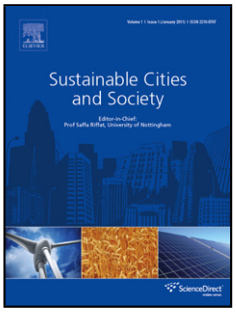

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Short and medium- to long-term impacts of nature-based solutions on urban heat

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Highlights

- Nature based solutions were used to reduce urban heating and mitigate urban sprawl.
- The effects were measured in the urban heat fluxes.
- WRF-SUEWS and SULD constitute a useful tool for policy decision.
- Urban compacting reduces the effect of nature based solutions on urban heat.

Abstract

Most cities are growing and becoming more densely populated, resulting in land use changes, which promotes an increase in urban heating. Nature-based solutions (NBS) are considered sustainable, cost-effective and multi-purpose solutions for these problems. While various studies assess the effects of NBS on urban heat or urban sprawl/compaction, no studies assess their cumulative effect. The main objective of this study is to assess the short-term and medium- to long-term impacts of NBS on urban heat fluxes, taking as a case study the city of Eindhoven in The Netherlands. An integrated modelling approach, composed of a coupled meteorological and urban energy balance model (WRF-SUEWS) and an hedonic pricing simulation model (SULD), is used to assess urban heat fluxes and urban compaction effects, respectively. Results show that, in the short-term, NBS have a local cooling effect due to an increase in green/blue spaces and, in the medium to long-term, an urban compaction effect due to attraction of residents from peripheral areas to areas surrounding attractive NBS. This study provides evidence that NBS can be used to reduce the effects of urban heating and urban sprawl and that an integrated modelling approach allows to better understand its complete effects.

Keywords: heat fluxes, integrated modelling, nature-based solutions, urban areas, urban sprawl.

1. INTRODUCTION

Urban areas are one of the main sources of greenhouse gas (GHG) emissions, with between 70% and 90% of CO_2 emissions being generated in cities (European Environment Agency, 2017a), and significantly contribute to global climate change. Considering that urbanization is expected to increase further, with 68% of the world population living in cities by 2050 (United Nations Department of Economic and Social Affairs, 2018), it can be anticipated that this issue will continue to grow over the coming decades (European Environment Agency, 2017b). One of the problems of growing urbanization is that it translates into a conversion of rural to more urban landscapes (Seto et al., 2011), resulting in a rapid increase in impermeable surfaces, substantial loss of green spaces and spread of cities into undeveloped areas (Estoque & Murayama, 2017; European Environment Agency, 2016; Seto et al., 2011). This leads to an increased use of private and public transport and, in turn, leads to increased CO_2 and air pollutant emissions (Kennedy et al., 2011). These changes to the environment alter the ecology of cities, disrupting energy and water balances (urban fluxes) that cause effects, such as, increases in temperature and subsequent creation of urban heat islands, increases in the production of carbon dioxide (CO_2), and decreases in the amounts of stored carbon (Flagg & Taylor, 2011; Whitford et al., 2001). This situation seems to be growing and requires attention, as it can have negative effects on human health and well-being (International Panel for Climate Change, 2013).

Ecological planning approaches should be considered to provide environmentally sensitive urban development (Cetin, 2015). One apparent solution comes in the form of nature-based solutions (NBS) that are defined as actions, inspired by, supported by or copied from nature, that use features and complex system processes of nature, to achieve desired outcomes, while enhancing and maintaining the natural capital (European Commission, 2015). They promote the maintenance, enhancement and restoration of biodiversity and ecosystems, while addressing various concerns simultaneously (Kabisch et al., 2016; Somarakis et al., 2019) and providing multiple ecosystem services, supporting an environmentally sustainable development and socially resilience (Everard & McInnes, 2013; Somarakis et al., 2019). The benefits of NBS are increasingly recognized, and include improved quality of life and mental/physical health (Kenigerv et al., 2013), improved air quality, temperature reduction and storm water management (European Commission, 2015), urban compaction and real estate value appreciation (Roebeling et al., 2017). These benefits can be achieved by the implementation of, for example, green roofs, green walls, green spaces (e.g. parks and community gardens) and blue spaces (e.g. lakes and ponds). These solutions are sustainable, cost-effective and multi-purpose, and help to define a path towards a more resource-efficient, competitive and greener economy (European Commission, 2015).

Most studies focus on the short-term impacts of NBS, defined as the impacts in the area surrounding the NBS that occur in the short-term after their implementation, such as improvement in air quality (European Commission, 2015; Marando et al., 2016), mental and physical health benefits (Kabisch et al., 2016; Keniger et al., 2013) and urban cooling (Feyisa et al., 2014; Meerow & Newell, 2017; Ng et al., 2012; Rafael et al., 2017; Shih, 2017; B. Zhang, et al., 2014; Y. Zhang et al., 2017), especially in urban environments. These impacts are effective at macro- and micro- levels. The medium- to long-term impacts of NBS, defined as the impacts in a larger area surrounding the NBS that happen in the medium- to long-term, are however less well known and studied. Because of the, in particular, cultural services and values provided by some of the more attractive NBS (such as retention parks and day-lighted rivers), households are attracted to the areas surrounding these NBS and, hence, cities are expected to become more compact, more densely populated as well as suffer an increase in rental values and gentrification (Oh et al., 2017; Roebeling et al., 2017; Saraiva et al., 2017; Sushinsky et al., 2017; Wolch et al., 2014). These effects depend on various factors, such as quality and size of the intervention, the location of the intervention and the social classes attracted to the intervention area (Roebeling et al., 2017), and may, in turn, attenuate some of the abovementioned short-term impacts from NBS.

Although there have been studies focused on both the short term and medium- to long-term impacts of NBS, the relevance of this study comes from the fact that there are no studies evaluating the interconnecting and/or cumulative effects of NBS on, both, urban heat and urban sprawl/compaction, making this a multi-disciplinary research work that is essential to comprehend the complex urban environment It can also add knowledge to the debate on whether urban sprawl or urban compaction is better for a city (Williams et al., 2013).

NBS are likely to change the properties of the land surface locally and, due to the feedbacks between the surface and the atmosphere, the surface energy balance and the partitioning between latent and sensible heat fluxes may thus also change – with consequences for temperature and moisture storage of the surface and near-surface air (Wilson et al., 2002). For example, vegetation established around a building can alter the energy balance and cooling energy requirements of the building, while the establishment of green spaces throughout the city (e.g. in the form of urban parks or natural reserves) can modify the energy balance of the entire city through adding more evaporating surfaces (Chen & Wong, 2006). In this sense, and due to the importance of the surface energy balance to the urban microclimate, there is a need to assess the implications of the European NBS strategy on urban heat. This type of knowledge is vital to address the challenges of urban planning and sustainability, for example for managing resources, mitigation and adaptation to climate change, and air pollution (Lietzke & Vogt, 2014).

The objective of this study is to assess the short-term and medium- to long-term impacts of selected NBS on urban heat, by analysing the changes in land use and population density and their effect on the surface energy balance. To this end, an integrated modelling approach, composed of a coupled meteorological and urban energy balance model (WRF-SUEWS) and a hedonic pricing simulation model (SULD), is used to simulate meteorological fields and energy/heat fluxes as well as population dynamics and urban compaction, respectively. The WRF model is used to estimate the meteorological variables needed to force SUEWS as well as to characterize the land cover and the related parameters; SUEWS is used to estimate each component of the energy balance. Both models are widely used, have been extensively tested and shown to produce robust and realistic results (Järvi et al., 2011; Monteiro et al., 2015; Rafael et al., 2016; Ward et al., 2016). Besides that, the SUEWS model was selected as urban energy balance model for three main reasons: i) it simulates the latent heat flux considering irrigation and runoff processes, and it has an integrated approach to the inclusion of urban vegetation, factors pointed as extremely important for energy fluxes modelling by the International Urban Surface Energy Balance Model Comparison Project (Grimmond et al., 2010); ii) the surface resistance scheme is parameterized explicitly for urban areas rather than using schemes originally designed for non-urban areas (Järvi et al., 2011); iii) the model has the ability to estimate the anthropogenic heat flux based on population density (Järvi et al., 2011).

