

Micro-climate of nature-based solutions in Stockholm Royal Seaport

Artur Branny^{a,*}, Erik Andersson^{a,b,c}, Timon McPhearson^{a,d,e,f}

^a Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden

^b Ecosystems and Environment Research Programme, University of Helsinki, Helsinki, Finland

^c Research Unit for Environmental Sciences and Management, North-West University, Potchefstroom, South Africa

^d Beijer Institute of Ecological Economics, Royal Swedish Academy of Sciences, Stockholm, Sweden

^e Urban Systems Lab, The New School, New York City, NY USA

^f Cary Institute of Ecosystem Studies, Millbrook, NY, USA

*Artur Branny, Stockholm Resilience Centre, Stockholm University, Albanovägen 28, 106 91 Stockholm, Sweden, artur.branny@su.se, art.branny@gmail.com

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1. Introduction

Extreme weather events are on the rise [1] and increasingly impacting cities and urban regions [2]. Urban populations are at risk from multiple types of extreme events including heat waves, drought, wildfires, extreme precipitation, and coastal storms. At the same time, urban greening and nature-based solutions (NbS) have emerged as key approaches to address climate and weather extremes [3] while also seeking to have a positive impact on urban social and environmental inequities. Both NbS and the concept of ‘green infrastructure’ have been used to elevate urban nature to the same status and treatment as other infrastructures like transportation or electricity [4]. Nature-based solutions, which are “actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits” [5] are increasingly seen and used as broad adaptation and mitigation strategies, and one that comes with additional benefits rarely associated with grey infrastructure [6,7]. However, framing NbS as infrastructure comes with a potential problem: If the fundamental differences between (semi) natural and built infrastructures - that the former is comprised of living entities - are lost in translation and NbS are treated like technical, engineered solutions, they may become vulnerable to the same weather events that they are expected to help cities cope with [8]. The functions NbS rely on are based on biological and ecological processes, many of them variable over time and strongly influenced by circumstances (life stage, vitality, community composition) (Grilo et al. in review). For example, different tree species are more or less sensitive to droughts that often coincide with heatwaves, making their contribution to urban cooling far from given [9–11]. Additionally, NbS interventions are often hyper-local and contain novel ecological entities, with unknown capacity to deal with different pressures and disturbances [12–14]. Thus, there is an urgent need to build knowledge around how, when, and under what circumstances different NbS

can be expected to perform as intended [15]. One step towards building, and then constantly updating, such knowledge is to establish practices for monitoring and evaluating NbS.

However, context always matters. Exposure and vulnerability to emerging weather patterns are unevenly distributed in space and across different groups of urban residents e.g. [16,17]. Such inequities call for targeted, context-specific, and reliable interventions that can address disproportionate impacts and risks. Natural spaces in cities fit inside the built environment and are impacted by social processes, human activity, and management choices of management. We conceptualise cities as complex social-ecological-technological systems (SETS) [7,18], and understanding any particular dynamic requires working with a range of social, ecological, and technological processes that both have their dynamics, but also interact with each other to produce sometimes complicated or even complex urban system dynamics that underpin any individual or collection observed pattern. For example, NbS performance such as the cooling provided by urban trees may depend on (i) a Social system component - whether local management is active, such as watering during hot or dry summer months, on the size and age of trees (young trees are more susceptible to drought or human impacts and also provide less shading and evapotranspiration than mature trees), on (ii) a Technological system component - whether nearby buildings shade trees and limit photosynthetic activity, as well on (iii) an Ecological system component - the quality of soil concerning nutrient availability and whether soil may be compacted by human activity or other means that may limit water infiltration. Thus, a host of Social, Ecological, and Technological factors can affect the performance of NbS, not only concerning urban trees for cooling but also NbS across a range of urban environments both within and across cities.

We suggest that monitoring NbS is essential to improve understanding of NbS performance and so will require measuring NbS performance across a range of social, ecological, and technological infrastructure contexts and potential impacts or filters [19] (Grilo et al. in review) in any given city or neighbourhood to improve our understanding and potential for effective management of how NbS function and deliver (or not) core benefits for climate and weather regulation.

To provide useful knowledge, monitoring of urban climate needs to be done with appropriate, context-driven spatial and temporal resolutions to match short timescales and hyper-local distribution of local flooding and heat wave events that are additionally modified by locally heterogeneous and complex urban infrastructure. Monitoring methods for assessing urban climate, and heat in particular, include modelling, remote sensing, mobile sensors, and ground-based sensors. Recent technological advancement has made high-quality ground-based sensors available at relatively low cost, enabling deployment in relatively large numbers. Deployment and experimental designs can also be very flexible thanks to self-sufficient, low-power operation, and widespread wireless connectivity to internet cloud services via long-range, low-frequency networks.

In this study, we focus on the use and utility of ground-based sensors for monitoring NBS performance over time. The study asks how different green elements, or potential NbS, perform under different conditions. To do so, it develops a novel analytical approach drawing on the high-resolution, continuous data from our sensor array. In the next sections we first describe the methodological and analytical approach and then discuss the outcomes, both in terms of NBS performance and the utility of ground-based sensors.

2. Material and methods

2.1. The case study - Stockholm Royal Seaport

Since 2010, the Stockholm Royal Seaport (SRS) district, situated north of the old town (see inset in Fig.1), has been the flagship of sustainable urban development in Stockholm [20]. It became a testbed for both piloting Stockholm's green area factor (GAF) and green space index (GSI) - a tool for ensuring that more green elements are built into development projects, more information in a later section. Also, through various collaborations with academia new ways of working and uses of new technology are being piloted [20]. As such, it provides a relevant natural experiment for evaluating whether such state-of-the-art sustainable districts and their NbSs provide sufficient climate adaptation and mitigation capacities. This work addresses this unmet need by evaluating the cooling performance of 5 distinct nature-based solutions and strengthening ecological-technological linkages and interactions.

