Urban planning and design for local climate mitigation
A methodology based on remote sensing and GIS

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1. Introduction

The Urban Heat Island phenomenon is defined in literature as the difference in temperature between urban areas and the rural ones [12].

Even if in cities located at higher latitudes and elevations the winter warming effects of the heat island could be seen as beneficial, in cities located at lower latitudes, the effect of the summer heat island produce many problems.
The overheating of the urban areas increases the need of energy for cooling the buildings and reduces the overall thermal comfort and quality of life of the urban settlements [12; 3]. The phenomenon is increasing especially in the megacities of the developing world because of the rapid urbanization process and the consequent rapid growth of some cities.

During the hot season some more degrees in these cities means:

- diminished thermal comfort;
- increased cooling demand;
- increased energy demand for cooling systems;

Considering that according to United Nations [18] more than 75 per cent of the world's population lives in urban and suburban areas, and considering that the global warming is increasing the temperatures all around the world, urban heat island impacts are an actual and emergent problem to solve.
Despite the global importance of the phenomenon and its implications in terms of sustainability and quality of life of cities, very few operational instruments are available to design local climate mitigation strategies and plans at urban scale [2].

According to the literature the Urban Morphology has an important role in the shaping of Urban Heat Island phenomena. Intelligent city planning can neutralize, for instance, the intensified heat island effects brought about by unlimited growth of cities, raising densities, and climate change effects. Intelligent use of cladding materials and surfaces can decrease temperatures in zones where this is required, e.g. on roof tops in summer and above pavements [15].
For this reason the urban design and planning disciplines should be involved in the research of the solutions for this problem.
Several authors [3; 10; 11; 12; 13; 14; 15]] reported in fact the relationship between structural and morphological aspects of urban settlements is clear:

- the air temperatures are driven by the heating of urban surfaces, since many man-made surfaces absorb more of the sun's heat than natural vegetation does.
- the urban building materials are impermeable and watertight, so moisture is not readily available to dissipate the sun's heat;
- the areas with the least vegetation and greatest development tend to be hottest;
- temperatures of dark, dry surfaces in direct sun can reach very high temperature during the day
- vegetated surfaces with moist soil under the same conditions reach only lower temperature.
- dark materials in concert with canyon like configurations of buildings and pavement collect and trap more of the sun's energy;
- heat islands tend to become more intense as cities grow larger.

From an urban morphology point of view these characteristics can be sorted into the four main causes of heat island formation:

- reduced evaporation
- increased heat storage
- increased net radiation
- reduced convection.

According to [3] the relationships contributing to heat island formation are:

Lack of vegetation	Reduces evaporation
Widespread use of impermeable surfaces	Reduces evaporation
Increased thermal diffusivity of urban materials	Increases heat storage
Low solar reflectance of urban materials	Increases net radiation
Urban geometries that trap heat	Increases net radiation
Urban geometries that slow wind speeds	Reduces convection
Increased levels of air pollution	Increases net radiation
Increased energy use	Increases anthropogenic heat

But even if some causes-effects of the UHI phenomena were coded by literature and related to urban morphology aspects, what is still not clear is the proportions the urban morphology elements spatially affect the overeating of urban areas.
The open questions are:

- How to geo locate those city's areas that are more subjected to the overheating phenomena?
- How to understand and describe what happens, from the urban morphology point of view, in those urban areas that corresponds to UHIs?
- How to drive or suggest solutions to the UHI phenomena from an urban design and spatial point of view?

The understanding of these issues could improve the efficacy of the urban design and planning solutions to mitigate the UHI phenomena. It could address more efficient interventions in specific sectors and areas.
Since some decades the only way to spatially visualize the UHI phenomena was interpolating different temperature surveys recorded by terrestrial sensors. The low spatial density of these sensors, even if their precision were very high, never permits to obtain maps with a high spatial resolution. According to [3] the magnitude and the spatial importance of a heat island were not fully appreciated until they were first visualized from the air in the 20th century thought the urban surface temperatures maps. Satellites and specially equipped aircraft are able to map temperatures on the Earth's surface and have found very distinguishable hot spots in and around urban areas all over the world. "Remote sensing can be used to find temperatures and other characteristics of *surfaces*, for example, roofs, pavements, vegetation and bare ground, by measuring the energy reflected and emitted from them. Specialized equipment on aeroplanes or satellites is used to take pictures of the visible and invisible energy radiating from cities and their surroundings".

