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Modelling the effect of urban design on thermal comfort and air quality: the SMARTUrban Project

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Abstract

More than half of the world population lives now in urban areas and therefore the quality of the urban environment has become a key issue for human health. In this context, it is important to evaluate and document any action that contributes to improvements in thermal comfort and air quality. The aim of this paper is to present a system for the design of urban spaces developed in the framework of the SMARTUrban project. Such a system aims at giving administrators and design professionals a strategic tool for the sustainable management and planning of urban areas. SMARTUrban is a prototype of an urban space design software that estimates the effect of design modification or of new design on thermal comfort, carbon sequestration and air pollutants removal.

1 Introduction

The strong contribution of cities to local and global warming is well documented (Grimmond, 2007). It is recognized by many international studies that the concentration of population and buildings in a small portion of territory alters its characteristics to the point of creating a significantly different local climate from surrounding rural areas (Oke, 1982). This affects weather variables including temperature distribution and intensity: cities, because of the materials from which they are constructed modify soil permeability and contribute to storing energy and re-dispersing it in the form of heat, and are by themselves warmer (Dirmeyer et al., 2010). One of the main drivers of global warming is CO_2, and cities are known to be major sources of this gas. Indeed, a compensation of CO_2 emitted by human activities is achievable through sustainable urban planning. Urban greening, in particular, can contribute effectively to CO_2 atmospheric reduction by assimilation and storage, as CO_2 is converted into organic carbon by photosynthesis then stored as woody biomass for long-term (Mori et al., 2016). Finally, urban sites are characterized by high pollution load, and close to 7 million premature deaths each year can be attributed to urban air pollution (WHO, 2014). It was estimated that in Italy, in 2010, 34143 inhabitants died because of exposure to transport-related pollution (Mori et al., 2015). Trees and shrubs have the potential to remove large quantities of gaseous and solid (i.e. PM) pollutants, with plant leaf area and density, as well as leaf anatomical characteristics playing a major role in determining the amount of pollutants sequestered (Mori et al., 2015).
In this general context of ongoing urbanization, the number of people experiencing stressful urban environmental conditions is increasing. At our latitudes, the negative impacts of urban climate on human

health is stronger during the summer season. Among air pollutants, ozone reaches higher concentrations during summer, while other pollutants like particulate matter, nitrogen and sulphur oxides peak during winter. Moreover, cities contribute to carbon dioxide emissions both locally and globally (Satterthwaite, 2008).

It is necessary to have spaces in the city that contribute to mitigating the negative effects of the urban environment on the health of the population and on the environment (Petralli et al., 2014). All this means that knowledge of the urban environment and its peculiarities is the basis for the planning of future urban sustainable development (Brett, 2003). Although there are many studies in the literature on the environmental dynamics of the urban environment, there is a need to make this information easily accessible to urban planners and policymakers (Eliasson, 2000; Roth et al., 2011; Massetti et al., 2014; Ugolini et al, 2015).

In this context the SMARTUrban project (Monitoring system and territorial urban research) was conceived. The aim of the project is to develop a prototype user-friendly system for the design of urban spaces and the evaluation of their environmental impacts. The evaluation of the environmental effects of these urban areas can be performed on different aspects: human thermal comfort, air pollution, CO_2 storage and sequestration and sensible heat evaluation.

This paper presents the prototype of a software tool, realized within the SMARTUrban project, that aims to facilitate the evaluation of the impact of an urban space design – providing an easy-to-use interface for both the design and the estimation phases.

2 Material and methods

The SMARTUrban software is composed of a graphic interface for the design of urban spaces, georeferenced through a GIS system and a set of functions to calculate indices of environmental performance. The user can work on a new layer or import the working area from Google Maps or from other GIS layers (including objects like buildings, plants and green infrastructure, and their characteristics, like colour, tree height, tree species, type of surfaces, etc.). This system gives the possibility of changing the characteristics of the objects or adding new objects to the work area (Figure 1). This is possible thanks to a database of materials and plants set up for this software. Each material is characterised according to its thermal and radiative properties (albedo, heat capacity, conductivity and emissivity), and also by permeability (permeable or impermeable). Tree species were clustered according to their similarity and characterized in terms of crown shape and size, leaf area index (LAI) and growth curves.