2.2. Typology of Nature-based solutions and locations under investigation

The SRS district features a diverse range of green infrastructure elements. We investigate a representable subset that includes 5 distinct urban green elements - forest parks, green courtyards, rain beds, lawns, and green sedum roofs, and contrast them against non-green reference sites. Our categorisation is based on previous work [21] where NbSs can be distinctly placed on the green-grey spectrum [22]. We identified 3 locations for each NbS type that act as replicas, bringing the total number to 18 locations. The spatial distribution of the sites is presented in Figure 1a and photographs provide a visual representation of each NbS type. The weather stations were attached to lamp posts, at the height of 2 m, often at the boundary of NbS. All sensor locations fall within a circle with a 1 km diameter, covering an area of 78.5 ha. The average distance between sensors is 503 m. Site selection covers a wide range of the area-volume of vegetation - from low area-volume green roofs and lawns to moderate rainbeds and courtyards, to high forest parks, as summarised in table 1, including a wide spread in Green Space Index (GSI, see fig.1a inset) We focus on small-scale NbSs because they are widely used in cities and are considered as sufficiently green interventions. However, the knowledge about their performance in the Swedish urban context remains limited.

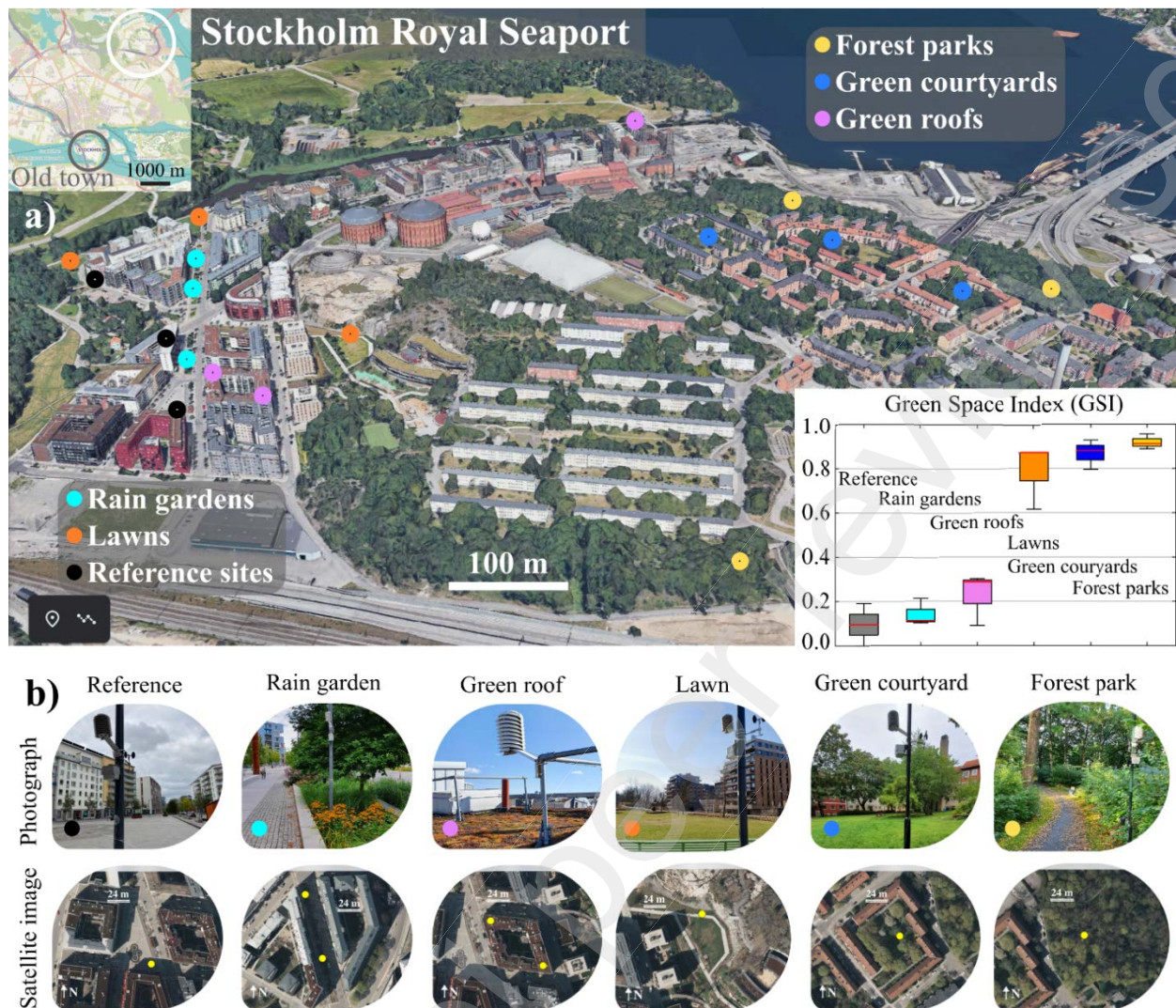


Figure 1. a) A 3D map of the Stockholm Royal Seaport district (Google Earth) and its relative location, marked by the white circle, to the old town (upper left inset). Colour-coded locations of 18 weather stations indicate 6 site types under investigation with their respective colour-coded Green Space Index (lower right inset). There are 5 green elements, forest parks (white), green courtyards (yellow), green roofs (violet), rain gardens (cyan), lawns (green), and 1 non-green reference site (red) **b)** The top row shows representative photographs of each site type and the bottom row shows the top view, where yellow dots indicate weather stations.