SULD is used for the assessment of the environmental-economic impacts of population growth and urban development, the socio-economic impacts of location-specific urban green/blue space and infrastructure projects on urban development patterns (Roebeling et al., 2014, 2017), the impacts of urban sprawl on the real estate market and the economic and social benefits of green and blue spaces in changing urban patterns, making it ideal for this study. A case study is provided for NBS in the city of Eindhoven in The Netherlands, including river-daylighting, de-paving and green/blue space requalification.

The remaining of this paper is structured as follows: Section 2 presents the case study selected for this study, describes the modelling setup and data requirements, and the scenarios considered to answer the study objectives; Section 3 is devoted to the presentation of results and discussion of the main findings; finally, Section 4 draws the main conclusions, and reflects on the limitations of the current study and on future research needs.

2. METHODOLOGY

This section starts with characterizing the case study, followed by the description of the modelling setup and integrated modelling approach, including a detailed description of the individual models and data requirements, and finally, a description of the scenarios to be modelled.

2.1. Case Study

A case study is provided for the city of Eindhoven, located in the south-east of the Netherlands, and characterized by strong economic and demographic growth (Westerink et al., 2017) as well as rates of urban sprawl (EEA, 2016). Eindhoven is the fifth largest city in the Netherlands, with 224,755 inhabitants in 2016 and an area of 89 km^2 (Centraal Bureau of Statistiek (CBS), 2017), resulting in a population density of ~2530 inhabitants.km^2. It is situated at the confluence of two small rivers (Gender and Dommel) and various streams.

The Eindhoven case study focuses on the inner-section of the city of Eindhoven, which comprises 23 neighbourhoods and is surrounded by a circular road (Figure 1). Eindhoven consists mostly of urban area and is serviced by 4 highways (A2, A58, A67 and A270), 8 provincial roads, a railway station and an international airport. Twenty-one environmental amenities can be found in the city (numbered in Figure 1), including 6 urban parks, 4 neighbourhood parks, 10 local parks and water bodies. There are 12 urban centres (marked with white dots in Figure 1), including a central shopping centre, five local shopping centres, three industrial areas, a railway station, a town hall and the Technical University of Eindhoven (Roebeling et al., 2014).

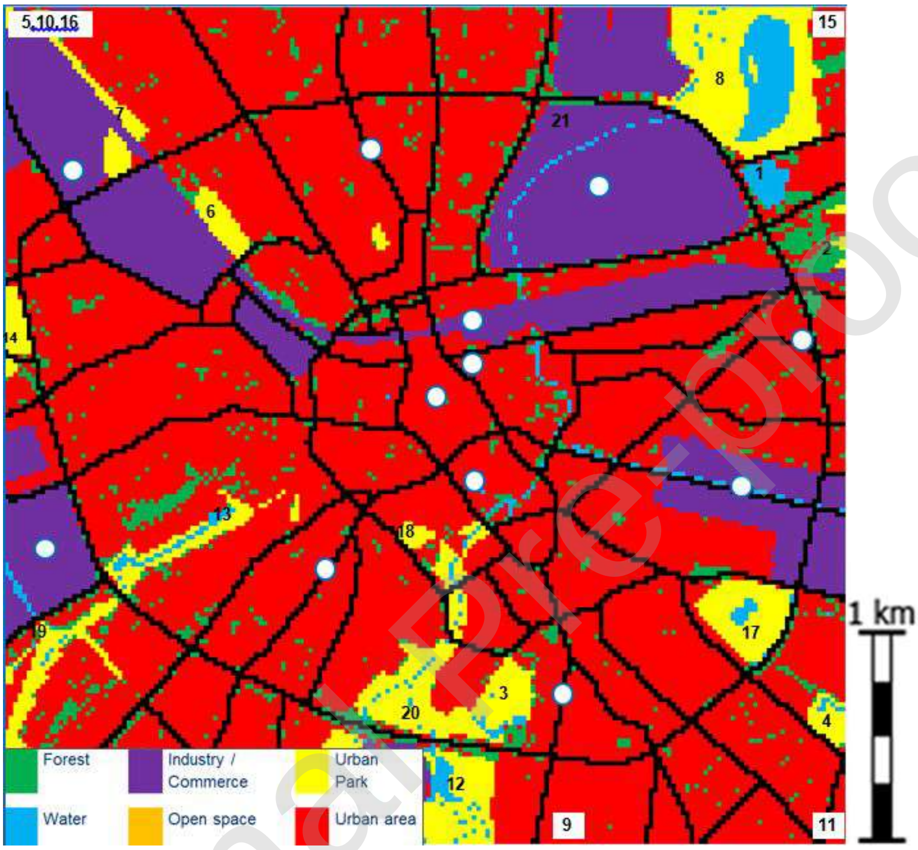

Figure 1. Land use in and around the city of Eindhoven (source:(Roebeling et al., 2014); Colour print).

2.2. Modelling setup

Most modelling studies assess the short-term impacts of NBS on urban heat and well-being. However, the medium- to long-term impacts of NBS are not well addressed in literature, or they are represented in a disconnected way. In this work, an integrated modelling approach is used to simulate the urban-surface atmosphere exchanges and the socio-economic exchanges caused by the implementation of NBS. Meteorological fields and energy/heat fluxes are modelled using WRF-SUEWS (Järvi et al., 2011), and population dynamics and urban sprawl are modelled using SULD (Roebeling et al., 2017). As shown in Figure 2, the short-term impacts from NBS on temperature and heat fluxes are assessed using WRF-SUEWS (based on meteorological variables, land use and urban parametrizations), while the medium- to long-term impacts from NBS on temperature and heat fluxes are assessed using WRF-SUEWS based on SULD scenario simulation results (based on land use and population density data).

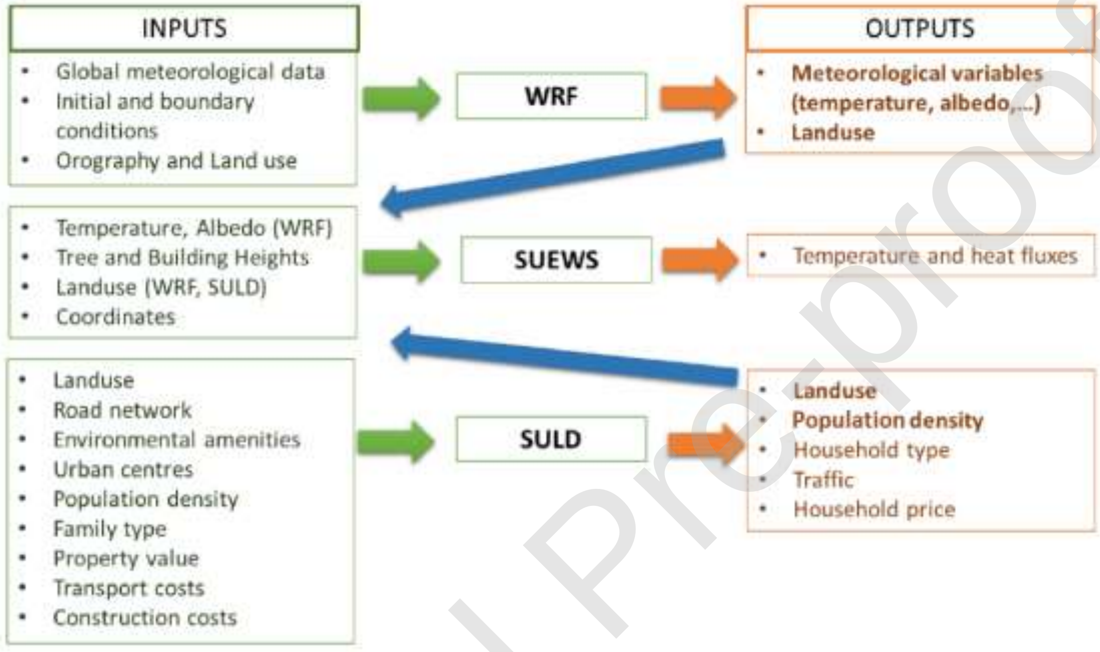

Figure 2. Relationship between WRF-SUEWS and SULD models inputs and output data (Black and white print).