Various studies have been done to determine how surface temperatures affect air temperatures in urban areas [4; 5]. Relationships have been found between the remotely sensed surface temperatures and the air temperatures for different cities. These relationships have been found to be highly dependent on spatial patterns, geography and weather conditions, so in cloudy, windy weather, the effects of surface temperatures on air temperatures are diminished. However, even if windy conditions could mitigate the overheating phenomena of urban areas, the structural determinants of the UHI effect can be spatially identified and mapped.
Unfortunately the relationships between surface temperature and urban characters generally apply to a particular urban area only, so the correlation for Paris or London [21] cannot be extended to a city with different climate, geography or development patterns. [3] Heat islands in urban areas tend to display typical characteristics, but the intensity and timing of heat islands vary at each location. The heat island in each community ultimately finds its own unique balance between temperatures and energy flows, based on the area's terrain, construction and weather conditions.

For these reasons the aim of the research described in this paper is to contribute to obtain an easy and replicable methodology to analyze the surface temperature of a city and to correlate it with the urban morphology elements.

2. Methodology

The proposed methodology, as stated before, starts from the hypothesis that a spatial relationship exists between surface temperature of urbanized areas and some urban morphology elements.
In particular, according to the literature, these urban morphology aspects are analyzed:

- reflectance capacity of the surfaces;
- visibility of the sky;
- vegetation presence and density;
- solar irradiance;
- terrain elevation.

For each morphological aspects one or more spatial indicators are selected and mapped using the available datasets.
According to the analytical framework published in [20] different aspects of the UHI are related to different spatial scales. To preserve the multi-scalar dimension of the UHI the indicators are calculated, where possible, at different spatial resolutions.

The final indicators set was:

Morphology aspect	**Related spatial indicator**	**Spatial resolution reference**
reflectance capacity of the surfaces	Albedo (ALB)	30m/px
visibility of the sky	Sky view factor (SVF)	1m/px
	Sky view factor density (SVFD)	30m/px
vegetation presence and density	Normalized Difference of Vegetation Index (NDVI)	30m/px
solar irradiance	Beam irradiance in Watt/m^2 (IRR)	1m/px
terrain elevation	Digital Elevation Model (DEM)	10m/px
Building Compactness	Surface/Volume ratio	20m/px
Surface temperature	Temperature in C°	60m/px

The Geographic Information System (GIS) tools, and in particular the spatial analyst tools, is used to obtain comparable maps and to resample the maps to a final resolution of 30m/px.
Afterwards to analyze the map set the Multivariate Statistical Analysis applied to raster images (MSARI) is selected.
The MSARI technique allows exploration of relationships between many different data layers or types of attributes [6; 4] .
The Multivariate statistics is a form of statistics encompassing the simultaneous observation and analysis of more than one statistical variable. In particular the Principal Component Analysis (PCA) involves a mathematical procedure that transforms a number of possibly correlated variables into a smaller number of uncorrelated variables called principal components. It is mathematically defined as an orthogonal linear transformation that transforms the data to a new coordinate system such that the greatest variance by any projection of the data comes to lie on the first coordinate (called the first principal component), the second greatest variance on the second coordinate, and so on [6].
With this tool is it then possible to spatially relate the surface temperature to different morphological aspects of urban settlement to obtain an analysis of the contribution of the urban morphologies in the UHI shaping.

3. Case study and procedure

3.1 The case study

The methodology was tested on a case study located in Italy: an area of the city of Trento. This city is settled in a valley floor and is classifiable as a medium density center.