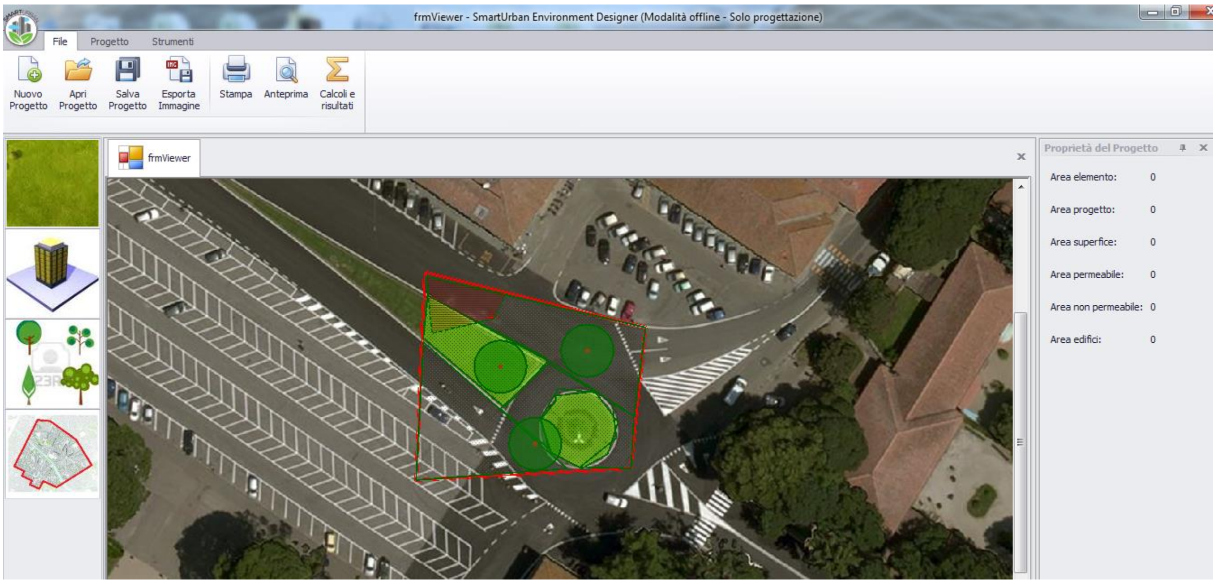

Figure 1: User interface of the prototype realized in the framework of the SMARTUrban project

Once the work area is designed and each element is defined, the user can proceed with the environmental indices calculation.

The environmental indices that the SMARTUrban software can calculate are:

a) Thermal comfort:
   - ATI (°C) - Apparent Temperature Index (Steadman, 1994)
   - UTCI (°C) – Universal Thermal Climate Index (Jendritzky et al., 2012)

b) Sensible heat – Q (W m-2): Computed through a one-dimensional energy balance model coupled with a routine for estimating the effect of plant canopies on surface heat transfer (Napoli et al., 2016). The model computes the shortwave and longwave radiation exchange by taking into account the shadow effects due to buildings and tall vegetation (tree, hedges, etc.) and the reflections on urban facets (pavements, walls, etc.). Mutual shading, heat emission and reflection between buildings, trees and pavements are included.

c) CO_2 storage and sequestration: carbon storage was calculated after grouping tree and shrubs species into eleven classes based on growth rate, longevity, and final dimension at maturity. Average longevity and size at maturity were identified per each species. A growth curve relating age, diameter, and biomass was constructed per each vegetation class based on literature data. Carbon stored was calculated as 0.5 * estimated plant dry weight. Carbon assimilation was estimated as the annual increase in carbon storage, corrected for plant health status and irradiance.

d) Air pollutant removal:
   - PM_{10} and $PM_{2.5}$
   - NO_2, O_3 and SO_2

was calculated using the dry deposition model.

