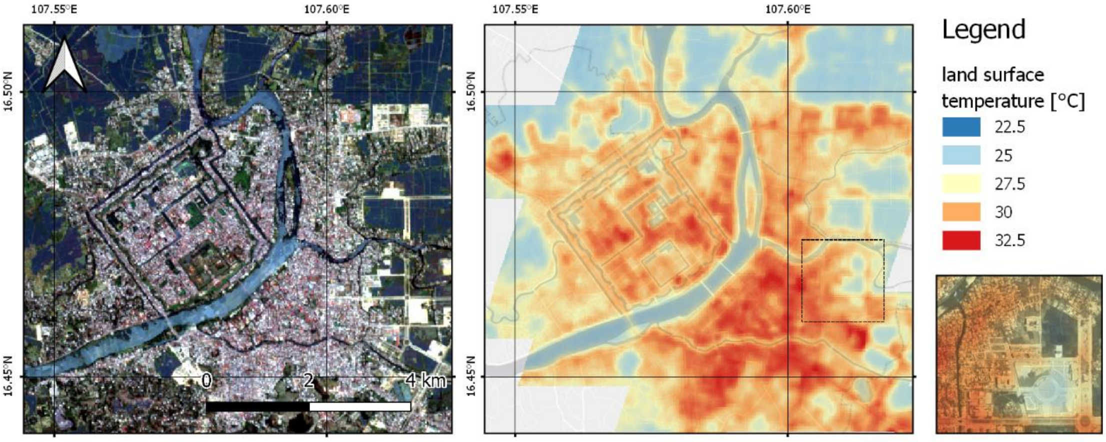

Figure 3. Sentinel-2 image of Hue (left) and surface temperature in the highly urbanized areas (right).

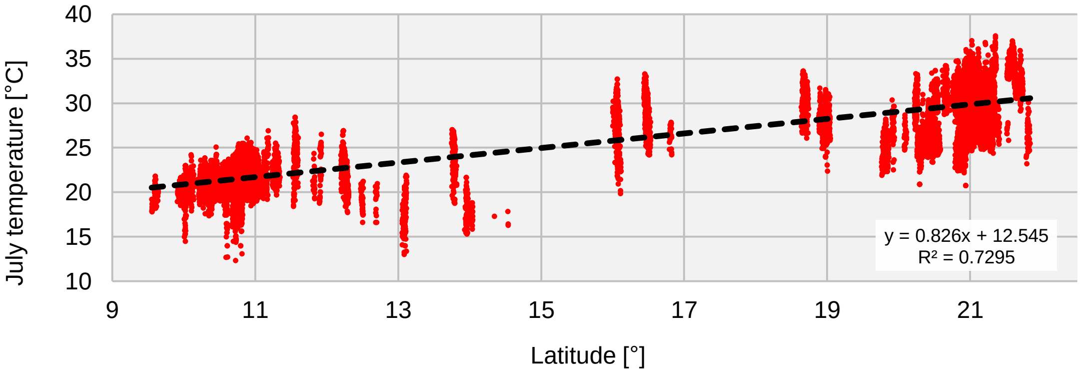

Figure 4. Relationship between July temperature and latitude of urbanized areas in Viet Nam.

3. RESULTS AND DISCUSSION

3.1. Validation and integration of external data

To assess how well the density computed from the GHSL (see section 2.1) matches actual conditions, we used building footprints of the city of Hue provided by our Vietnamese partners within the FloodAdaptVN project which were assessed based on visual interpretation and digitization. These footprints were used to calculate the building density within a radius of 100 meters (Figure 5, left) and compared to the density measure of this study (Figure 5, right). As shown in the scatter plot, both datasets are well correlated (black dashed line).