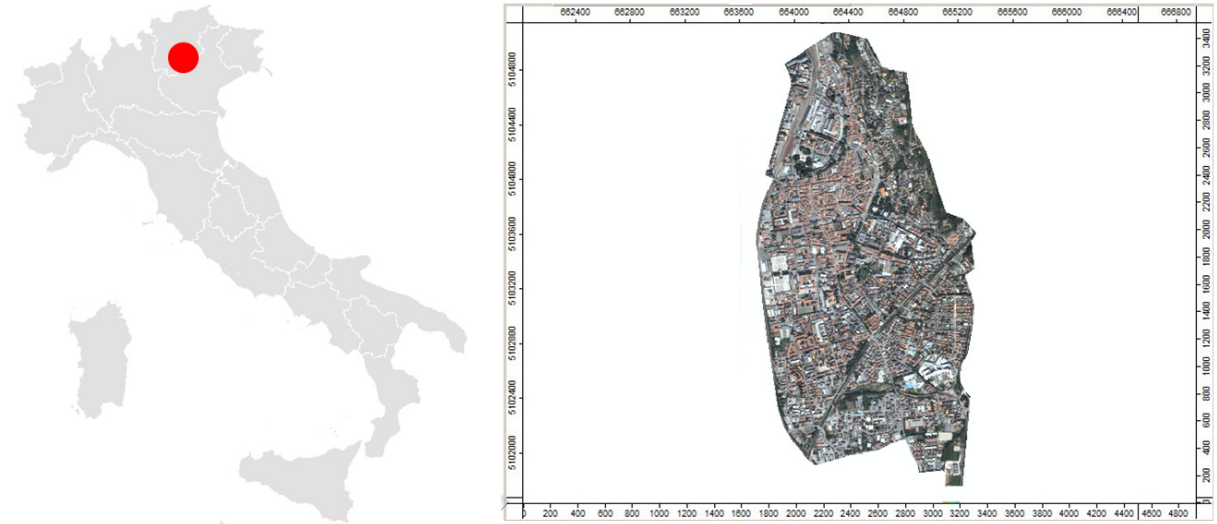


Fig1: Case study's location and orthophoto.

3.2 GeoDataset construction

To build up the geodatabase several datasets were used and elaborated by GIS tools mainly embedded in the open source SAGA GIS.
In particular a Landsat ETM+ scene was used to obtain information about:

- NDVI
- Surface temperature
- Albedo

The used Landsat ETM+ [8] scene (downloaded from edcsns17.cr.usgs.gov) was captured on 26th of August 2001.

Data acquired	WRS Path	WRS Row	Cloud Cover	Sun Elevation	Sun Azimuth
2001/08/26	192	028	5.34	49.7916695	145.7333527

Table 1: LandSat ETM+ scene details.

The recording time was estimated from the Sun elevation and Azimuth on 10.45 AM.

A 1 meter resolution Digital Surface Model derived form a LiDAR survey provided by the Province of Trento (2008) was used to obtain the:

- Sky view factor
- DEM
- Building compactness

An irradiation model implemented in GRASS GIS was used to obtain the solar irradiation map based on the Digital Surface Model derived by the LiDAR survey (for the procedure see Vettorato & Geneletti 2009).

The NDVI was calculated using the ETM+ bands 3 (Red, 30 m/px) and 4 (Near InfraRed, 30 m/px) and applying the formula published in literature by several authors [17] :

$$\text{NDVI} = \frac{\frac{\text{Red}}{\text{NIR}} - 1}{\frac{\text{Red}}{\text{NIR}} + 1}$$

The Surface temperature was calculated using the ETM+ band 6(2-lowgain) and applying the formula and the coefficients provided by Landsat [7] that converts the Radiance (given in Digital Numbers) to Kelvin (is the inverse of the Planck function), and that converting the Kelvin to Celsius.
The formula is:

$$T = \frac{K_2}{\ln\left(\frac{K_1}{CV_R} + 1\right)}$$

Where
T is degrees in Kelvin
CV_R is the cell value as radiance
K_1 is a given conversion coefficient that for ETM+ is 666.09
K_2 is a given conversion coefficient that for ETM+ is 1282.71

The temperature value where compared with the air temperature recorded by 2 meteo stations (Borgo valsugana and Trento sud) on the same date and time and for the location of the meteo stations. The results shown surprisingly a very good matching between the Surface Temperature values reordered by the satellite and the air temperature values recorded by the meteo stations with an average difference of + 0.2 °C. (For this reason it was possible to hypothesize that for the case study area and for the climate and meteo conditions of analyzed moment the surface temperature given by the remote sensor was a good proxy for the estimation of the air temperature).

