NEW GREEN INFRASTRUCTURE FOR EUROPEAN CITIES: MULTIPLE WAYS FOR IMPROVEMENT AND CLIMATE CHANGE ADAPTATION

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ABSTRACT
The establishment and improvement of nature-based solutions (NBS) to reduce impacts by climate change and improve air quality are a challenging task for urban planning and management. Despite the great interest and willingness to improve the situation, many concerns and questions arise when planning details for the implementation of NBS and green infrastructure. For example, to what extent can improvements be achieved with regard to microdust? Which green infrastructure brings the greatest particulate reduction or greatest temperature reductions for hot summer days? This paper investigates which NBS can be applied in European cities for which purpose based on current scientific literature. Based on an extended literature review the paper gives an overview and illustrates to what extent implemented NBS currently may contribute to tackling challenges regarding climate change. Against this background the paper gives recommendations for urban planning and development under conditions of climate change.
Keywords: nature-based solutions, urban green infrastructure, climate change adaptation, sustainable urban development.

1 INTRODUCTION

Many European cities are seeking to improve their urban environments as a mean to address climate change mitigation and adaptation while simultaneously improving quality of life for their residents through green infrastructure and nature-based solutions (NBS). The European Commission defines green infrastructure as a "strategically planned network of natural and semi-natural areas" aiming to deliver ecosystem services like water purification, air quality, climate change mitigation and adaptation and space for recreation [1]. While the European Commission locates the backbone of green infrastructure in the Natura 2000 network of protected nature areas [1], the World Green Infrastructure Network points out the importance and necessity of green infrastructure in cites for sustainable urban development [2]. NBS, as a part of green infrastructure, are solutions inspired and supported by nature. By utilizing nature and natural features and processes as a response to challenges, they are an addition or replacement to purely technical solutions, adding further ecological, economic and social values by their multifunctional traits [3].

Local governments can chose from a variety of tools and instruments to implement urban green infrastructure: For example, Belfast (Northern Ireland) is working on planting one million trees by 2035 to gain multiple benefits like reduction of carbon and flooding, improvement of air quality and urban cooling, as well as supporting biodiversity and improving the physical and mental health and wellbeing of its citizens [4]. The City of Stuttgart (Germany) installs ventilation corridors and green–blue infrastructure to reduce extreme temperatures and improve the air quality [5]. Bratislava (Slovakia) is investing in

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tree planting, green roofs and rainwater retention facilities to mitigate intense rainfalls and heat through the project "Bratislava is preparing for climate change" [6]. Maribor (Slovenia) has developed a "Strategy for the transition to circular economy in the municipality of Maribor" [7], which includes the regeneration of degraded areas through the implementation of blue and green infrastructures and natural solutions. Budapest (Hungary) promotes NBS in several strategic documents to improve the environment, sustainability and quality of life in the city. Furthermore, Budapest is implementing several projects to bring more green into the city and tackle challenges regarding climate change issues [8]. Transitioning to greener urban environments has been gaining political interest, so it comes as no surprise that the "EU Mission: Adaptation to Climate Change" has been showing interest in possible avenues to assist in greening cities [9]. Although interventions through NBS bring many benefits to both the city climate and the citizens' quality of life and well-being, they need to be carefully planned in order to realize their full potential. Questions concerning land competition, refinancing and the desired type of green structures dominate the discussion between urban stakeholders. As listed in the examples above, NBS are applied for a broad field of targets and goals, since they cover a wide spectrum of interventions. For this reason, cities need to know where, what size and what purpose the implemented green infrastructure need to fulfill to address their specific needs and choose the option which will truly achieve the desired outcome.

2 NBS ADDRESS CURRENT URBAN ISSUES

Current literature on the implementation of NBS for climate change mitigation, identifies several prominent issues these measures are meant to solve. The discussions focus on temperature reduction, air quality issues such as the reduction of microdust [10]–[13] and nitrogen oxides [14], [15], or the crucial role of urban green spaces and green infrastructure for biodiversity [16]. Li and Wang [17] summarized benefits of urban greening for carbon emissions. They point out that the biogenic CO_2 from urban greening spaces should be neglected. The carbon sequestration by urban vegetation (lawns, parks, and residential gardens) can partially offset vehicular CO_2 emission for example. Some densely vegetated areas can even achieve carbon neutrality during warm months due to active plant CO_2 uptake.