2.3. Green Space Index (GSI)

The SRS is the first district in Stockholm to use GSI (Grönytefaktor, GYF in Swedish, also known as Green Area Factor, GAF) for integrating green and grey infrastructures on a local level of a single plot to achieve 0.6 GSI. The green space index means that the green elements are integrated into new housing blocks from the very beginning, from the first planning documents to the detailed drawings (See Boverket guides [link](#)). GSI describes a geometrical area-based ratio, not the volume, between grey and green components of an urban landscape. Special infrastructure features such as trees, bushes, and permeable surfaces can boost the GSI index. This is calculated by using additional coefficients which appear to be arbitrary not least because

it is unclear to which ecosystem services they refer. For this reason, in our work, we used area-based calculations only. We used satellite imagery to calculate GSI for each location within a 50x50m plot area where average GSI for the respective sites is for reference sites 0.06 ± 0.09 , rain gardens 0.14 ± 0.05 , green roofs 0.22 ± 0.10 , lawns 0.79 ± 0.12 , green courtyard 0.87 ± 0.05 , forest parks 0.92 ± 0.03 . To be relevant for climate adaptation efforts in cities, GSI needs to include volume or vertical surfaces and establish an evidence base that captures the climate mitigation performance of vegetation. This work connects the GSI index with the cooling performance of NbS.

Many courtyards in the north of SRS meet the 0.6 GSI target. They do not feature in our study due to a diverse ownership structure that significantly slowed down the permission process of installing weather stations. Instead, we monitored green courtyards, located in an older part of SRS, on city-owned ground, marked by blue circles in Figure 1a, which were built before the inception of GSI. However, they would meet the 0.6 GSI target.

	Vegetarian type, biodiverse	Site conditions	Average area, dimensions, sensor placement wrt NbS
Forest parks	Trees, dominantly mature pine and spruce, highly biodiverse	Large area, often on a slope, shaded, sheltered from wind	>2ha (100 -120) x (200-300) m middle
green courtyards	Mixed, 10+ mature trees, bushes, large-area grass, mod. Biodiverse, raised garden beds	Moderate area, enclosed by building	0.42 ha (60-65) x (50-115) m middle
Sedum roofs	Moss alike, low biodiverse	Small to Moderate area, open, elevated, exposed to sun and wind	0.23 ha 13 x 190 m middle
lawns	Grass, low biodiverse	Moderate area, open but still in between buildings	0.2 ha (25-70) x (25-55) m edge
Rain beds	Mixed, 10+ young trees, long grass, flowers, highly biodiverse	Small area alongside roads and mid-rise tenant buildings	0.03 ha 6 x 50 m edge

Table 1. Differentiating the sites through their character is arranged by descending average area.

2.2. Embedded NbSs - typology of the urban landscape

Urban landscapes modify local microclimate, leading to the urban heat island phenomenon. That is when cities' interiors are warmer than suburban and rural areas. This is because cities are densely populated and compact. They consume electricity and fuel in large quantities, have less

vegetation to provide shade and cooling, and are built of materials that store and absorb energy from the sun. Reversing these trends constitutes the roadmap toward reducing temperature in cities and improving outdoor thermal comfort. A comprehensive example is the cooling strategy of Singapore City featuring 80+ measures that utilise vegetation, urban geometry, air flow, water bodies, infrastructure, material and surfaces, shading, transport, and energy [23]. Each of these factors individually can raise and reduce urban heat locally. Collectively, they produce distinct urban microclimates. When comparing urban heat between two different locations or NbSs, these factors might work together or against each other to exacerbate or diminish differences. [24] categorised a subset of these factors into local climate zones by focusing on the surface cover, structure, and geometry. Their work demonstrates rising air temperatures with higher urban density. Using this framework, NbSs under investigation resides in two local climate zones: mid-rise (6-8 stories) open at the centre of SRS and mid-rise compact to the north and west (see Fig. 1). All these factors are fundamental when studying differences in cooling performance between urban NbSs which we cover in the discussion section.

2.5. Heterogeneity of urban landscape, the proximity of NbSs, and spatial resolution of sensors

Green and blue infrastructure in SRS are accessible, diverse, and in high supply [25]. The compact and heterogeneous urban landscape makes separating contributions of individual NbSs challenging. We selected locations that reduce heterogeneity as much as possible by examining maps and pictures before the installation. In addition to GSI, table 1 compares the sites in terms of vegetation type, site conditions, and areas. After installation, the replicability and proximity is captured by data and can be assessed through variance analysis between and within site types (see Fig. 2). Sensors integrate nearby environments and record the local character of a place with a sufficient spatial resolution. The sensors' spatial resolution depends on the urban landscape. For instance, in open landscapes, such as lawns and green roofs, weather stations have a smaller spatial resolution as they integrate bigger areas than those placed at compact, enclosed places such as courtyards surrounded by buildings or rain gardens along narrow street canyons. The lower spatial resolution also softens the requirement of placing a sensor at the centre of NbS, which is often impractical and unavailable, for example, due to the lack of proper infrastructure (i.e. bespoke posts, fences). Instead, it is much more practical to install sensors at the boundaries of NbS and use already existing infrastructure, such as lamp posts.

2.6. Sensors

In this work, we used wireless solar-powered weather stations from Barani (<https://www.baranidesign.com/>) that do not require an external power supply. This significantly simplified installation and increased flexibility for choosing optimal locations. The weather station included a set of 3 sensors. First, MeteoHelix measures air temperature, humidity, and pressure and meets quality standards set by the World Meteorological Organisation. Second, MeteoRain records precipitation with 0.2 mm resolution (0.2 litres per square metre) with 2% accuracy. Third, MeteoWind detects wind speed and direction. All weather stations were installed on lamp posts at around 2.5 m above the ground, except green rooftops. All sensors

were connected to a web-based online platform via the widely available Sigfox network in Stockholm. The platform provides a flexible dashboard for data visualisation, download, and forwarding to external data platforms, for example, managed by municipalities.