The Albedo was calculated using the procedure published by Liang and Chen (2002) following the formula for the calculation of the albedo for the total shortwave:

$$\alpha_{short} = 0.356\alpha_1 + 0.13\alpha_3 + 0.373\alpha_4 + 0.085\alpha_5 + 0.072\alpha_7$$

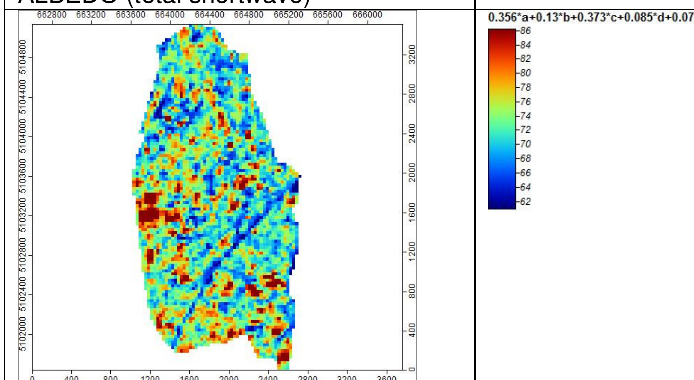
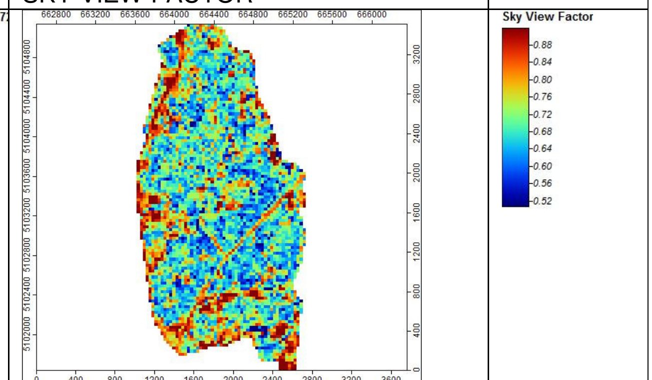
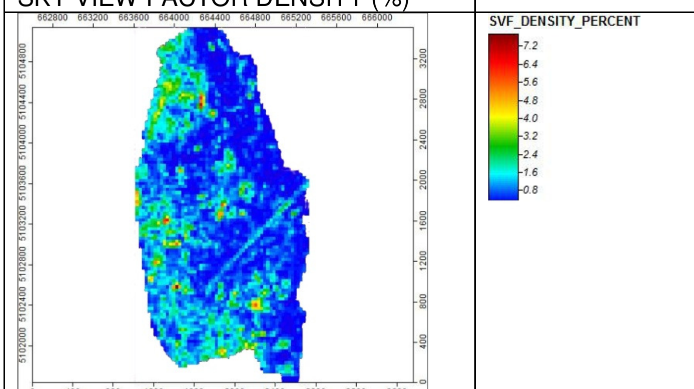
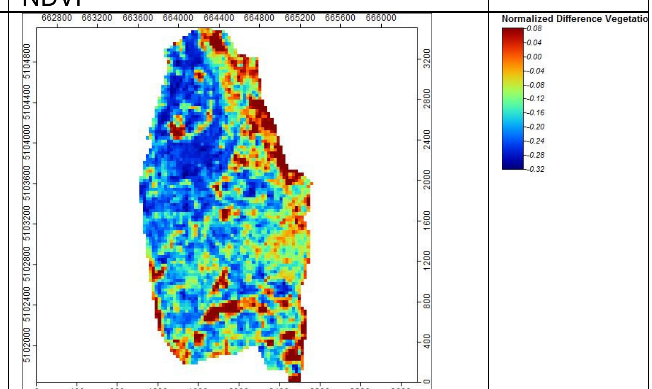
Where α_i represents the land surface ETM+ spectral reflectance.

The sky view factor was calculated according to the formula published by [1] and implemented in SAGA opensource GIS.
The sky view factor density was calculated starting from the sky view factor analyzing the variation of the cells values, in the analysis window, form the center cell value.

The building density was derived from the surface / volume ratio of the buildings analyzing the variation of the cells values, in the analysis window, form the center cell value.
The table 2 summarize the geodatabase construction scheme providing information about the data sources and the final elaborated products (in bold).