With climate change and increased sealing in cities, urban microclimates have shown increasing temperatures in the form of heatwaves and tropical nights and the effects of urban heat islands for citizens and urban environments have been growing [18]. These issues have negative effects on human health and well-being [19]. Temperature reduction is thus an increasing concern of public health and, therefore, local governments are interested in addressing the issue for their residents. Similarly, microdust and NO_2 are also matters of public health, as high pollution levels lead to increased cardio-vascular disease and decrease life expectancy [20]. Biodiversity loss has been a worldwide issue, but growing urbanism in its current form can pose irreversible damage [21]. As cities expand and are facing growing sealing and construction, expertise on local biodiversity and cooperation between local institutions are needed to develop public space in a manner which will integrate the needs of nature to ensure ecosystem services are upheld [22].

The examples mentioned in the introduction illustrate that there is a general interest and willingness to increase and upgrade urban green infrastructure at both local and international levels. However, many concerns and questions arise when planning the details for implementation. For example, to what extent can improvements be achieved with regard to microdust, which green infrastructure brings the greatest particulate reduction or greatest temperature reductions for hot summer days? The paper at hand investigates which NBS can be applied in European Cities for which purpose based on current scientific literature. We will give an overview and illustrate to what extend implemented NBS currently may contribute to tackling challenges regarding climate change. Against this background the paper gives recommendations for urban planning and development under conditions of climate change. Therefore, the main aim of the paper is:

- to analyze and quantify possible improvements by NBS,
- to summarize recommendations for urban planning, and
- to discuss further challenges in this context.

3 METHODOLOGICAL APPROACH

To get an overview on the development of scientific literature on nature-based solutions and their effects on the urban environmental conditions a literature review was carried out, focusing on the last decade. Specific focus was laid on methodological settings and measurement methods used in relation to NBS. Following keywords were used for the search: Nature based solutions, NBS, green infrastructure, urban, cities, NO_2, NOx, temperature, temperature reduction, microdust, microdust reduction, particulate matter, PM, biodiversity, air quality, city trees, street greening, rain garden, participation, barriers, choice experiment, waste bin charges. The main literature search engines were BOKU:LITsearch (Search Engine of the University of Natural Resources and Life Sciences, Vienna) and Scopus. Case Studies were retrieved in English and German. They were categorized using a table to summarize the main results of each. Studies from non-European countries (e.g. India, Australia, USA) were also taken into consideration. These studies often show a similar improvement of environmental conditions through vegetation in comparison to studies from Europe. However, these studies were not listed in the tables found in the results because of differences in climate and applicable plant species in European cities.

4 RESULTS

Over the past decades an increased interest in the topic green infrastructure and nature-based solution in scientific research and literature can be observed. For the paper at hand, 77 case studies have been investigated from across the globe. It has been found that the distribution of urban issues which address applied NBS and their achieved results are not equally distributed regionally. Some of the urban issues are found predominantly in certain regions of the world: e.g. many southern European countries focus on heat stress, while Asian cities (such as Hong Kong and Shanghai) were found to address issues of air quality, microdust and air pollution more frequently. In the following we present the findings on European case studies.

4.1 Temperature reduction

The studies showed different approaches to measure temperature differences due to vegetation (Table 1). Most commonly the method applied was to conduct the measurement of air temperature at a certain height and also the measurement of surface temperature differences [23]–[25]. These studies investigated surface temperatures in summer between areas exposed fully to the sun and ones located in the shade, or differences between surfaces e.g. asphalt versus grass. All of these studies showed that NBS are able to significantly reduce temperatures in cities. However, the size of the green area, the respective surrounding infrastructure and the type of vegetation are crucial for the overall effectiveness. Rink and Schmidt [26] showed that the cooling effects of urban forests can extend up to 400 m into the surrounding urban area. Smaller NBS such as singular trees were measured only on site and

Table 1: Literature on temperature reduction.

Study	Main issue	Methodological approach	Results	Study area	Recommendations
Georgi and Dimitriou [29]	Improvement of microclimatic conditions through trees	Daily measurements over 16 days	Temperature under the trees of different species decreases with the increase of evaporation, mean reduction of 3.1°C	Chania-Crete, Greece	The choice of species should reflect the local requirements (aesthetics, functional, ecological, and bioclimatic)
Alavipanah et al. [24]	Influence of vegetation cover on land surface temperature	Remote sensing and land use/land cover data to assess the cooling effect of varying urban vegetation cover	Greatest cooling is achieved in grids with a vegetation cover of 70–79%	Munich, Germany	Since location of urban vegetation and its distance to built-up areas play an important role for cooling strategic planning is crucial
Lindén et al. [28]	Microclimate cooling induced by trees	Climate sensors	Maximum difference of 3.9 K was measured between park and street sites	Mainz, Germany	Carefully consider how surrounding geometry may impact variations of the cooling effect
Rahman et al. [25]	Comparing transpirational and shading effects of two urban tree species	Sensors/on site measurements	Linear regression indicated a decrease of 3°C with every unit of leaf area index for grass surface, but 6°C for asphalt surface	Munich, Germany	Species with higher canopy density can be preferred over asphalt surfaces, but species with lower canopy density and low water use can be preferred over grass surfaces
Speak et al. [23]	Reduction of summer surface temperatures by trees	Thermal images were taken at 1 m height pointing to the ground with a thermal camera on eight clear, sunny days with low winds	Mean cooling of 16.4°C for asphalt, 12.9°C for porphyry and 8.5°C for grass	Bolzano, Italy	Trees with a broad canopy and high leaf area index are recommended, since the study suggested that tree height is not as important as crown width for cooling