2.2.1. WRF

For this study, the WRF v3.7.1 (Weather Research and Forecasting) model is applied. WRF is a three-dimensional, compressible and non-hydrostatic meteorological model (Skamarock et al., 2008) that has been used in a wide range of applications and research and found to have good performance regarding temperature and precipitation. The meteorological model (WRF; (Grell et al., 2005)) is applied to three domains, using two-way nesting techniques for the study period of July of 2013. This study period was selected because the year 2013 averages the period of 2012-2015, in terms of temperature, that represents the present time. As for the month, July was selected because it is the month with highest temperatures. Figure 3 shows the model domain setup: Domain 1 (D1) at 25-km grid spacing, covering Europe and a part of North-Africa (180x155 horizontal grid cells); Domain 2 (D2) at 5-km grid spacing, covering The Netherlands and parts of Germany, France, Belgium and the United Kingdom (96x91 horizontal grid cells); Domain 3 (D3) at 1-km grid spacing, covering Eindhoven (51x41 horizontal grid cells). The meteorological initial and boundary conditions for WRF are initialized with ERA-Interim data from the European Centre for Medium-Range Weather Forecasts (ECMWF) global analysis, with a horizontal resolution of 1ºx1º and with a temporal resolution of 6-hour intervals.

The WRF model configuration for the 1-km grid spacing includes the Noah land surface model (Tewari et al., 2016), the Rapid Radiative Transfer Model (RRTM) longwave radiation scheme (Mlawer et al., 1997) and the Mellor-Yamada-Janjic planetary boundary-layer scheme (Janjic, 2002). It considers 38 vertical layers, with the lowest model sigma level at approximately 10-m of height and model top at 50 hPa. It uses the 24 land use categories from the United States Geological Survey (USGS) to remap the Corine Land Cover data (http://land.copernicus.eu/pan-european/corine-land-cover).

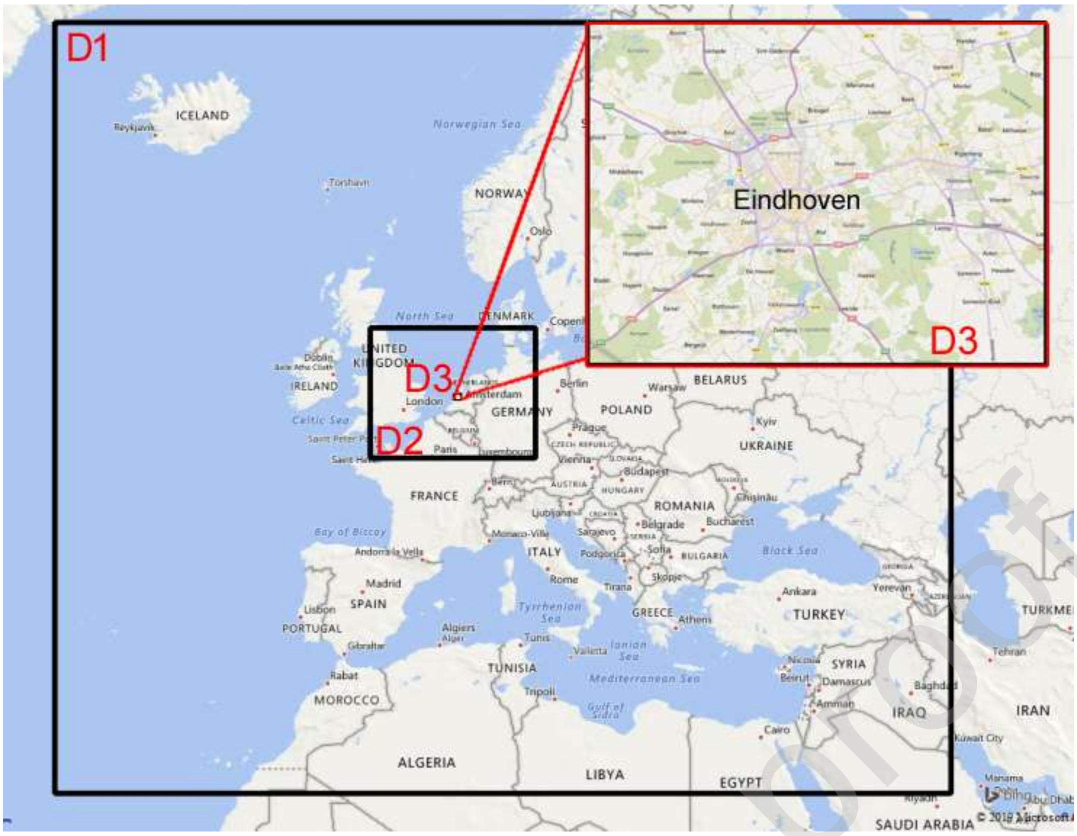

Figure 3. WRF meteorological modelling domains, D1: Europe and part of North-Africa; D2: The Netherlands, and other parts western Europe; D3: The Netherlands (Black and white print).

The WRF model is one of the most widely used models employed in climate research and weather forecasting in the world and has been extensively tested and evaluated for different European study areas, producing robust and realistic results. To guarantee the quality of the results, the model performance is evaluated by comparing modelled and measured data for the study period (July of 2013), on a daily basis. Only temperature is considered in the analysis as there is a lack of data for other variables such as radiation and wind. The statistical analysis, exhibits a good model performance with a correlation factor (r) greater than 0.9, a reduced BIAS less than 0.5 ºC, and a root-mean-square error close to 1.

Only one month is selected for this analysis as the focus of this study is on the evaluation of the short-term and medium- to long-term impacts of NBS on heat fluxes and, hence, a temporal analysis is not relevant at this stage. The measured average temperature is

19.99 ºC and the modelled average temperature is 19.57 ºC, which results in a RMSE of 1.113, and r of 0.935 and a Bias of 0.423

2.2.2. SUEWS

The Surface Urban Energy and Water Balance Scheme (SUEWS) model can simulate both energy and water fluxes at the neighbourhood scale and is used to simulate the urban fluxes for the case of Eindhoven. SUEWS requires a relatively small set of input data, such as common hourly meteorological variables (mean wind speed, relative humidity, air temperature, air pressure, precipitation and incoming shortwave radiation), the study area surface fractions (provided by OSM), building and tree heights (provided by the municipality of Eindhoven), albedo, emissivity, moisture storage capacity and population density (provided by SULD). In return, it calculates complete energy balances (radiative, convective and conductive fluxes) at the interface between the urban surface layer and the atmosphere (Järvi et al., 2011).

