Sensors for multifunctional climate adaptation
– from monitoring to evaluating and managing nature-based solutions

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Extreme weather, nature-based solutions and technology in cities

- Extreme weather events, (heatwaves, droughts, wildfires, heavy precipitation, and coastal storms) are becoming more frequent and are increasingly affecting cities and urban areas. (Chpt. 11, IPCC 2021, Dodman et al., 2022)

- Urban greening and nature-based solutions (NBS) have emerged as key strategies to address climate-related challenges while also addressing urban social and environmental inequalities. (Frantzeskaki and McPhearson 2022)

- NBS are being elevated to the status of traditional infrastructure, like transportation or electricity, but this can lead to potential issues if the unique characteristics of NBS, which involve living entities, are overlooked. (Grabowski et al. 2022)

- NBS rely on biological and ecological processes that can be influenced by various factors, such as tree species sensitivity to droughts during heatwaves. (Nock et al. 2013, Sjöman et al. 2018, Schuldt et al. 2020)

- Inequities in exposure and vulnerability to extreme weather patterns exist across urban residents, in particular for children and seniors, and require targeted, context-specific interventions.

- Monitoring and evaluating NBS are crucial to understand their performance under different social, ecological, and technological contexts and to ensure they deliver their intended benefits for climate and weather regulation.
  
  - NBS performance, such as urban tree cooling, depends on social factors (local management), technological factors (buildings’ shading), and ecological factors (soil quality).

- Monitoring urban climate with appropriate spatial and temporal resolutions is essential to address hyper-local variations in flooding and heatwaves, which can be influenced by complex urban infrastructure.

- Ground-based sensors are valuable tools for monitoring urban climate, and recent technological advancements have made them cost-effective and adaptable.

- The study focuses on the use of ground-based sensors to assess how different green elements and potential NBS perform under diverse conditions and discusses the outcomes of this analysis.

Recommendations for urban planners and researchers

**How to be smarter and greener in your plans?**

- We need up to date, real-time information about urban nature-based solutions (NBS).

- Local wireless sensors are an efficient, flexible and inexpensive way of tracking whether NbS perform as expected, e.g. by monitoring the impact of NBS on local climate.
  
  - The sensor market still needs to mature to accommodate for more sophisticated parameters such as NPK in soil and mean radiant temperature.
  
  - For resilient and long-term service cities need to provide a reliable network.
Situated solutions – scale and context

- Do not take ecosystem functions and services for granted!
- At the very local level, only forest parks provide statistically different air cooling up to 2°C. Other types of NBS, like green courtyards, rain gardens, or lawns provide little and similar cooling. Green roofs are the warmest NbS.
- Cooling performance depends on circumstances. We observe the biggest differences during the hottest summer days, above 25°C.
- Interventions to improve local climate need to be considered at the district scale. Local NbS, almost regardless of type, need to add up to a substantial total green cover before they can be expected to have an impact.
- However, already at the local level urban NBS provide multiple functions 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.

Layers of resilience

- Many NBS are not self-sufficient, self-regulating ecosystems. They may require high maintenance, and management will be one of the factors determining their performance especially when under pressure.
- With climate change and other ongoing changes in the urban environment sensor information can provide real-time information input to support green space adaptive management.

Monitoring Technology for cities

Methods for monitoring urban climate, especially heat and flooding levels, encompass modeling, remote sensing and ground-based sensors. Table 1 below provides a brief overview of approaches with their strengths and weaknesses. It is crucial to understand these aspects before choosing a particular type of technology for supporting climate adaptation efforts in cities.

<table>
<thead>
<tr>
<th></th>
<th>A short description</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
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<tbody>
<tr>
<td>Modeling</td>
<td>A simplified virtual city on a computer.</td>
<td>- Tests scenarios&lt;br&gt; - Predicts&lt;br&gt; - Integrate other sources of data, remote and ground sensors&lt;br&gt; - Cost-effective&lt;br&gt; - Customizable</td>
<td>- Simplifications leading to errors and large uncertainty&lt;br&gt; - High-quality input data requirements&lt;br&gt; - Large computational resources for high resolution simulations</td>
</tr>
<tr>
<td>Remote sensing</td>
<td>A camera on a satellite taking pictures of a city.</td>
<td>- Large-scale coverage&lt;br&gt; - Consistent and historical data&lt;br&gt; - Widely accessible data for predefined variables</td>
<td>- Limited spatial and temporal resolution for capturing fine-scale variations within cities&lt;br&gt; - High costs</td>
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In Muklis, we worked with a mix of all technologies to a certain degree but with a special focus on the ground-based sensors. Due to recent advances in technology, high-quality ground-based sensors are currently accessible at an affordable price, allowing for their widespread deployment in sufficient quantities. Furthermore, their deployment and experimental designs offer flexibility due to their self-sufficiency - low power consumption, and wireless connectivity to internet cloud services through long-range, low-frequency networks. This means that the distribution of sensor array can be changed after the Muklis project allowing to investigate the performance of other multifunctional nature-based solutions in other regions of the city.