Table 1: Continued.

Study	Main issue	Methodological approach	Results	Study area	Recommendations
Rink and Schmidt [26]	Urban forests and their influence on urban climate and recreation	The influence on temperature development was investigated through measurements by specially established climate station as well as mobile measurement tours	Temperature inside the urban forest up to 5–6 K lower than in the city center, cooling effects can extend up to 400m into the surrounding urban area	Leipzig, Germany	Urban forests are recommended for shrinking or shrunken cities, and also to revitalize brownfield sites
Lehnert et al. [27]	Effects on thermal comfort by blue and green features in city centers	On-site measurements	Cooling effect of trees from 5.5 to 8.5°C, cooling effect of low vegetation (largely lawns) was 0.9°C on average, similar for fountains	Brno, Olomouc, Ostrava and Plzeň, Czech Republic	Trees have significant influence on reducing heat stress in urban centers, blue features may have an influence on the psychological component of thermal comfort
Kraemer and Kabisch [30]	Air temperature regulation under condition of drought and summer heat	Temperature loggers on-site and high-resolution remote sensing	Cooling by urban green spaces compared to built-up surroundings was approximately 1°C	Leipzig, Germany	Emphasize the need for larger green spaces, complemented by well-distributed small-scale green infrastructure

achieved temperature reductions between 3°C and 8.5°C [25], [27]–[29]. These studies did not investigate changes in temperature to surrounding areas. Two studies focused on changes in surface temperature. One of these, found very high temperature reductions between trees and asphalt (16.4°C) but also between trees and grass (8.5°C) [23]. For greatest cooling, areas with 70–79% vegetation cover were determined to be most effective [24].

4.2 Microdust reduction

Measurement methods for microdust (also known as particulate matter (PM)) reduction through NBS vary a lot depending on the hypothesis for each study. Some use sensors for air quality before and after the implementation of NBS. For hedge rows near streets the measurement of PM levels on both the roadside and behind the hedge is reported [11], [13]. Other studies, focusing on the removal capacities of different species also use air quality sensors, but since they are often interested in the correlation of leaf traits and removal efficiency, often leaf samples are prepared with vacuum filtration, leaching or with microscopic imaging techniques [12], [31].

Different results regarding leaf traits and their particulate matter removal efficiency can also be based on different measurement methods [31]. Besides PM levels in the air and the selection of plants, many studies show that wind conditions play a major role for microdust reduction and deposition [32]. Therefore, aspects of design and layout of open spaces and streets need to be taken into consideration. Evergreens [10], [33] and meadows [12] were found to be more effective in microdust reduction compared to deciduous species and lawns. Kumar et al. [13] state that concerning roadside microdust reduction a height of 1.7 m is required and other authors add that plant species [31] and vegetation cycle [11] must be considered. As shown by the studies in Table 2, NBS reduce microdust, however, factors such as size, type and vegetation cycle will influence the results achieved during measurement.

4.3 NO_2 reduction

NO_2 reduction through vegetation is often investigated using computer models based on on-site measurements, or validated with on-site samples. Only studies, which are based on measurements in the study area and did not use computer models are listed in Table 3.

Since traffic is a main cause for gaseous air pollution, new technologies can affect air quality in different ways, meaning that the possible reduction is often not consistent for different pollution [32]. As with microdust, leaf emergence [15] or type of plant [14] will influence the reduction of pollution and air quality changes. Recommendations for NO_2 reduction in combination with NBS state that further measurements are needed in varying climates and environments [14]. A further suggestion includes separating people from the source of the pollution in measures which encourage greater green infrastructure application [15]. The results of Table 3 indicate the NO_2 reduction is linked to leaf traits and performance of plant species chosen for the NBS.