2.7. Raw data

The raw data are time traces of local weather variables from 18 locations, displayed in Figure 2, and fully accessible through the data repository [26]. The variables include air temperature, relative humidity, solar irradiation, and precipitation, each recorded every 10 minutes, during March and September 2021 (left column) and a 25-day time window in July (right column). Each colour-coded time trace represents an average of three sites of the same NbS type. Aggregating gives rise to distinct means and standard deviations, displayed as solid line and shaded areas, respectively. They were used to quantify differences between the sites. Figure 2 displays daily sums, maxima, means, and minima for the variables, as indicated. These traces constitute a complete database in the analysis. In this paper, we present results on how air temperature and solar irradiation vary as a function of GSI.

Real-time variables across NbS and non-green sites

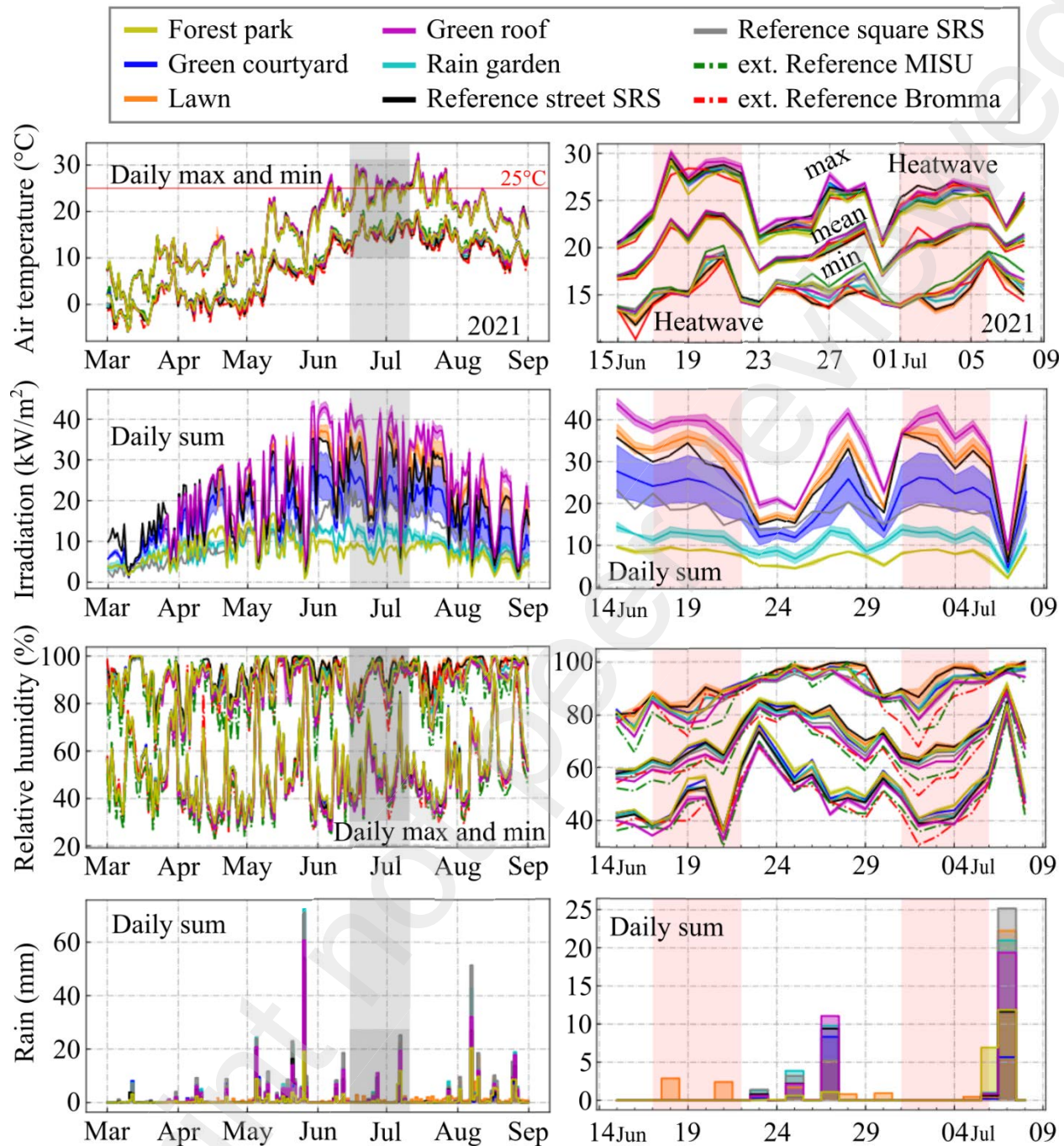


Figure 2. Real-time traces of variables collected by wireless weather stations at 18 locations, including 5 NbS types and non-green references. Each line represents an average reading calculated from three individual sites apart from reference sites, where individual traces are plotted due to high variability. The grey-shaded areas indicate periods displayed in the right column, while the red-shaded areas indicate two heatwaves when air temperature exceeds 25°C for at least five consecutive days. MISU and Bromma references are located outside the SRS district area, at the Meteorological Institute of Stockholm University and Bromma airport.

3. Calculation and Analysis

The analysis employs a mixture of time-invariant statistical and analytical methods. Analysis period includes June and July 2021, unless specified. Being the warmest months in Sweden, we expect the biggest differences. Daily values were used throughout the data analysis.