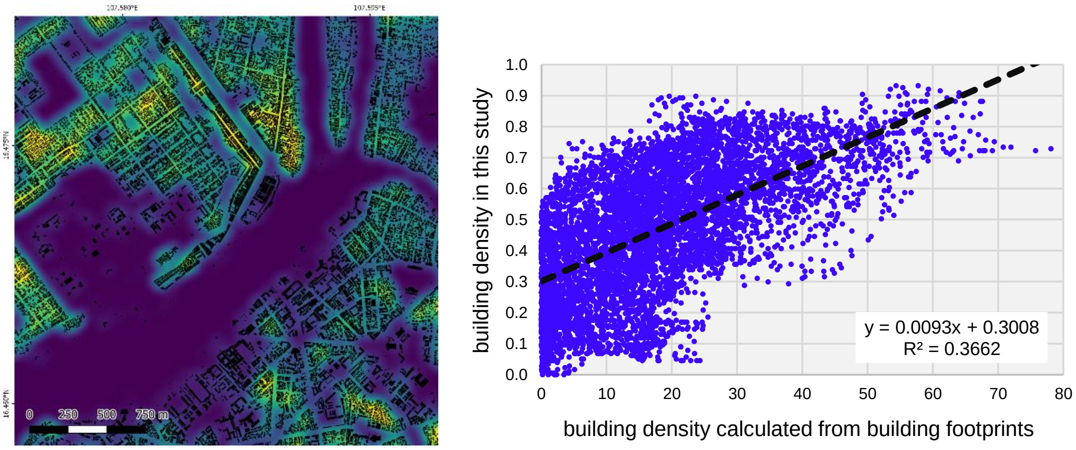

Figure 5. Building density in Hue (left) compared with building density of this study (right).

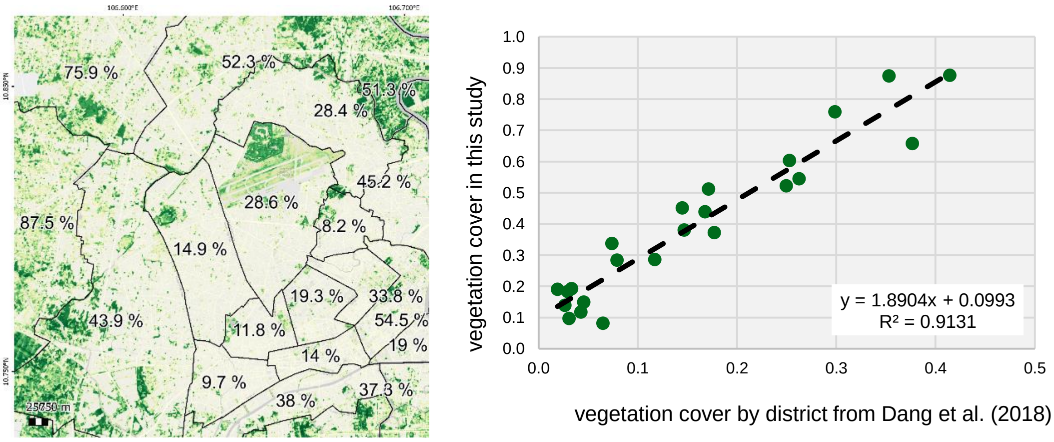

Figure 6. Vegetation density in Ho Chi Minh by Dang *et al.* (2018) [17] compared with data of this study.

Although a certain degree of overestimation (points above the line) and underestimation (points below the line) can be observed, this analysis proves that the density used in this study calculated from globally available GHSL is a valid proxy measure for the building density. Similarly, we compared the average vegetation cover by district in Ho Chi Minh city (colors in Figure 6, left) with the green areas per district reported by Dang *et al.* (2018) [17] (numbers in Figure 6, left). Again, the scatter plot (Figure 6, right) confirms a high agreement between the indicators used in this study and independent validation data. We therefore conclude that both vegetation cover and building density assessed at the national scale are correct.

To put the results of this study into another perspective, we compared the surface temperatures with a dataset of urban structure types of the city of Da Nang [31]. It is a morphological description of the architectural structure at the building block level which was derived from the analysis satellite imagery of the Pléiades mission. Its spatial resolution of 0.5 meters allows the derivation of single buildings, their heights, shapes and densities which led to a classification of nine structure types (Figure 7). As they originate from data which is created independently from the land surface temperatures, an objective comparison of both is possible. The comparison shows that, on average, the LST of rural areas (28.8 °C) is lower than of unbuilt urban areas (29.3 °C). Also, that openly built urban areas (30.2 °C) have lower LSTs than urban areas of compact architecture (31.0 °C). Moreover, this temperature difference Δt increases with smaller building structure: Large (Δt = 0.51 K), Mid-size (Δt = 0.69) and Small (Δt = 1.84 K). This underlines that, in terms of urban heat effects, cities benefit from open architecture and smaller buildings.

Figure 7. Urban structure types in Da Nang [31].