The calculation of all indices requires the following hourly environmental data (
Table 1 and 2). Meteorological and air pollutant data should be collected in a station representative of the study area (globe thermometer data must be collected in situ). For thermal comfort evaluation, the software includes coefficients of correction of air temperature related to different surfaces type and shading. These coefficients were empirically derived from a 2-year data monitoring and analysis (Brandani et al., 2016).

Table 1: list of input variables required for the calculation of the indices

Variable	Unit	Name	Index
Air temperature	°C	Ta	all
Wind speed	ms^{-1}	v	all
Relative humidity	%	Rh	all
Global solar radiation	Wm^{-2}	rad	all
Rain	mm	p	PM_{10}, $PM_{2.5}$, O_3, NO_2, SO_2, Q
Black globe thermometer	°C	Tg	UTCI
Particulate Matter <10 microns	μgm^{-3}	PM_{10}	PM_{10}
Particulate Matter <2.5 microns	μgm^{-3}	$PM_{2.5}$	$PM_{2.5}$
O_3	μgm^{-3}	O_3	O_3
NO_2	μgm^{-3}	NO_2	NO_2
SO_2	μgm^{-3}	SO_2	SO_2

Table 2: list of input variables needed for the calculation of CO_2 storage and CO_2 assimilation

Variable	Unit	Name	Index
Tree/shrub species	qualitative	Sp	CO_2 storage and CO_2 assimilation
Stem diameter at 1.3 m	cm	DBH	CO_2 storage and CO_2 assimilation
Tree health	qualitative	S	CO_2 assimilation
Tree exposition	qualitative	E	CO_2 assimilation
N days without frost per year	day	G	CO_2 assimilation

The user can select the period of the simulation. ATI, UTCI and Q are calculated hourly for the selected period. Average values (from 1 pm to 3 pm) of UTCI and ATI are displayed in a map of the work area.

The energy balance results are expressed as the mean of hourly sensible heat of the whole period. Air pollution outputs are expressed by a value cumulated at the end of the selected period. The CO_2 outputs depict the actual storage and accumulation and allow predictive estimates of CO2 storage after 10, 35, 75, and 100 years (or until predicted tree death if shorter than these time-spans).

The user can select one or more index and should provide only the input data required for the selected indices.

The SMARTUrban software was designed to compare the environmental performance of an existing situation with the design of a new urban area.

3 Results and discussion

In this section, an example of the environmental performance of an existing situation and a new design of an urban area located in Arezzo is presented (Figure 2).

Figure 2: Google satellite image of the urban area selected for the case study in Arezzo

After the Google image is imported in the software, the study area is delimited and then the surfaces and features (buildings and trees) are classified by the user (Figure 3A). Now the designer can modify the study area to simulate different solutions by changing surfaces and adding trees or changing tree species. In our case study, the designer changed some areas covered by asphalt and bare soil with grass, and added some tress of different species and age (Figure 3B).

In this case study, the meteorological data inserted were related to summer 2014 and the results for ATI are presented in figure 4A (existing situation) and 4B (project situation). In this case, UTCI was not calculated because Tg data were not available.

The project of the study area gives a mean value for the ATI during the summer 2014 of approximately 2 °C less than the existing situation. The introduction of trees locally reduced the ATI by approximately 4 °C. This reduction refers to the average calculated between 1 pm and 3 pm.