SUEWS utilizes several sub-models to minimize the number of variables required. These sub-models calculate the energy heat fluxes (net all-wave radiation, Q^*; anthropogenic heat flux, Q_F; turbulent sensible heat flux, Q_{H}; latent heat flux, Q_E; net storage heat flux, ΔQ_S) and provide an initial estimation of the atmospheric stability. Urban heat fluxes and urban microclimate interconnect in different ways. Sensible heat is the energy carried by the atmosphere in its temperature and latent heat is the energy lost by evaporation of surface water. The latent heat of the water vapour converts to sensible heat in the atmosphere through condensation that, in turn, returns to the surface in the form of precipitation. If soil water is not enough, the extra radiative energy beyond what is required to evaporate this water will heat the surface, causing higher temperatures. Vegetation can help prolong the availability of soil water and thus, increase the latent heat flux and that can, in turn, result in lower temperatures (Rafael et al., 2016). A more detailed explanation can be found in (Järvi et al., 2011).

SUEWS (version 2014b;(Järvi et al., 2011)) is applied to a fourth domain, D4 at 1-km grid spacing, a sub-domain of D3 covering the centre of Eindhoven (4x4 horizontal grid cells), corresponding to the study area (Figure 4). The meteorology inputs are supplied by WRF. Due to its formulation and approach, SUEWS must be applied to each one of those 16 grid cells. SUEWS's parameterization by Rafael et al. (Rafael et al., 2017) for the city of Porto is adapted for the city of Eindhoven, which included changes to land use cover fractions, albedo, population density and precipitation. The WRF-SUEWS modelling system has been applied successfully to the city of Porto (Portugal) and verified against measured data (Rafael et al., 2017, 2019).

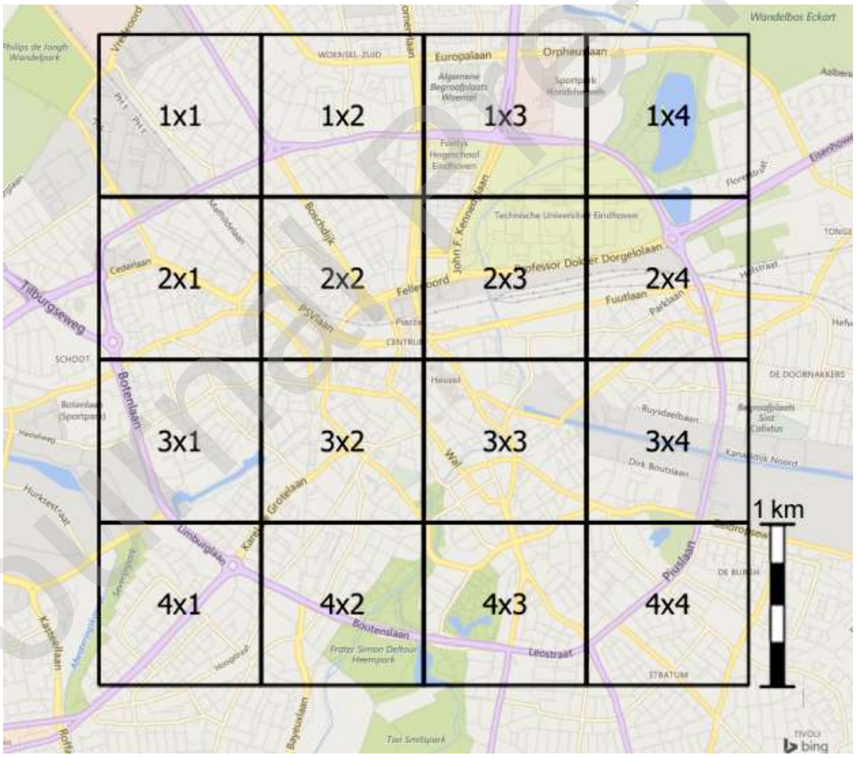

Figure 4. Sub-domain 4, which includes the city of Eindhoven, composed of 16 1kmx1km cells (Black and white print).

2.2.3. SULD

SULD is a GIS-based hedonic pricing simulation model, based on an analytical urban-economic model with environmental and urban amenities, developed to assess the impacts of green/blue space, infrastructure and social-economic scenarios on the location of residential development, population density, housing quantity, living space, and real estate values as a function of distance to urban centres and environmental amenities (Roebeling et al., 2017). It has also been used to assess the environmental-economic impacts of population growth and urban development on marine ecosystems (Roebeling et al., 2007).

The model is divided into a "demand" side, and a "supply" side (Roebeling et al., 2007). The demand side (Eq. 1) is represented by households and their preferences for a certain set of goods, services, residential space (S) and environmental amenities (e). Households maximise their utility (U) at a particular location (i), depending on their preferences (η; ε) and distance to environmental amenities, and subject to a budget constraint (income y) that is split between housing expenses ($p_i^h S$), goods and services (Z), and transportation between the location (residential area) and the closest urban centre ($p_x x$), such that:

$$Max_{S_i,Z_i} U_i(S_i, Z_i) = S_i^{\eta} Z_i^{(1-\eta)} e_i^{\varepsilon} \quad (1)$$

$$\text{subject to } y = p_i^h S_i + Z_i + p_x x_i \quad (1a)$$

The supply side (Eq. 2) is represented by real-estate developers that maximise their profit (π) by trading off returns from housing development density ($p^h D$) net of associated development costs ($l + D^{\eta}$) and subject to households' willingness to pay for housing, such that:

$$Max_{D_i} \pi_i(D_i) = p_i^h D_i - \left(l_i + D_i^{\eta}\right) \qquad (2)$$

$$\text{with } D_i = n_i S_i \qquad (2a)$$

where p_i^h is the rental price of housing, l_i is the opportunity cost of land, D_i^{η} is the construction cost function, η is the ratio of housing value to non-land construction costs, and where n_i is the household density.

Equilibrium (Eq. 3) between demand and supply occurs when supply for housing equals demand for housing, and the equilibrium land rent price (r_i) is given by:

$$r_i = \left(\frac{k e_i^{\varepsilon}(y - p_x x_i)}{u}\right)^{\frac{\eta}{\mu(\eta-1)}} \qquad (3)$$

$$\text{with } k = (\mu m)^{\mu}(1-\mu)^{(1-\mu)} \qquad (3a)$$

Hence, development patterns for a certain population size and composition are determined given the location of urban centres and environmental amenities (Roebeling et al., 2017).

The SULD study area consists of the inner-city ring of Eindhoven (see Figure 1), comprising 23 neighbourhoods. It encompasses an area of 4.07 km by 4.07 km (=16.56 km^2), covered by a grid layer of 185 by 185 (=34,225) cells of 22 m by 22 m and coinciding with domain D4. SULD has been parameterized, calibrated and validated for the city of Eindhoven (Netherlands) by (Roebeling et al., 2014), and is used to assess the impacts of NBS on land use and population density. SULD results were used as input for SUEWS application as described in section 2.3.

2.3. Scenarios description

To evaluate the short-term and medium- to long-term impacts of the NBS to be implemented, two main scenarios are simulated: i) Baseline scenario, that models the baseline in terms of temperature and heat fluxes, based on the current characteristics of land use; ii) NBS scenarios, that model the implementation of the NBS. Within the NBS scenarios, three different impacts are developed to allow for the assessment of the short-term and/or medium- to long-term impacts of NBS on urban heating. In particular:

- The short-term impact (S) aims at representing the short-term impacts on urban temperature and heat fluxes due to the implementation of the NBS (i.e. corresponding to a change in land use);

- The medium- to long-term impact (ML) aims at representing the urban compaction that occurs due to the implementation of the NBS, and that result in a change in land use and population density (i.e. these indicators are representative of the changes in urban form); and
- The short-term and medium- to long-term impact (S+ML) aims at representing the combined effects of the short-term and medium- to long-term impact scenario.