SOURCE	1st DERIVATION	2nd DERIVATION	3rd DERIVATION	4rd DERIVATION
LiDAR	DSM 1m/px	SKY VIEW FACTOR 1m/px	SVF DENSITY 1m/px	**SVF DENSITY 30m/px**
			SKY VIEW FACTOR 30m/px	
		BEAM IRRADIATION 1m/px	**BEAM IRRADIATION 30m/px**	
		BUILDINGS VOLUME 30m/px	SURFACE / VOLUME RATIO 30m/px	**BULDING'S DENSITY30m/px**
	DTM 1m/px	**DTM 30m/px**		
LANDSAT ETM+	BANDS 3 & 4 ; 30m/px	**NDVI 30m/px**		
	BANDS 1,3,4,5,7 ; 30m/px	**ALBEDO 30m/px**		
	BAND 6 ; 60m/px	SURFACE TEMPERATURE 60m/px	**SURFACE TEMPERATURE 30m/px**	

Table 2: geodatabase construction scheme

ALBEDO (total shortwave)		SKY VIEW FACTOR	
			
SKY VIEW FACTOR DENSITY (%)		NDVI	
			
IRRADIATION (W/m^2)		DEM	

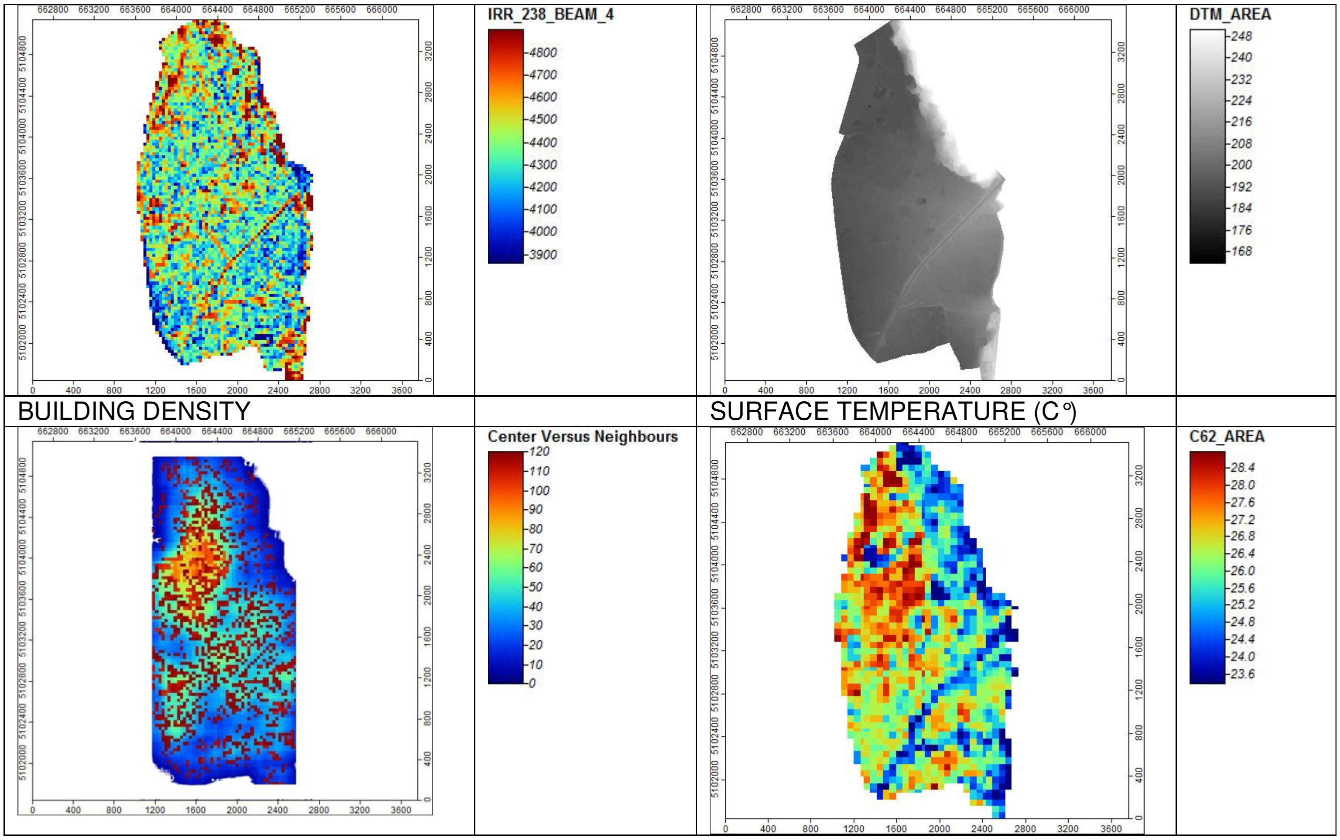


Figure 2: Mapped indicators

3.3 MultiVariate Statistical Analysis

The obtained raster maps were normalized ad transformed in a matrix where each pixel was corresponding to a record and each indicator was corresponding to a variable .
Afterwards the matrix was imported and analyzed in a statistical software.
Firstly a Principal Component Analysis was performed.
Each variable were treated as principal except for the surface temperature that was included in the analysis as supplementary. The aim of this analysis was to find if any correlation exists between one or more urban morphology indicators and the surface temperature values.