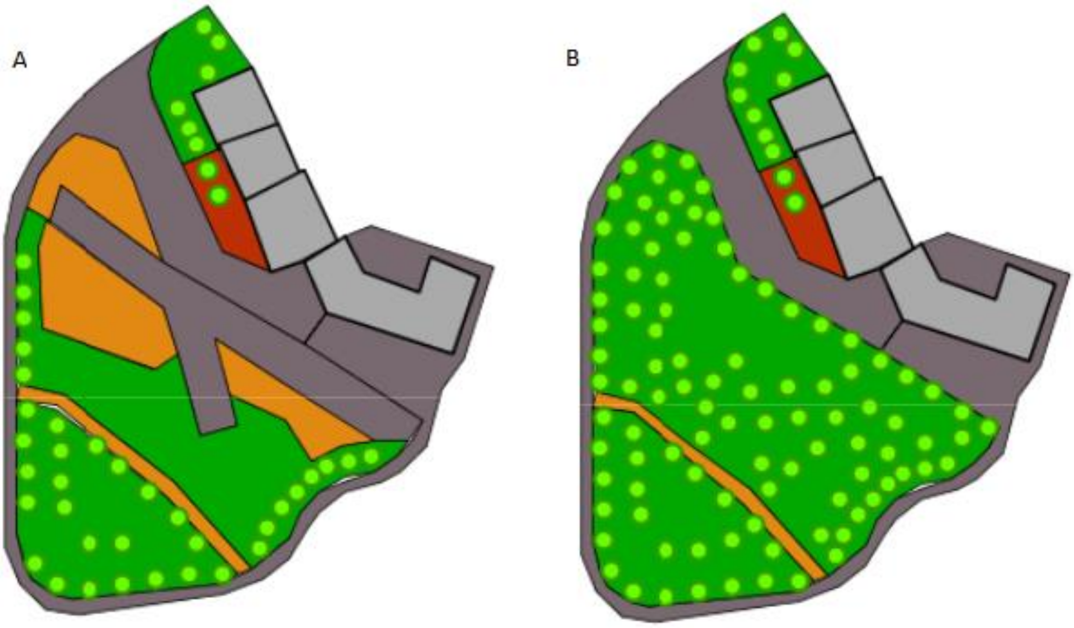

Figure 3: Study area: 2A) design of the existing situation; 2B: design of the project (gray: asphalt; orange: bare soil; green: grass; light green: trees; light gray: buildings; brown: bricks)

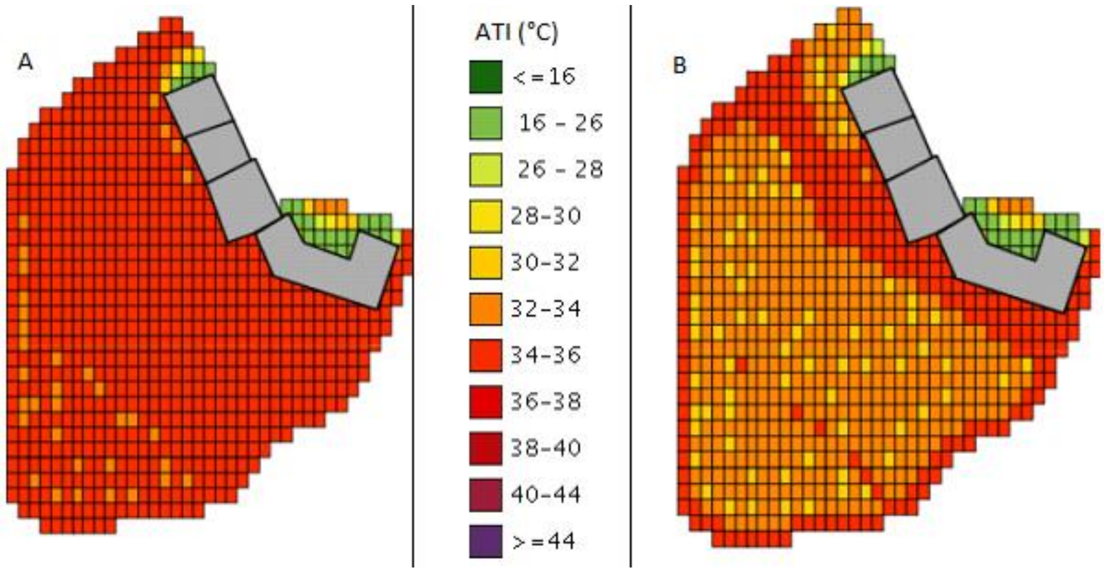

Figure 4: Average ATI (°C) during summer 2014 between 1 pm and 3 pm of the existing situation (A) and of the project situation (B).