To allow for the comparison between scenarios and the different impacts, and to clearly identify the influence of NBS, the meteorological conditions are kept constant across all scenarios. Hence, only the land use cover fraction and population density are changed according to the scenario under analysis.

For the Baseline scenario, the area surface fractions are required to represent the land use. These are adapted from the ones developed for the city of Porto in Rafael et al. (2017), based on existing built and water areas for Eindhoven. These surface fractions include: build: surface fraction of buildings; paved: paved areas; unman: unmanaged land: ET_sh: evergreen trees; DT_sh: deciduous trees; UG: non-irrigated grass; IG: irrigated grass; and wtr: water.

For the S impact, land use cover fractions were changed while the remaining parameters, such as population density and meteorological conditions, were kept constant. So, for each cell, the area of NBS implemented is calculated and divided according to the type of land use it refers to. For example, “Daylighting river” adds blue area (water) and “De-paving” adds green area (evergreen trees, deciduous trees, unirrigated and irrigated grass) while decreasing the built and/or and paved area.

The nature-based solutions modelled are represented in Figure 5, and include Daylighting the river Gender (A-D, open the river in road- and building-side areas), De-paving (E-N, converting impermeable parking lots and office buildings into parks and/or permeable parking spaces) and Requalifying the Genderplantsoen park (O, improving the existing built and natural infrastructures and cleaning the polluted soil, thus increasing the ecological value of the park) (Roebeling et al., 2014).

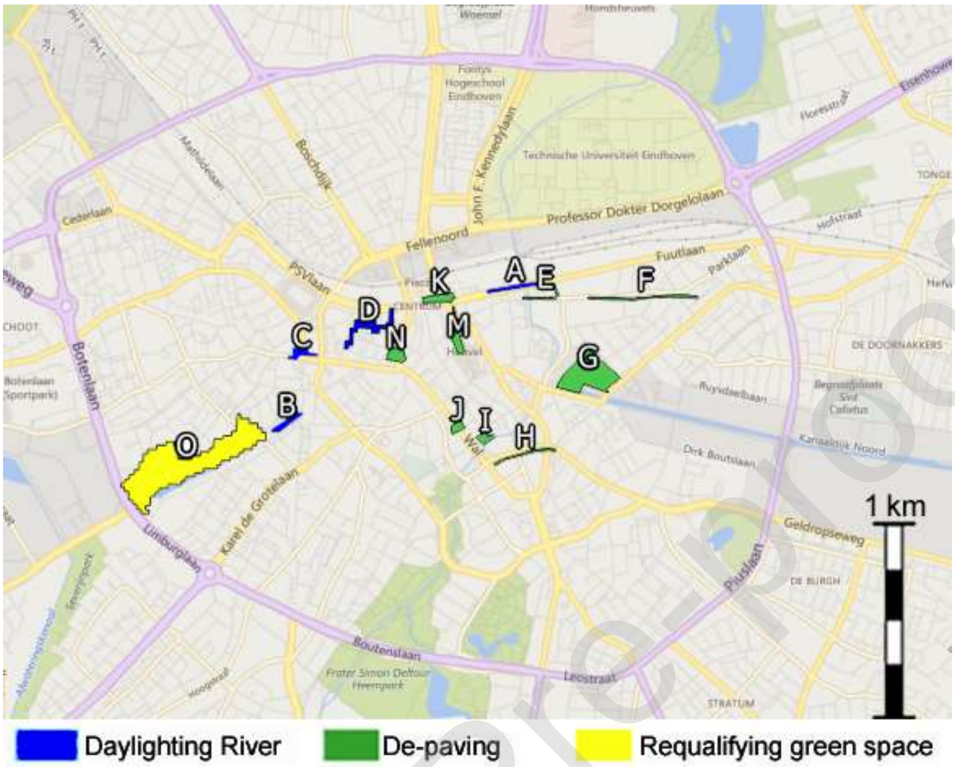

Figure 5. The 15 NBS (A to O) planned to be implemented in the case study area (Roebeling et al., 2014) (Colour print).

For the ML impact, both land use and population density were changed. These changes were made according to the results obtained from the SULD model simulations, as developed in Roebeling et al. (Roebeling et al., 2017). These results, shown in Figure 6, represent the differences between the Baseline scenario and the NBS scenarios and are adapted to the domain D4.

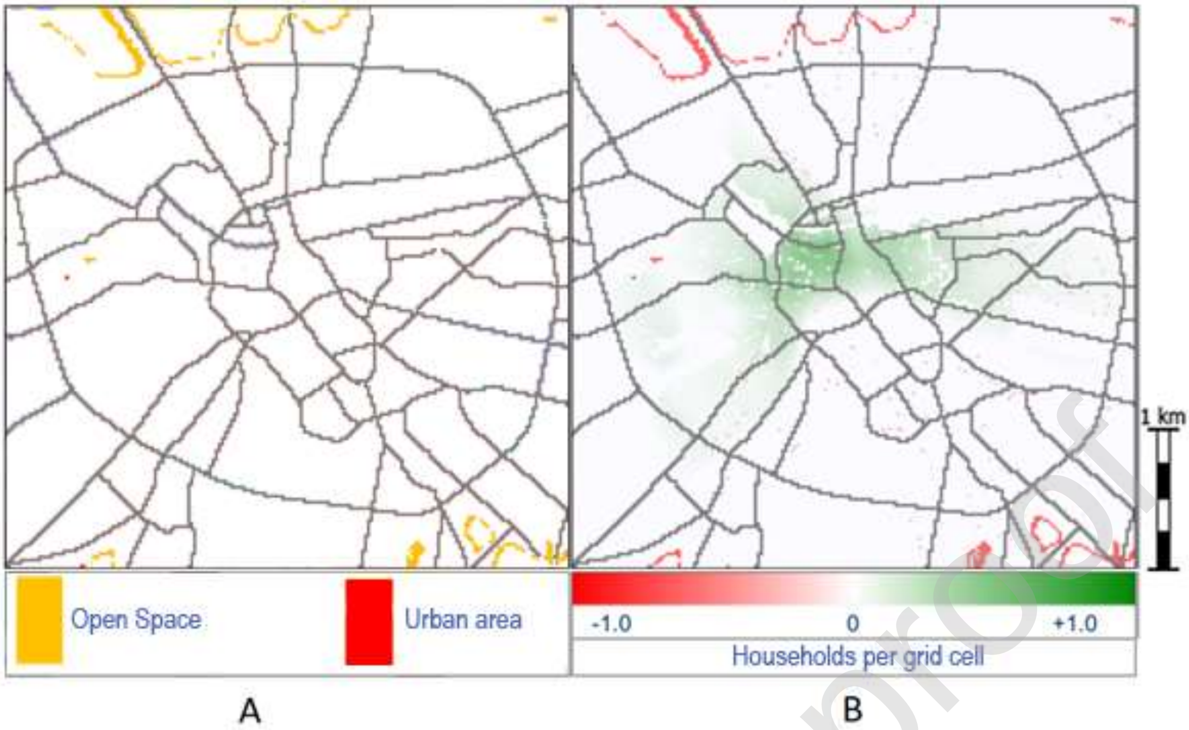

Figure 6. SULD scenario simulation results, representing changes in land use (A), and household density (B), after the implementation of NBS (source: (Roebeling et al., 2014) (Colour print).

From Figure 6A it can be observed that there is an increase in open space in the periphery of the city, and from Figure 6B it can be observed that there is an increase in population density in the areas surrounding the more attractive NBS (note that the average household size in Eindhoven, shown in Figure 6, is 2.16). These changes are a result of the establishment of the NBS, which attracts households to the more attractive new or requalified green/blue spaces in the centre of Eindhoven. In sum, there is an increase in population density in the centre of Eindhoven, where the NBS are implemented, and a decrease in the urban area in the periphery.