All variables from the weather station are non-stationary, as confirmed by the Augmented Dickey-Fuller (ADF) test. For non-stationary time series, subtraction of a reference time series (i.e. differentiating step) is necessary before standard statistical analysis (such as t-test) can be performed to quantify differences between sites. However, from the onset, the differentiating step becomes problematic due to the heterogeneity of the urban landscape because there is not a site with 'average' climate conditions. Therefore, we refrain from selecting an arbitrary urban site that acts as a differentiating reference as it would artificially embed this urban landscape together with its unique local climate in the analysis, leading to biased results. To circumvent this, we take advantage of the dense grid of weather stations and use the site under investigation as a differentiating reference, allowing us to quantify how each NbS differs from all its neighbouring sites, individually and collectively.

Figure 3 shows an example of a differentiating step for the *daily maximum* air temperature at three sites - a green roof, a non-green square, and a forest park. Each line is the result of daily $\Delta T_{MAX} = T_{green_roof_1} - T_{site_x}$, where the site_x is another site from the SRS area. Please note that the site_x excludes sites of the same type (i.e. $T_{green_roof_2,3}$). Then, all values are collected in a histogram which follows a normal Gaussian distribution and therefore can be used for standard statistical analysis. Histograms can be seen as a distinct thermal micro-climate for each site compared to the collective, Stockholm district-wide conditions. For instance, a green roof, a non-green square, and a forest park exhibit air temperatures that are *on average* warmer ($\mu_{\Delta T_{max}} = 0.49^\circ\text{C}$), neutral (0.03°C), or cooler (-0.88°C), respectively. The full set of values is displayed in Figure 4.

Figure 3 also displays short periods when the air temperature largely deviates from the average. This means that the non-stationarity of data was significantly reduced but not completely removed. For instance, in the first week of June, the green roof was warmer by at least $\Delta T_{MAX} = 1.0^\circ\text{C}$ than the SRS district and up to 2.5°C warmer than the forest park, in contrast to the overall average $\Delta T_{MAX} = 0.49^\circ\text{C}$. In the second week of June, this difference almost disappeared. Local air temperature at forest parks shows a similar temporal response but with the opposite cooling effect (see Fig. 3). Such short-term differences coincide with rainy and cloudy conditions and are simply missed by widely used statistical analyses and sparse temporal resolution. However, they are still experienced by residents and nature. Therefore, reducing the cooling performance of NbS to a single number requires caution and detailed temporal consideration which can be addressed via real-time monitoring and careful analysis.

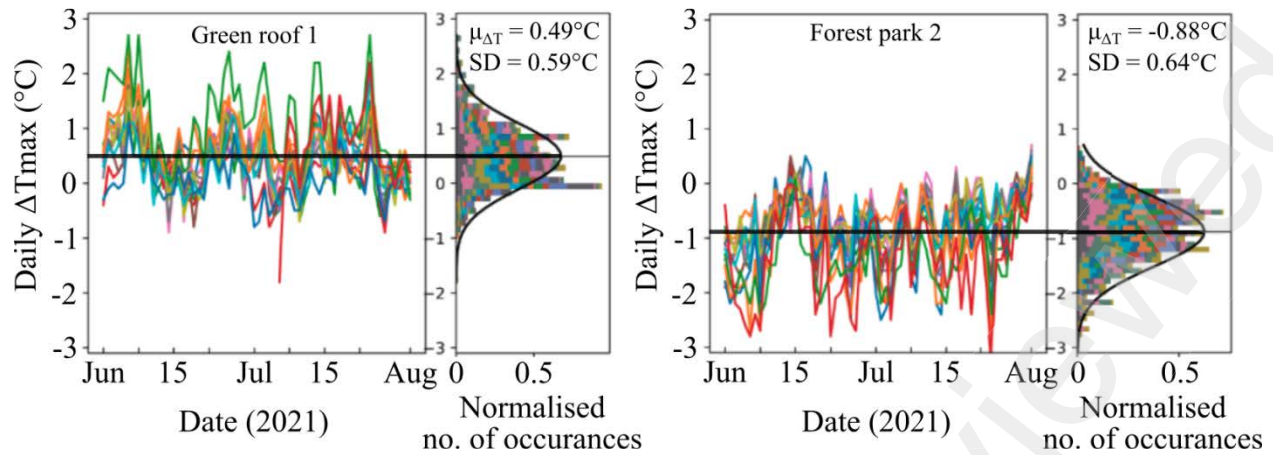


Figure 3. Analytical method for defining a thermal micro-climate at NbS sites. Each time trace is a result of a differentiation step $\Delta T_{\text{MAX}} = T_{\text{green_roof_1}} - T_{\text{site_x}}$. The adjacent histogram aggregates all daily ΔT_{MAX} values, giving rise to a thermal difference for the district-wide conditions.

4. Results

Figure 4 gathers fitting parameters for all sites, as described in the analysis section. They are plotted against GSI for daily ΔT_{MAX} , averaged across June and July (Fig. 4a), and during May only (Fig. 4b). While most sites reside within the temperature band $\Delta T_{\text{MAX}} = \pm 0.25^\circ\text{C}$, some end up in one of four quarters marked by two axes: cold-hot (ΔT_{MAX}), green-grey (GSI) such as cold-grey Rain Gardens. However, with standard deviations as large as 0.6°C , differences between sites are statistically insignificant, however present. This was confirmed by time-invariant statistical analysis (i.e. Pearson t-test, Student t-test, Kruskal-Wallis test), resulting in an almost perfect correlation ($c \cong 1$) with no significant difference ($p > 0.05$). The only significantly different pair is Forest Park (yellow pentagons at the cold-green quarter) and Green Roof (pink squares at the hot-grey quarter). They correspond to the coolest and the warmest NbS in the SRS area, respectively, reaching ΔT_{MAX} up to $\pm 0.75^\circ\text{C}$. There are also days when ΔT_{MAX} rises to up to 2.5°C (Green Roof 1) and drops to -3.0°C (Forest Park 2).