5 DISCUSSION

5.1 Transferability of the results and related recommendations

The results in Tables 1–3 have shown that NBS influence temperature, microdust and NO_2 in many ways. However, the transferability of the presented results are limited and require a

Table 2: Literature on microdust reduction.

Study	Main issue	Methodological approach	Results	Study area	Recommendations
Bottalico et al. [10]	Air pollution removal by green infrastructure and urban forests	Computer modelling and sensors	Annual pollution removal for PM_{10} by urban forests: coniferous 0.0204 tons/ha, deciduous broadleaved 0.0152 tons/ha, evergreen broadleaved 0.0176 tons/ha, mixed broadleaved and coniferous 0.0247 tons/ha	Florence, Italy	The role of urban forests for air quality improvement has to be assessed together with other positive effects on human well-being
Marando et al. [33]	Seasonal particulate matter (PM_{10}) removal capacity of evergreen and deciduous species	Remote sensing and GIS	Annual PM_{10} removal efficiency is 20–27% higher for evergreen species compared to deciduous broadleaved, PM_{10} removal for deciduous broadleaves is higher in the vegetation period	Rome, Italy	Urban development strategies should be enhancing the natural and artificial green infrastructure network
Sgrigna et al. [31]	Particulate matter capture efficiency of twelve tree species	Vacuum filtration and scanning electron microscopy imaging	Combination of different micro and macromorphological traits is a key factor to enhance PM capture	Terni, Italy	An Accumulation index based on micro and macromorphologies and the PM_{10} load for 12 tree species is presented
Ottosen and Kumar [11]	Influence of vegetation cycle on air pollution by roadside hedge	Air quality monitors on both sides of the hedge	PM reduction up to 52% after the green-up	Guildford, UK	–
Przybysz et al. [12]	Particulate matter accumulation by urban meadows	Plant material samples and sensors	Urban meadows accumulate more PM than lawns, produced biomass and canopy structure seem to influence the capacity	Warsaw, Poland	When planning species compositions to reduce PM pollution, plants with different development cycles are worth consideration
Kumar et al. [13]	Effects of roadside hedges on horizontal and vertical distribution of air pollutants	Sensors on both sides of the hedge	Maximum reduction of PM_1 (−19%), $PM_{2.5}$ (−18%) and PM10 (−17%) at 1 m height	London, UK	Green infrastructure can reduce traffic-related pollution up to 1.7 m height next to a road

Table 3: Literature on NO_2 reduction.

Study	**Main issue**	**Methodological approach**	**Results**	**Study area**	**Recommendations**
Fantozzi et al. [14]	Ozone and nitrogen dioxide concentrations under urban trees	Passive samplers 2 m above the ground	Holm oak trees decrease the NO_2 pollution in all seasons	Siena, Italy	Further measurements in a variety of climatic and environmental conditions to assess the effective role in air pollution removal
García-Gómez et al. [34]	Atmospheric pollutants in peri-urban forests	Air pollution monitoring during 2 years using passive samplers	NO_2 reduction below-canopy ranged from 0 to 41%	Near Barcelona, Madrid and Pamplona, Spain	Because of the high variability found across sites and seasons, environmental factors involved in air pollution removal must be considered
Klingberg et al. [15]	Influence of urban vegetation on air pollution	Measurements 2.5 m above the ground with passive diffusion samplers	NO_2 reduction of up to 25% after leaf emergence	Gothenburg, Sweden	Pollutant exposure for people can be reduced by separating people from traffic, promoting urban green spaces

careful consideration by urban planning. For example, the effects on microdust reduction are only relevant, if the green infrastructure protects areas for pedestrians. While local government and policies speak about city wide targets, the effects are often only measured in the direct surroundings of the implemented NBS [11], [13]–[15], [23], [25], [27]. Furthermore, several authors [11], [25], [27], [31] base their findings on specific plant species and recognize that different plant types and their growth development will influence the results. Those responsible for implementing NBS must consider that they cannot copy what other cities have done or base their decisions on aesthetics only. This also connects to the recommendations of the Global Assessment Report on Biodiversity [21]. Expertise is needed to decide which tailored solutions will reflect not only their urban development strategy targets but also climate and plant species that can flourish in the given environment. NBS can provide multifunctional solutions to climate adaptation issues, if planners connect their selection of NBS with the variety of ecosystem services they can provide based on correct selection of plant species. To achieve the greatest possible effect, main goals to pursue and other framework conditions to be complied with must be defined. Based on this, plant species, suitable locations and the size of the measure can be defined. Possible interactions, constraints and obstacles already common must be considered in the implementation of new NBS from early planning stages. The presented results should encourage cities to connect with experts to find tailored solutions based on NBS and to strengthen the collaboration between city's officials and other local actors to ensure the suitability of the NBS [35]. The EU would be in a position to use financial and policy instruments to assist (local) governments in this regard, as they are already encouraging member states to apply NBS as indicated in policy documents and project funding [3], [9].