As expected the results show that any strong correlation exists between one single morphology indicator in particular and the surface temperature. The DEM (negative) and the Building Density (positive) shows a medium correlation with the surface temperature. The SkyViewFactors shows a high positive correlation with the Solar Irradiation.
According to the literature,anyway, the complex phenomena of the UHI is related to several different variables.
The following table shows the correlation matrix.

Variable	ALBEDO	DEM	IRR	SVFD	SVF	BC	NDVI	*TEMP
ALBEDO	1,000000	-0,139692	0,126354	0,240010	0,283885	0,023959	0,002845	0,075851
DEM	-0,139692	1,000000	0,143669	-0,327342	0,016590	-0,225340	-0,012850	-0,269476
IRR	0,126354	0,143669	1,000000	0,327096	0,713103	-0,193000	0,033430	-0,020337
SVFD	0,240010	-0,327342	0,327096	1,000000	0,430688	-0,099331	0,064378	0,090130
SVF	0,283885	0,016590	0,713103	0,430688	1,000000	-0,280751	0,024608	-0,067209
BC	0,023959	-0,225340	-0,193000	-0,099331	-0,280751	1,000000	-0,009210	0,224044
NDVI	0,002845	-0,012850	0,033430	0,064378	0,024608	-0,009210	1,000000	-0,029107
*TEMP	0,075851	-0,269476	-0,020337	0,090130	-0,067209	0,224044	-0,029107	1,000000

Table 3: Correlation Matrix

The screenplot (figure 3) shows that 4 factors could describe the 78,4% of the cases. The projection of the variables on the factor plane 1-2 give a graphical idea of the relationship between the TEMPerature and the other indicators.

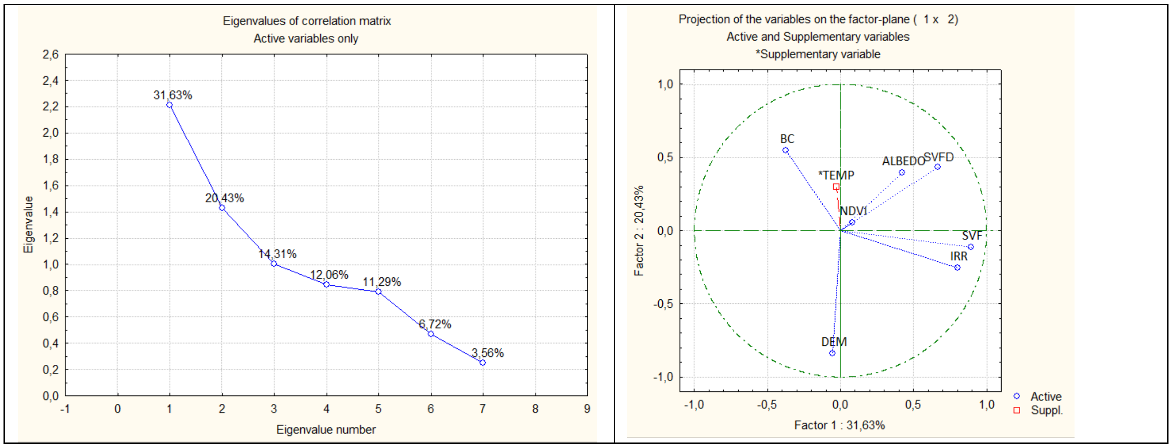


Figure 3: Screenplot of the correlation matrix and projection of the variables in the factor plane 1-2.