Table i presents the changes to land use and population density resulting from the application of the NBS. In green, the short-term impacts that represent the NBS implemented (green and blue spaces) and in blue, the medium- to long-term impacts, that represent the urban compaction (loss of built area and population density in the periphery and increase in population density surrounding the NBS). In the most northern and southern cells, it is observed a decrease in built area and an increase in non-irrigated grass areas, as households move from the peripheral areas to the areas surrounding the more attractive NBS – as reflected in the decrease in population density. In the centre cells, an increase in water, evergreen and deciduous trees, non-irrigated and irrigated grass areas (due to the establishment of NBS), and a decrease in paved area (mainly due to the NBS de-paving) are verified.

Table i. Land use fraction and population density changes for the short-term impact scenario (green) and the medium- to long-term impact scenario (blue).

Grid cell[1]	build[2]	wtr[2]	unman[2]	ET_sh[2]	DT_sh[2]	UG[2]	IG[2]	paved[2]	population density
1x1	-5.41%					5.41%			-8.89%
1x2	-2.65%					2.65%			-3.79%
1x3	-1.23%					1.23%			-1.80%
1x4	-0.38%					0.38%			-0.67%
2x1	-0.23%					0.23%			0.35%
2x2		0.46%		0.20%	0.20%	0.07%	0.06%	-0.98%	10.35%
2x3		0.68%		0.39%	0.39%	0.14%	0.12%	-1.72%	6.10%
2x4				0.14%	0.14%	0.05%	0.04%	-0.37%	1.15%
3x1									1.76%
3x2	0.28%	1.27%		0.06%	0.06%	0.02%	0.02%	-1.71%	4.61%
3x3				2.03%	2.03%	0.70%	0.63%	-5.40%	0.89%
3x4									0.53%
4x1	-0.74%			0.02%	0.02%	0.70%	0.01%		-0.86%
4x2	-0.05%					0.05%			-0.13%
4x3	-1.84%					1.84%			-3.03%
4x4	-3.88%					3.88%			-5.83%

Notes: [1] See Figure 4.

[2] build = surface fraction of buildings; wtr = water; unman = unmanaged land: ET_sh = evergreen trees; DT_sh = deciduous trees; UG = non-irrigated grass; IG = irrigated grass; paved = paved areas. As per (Rafael et al., 2017) (Black and white print).

3. RESULTS AND DISCUSSION

This section is divided into two parts: Firstly, the energy fluxes assessment that includes the results obtained from the application of the WRF-SUEWS-SULD modelling system for the Baseline and NBS scenarios. Secondly, the caveats and limitations of the case study and the applied methodology.

3.1. Energy fluxes assessment

The results obtained from the application of WRF-SUEWS-SULD modelling system for the Baseline as well the NBS scenario were treated and analysed in terms of the spatial distribution of heat flux monthly averages (Figure 7) and daily profiles (Figures 8 and 9) for the month of July 2013.

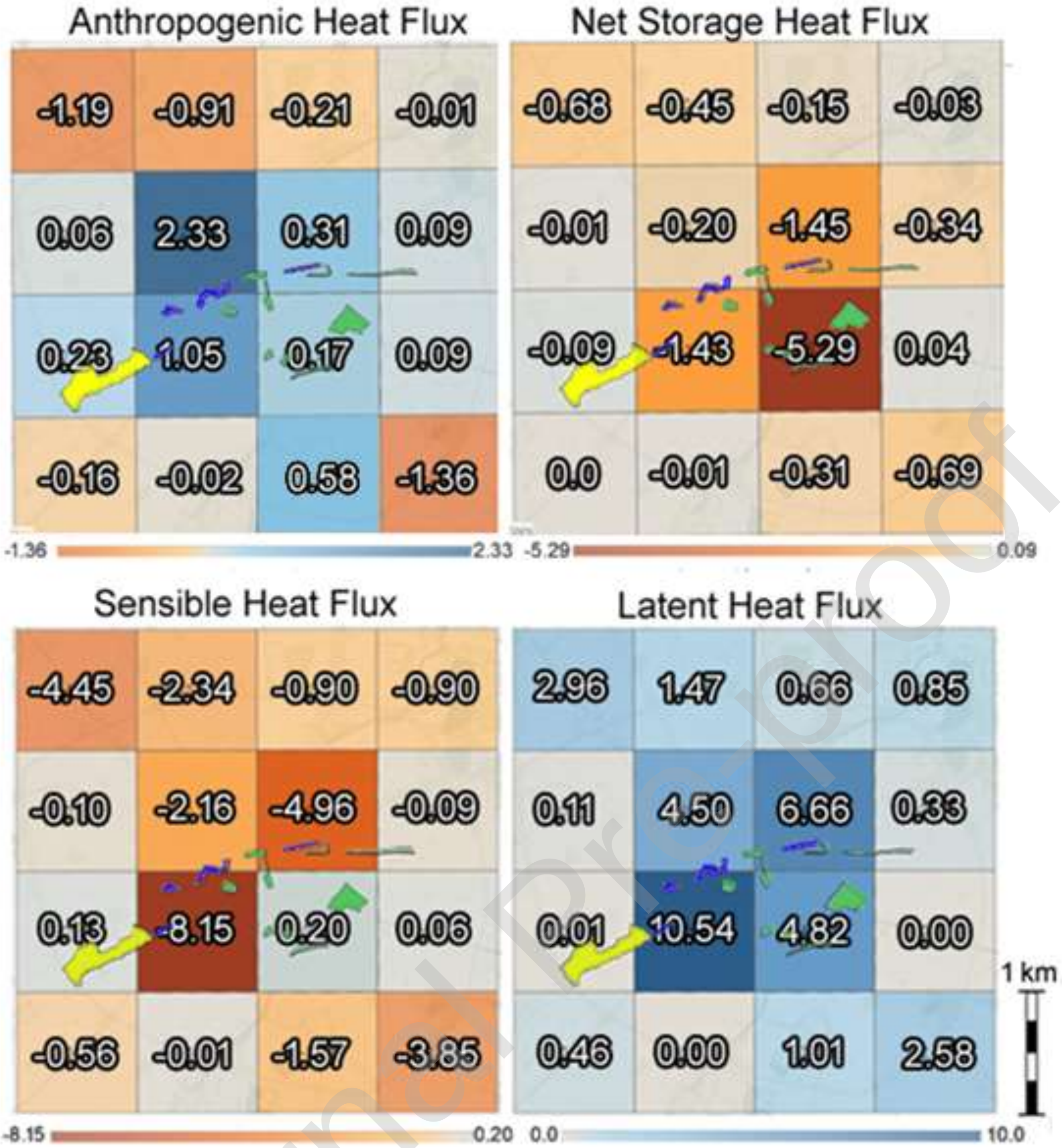

Figure 7. Monthly (July) differences in average heat fluxes (W/m^2) for the short-term and medium- to long-term impact (S+ML), relative to the Baseline scenario (Colour print).