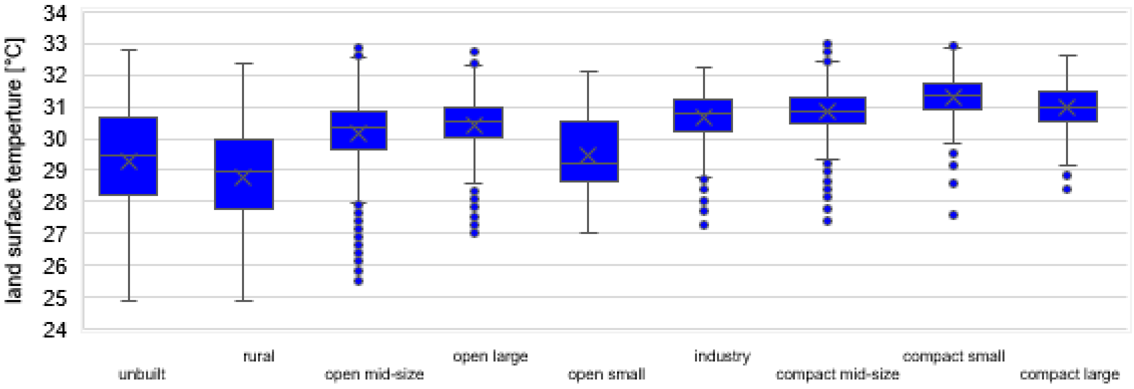

Figure 8. Box plots of land surface temperatures of different urban structure types in Da Nang.

Figure 8**Error! Reference source not found.** shows the average temperatures of the different urban structure types and their value ranges as box plots. It confirms that areas of compact building structure and industrial areas have significantly higher temperatures than those of open, rural or unbuilt structure. This supports the hypothesis that an open building structure helps reducing urban heat.

3.2. Results at the ward level

To test if building density and vegetation cover have an impact on land surface temperature, we compared these values to the land surface temperatures at the ward level and calculated the Pearson correlation coefficient r, because it has been proven to be robust against violations of statistical basic assumptions of normal distributed data and data of different scales [32]. This resulted in r = -0.217 for vegetation, confirming a slight negative correlation between vegetation cover and urban temperatures (Figure 9, green). Accordingly, areas with higher vegetation cover have lower temperatures throughout all Vietnamese cities. The correlation was positive for building density with r = 0.392, indicating that dense areas have higher temperatures (Figure 9, blue). Lastly, if both variables are merged into one (building density divided by vegetation cover) the positive relationship is even stronger with r = 0.435 (Figure 9, red).