Secondly an analysis of the morphology composition was performed for each Surface Temperature class.
The Surface temperature class was divided in 4 classes with the natural breaks method as show in figure 4.
As expected different surface temperature show differences in the related urban morphology composition. In particular is important to report that:

- the T1-low temperature area corresponds to: high albedo, low building density, medium presence of vegetation, high solar irradiation factor, medium sky view factor density, high sky view factor, medium elevation.
- the T2-medium-low temperature corresponds to: medium albedo, low building density, high presence of vegetation, high solar irradiation factor, high sky view factor density, medium sky view factor, medium elevation.
- the T3 – medium-high temperature corresponds to: very low albedo, low building density, very low presence of vegetation, low solar irradiation factor, very low sky view factor density and very low sky view factor.
- the T4 – high temperature corresponds to: high albedo, high building density,very low presence of vegetation, low solar irradiation factor, high sky view factor density, low elevation.

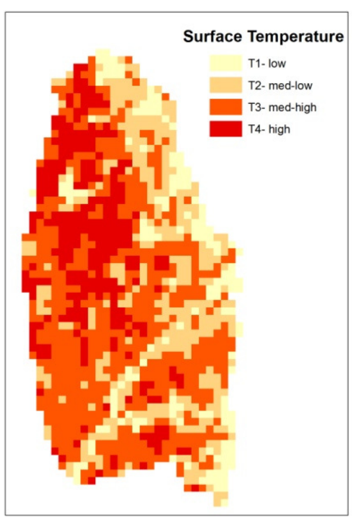


Figure 4. Surface Temperature classes.

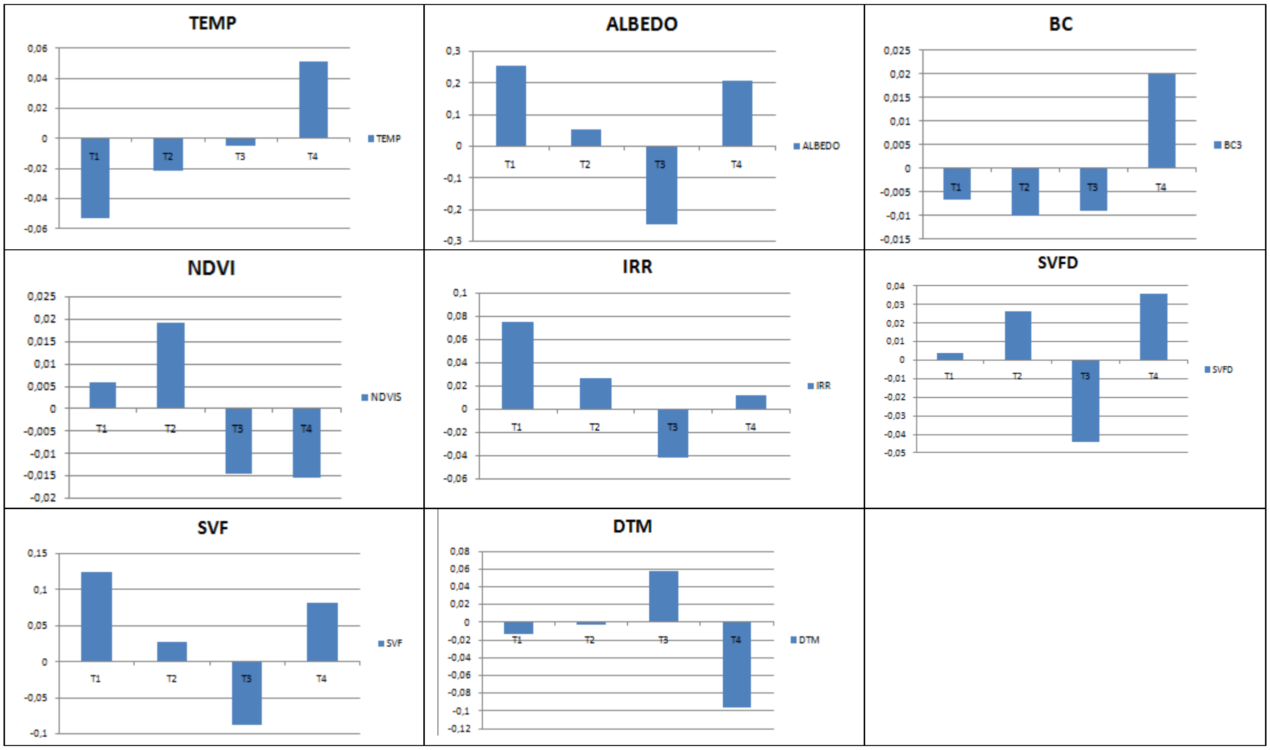


Figure 5: Average of the normalized values of each indicator for the 4 temperature classes (T1,T2,T3,T4).