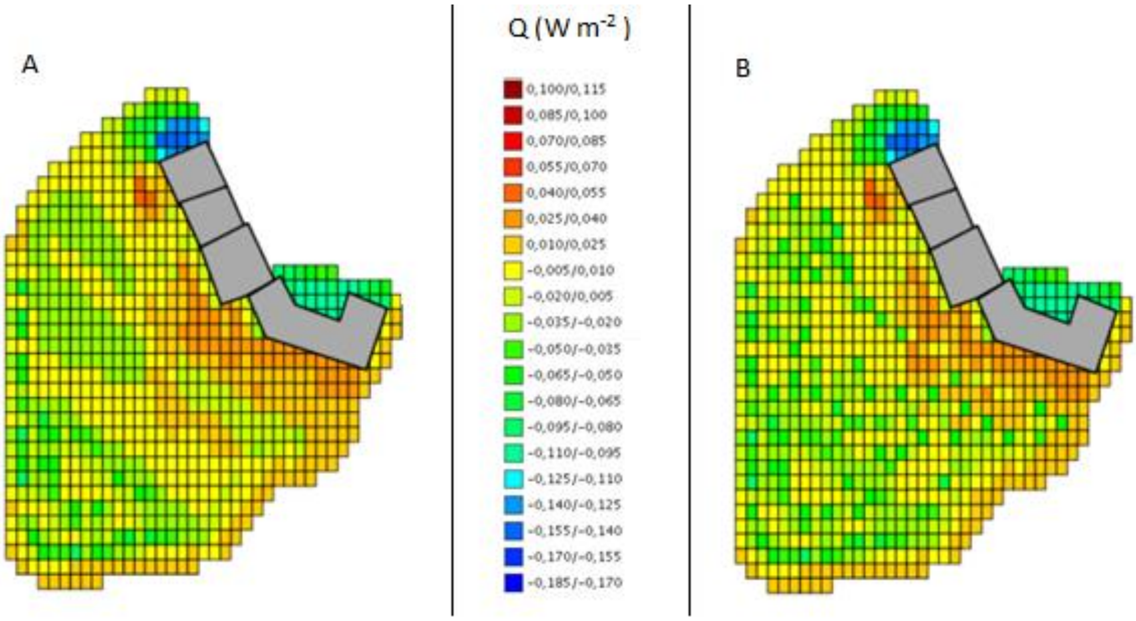

Figure 5: Average sensible heat (W m^{-2}) per hour in Summer 2014 of the existing situation (A) and of the project situation (B)

Sensible heat results are presented in figure 5: figure 5A shows the existing situation and figure 5B the project situation. The project situation shows a reduction in mean summer sensible heat per hour of almost 1 W m^{-2}.

Results for air pollutant removal and carbon storage and sequestration are presented in Figure 6, comparing an existing industrial area in the suburbs of Florence with a proposed alternative design of the site.

It is possible to see how the planting of long-lived species, such as holm oak, may provide significant benefits in terms of carbon storage and pollution removal. In its current state, the site vegetation consists only of grass, with no trees, which results in the assimilation of about 700 kg C/year, but little carbon storage. Planting trees increases both CO_2 assimilation and storage, particularly after the 10th year since planting when trees are fully established and they approach maturity. Using long-lived trees assures that this benefit will increase progressively for over 100 years, whereas planting species with shorter life-span (e.g. poplar), may reduce benefits as soon as trees reach senescence and need to be replaced. Pollution removal increases proportionally with tree size and canopy area, with a larger impact seen for the projected tree plantings on O_3 and NO_2.