It is important to point out that the market currently offers ground-based sensors that measure only basic climatic parameters such as air temperature and relative humidity. Sensors for more sophisticated parameters of interest are relatively much less developed and require much more input before they can be employed. They include sensors for mean radiant air temperature and soil content - concentrations of Nitrogen (N), Phosphorus (P), Potassium (K) and Salt (NaCl).

### Choosing the right sensor

There are a lot of aspects to consider when selecting a sensor. This includes capacity and resolution of measuring desirable parameter inside intended matrix (e.g. air, water, soil, gravel), whether size and design are suitable for the site, access to power, data storage and data connectivity requirements. When selecting a sensor for outdoor urban applications the number of suitable sensors drastically decreases. This is due to variable and harsh weather conditions, urban maintenance, risk of sabotage and theft, lack of access to power and wireless data connectivity. It is often also requested that the sensor can operate for a long period of time before needing maintenance such as calibration and battery replacement. Most sensors on the market work with LoraWAN network to transmit data and connect to the cloud services. The city of Stockholm does not provide or maintain LoraWAN infrastructure which narrowed the range of suitable sensors even further.

In the MuKlis project discussions also covered what would be of interest to measure in the substrate of the tree beds, in addition to the water tension. Parameters such as water quality and content of the effluent water and nutrients accessible for the roots were listed as parameters of highest interest. As measuring on the effluent water from already constructed tree pits was not possible without a lot of digging and reconstruction work, which was not included in the in the project budget or timeframe, this wish was not pursued. Putting sensors into the tree pits was much more doable.

Looking into sensors for nutrient, we found one NPK-soil sensor, but going into details it only measured the conductivity of the soil from which NPK concentrations were calculated. There are many other conductivity sensors also on the market that probably can be used in a similar way. It was not mentioned how these NPK-measurements are affected by presence of other ions and substances, but it was stated that the sensor is only intended for use in soil, and not in gravel or water. In MuKlis we wanted to use this kind of sensors in the tree pits, where biochar, gravel and compost are used in various proportions instead of regular soil substrate. So, this sensor was never tested in the project. But it is still of interest to find a way to monitor nutrient concentrations in this kind of matrix by using wireless sensors. This indicates a gap of sensors that needs some focus in a next step project.

| Remote sensing | Ground-based sensors | - High resolution, high quality real-time data  
- Direct measurement  
- Localized context and specific insight  
- Enables for local engagement and adaptive management  
- New generation of wireless, low-maintenance, cloud-based, moveable sensors | - Indirect measurement  
- Sophisticated data analysis and interpretation  
- Limited coverage  
- Sensor placement  
- Maintenance and calibration  
- Data integration incl. network  
- Navigating data ownership and sharing |
|---|---|---|
Sensors for Urban Heat

For this project we worked with wireless weather stations from Barani (https://www.baranidesign.com/). A weather station included 2 sensors:


2. MeteoRain that records **precipitation every 10 minutes** with 0.2 mm resolution (0.2 litres per square metres) with 2% accuracy. https://www.baranidesign.com/meteorain-iot-compact

These weather stations do not require external power supply which significantly simplified installation and increased flexibility for choosing optimal locations. They were installed on lamp posts at around 2.5 m above the ground, were connected to a web-based online platform via the widely available, externally managed Sigfox network in Stockholm. LoraWAN is an alternative open-source network which requires initial resources of setting it up but it provides a more resilient and long-term solution. An online platform was set up to provide a flexible dashboard for data visualisation, download and forwarding to external data platforms, for example managed by municipalities. Further data analysis had to be performed to understand the local conditions and contribution of nature-based solutions to urban cooling (see section below for details).