In the areas where the NBS are established there is a reduction in the net storage and sensible heat flux (see Figure 7) due to the increase in permeable, vegetated and shaded areas and, especially, blue areas that have a notable impact on these fluxes (as shown in previous studies, such as Coutts et al., 2007; Rafael et al., 2017). The net storage heat flux also decreases with the increase in population density, as the net storage flux given by the sum of all-wave radiation and anthropogenic heat flux (Grimmond & Oke, 1991; Järvi et al., 2011;

Ward et al., 2016). The anthropogenic heat flux, which increases with population density (Grimmond & Oke, 1991), increases due to the attraction of households from the urban fringe to the area surrounding the NBS (urban compaction). Due to the decrease in built area, and subsequent increase in areas for evapotranspiration (vegetation and blue areas), the latent heat flux increases - reinforcing the strong dependence on the existence/absence of green/blue (Rafael et al., 2017). The size in water bodies directly affects the magnitude of the turbulent heat flux, and consequently the energy balance. As the size of the water body increases, the magnitude of latent heat flux increases as well as the evaporative cooling effect through the evaporation of water (Rafael et al., 2017).

For the areas where the NBS are not established, all changes result from the medium- to long-term impacts. Hence, the decrease in the anthropogenic, sensible and net storage heat flux derive from urban compaction (i.e. decrease in built and paved areas) as well as the decrease in population density in the periphery of the city (i.e. reduced anthropogenic emissions).

Energy fluxes vary during the day, following the diurnal cycle of solar heating and urban activities. Figures 8 and 9 present the daily energy fluxes profiles for the cells where NBS are and are not established, respectively.

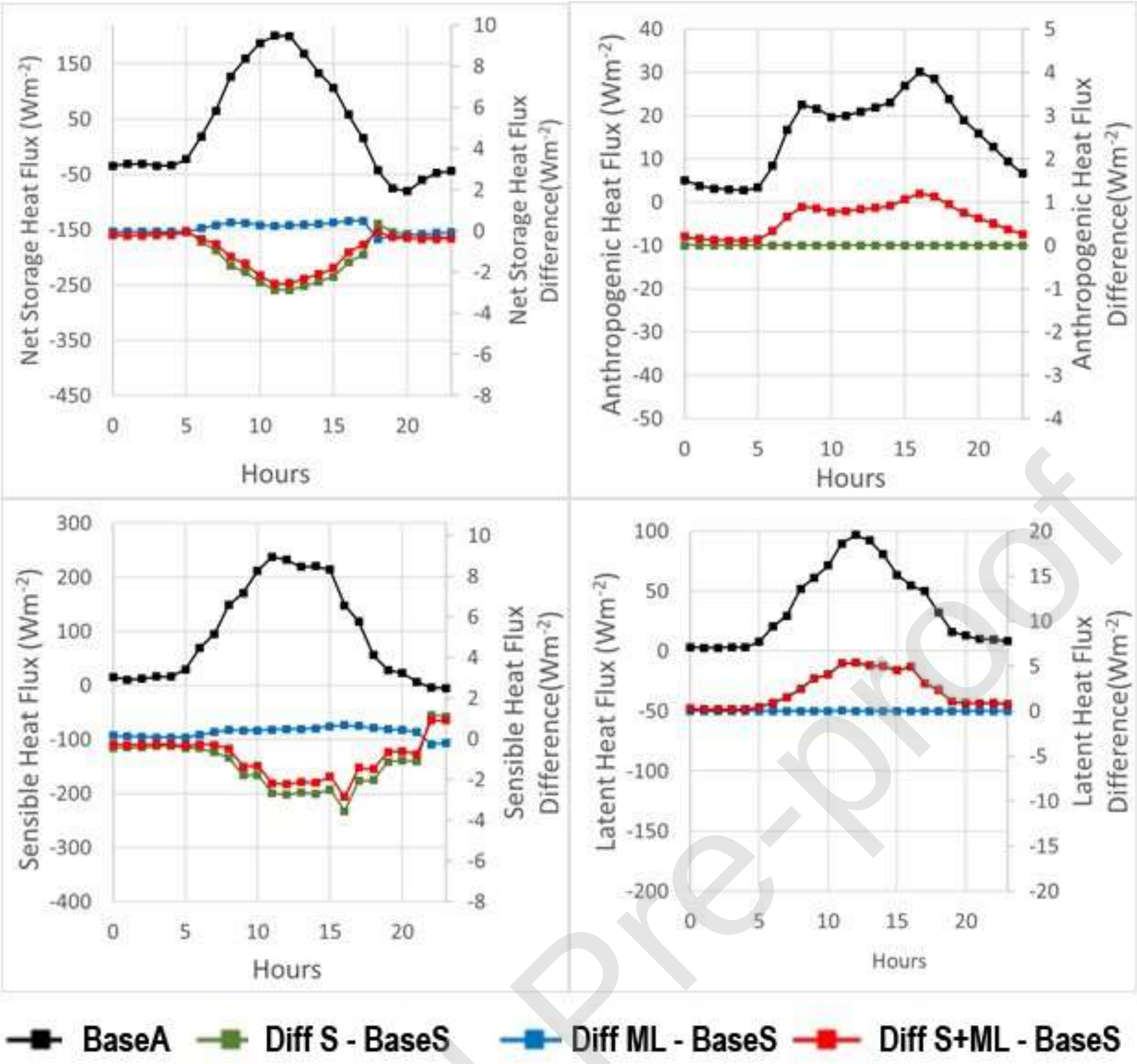

Figure 8. Hourly average heat fluxes over the month (July) across the cells where NBS are established, for Baseline (BaseS; black line), short-term (S; green line), medium- to long-term (ML; blue line) and short-term+ medium- to long-term (S+ML; red line) impacts (Colour print).

For the cells where the NBS are established (Figure 8) the net storage heat flux and the sensible heat flux show a small decrease for S and S+ML impacts, and a small increase for the ML impact. This increase for the ML impact, due to the increase in built area (associated with the urban compaction) reduces the effect of the S impact. Regarding the anthropogenic heat flux and the latent heat flux, these show an increase and follow the pattern of the Baseline scenario (higher values during the day) due to, respectively, the increase in population density (caused by the urban compaction), and the increase of permeable areas.