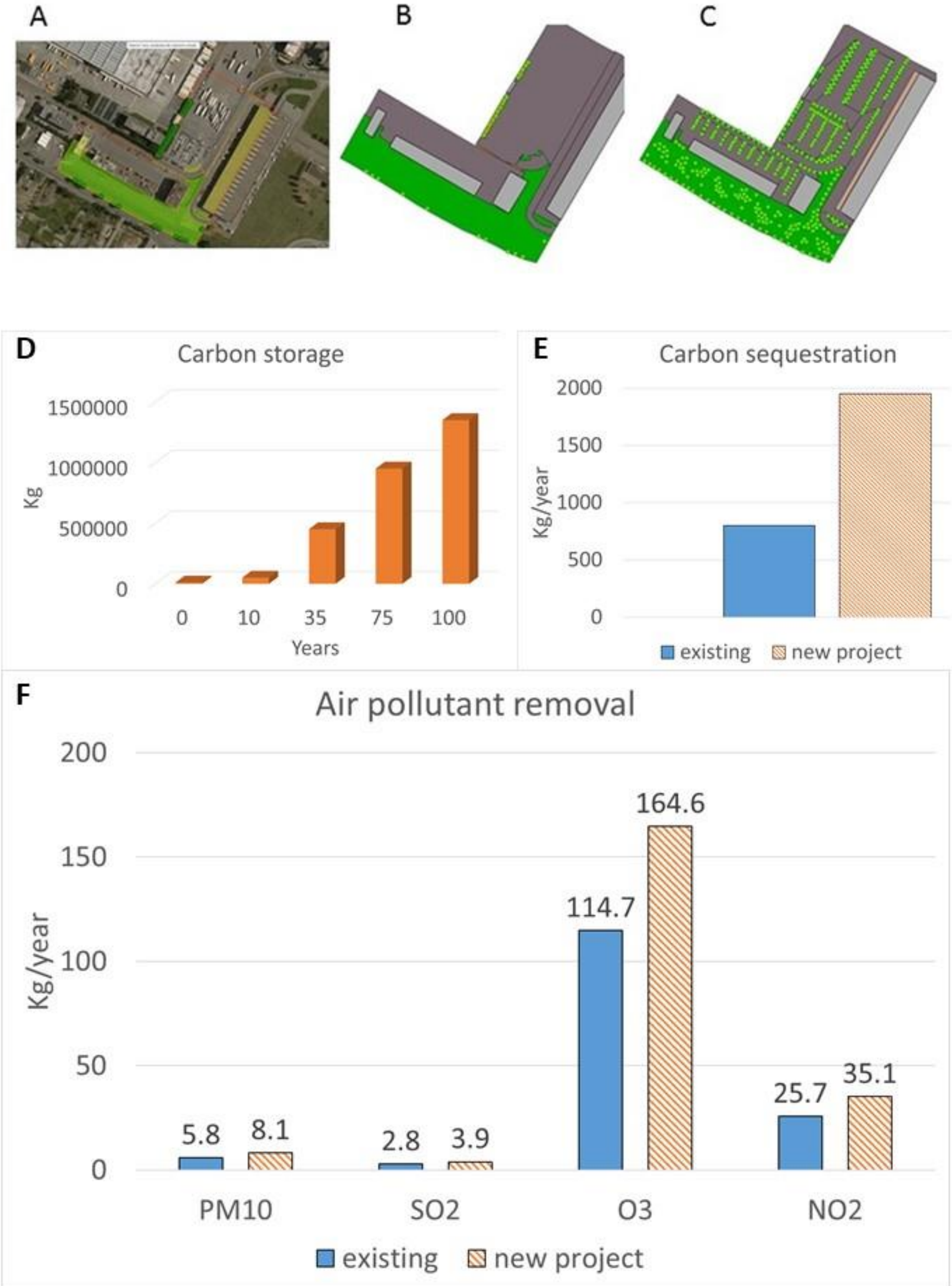

Figure 6: Industrial area in the suburbs of Florence (A) selected for estimating the environmental performance of the existing area (B) and the new projected area (C), and comparison between B and C in terms of carbon storage (D), carbon sequestration (E) and air pollutant removal (PM_{10}, SO_2, O_3 and NO_2) (F).

4 Conclusion

The SMARTUrban software is still a prototype, but it promises to be an easy-to-use tool that can provide quantitative results for sustainable urban environmental design. The system can calculate several performance indicators of thermal comfort, sensible heat, carbon sequestration and air pollutants removal. The system evaluates the environmental quality of an urban design by the total value of each indicator for the project and detailed maps for thermal comfort and sensible heat variability.

The maps of thermal comfort and sensible heat helps to immediately evaluate the impact of a design and identify critical points. Then, the user can revise, through a graphical interface, properties and position of any single element of the project.