4. Results and conclusions

Starting from the previous assumptions is then possible to state that for the case study area:

- the elevation is negatively related to the surface temperature but it is not a determinant factor to reduce the surface temperature;
- the high albedo can reduce the surface temperature but it is not sufficient if the building density is high;
- the building density with low vegetation and low albedo is positive correlated to high surface temperatures;
- the presence of vegetation is related to low temperatures. In the area T1 we have low temperature and medium presence of vegetation but the area includes a river.
- the irradiance factor is negatively related to the surface temperature;
- the high sky view factors can reduce the surfaces temperature but only in presence of a vegetation cover or a very high albedo;
- it is possible to make the hypothesis that the more the surfaces are pleated and the building density is high and the vegetation is low, the more the surface temperature is high;

With these methodology applied to the case study it is possible to suggest some spatial strategies for the urban design and planning in order to contribute to the reduction of the Surface UHI effect in Trento.
The areas T3 and T4 show to be the most affected by the Surface Heat Island Effect. In the area T3 probably the Albedo should be improved as well as the presence of vegetation and the sky visibility. The relative high elevation of the T3 area didn't show many benefits.
In the T4 area even if the albedo is high the building density affects the temperatures. The thermal comfort should be probably improved enhancing the vegetation cover. In those areas characterized by a high sky view factor (big roads, big squares, the railway station area, etc.) the vegetation cover is determinant to reduce the surface temperature.
Learning from the T1 and T2 areas it is possible to state that the low building density reduce the surface temperature only if the surfaces are covered by vegetation or water.

5. Discussion

The proposed methodology can contribute to the debate on the effect of the urban morphology on the UHI effect. In particular the spatial variable was included in the methodology allowing to make some consideration on the spatial distribution of the UHI effect. The spatial variable allows also to analyze the characteristics of different areas from an urban morphology point of view enabling the possibility of a spatial multivariate statistical analysis.
The multivariate statistical analysis applied to raster images shows to work properly and to be a powerful analytical instrument.
The construction of the geodatabase and the dataset availability was a determinant factor for the quality of the analysis. Fortunately many dataset (i.e. the LandSat images) are available on-line at a very low cost. The availability of some open-source GIS software that embedded several spatial analysis tools reduced the elaboration time.
Further improvements of the procedure will include several thermal images covering a wider time-scale, during the same day and in different seasons.
Even the selection of the spatial indicators will be probably subject of a critical review: some other spatial indicators could be introduced in the analysis (i.e. water presence, leaf area factor, relative humidity, urban canyon temperatures) to obtain a more precise description of urban morphologies and microclimate.
Anyway the introduction of urban morphology spatial indicators in the analysis of UHI shows to be very interesting form the potential results obtainable in terms of urban design and planning strategies elaboration.
The methodology is replicable and customizable and, if used, could allows to understand some spatial relations between the urban morphologies and the UHI phenomena in other cities and geographical contexts. In particular this methodology can contribute to answer to some policy makers and urban planners questions like:

- How to easily geo locate those city's areas that are more subjected to the overheating phenomena?
- How to understand and describe what happens, from the urban morphology point of view, in those urban areas that corresponds to UHIs?
- How to drive or suggest solutions to the UHI phenomena from an urban design and spatial point of view?

Starting from the results obtained with the proposed method the urban morphology and vegetation design could be successfully used to promote a climate sensitive and sustainable urban design for the critical zones. In particular the possibilities are:

- to optimize the morphology to enhance the shading of buildings and public spaces during thermally critical times of the day (by manipulating urban geometry).
- to use the urban vegetation for sheltering and shading buildings and public spaces;
- to consider in the design the role of vegetation also for CO_2 absorption, ecosystem connections and water retention.

6. References

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