Figures 4a and b also include distant reference sites, such as Bromma Airport (8.7 km away from SRS) and the Department of Meteorology of Stockholm University (MISU, 2.5 km away). Despite their different urban landscapes they still show a statistically insignificant deviation from SRS-district-wide background temperature, $\Delta T_{\text{MAX}} = \pm 0.25^\circ\text{C}$.

Micro-climate comparison (June - July 2021)

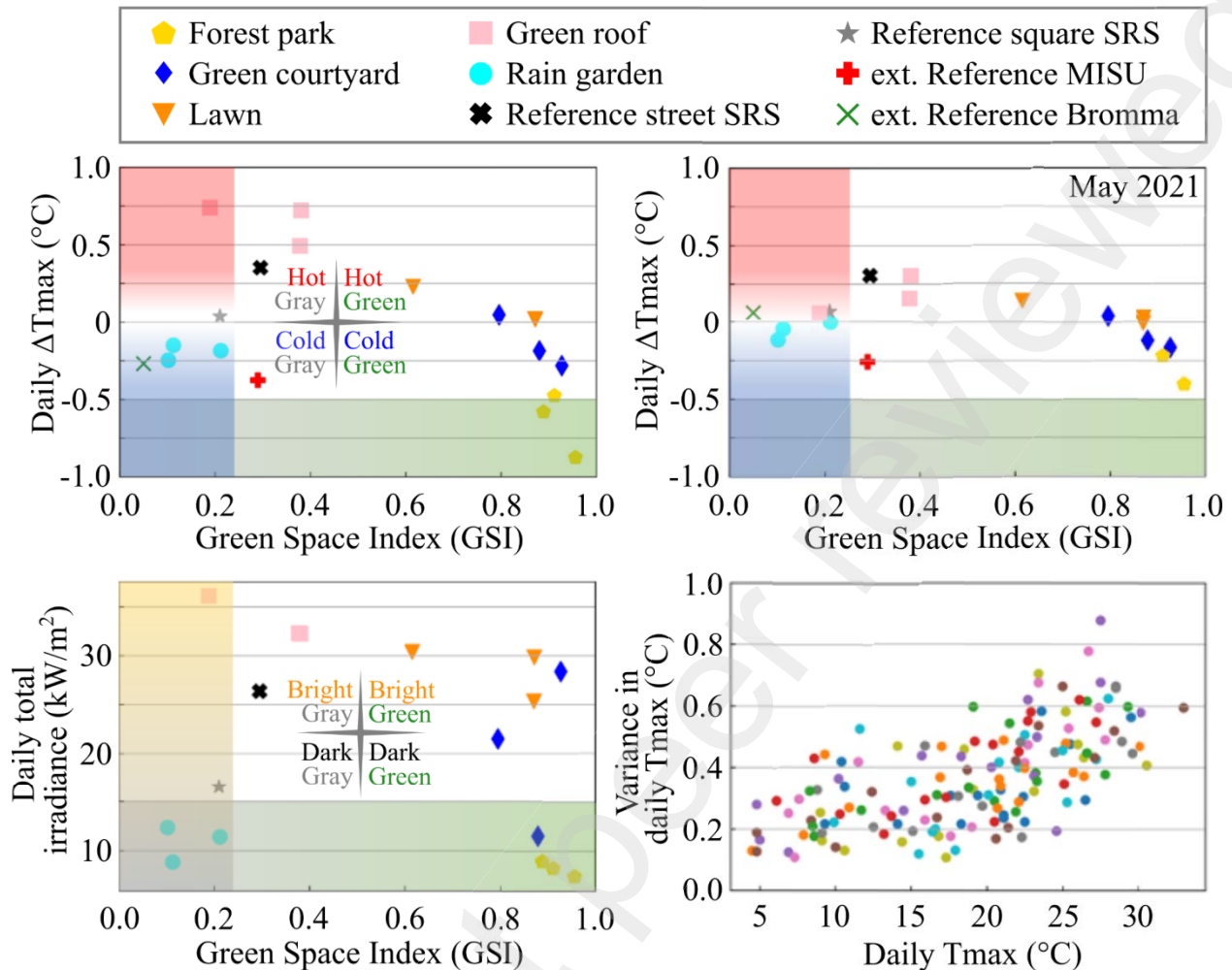


Figure 4. a,b) Thermal micro-climate comparison concerning SRS-wide conditions for five types of NbS and reference sites as a function of GSI in **a)** June and July and **b)** during May only. **c)** Daily sum of solar irradiance at each site. **d)** Variance in daily T_{max} among all the sites showing a deflection point at 21 °C, where the differences start to increase.

Figure 4c shows a daily dose of *solar irradiance* (I), defined as the total amount of light energy (radiant flux) received by a surface per unit area, per unit time, measured in kW/m², ($W = J/s$). Interestingly, solar irradiance varies four-fold across the sites during June and July, ranging from sub-10 kW/m² in the Forest Parks to above 40 kW/m² at the Green Roofs. These differences decrease outside of the summer months as seen in Figure 2, where each site features a distinct seasonal parabolic-shaped response with different peak values. We also notice an ordering which to a large extent follows an increase in the relative amount of vegetation - the greener the site the lower solar irradiance, due to shading. Rain Gardens are an exception to this trend as they are situated within narrow street canyons running from south to north, that provide consistent shading with as little sunlight as in the Forest Parks despite little vegetation. There is a site in each quarter defined by two axes: dark-bright (I), and grey-green (GSI), for example, dark-grey Rain Gardens and bright-green Lawns and Courts.

Figure 4 b exemplifies how seasons drive differences in $\Delta T_{\max}$ between NbS, as they become smaller before and after the summer months. Figure 4 d shows the same phenomenon by plotting how the variance in $T_{\max}$ between all sites varies with overall $T_{\max}$. As long as $T_{\max}$ remains below 21°C , the differences stay relatively constant, within the $0.1 - 0.4^{\circ}\text{C}$ range. Above 21°C , the differences increased with the characteristic slope of 0.055, reaching up to 0.8°C .