![Figure 1 - Sensors for urban heat. a) Pictures of barani design sensors including MeteoRain (the black cap), MeteoHelix (the white spiral) and MeteoWind (the panel directly below). b) Deployed sensors in the field, Stockholm Royal Seaport. Inset: a list of measured variables. c) Information sticker with a QR code enabling residents to access the data. d) An example of data time series with air temperature in red and rain in blue.](image)

Sensors for Urban Flooding

Teros 32 from the Meter group was chosen for the purpose of measuring the flooding mitigation performance of rain beds. Favorable features of the sensor included low-maintenance and use such as plug-free and simple installation, wireless data integration, communication based on mobile cell network (e.g. Telenor, Telia alike), relatively low cost, high quality of data, suitability for Swedish winter freezing conditions, capabilities of measuring water potential in soil (water available for the plant roots) as well as the level of standing water above the sensor. For more details about the sensor please visit (https://www.metergroup.com/en/meter-environment/products/teros-32-soil-tensiometer)
Case studies
Muklis project members identified the scope and worked with the following case studies:

1. Sofiaskolan, Stockholm, heat in focus
2. Hässelbygårdsskolan, Stockholm, heat in focus
3. Rålambshovsparken, Stockholm, flooding in focus
4. Sockenvägen, Stockholm, flooding in focus
5. Sättra, Västerås, heat in focus
6. Norra Djurgårdsstaden, heat in focus (a relevant parallel study)

Locations are displayed on the map in figure 2.

The purpose was to (i) provide real-time weather monitoring at strategic places with high risks, (ii) establish baselines of climatic conditions and (iii) evaluate climate adaptation performance of existing and new nature-based solutions.

Figure 2 - Case study locations including Stockholm Royal Seaport

Heat-focus case studies

Two case studies, Sofia Skolan and Hässelbygårdsskolan were chosen in Stockholm based on satellite images of surface temperature, taking advantage of large area coverage (link to open-source map here (https://miljodataportalen.stockholm.se/)). These schools also reported high air temperatures during the summer and the city plans to implement cooling solutions in these courtyards as their environment is currently dominated by concrete surfaces (see fig. 3).

Norra Djurgårdsstaden in Stockholm (also known as Stockholm Royal Seaport (SRS), (https://norradjurgardsstaden2030.se/en)) is the newest and the biggest sustainability flagship of sustainable development in Sweden, where many new designs of NBS were implemented. We used the insights from the parallel study taking place in Norra Djurgårdsstaden, which identified the cooling performance of 5 types of NBS, including green roofs, lawns, green courtyards, rain beds and forest parks (see fig. 3). In Muklis, we applied these insights into new locations.
Flooding-focus case studies

Identification of the case studies were informed by a flooding model, available on Stockholm’s data portal (https://miljodataportalen.stockholm.se/).

Rain/flower bed in Rålambshovsparken is one of the first multifunctional solutions for managing every-day and extreme rainfalls, built in Stockholm (more details here link1, link2) (see fig.3). While design was based on modeling, the role was to identify and test sensors that would work.

Rain/tree beds along Sockenvägen in Gamla Enskede, in Stockholm contain standardized and new compositions of substrates, including charcoal, vertically-graded gravel and mulch in various ratios. Knowledge on how these designs behave during droughts and heavy rainfalls help improve future implementations. In Muklis, we also monitored precipitation at these locations allowing us to identify dry periods and intense rainfall events.

Figure 3 - Urban landscapes of Muklis case studies (top panel) and Stockholm Royal Seaport (bottom panel)

Sätra

Sätra is a new district in Västerås (https://www.vasteras.se/kommun-och-politik/vasteras-utvecklas/satra.html). Construction has started in 2022 and the completion is scheduled for 2024. The role was to monitor change in local climate while the construction takes place and measure new climatic baseline for the neighborhood. In Muklis, we gathered three months of data before the network provider, Sigfox was bought by another company which dramatically reduced the coverage of the network, including the Sätra region. Since this point in time even Stockholm-based sensors has begun to experience irregular gaps in data. Currently, to achieve long-term and resilience deployment of sensors, centrally managed network (e.g. LoraWAN, 0G, 5G) is required. This is another gap that the Muklis project has identified.

1 https://miljobarometern.stockholm.se/content/docs/tema/klimat/skyfall/Ralambshovsparken/Slutrapport-Genom%C3%B6rda-%C3%A5tg%C3%A4rder-R%C3%A5lambshovsparken-2021.pdf
2 https://miljobarometern.stockholm.se/content/docs/tema/klimat/skyfall/Ralambshovsparken/Sk%C3%B6tselplan-dagvatten-och-skyfallsanl%C3%A4ggningar-R%C3%A5lambshovsparken.pdf
Results
Heat in focus case studies

The study in Stockholm Royal Seaport showed that increasing the amount of vegetation (GSI) and shading reduces an average air temperature in summer months, June and July, compared to district-wide conditions (fig. 4). On average green and shaded areas such as forest parks are cooler by -0.75 °C, only shaded without substantial greenery such as rain beds along a street are cooler by -0.25 °C, exposed to sun lawns are warmer by 0.25 °C while green roofs are warmer by 0.75 °C. Please note that averages do not capture larger and short-lived differences that occur in the area. For example, there are days when forest parks were up to 3.0 °C cooler. We also observed that differences in air temperature becoming greater as the district-wide temperature rises above 25 °C. While, before and after the summer, these differences shrink significantly, when most locations show very similar air temperatures.