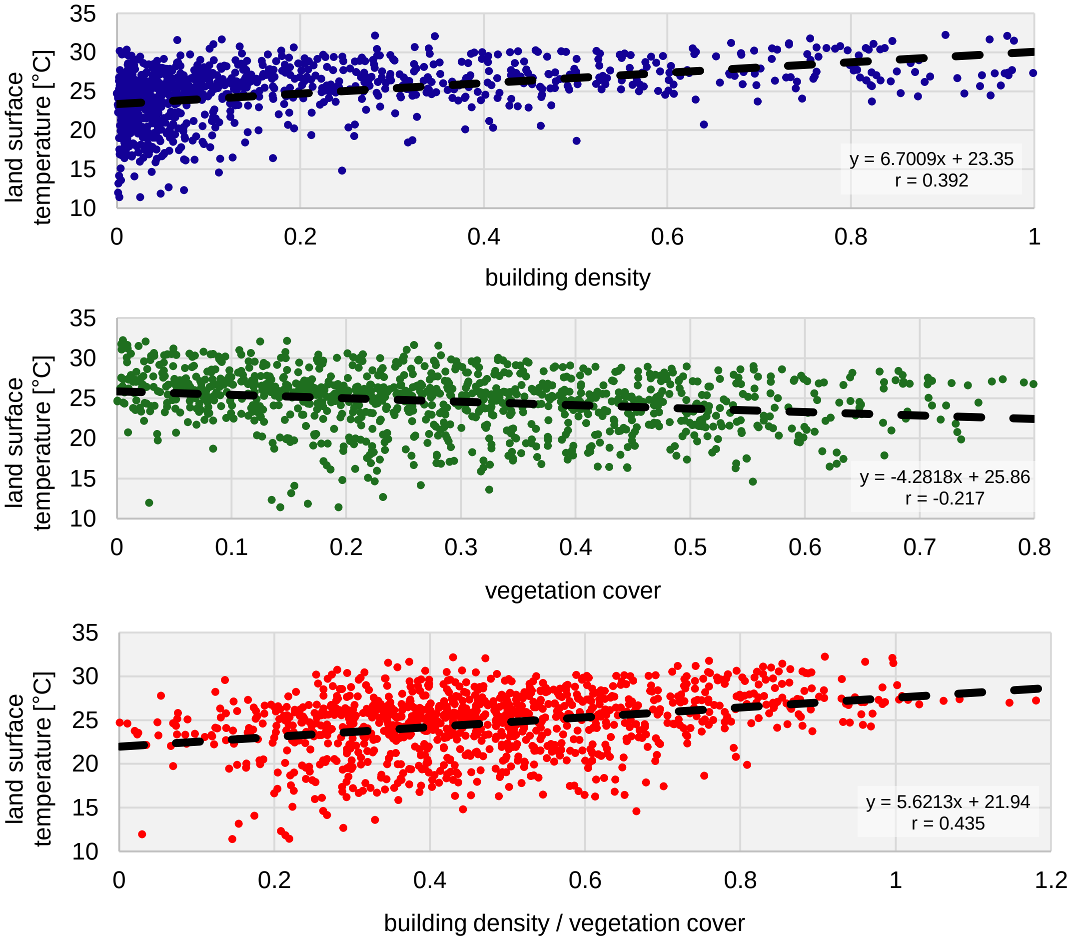

Figure 9. Correlation between land surface temperature with building density and vegetation cover (x-axis limited to the range from 0 to 1.2 for better readability).

These comparably low correlation coefficients are explained by the latitudinal range of Viet Nam which causes temperature gradients between 10 and 35 °C. Although all of them confirm the positive and negative relationships, unsurprisingly, they still show considerable variation. The next section will provide more detailed looks for selected districts.

3.3. Results at the district level

Analyzing the correlations between land surface temperature and the two urban variables by district reveals more insights. As shown in Figure 10, the comparably low correlation coefficients presented in the previous section have different reasons. Firstly, the correction by latitude could reduce inter-urban temperature variations, but the absolute differences are still large. At the same time, the value ranges are inconsistent between the districts. For example, temperatures in Da Nang range between 28 and 32 °C (light blue), while temperatures in Ha Noi are between 14 and 21 °C (orange). Secondly, not all districts have the same strong relationship between the observed variables. For example, clear trends are observed for the districts of Thua Thien Hue (yellow) or Thanh Hoa (purple), but large variations are observed in Nghe An (pink) or Ho Chi Minh (black). Accordingly, some of the strong relationships at the district level are not well represented by the Pearson correlation coefficient for entire Viet Nam. For this reason, Table 1 shows the five districts which have the strongest correlation with building density and vegetation cover at the district level. It is clearly shown in Figure 10 and Table 1 that in these regions, the Pearson correlation coefficient is significantly larger, indicating a stronger relationship between urban features and land surface temperature.

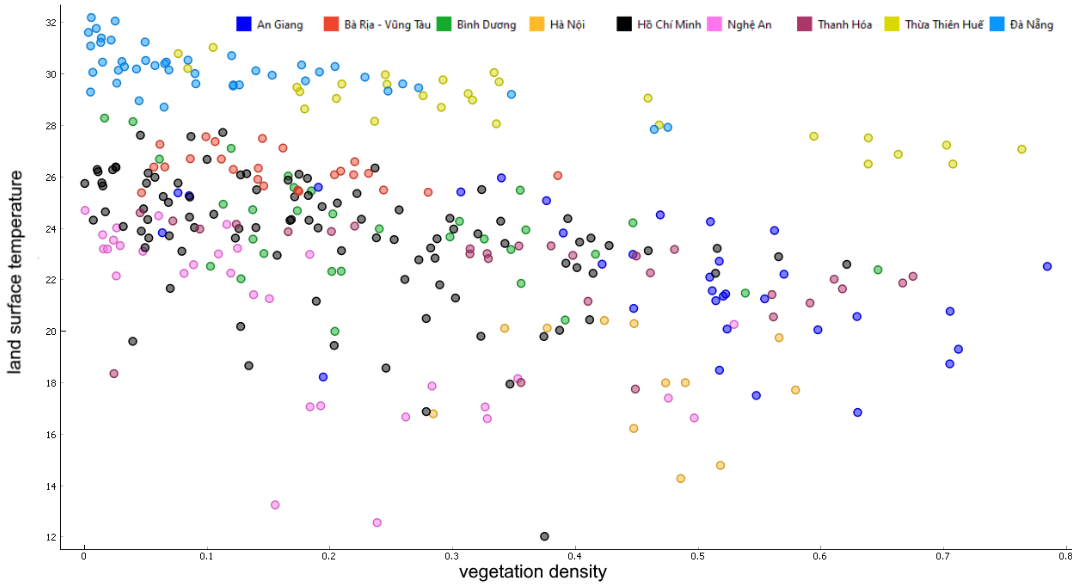

Figure 10. Relationship between vegetation density (x) and land surface temperature (y) for selected districts.