The goals for the future are to improve the prototype by integrating it with other indices, such as the Index of Thermal Stress - ITS (Givoni, 1976; Pearlmutter et al; 2014), or other air pollutants – and finally, to transform the prototype into a complete software package.

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References

Brandani, G., Napoli, M., Massetti, L., Petralli, M., Orlandini, S. (2016). Urban soil: Assessing ground cover impact on surface temperature and thermal comfort. *Journal of environmental quality*, **45**, 90-97.

Brett B.A. (2003). Physical environmental modeling, visualization and query for supporting landscape planning decisions. *Landscape. And Urban Planning*, **65**, 237-259.

Dirmeyer, P. A., Niyogi, D., de Noblet-Ducoudré, N., Dickinson, R. E., Snyder, P. K. (2010). Impacts of land use change on climate. *International Journal of Climatology*, **30**, 1905-1907.

Eliasson, I. (2000). The use of climate knowledge in urban planning. *Landscape and urban planning*, **48**, 31-44.

Givoni, B. (1976). Man, Climate & Architecture. *2nd Edition, Applied Science Publishers, Ltd., London*, PP. 483.

Grimmond, S. (2007). Urbanization and global environmental change: local effects of urban warming. *Geographical Journal*, **173**, 83–88. doi:10.1111/j.1475-4959.2007.232_3.x

Jendritzky, G., De Dear, R., Havenith, G. (2012). UTCI - why another thermal index? *International Journal of Biometeorology*, **56**, 421 – 428.

Massetti, L., Petralli, M., Brandani, G., Orlandini, S. (2014). An approach to evaluate the intra-urban thermal variability in summer using an urban indicator. *Environmental pollution*, **192**, 259-265.

Mori, J., Saebo, A., Hanslin, H.M., Teani, A., Ferrini, F., Fini, A., Burchi, G. (2015). Deposition of traffic related air pollutants on leaves of six evergreen shrub species during a Mediterranean summer season. *Urban Forestry and Urban Greening.* **14**:264–273.

Mori J., Fini A., Burchi G., Ferrini F. (2016). Carbon Uptake and Air Pollution Mitigation of Different Evergreen Shrub Species. *Arboriculture & Urban Forestry*. **42**: 329–345.

Napoli, M., Massetti, L., Brandani, G., Petralli, M., Orlandini, S. (2016). Modeling tree shade effect on urban ground surface temperature. *Journal of environmental quality*, **45**, 146-156.

Oke, T. R. (1982). The energetic basis of the urban heat island. *Quarterly Journal of the Royal Meteorological Society*, **108**, 1-24.

Pearlmutter, D., Jiao, D., Garb, Y. (2014). The relationship between bioclimatic thermal stress and subjective thermal sensation in pedestrian spaces. *International Journal of Biometeorology*, **58(10)**, 2111–2127

Petralli, M., L. Massetti, G. Brandani, Orlandini, S. (2014). Urban planning indicators: Useful tools to measure the effect of urbanization and vegetation on summer air temperatures. *International Journal of Climatology* **34,** 1236–1244. doi:10.1002/joc.3760

Roth, M., Emmanuel, R., Ichinose, T., Salmond, J. (2011). ICUC-7 Urban Climate Special Issue. *International Journal of Climatology,* **31(2)**, 159–161.

Satterthwaite, D. (2008). Cities' contribution to global warming: notes on the allocation of greenhouse gas emissions. *Environment and urbanization*, **20(2)**, 539-549.

Steadman, R.G. (1994). Norms of apparent temperature in Australia. *Australian. Meteorolological. Magazine*, **43**, 1–16.

Ugolini, F., Massetti, L., Sanesi, G., Pearlmutter, D. (2015). Knowledge transfer between stakeholders in the field of urban forestry and green infrastructure: Results of a European survey. *Land Use Policy*, **49**, 365-381.

WHO, (2014) 7 million premature deaths annually linked to air pollution. *World Health Organization Regional Office for Europe*. http://www.who.int/mediacentre/news/releases/2014/air-pollution/en/