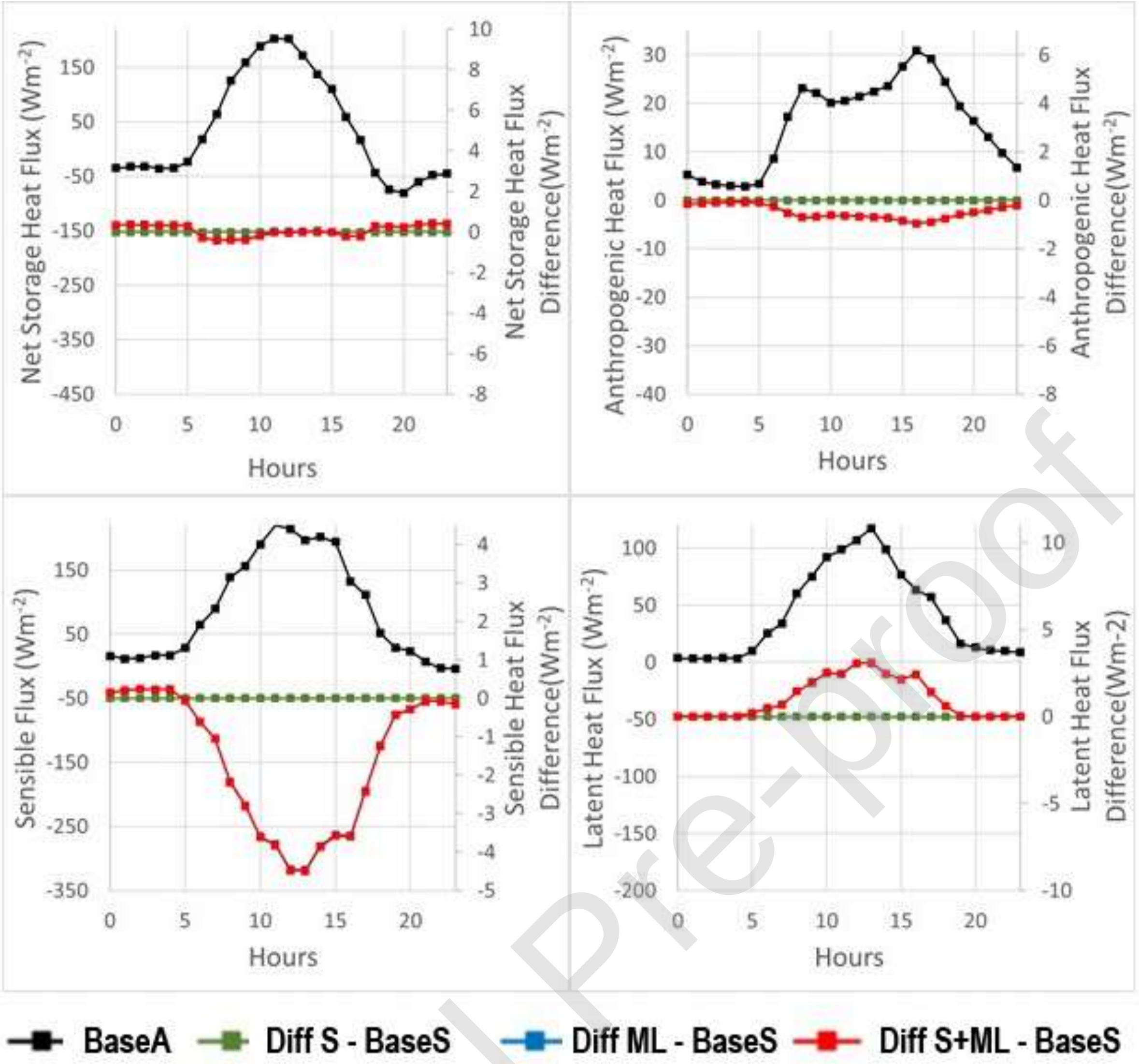

Figure 9. Hourly average heat fluxes over the month (July) across the cells where the NBS are not established, for the Baseline (BaseS; black line), short-term (S; green line), medium- to long-term (ML; blue line) and short-term+ medium- to long-term (S+ML; red line) impacts (Colour print).

For the peripheral cells (Figure 9), the differences, as previously mentioned, are smaller due to the absence of the effect of the S impact. So, for the ML impact, the anthropogenic heat flux shows a decrease during the day, because there is a decrease in population density and, therefore, less cooling energy requirements. Because of the connection with the anthropogenic heat flux, the net storage heat flux exhibits a small increase during the night and a small decrease during the day. For the sensible heat flux, there is a decrease during the day. Finally, for the latent heat flux, there is an increase due to the ML impact, also during the day.

As shown in Figures 8-9, the sensible heat flux presents higher values across all fluxes, and are in line with the values observed in more densely built areas (Coutts et al., 2007). However, SUEWS underestimates the latent heat flux and causes an overestimation of the sensible heat flux (Järvi et al., 2011). This dominance of the sensible heat flux is expected because the study area is densely built and characterized by extensive impervious surfaces (including buildings and pavements) where runoff water drains quickly, and thus, leaves less surface water available for evapotranspiration.

One aspect that is common to all fluxes is that the differences are relatively small. This is most likely due to the size of the established NBS. In similar studies, where larger NBS are simulated, the differences are also bigger (Rafael et al., 2017). Finally, with a reduction in the sensible heat flux, it is expected that the temperature will also reduce, as temperature is a measure of the air's sensible heat content. However, the reduction in sensible heat flux is very small and, hence, the changes in temperature would also be small.

Table ii. Summary of changes in heat fluxes for each scenario and impact, across the cells where NBS are established (A) and across the cells where NBS are not established (B).

	anthropogenic heat flux		**net storage heat flux**		**sensible heat flux**		**latent heat flux**	
	A	B	A	B	A	B	A	B
S	-	-	↓	-	↓	-	↑	-
ML	↑	↓	↑	↓	↑	↓	↑	↑
S+ML	↑	↓	↓	↓	↓	↓	↑	↑

Summarizing the results (see Table ii), it can be concluded that in the short term (S) and in the area surrounding the nature-based solutions, NBS are effective in reducing the net storage heat flux and the sensible heat flux (due to the increase in green and blue areas) while leading to an increase in the latent heat flux. In the medium- to long-term (ML; S+ML) nature-based solutions are expected to lead to urban compaction and an increase in population density surrounding the more attractive NBS. In the area surrounding the nature-based solutions, this leads to an increase in the sensible heat flux, net storage heat flux and anthropogenic heat flux – attenuating the short-term reductions in net storage heat flux and the sensible heat flux. In the periphery, however, there will be a decrease in sensible heat flux, net storage heat flux and anthropogenic heat flux (due to the decrease in built area and increase in vegetated area).

3.2. Limitations and challenges of the study

After the completion of this study, there are a few caveats that remain. First, the study addresses that cities are growing, and although this is true for Eindhoven, it is not true for every city. At least 370 cities over 100.000 inhabitants have shrunk at least 10% over the last fifty years, and that poses a challenge in planning as well (Pallagst et al., 2009), and should be taken into account when replicating this study.

Second, three different models are used, with different domains and different parametrizations. While all models carry uncertainties, the coupled modelling system WRF-SUEWS is well validated as are the three individual models. Third, SUEWS had a base parameterization for Porto and not Eindhoven, due to the lack of data, which could impact the results. However, the study focuses on the differences between scenarios, so this error is constant throughout and can be disregarded. Third, the size of the simulated nature-based solutions (approximately 0.107 km^2 in total) is relatively small as compared to the study area (16 km^2) and, hence, it is difficult to observe changes in, particularly, temperature. Finally, reduced anthropogenic emissions from reduced commuting distance, due to the relocation of households from the periphery to the area surrounding attractive NBS, are not considered and are likely to lead to reductions in anthropogenic heat flux as well as temperature. In order to handle the uncertainty that results from these issues, results should be interpreted in a qualitative way.

4. CONCLUSIONS

The aim of this study is to develop an integrated modelling approach, to help stakeholders understand the short-term, medium- to long-term, impacts of nature-based solutions (NBS) on urban heat fluxes in urban areas. It is important for planners and stakeholders to understand urban heat fluxes and how they vary with NBS so that they can anticipate the effects of different solutions and decide which solutions provide the best outcomes for stakeholders across the urban landscape.

This study provides evidence that NBS can be used to reduce the effects of urban heating and urban sprawl, depending on the type, size and location of NBS. Results show that, in the short-term, NBS have a local cooling effect due to an increase in green/blue spaces. In the medium to long-term, NBS have an urban compaction effect due to attraction of residents from peripheral areas to areas surrounding attractive green/blue spaces – attenuating the short-term local cooling effect while resulting in an overall urban cooling effect.

Three main policy implications can be derived from this study. First, the implementation of NBS can, when adequately designed, have positive environmental and socio-economic benefits and, hence, can be considered an opportunity to contribute to sustainable development. Second, the monitoring and evaluation of the planning and implementation process of the NBS, and the resulting consequences (intended or not) can provide an important framework for future projects, by providing crucial information, so that these can achieve their full potential, whether that is urban compaction, urban cooling or other. Finally, the implementation of NBS, when properly evaluated and accompanied by well-informed stakeholders, is conducive to a participatory planning process and public discussion. This type of process should be encouraged because it promotes transparency, that will ultimately lead to a clearer set of environmental and socio-economic goals that contribute to enhancing societal well-being. Studies like the one presented in this manuscript are essential to provide information to all the stakeholders involved in the NBS implementation process.

Declarations of interest

Declarations of interest: none

Aknowledgements

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