To test another approach, the concept of temperature anomaly was applied to the data which compares the temperature in the most densely built-up part of a city with the temperature of its rural surroundings [33]. As it characterizes their relative temperature difference, it is often used as a robust and comparable measure for the heat effects solely caused by the urban area itself. We computed one temperature anomaly per district by subtracting its 90th temperature percentile (representing the hottest parts of the city) from its 10th temperature percentile (representing the rural surroundings). This resulted in values between 0.9 and 8.2 Kelvin. Accordingly, high values indicate a strong temperature gradient between the rural and the urban parts of the city. We again computed the Pearson's correlation coefficients but found no statistical relationship between a city's temperature anomaly and its mean building density (r = -0.0091) and vegetation density (r = -0.068). Yet, as indicated above, there are strong differences between the cities: Figure 11 shows the temperature anomalies of all wards within selected districts. It shows that not only the median anomaly ranges between roughly two and four Kelvin, but also the variation between the wards of a district differs considerably. For instance, the wards of Ha Noi are largely concentrated around 2.7 Kelvin while the wards of Da Nang show a distinctively larger deviation.

Table 1. Highest Pearson correlations with LST at the district level.

Rank	Building density	Vegetation cover
1	Khanh Hoa (0.630)	Binh Dinh (- 0.710)
2	Binh Duong (0.614)	Can Tho (- 0.573)
3	Binh Dinh (0.605)	Da Nang (- 0.516)
4	Ninh Binh (0.559)	Binh Duong (- 0.501)
5	Hai Phong (0.484)	Hai Duong (- 0.485)

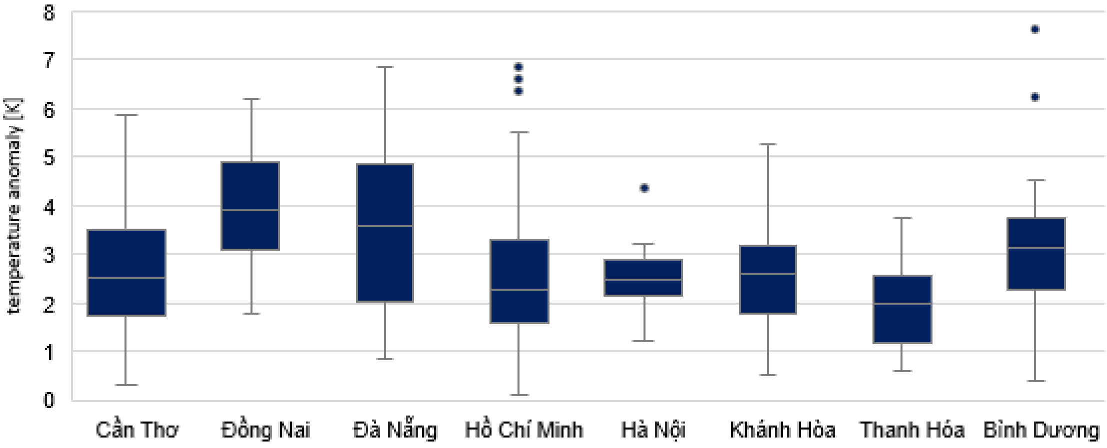

Figure 11. Box plots of temperature anomalies for selected districts and municipalities.