5.2 Additional factors influencing the planning of green and blue infrastructure

The literature review also reveals that three additional factors influence the capacity and effectiveness of NBS in urban planning: financial resources, biodiversity enhancement and the consideration of design and usability of green spaces for the local urban population.

Beside the costs for planning and implementation, the ongoing maintenance costs (maintenance, replacement plantings, etc.) must also be considered. The presented findings, e.g. by Horváthová et al. [36], show that the transformation from lawn to meadows will contribute to significant temperature reduction, in addition the adapted management will increase the cost efficacy [36], [37]. Here again, the tailored selection of NBS will greatly influence infrastructure investments and maintenance costs. In addition to material investments, human capital costs must also be considered from early stages of the planning process for participation, workshops or programs for schools or kindergartens. The costs for personnel and materials must be calculated here. Financial resources for monitoring, evaluation and modifications should be planned for sustainable NBS performance (e.g. may be necessary to use different plant species due to climate change or other environmental factors).

The role of biodiversity and its positive effects on the urban environment is another important point in favor of creating new green spaces. Studies show that biodiversity is perceived and valued by residents [38]. In connection with this, there are not only opportunities for people to perceive nature and an improvement in well-being, but also improve climate change adaptation in urban environments [39]. A contribution to climate change mitigation can be made if carbon sequestration takes place through NBS. In Leipzig, Germany, an urban forest was planted on brownfields resulting from urban shrinking [26].

In addition to the efficiency of individual measures described above, cities must also consider design and the usability of the facilities. Here, there is a need for social science research to determine residents' preferences. Cultural differences in how space is used or aesthetics for example will influence which NBS are accepted and which are not. Culture can also influence the interest in participation or engagement and sense of community [40], [41] and ownership of public space [42]. Recent research confirms this additional requirement focusing on participation [38], just distribution [43], a right to participate in design processes and possibilities to take action. Since the beginning of the COVID-19 pandemic, these social issues have also been gaining prominence and been increasingly included in discussions on what NBS can add to urban environments [44].

5.3 Recommendation for further research

To enhance the comparability across NBS and between urban environmental conditions we propose to standardize the methodological approaches and measurements. Current research states a lack of high-quality sensing systems and expertise within the cities beside the difficulties in financing a suitable infrastructure and an adequate monitoring systems [30]. A further standardization of NBS related research will also help to enhance the transferability and strengthen the societal and political valuation of NBS. Further research findings are needed to transfer these case study findings into detailed planning guidelines. This research has to address the complex urban climate, wind directions and speed, orientation of building and street canyons, barriers, turbulences etc. which influence both air exchange and transportation and deposition [11], [13], [15], [23], [45]. Still, few studies have investigated how big NBS need to be in order to reach certain goals for the temperature reduction and air quality improvement. These research gaps must be filled in order to implement NBS efficiently and effectively.

Finally, we see a need for an integrated research equally considering ecological, economic and social aspects related to NBS. Badura et al. [38] used a survey and choice experiment to investigate the preferences and valuation of citizens in the city of Prague. They found that respondents in general support the implementation of NBS, the support was even greater if they already had negative experiences with heat waves, which was reflected in their willingness to pay for NBS. According to the survey, the citizens value measures which support biodiversity and they prefer implementation of NBS in public spaces rather than on public buildings. Applying a choice experiment across a variety of cities would give greater insight into preferences of citizens in different regions and across cultures. Such a study would benefit urban planners and governments who must consider not only technical but also social aspects of NBS and green infrastructure construction.

6 CONCLUSION

The paper at hand illustrates the significant improvements for urban environments by NBS. It is of great importance to protect residents by avoiding further air pollution from traffic and reducing emissions and temperatures of urban heat islands. However, additional studies are needed to verify results from the presented case studies and related model calculations in real-world conditions. As planning is carried out for the benefit of residents and land use competition between different uses is already pronounced, social concerns must be increasingly integrated into political decisions in the future in order to secure the quality of life in cities in the long term. Therefore, further research is needed to understand the trade-offs between different improvements by NBS such as microdust reduction or temperature reduction not only from a purely technical perspective but also from a social science perspective. Overall the possible contributions by NBS need to be planned considering the contribution to climate change and human health, in the context of economic possibilities, biodiversity enhancement, social and societal needs in an integrated manner.

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