5. Discussion

5.1. Urban heat and cooling hypothesis of NbSs

The urban heat island phenomenon can be abated, according to the literature, by several interacting factors including the extent and composition of vegetation and its shading effect [27]. Our case study was designed to test the robustness of this hypothesis in a not well-studied Nordic context [28,29]. In our experiment, solar irradiation (I) and green area cover (GSI) show a trend that points towards the expected pattern of cooler air temperatures and increased relative humidity in greener and better-shaded locations. However, this was only a trend; we did not find statistically significant differences in the air temperature between most sites. The lack of differences is intriguing when compared with other studies [28–31]. There, day-time temperatures in small and medium urban parks (0.5 - 5 ha) were cooler than their urban surroundings, by $0.5\text{--}0.8^{\circ}\text{C}$ in Stockholm, Sweden [28] and by 0.7°C in Leeds, England [31]. Bowler et al. (2010) estimated an average of 0.94°C for 24 urban parks, which is modest in comparison to cities in southern Europe (e.g. $1\text{--}3^{\circ}\text{C}$ cooling in Lisbon, Portugal [30]). Contrary to common practice in the literature, such comparisons must be taken very cautiously; too often they disregard geographic and urban context, climatic gradients, varied reference sites, mixed variables (e.g. surface vs. air temperatures), sparse spatiotemporal resolution of data, and varied data treatment, which *de facto* make it impossible to generalise [32,33]. In our study, we suspect that prevailing winds in a small study location on the waterfront may strongly influence local microclimate measurements, a hypothesis that needs testing but points to the need to examine how regional weather patterns may affect local weather monitoring data. Therefore, our work opens the door to a richer conversation about the broader context of NbS which is underrepresented in current literature and practice. Namely, to what extent and in what circumstances can one expect local NbS to provide ecosystem services such as cooling? We structure this discussion by moving from large to small-scale factors, ending with practicalities of experimental design and analytics which have significant bearings on reported values.

5.2. Scale and context

NbSs are situated and embedded solutions, subjected to larger factors such as seasonal trends and the surrounding urban landscape. In the SRS-Nordic context, the cooling effect is not large enough to be pronounced statistically significant at the level of a single NbS. Therefore, we argue caution and not taking ecosystem functions and services such as cooling for granted. Interventions for improving local climate need to be considered at the district scale.

Our results demonstrate that regional dynamics dominate SRS's climate and that these are too strong to be significantly affected by local variation in the urban landscape. At larger scales, the cooling of vegetation is visible also in Stockholm, if of modest magnitude. Our results agree with an observation that cities with 30% urban green cover and annual average precipitation of 500-800 mm should expect the cooling magnitude to be within the range of 0.25 - 0.5°C [33]. The urban landscape of SRS which contains 30% of the green cover appears too homogeneous, and its local NbSs are too small to alter the regional climate. Such high levels of green cover likely have a smoothing effect on the SRS's thermal profile. Therefore, in the process of implementing NbSs, we argue that there is a need to identify thresholds for landscape heterogeneity to know at what size a single local NbS can be expected to have a cooling effect.

Another aspect of embedded solutions is the connectivity to larger ecological entities such as large parks and bodies of water. Our case study district shares its boundaries in equal parts with the brackish waters of the Baltic Sea to the East, the primarily green Stockholm National Urban Park to the West, and a compact urban area to the South. Each of these neighbouring areas is of comparable size relative to SRS (approx. 80 ha). The proximity to water and the large park should reduce the heat island effect inside SRS since their cooling is known to extend 20 - 300 m beyond their boundaries [30,34]. This influence is likely aided by good air circulation among SRS's mid-rise buildings.

Local NbSs, regardless of type, need to add up to a substantial total green cover before they can be expected to have an impact. In light of these findings, it is important to highlight that urban NbS, as long as healthy, will still provide multiple functions at the local level beyond regulation of local climate which shouldn't be overlooked, including facilitation of human-nature relations, providing habitat for biodiversity and supporting human mental and physical health [19,35].

5.3. Seasons and extreme weather

The background climate also determines the seasonal asymmetric trend seen in the intensity of urban-rural *surface* temperature differences [32]. The continental climate of Stockholm produces a seasonal response that drops sharply with the background temperature on both sides of the summer months [36]. Although differences in the surface temperature are much larger than in the air temperature we still observe a seasonal response in our data. Looking long-term, the relatively large difference in ΔT_{max} between Forest Parks and Green Roofs only occurs during the warmest months, June and July. Before and after the summer (Apr, May, Aug, Sept) ΔT_{max} at most sites converge to the band within $0 \pm 0.25^\circ\text{C}$ (see Fig. 4b). Note that the original order still holds. We attribute this effect to reduced solar irradiance and vegetation activity. The daily amount of solar irradiance dropped below 30 kW/m^2 and the absolute difference between sites was below 200 W/m^2 (max-min) due to cloud cover and the angle of solar incident. Reduced vegetation activity leads to lower evapotranspiration and less shading. One could also hypothesise that there would be bigger differences between NbSs during extreme weather events as they amplify heterogeneities locked in the urban habitat. However, the summer of 2021 was an average year for temperatures, including the number of heatwaves. This supports our

observations of unpronounced local differences that increase in a nonlinear fashion as days get warmer (see Fig. 4 d).

5.4. Shading and vegetation contributions to urban cooling.

Local air temperature data ($\Delta T_{\max}$ Fig 4a) resembles the parabolic shape of solar irradiance (Fig. 2), confirming that solar energy drives air temperature. However, solar irradiance does not account for the entire cooling effect. This is evident when comparing sites with similar solar irradiance. Still, with very different GSI scores, such as Forest Parks and Rain Gardens (see Fig. 4a). This allows us to separate contributions from shading and the amount of vegetation to urban cooling.