3.4. Interpretation and discussion

Combining land surface temperature with urban green spaces and data on built-up areas allowed us to quantify the relationship between urban heat and architectural measures on a city-wide scale. The Pearson correlation coefficients (r = -0.217 for vegetation, r = 0.392 for built-up areas) indicate that building density has a stronger correlation to land surface temperatures than vegetation. Yet, if both measures are combined into one variable, the positive relationship is even more pronounced (r = 0.435, Figure 9). Despite the temperature normalization over the latitudinal gradient of Viet Nam, these correlations are statistically weak to moderate at the national level. This is because temperatures in urbanized areas of Viet Nam are not equally correlated with these variables as revealed by a comparison of different districts (Figure 10). Following the indications from Table 1, reducing urban heat by vegetation is most effective in Binh Dinh, while the building structure of Khanh Hoa has the largest positive correlation with temperatures and some cities do not show a correlation at all. And as shown in Figure 11, temperature differences between densely and openly built areas are less pronounced in Ha Noi compared to those in Da Nang or Ho Chi Minh, for instance. We want to highlight at this point, that statistical correlation is not equal to causality [34]. Accordingly, based on our data, we cannot directly attribute lower temperatures to vegetation, nor higher temperatures to building density. We can only state that their relationship is consistent over entire Viet Nam. This was furthermore underlined by comparing the LSTs with urban structure types in Da Nang which showed that an open building structure has lower temperatures than close architectures. Once these urban structure types are assessed for all Vietnamese cities, for example based on convolutional neural networks [35], the dataset provided in this study can be studied in more detail to find out why the relationships between temperature and city architecture are stronger in some cities and weak or non-existent in few other cities. Especially the measure of temperature anomalies of cities needs more attention in further studies, also how they can be computed in a consistent way at the national scale.

From a methodological perspective, there are some points to discuss, because they potentially introduce errors in the analysis. The input datasets on urban temperatures, built-up areas and vegetation cover originate from different satellites and can therefore be seen as independent. Yet, all of them are spaceborne sensors. More robust identification of correlations could have been achieved by integrating in-situ measurements, for example of temperature distributions. As no consistent source of temperatures or building densities is accessible for entire Viet Nam, we preferred to use values which are comparable in terms of their origin and therefore used Earth observation data. Another weakness of this study is that we compare measured data (temperatures) with modelled indicators on building density and vegetation fraction. Each of the methods to derive proxies for the architectural design of a city (namely spectral unmixing for vegetation and spatial averaging for the building density) has its drawbacks, also are the spaceborne images limited by their spatial resolution. Accordingly, these variables have to be validated against independent data, as done in Figure 5 and Figure 6. Only if they provide a reliable estimate of the target phenomena, can they be used for statistical evaluation. In this study, validation was conducted in section 3.3., confirming high agreement with external data of higher quality from Ho Chi Minh and Hue.

It is arguable that temperatures from July are not representative enough for analyzing the relationship between urban heat and city morphology. Further studies should consider using more advanced dependent variables, such as temperature differences between day and night, seasonal ranges or trends expected with climatic change in Viet Nam [3, 36]. Once the characterization of urban heat is better understood and spatially expressed, more explanatory variables could be added as well to get a more holistic understanding of the contributions of different parameters besides building density and vegetation. Also, the definition on what is an urban area, and should therefore be included in the analysis, should not strictly be determined by the GHSL dataset of global coverage. Lastly, any attribution of values to administrative areas, as was done in Figure 6, is subject to the modifiable areal unit problem which states that these boundaries are rather a bias for spatial analysis [37]. This is underlined by the shown differences in the spreading of temperature anomalies between the wards of different districts (Figure 11). Both the number and the size of wards impact the statistical distribution of temperature values observed in the cities. Thus, whenever data is not compared pixel-wise as in this study, hexagons should be preferred as units of spatial aggregation.

4. CONCLUSIONS

The methods provided in this study allowed the investigation of the correlations between building density, vegetation cover and land surface temperatures throughout all highly-urbanized areas within Viet Nam. The analysis was based on a set of independent input datasets which are consistent throughout the entire country. Although the methods do not allow to draw final conclusions on the causal correlations, the results indicate that urban heat increases with higher building density and is reduced by urban vegetation cover. Future studies should now address why this relationship is more pronounced in certain cities while it is weak or even inverse in others. Possible explanations are false assumptions or systematic errors in spatial data processing and the unknown impact of further parameters, such as the size and heterogeneity of a metropolitan area and its location within the country. With this study, we hope to lay a foundation for further research on urban heat in Viet Nam at the national level.

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CRediT authorship contribution statement. Andreas Braun: Methodology, data analysis, writing. Carolyn Elizabeth Duffy: Writing, analysis. Gebhard Warth: Methodology, funding acquisition, writing. Volker Hochschild: Supervision, funding acquisition.

Declaration of competing interest. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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