While differences in the air temperature appear to be small, they are likely to lead to big differences in thermal comfort which is often measured as mean radiant temperature (T_mrt) using a globe sensor or is modeled by software such as SOLWEIG. Single trees can reduce T_mrt by up to 30 °C in Hjorthagen, SRS, Stockholm (Thorsson et al. 2014).

Figure 5a shows an example of real-time data. Seen in such way, one can notice that dips in the temperature perfectly coincide with dips in the solar irradiation (sunshine) and rain fall events (e.g. 15th May, 16th June, 1st July). Figure 5b displays the analysis used to compare the sites, where the blue dots mark temperature differences, seen every day, dT, between Sofia Skolan and forest2. These differences are not static and fluctuate around +0.5 °C, resulting in an average difference. Figure 6 gathers averages from all such pair-by-pair comparisons during mid-May until 1st Aug in a table. One can read vertically: “Sofia skolan is WARMer than court2 by +0.28 °C” or “Sofia Skolan is COLDer than Rålambshovparken, known as Rålis, by -0.13 °C” on average. Results demonstrate that most of Muklis sites are warmer than NbS in the SRS district. Although positive, the magnitude of cooling needs to be taken cautiously. The district-wide climate of SRS is influenced by surrounding sea and large urban park that provides additional background cooling. Therefore, each site is embedded in a district-wide context that determines the local climate, where solar irradiance and amount of vegetation play a significant role. For example, Rålis is the warmest site despite being an urban park, situated at the coast, but it receives the largest amount of solar radiation. Interestingly, sensors at Sofia Skolan have detected a small difference in the air temperature between exposed and shaded locations, showing that even small amount of vegetation such as three mature trees make an impact (see the cover image).
Figure 5 – a) Real-time data from Muklis case study sites. From the top, daily maximum temperature, solar irradiation and rain. b) Comparison of daily maximum temperatures between sofia skolan and forest2 and their averaged difference equal to 0.5 °C, marked by the center of the peak.

<table>
<thead>
<tr>
<th>15May - 1Aug</th>
<th>sofia - X</th>
<th>sofia_tree - X</th>
<th>hasselby - X</th>
<th>Ralis - X</th>
<th>Socken - X</th>
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</thead>
<tbody>
<tr>
<td>X_sofia</td>
<td>0.00</td>
<td>-0.07</td>
<td>-0.62</td>
<td>0.13</td>
<td>0.14</td>
</tr>
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<td>0.00</td>
<td>-0.55</td>
<td>0.21</td>
<td>0.22</td>
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<tr>
<td>X_hasselby</td>
<td>0.62</td>
<td>0.55</td>
<td>0.00</td>
<td>0.76</td>
<td>0.77</td>
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<tr>
<td>X_ralis</td>
<td>-0.13</td>
<td>-0.21</td>
<td>-0.76</td>
<td>0.00</td>
<td>0.01</td>
</tr>
<tr>
<td>X_Socken</td>
<td>-0.14</td>
<td>-0.22</td>
<td>-0.77</td>
<td>-0.01</td>
<td>0.00</td>
</tr>
<tr>
<td>X_forest2</td>
<td>0.57</td>
<td>0.50</td>
<td>-0.06</td>
<td>0.70</td>
<td>0.71</td>
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<tr>
<td>X_courtn2</td>
<td>0.28</td>
<td>0.21</td>
<td>-0.34</td>
<td>0.42</td>
<td>0.43</td>
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<tr>
<td>X_lawn2</td>
<td>0.23</td>
<td>0.15</td>
<td>-0.40</td>
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<td>0.35</td>
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<tr>
<td>X_rain1</td>
<td>0.29</td>
<td>0.22</td>
<td>-0.33</td>
<td>0.43</td>
<td>0.44</td>
</tr>
</tbody>
</table>

Figure 6 – Comparison of daily maximum temperatures between Muklis sites and NBS in SRS.

References

IPCC 2021, Chapter 11.
https://doi.org/10.1017/9781009325844.008


**Ytterligare information**

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