Shaded and grey Rain Gardens provided 0.25°C of cooling on average in June and July, while the cooling performance of shaded and abundantly green Forest Parks reached up to 0.75°C (3-fold improvement with 0.5°C of relative difference). Similarly, by comparing sunny places with different GSI scores, we observed that air at Green Roofs was hotter by $\Delta T_{\max} = 0.75^{\circ}\text{C}$ on average, while Lawns and Green Courts managed to reduce their $T_{\max}$ down to the district level and even below, $\Delta T_{\max} = 0^{\circ}\text{C}$ and -0.25°C (up to 1°C of relative difference), despite receiving similar amount of solar energy (see Fig. 4a). We attribute this effect to high GSI scores and enclosed urban morphology.

5.5. Implication of the experimental design

Up-to-date, real-time information about urban NbSs is much needed as cities and NbSs within them become increasingly more vulnerable to the changing climate, a factor potentially confounding climate adaptation efforts. In this study, we found local wireless sensors to be an efficient, flexible, and inexpensive way of tracking, with extremely high spatiotemporal resolution, *in situ* whether NbSs perform as expected. It is challenging to account for all contributing factors that influence the cooling performance of urban NbSs. The literature points to, among other factors, human population and precipitation [33], climate gradients [32,36], the ratio of impervious surfaces [37], wind patterns, vegetation, and shading [23]. Faced with such complexity, *in situ* measurements enabled by ground-based sensors appear to be a direct and reliable approach for quantifying the cooling performance of urban NbSs. However, many cities have less than a handful of weather stations, and existing academic knowledge on the air cooling performance of NbSs, not least in the Nordics, is based on very sparse spatiotemporal data sets [29]. Sensor technology can improve the quality and help establish long-term ecological urban observatories. Exemplary cities in this regard include Oslo in Norway [38] Bern, in Switzerland [39], and Leeds in the UK [31]. Our study adds Stockholm to this list. Thanks to a dense network of local sensors, our work reaffirmed the importance of the context including regional scale dynamics in the Nordics which should be accounted for in the following studies and addressed more thoroughly by the academic community.

However, to better capture the interplay between the regional context and the provisioning of ecosystem services in cities, we call for a mixed-method approach, rather than an apparent path of expanding the network of sensors even further. We believe that a mixed method that integrates a combination of ground-based sensors, remote sensing, and modelling would be better suited to generate a more holistic understanding of urban dynamics including the context-dependent cooling performance of NbS and other ecosystem services, leading to more resilient nature-based urban planning and adaptive real-time management of green spaces.

5.6. Implications of the Analytical Approach

In our study, a dense network of sensors with real-time monitoring provided a high-quality spatiotemporal resolution, allowing us to capture short-lived “extreme” events that are often missed by other types of methods, such as remote sensing, due to their inherently lower resolutions. Yet, the short-lived variations, for example in air temperature, can still get buried under time-invariant statistical methods that lack temporal sensitivity. To perform statistical tests such as T-test, the common practice is to remove day-to-day variations by subtracting a daily mean that disregards the data's temporal dimension. For instance, even when local air temperatures at local NbSs are statistically identical, large and intermittent differences still occur between them. In 2021, the largest temperature difference was up to 3°C in maximum at noon and 5°C in minimum at night. Therefore, we suggest presenting time traces and aggregated values side-by-side, as shown in Fig. 2, which we believe strikes the right balance between complexity and clarity. This balance can be altered by aggregating data on much shorter timescales, for example by computing weekly moving averages, rather than monthly, as presented here, to more accurately represent the real-time nature of the urban heat phenomenon. This approach can help increase consistency in reported values of $\Delta T_{\max}$, widely quoted in the literature.

The same network of sensors also enabled us to quantify district-wide conditions and perform a robust comparison between NbSs. This approach overcomes the challenges of finding a “representative”, yet illusive reference site due to a highly heterogeneous and dense urban landscape [31]. Choosing the district-wide condition as a reference also minimizes systematic bias in choosing a particular site that hinders meaningful comparisons between studies. This can be observed in Fig. 4a, where even the same types of NbSs, Courtyards, and Lawns, show dissimilar $\Delta T_{\max}$, implying that other factors than GSI have a bearing on the cooling performance.

6. Conclusions

Recent technological advances have made meteorological stations affordable and portable while preserving high measurement quality. We use this novel form of harnessing data to understand the performance of nature-based solutions across seasonal variation and under extreme weather conditions in terms of their direct impact on the local climate. Our results show that the relationship between vegetation and cooling is not straightforward and that care needs to be

taken when designing the experiment and analytical approach. While not explicitly part of the study design, we see an indication that scale and overall urban morphology may, at least in the urban context of our study, have a stronger effect on local climate than vegetation type. Furthermore, we found some support for the hypothesis that different vegetation types (the different NbSs) have different functional responses to dry spells and heat. Had the time series included more extreme conditions this may have been more clearly visible. Our results point to the need to better understand the scale effects and functional responses to extreme weather events for a better understanding of when urban vegetation can support tentative solutions to climate-related problems, and the importance of field-based monitoring and evaluation to advance understanding of the real-world performance of urban NbSs.

Declarations

The authors of this manuscript have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Generative AI was not used at any stage of manuscript development.

Authors contributions

AB: Methodology, Software, Validation, Investigation, Formal analysis, Visualization, Data curation, Writing - original draft, Writing - review & editing, Supervision, Project administration. TM and EA: Conceptualization, Methodology, Validation, Investigation, Resources, Writing - review & editing, Supervision, Project administration, Funding acquisition.

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