Green infrastructure for resilient urban design: the mapping and management of green roofs in Oslo

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Abstract: Achieving "Climate-Neutral and Smart Cities" is now very high on the agenda and the city of Oslo has set an even more ambitious goal of becoming a zero-emission city. However, the promotion of more compact development may lead to some negative effects such as the entrapment of polluted air, wind tunnel effects or urban heat islands. Green infrastructure (GI) can be used as a mitigation measure, bringing many benefits such as improving air quality, regulating thermal environment, reducing energy consumption, managing storm water, or promoting urban biodiversity. In this work, we aim to map the existing green roof infrastructure in Oslo and develop an evidence-base strategy for its further development, and enhance the understanding and supplement the existing policies developed by the local authorities. Interviews with stakeholders revealed the practical challenges such as structural limitations, high installation and maintenance costs, and regulatory compliance issues. However, they also recognized the significant environmental advantages that highlight the importance of green roofs in urban sustainability strategies. Geographical information system (GIS) tools are used to identify the potential areas for further green roof implementation, taking into account the spatial, morphological and environmental conditions. 91 Priority green roof areas (PRIOGRAs) and 13 Potential green roof areas (PGRAs) in Oslo are identified as the most suitable for green roof installations after applying filters like roof surface area greater than 250 m^2, and dominating roof area and slope criteria, exclusion of cultural heritage buildings and existing green roofs, tree density per person deficit, and building age. 2044 roofs can be considered as suitable without the criteria of building age. These findings will potentially help providing actionable insights for policymakers, urban planners, and the research community.

Keywords: Nature-based solutions, green infrastructure, green roofs, climate resilience, UHI, water retention, GIS tools.

1. INTRODUCTION

Modern cities today face unprecedented challenges in achieving sustainability goals due to the rapid growth of urban populations worldwide. Experts from United Nations estimate that by 2041, more than 6 billion people on earth will be living in urban areas (Affairs and Social, 2019). The higher population densities, increased pollution, loss of green spaces, extensive use of heat-absorbing materials like concrete and asphalt and strained energy consumption for heating and cooling are the primary causes of heightened Urban Heat Island (UHI) effect, where temperatures in urban areas become higher than surrounding non-urban areas. This, in turn, is associated with heat-stress-related public health issues and contributes to changes in the local climate as well as global warming effect (Deilami et al., 2018).

Nature-based solutions are recognized as the key response to the challenges posed by the UHI effect, offering a multifaceted approach to cooling urban landscape, at the same time bringing many other environmental benefits. According to a recent review, local green infrastructure can reduce local peak surface temperatures even by several degrees (Wong et al., 2021). However, due to the lack of open space in many urban areas, sometimes it is challenging to implement the necessary greening solutions to achieve such effects. For this reason, green roofs emerge as a compelling solution that utilize existing roof areas to address the shortage of ground-level green space. Green roofs can mitigate UHI by up to 3 degrees, compensating for the lack of green vegetation in cities, through surface water evaporation, evapotranspiration and decreased albedo effect (Bianchini and Hewage, 2012; Jamei et al., 2021).

Apart from their role in reducing UHI, several other important ecosystem services provided by urban green roofs are also noted in literature, related to energy, pollution or water management. To begin with, they contribute to air pollution control, enhancing local air quality, although this process is more effective when combined with green walls and green screens, especially in terms of reducing pedestrian level pollution concentration (Viecco et al., 2021). Another important aspect is the improvement of biodiversity, especially when proper design solutions, leading to rich habitat conditions, are implemented (Wang et al., 2022). In addition, existing buildings with retrofitted green roofs can benefit from improved thermal performance, especially during winter months in cold climates, leading to energy savings (Berardi et al., 2014). Finally, in terms of enhancement towards stormwater management, different roof types provide different water retention capacity, and extensive green roofs can reduce over 50% of the potential water runoff from single buildings (Mentens et al., 2006). More recent findings suggest that more technologically advanced blue-green roofs can capture between 70% and 97% of rainfall water during extreme precipitation events, which is considerably higher than that of conventional green roofs (Busker et al., 2022).

The environmental potential of green roofs varies depending on the local conditions. For example, their reported cooling potential is considerably higher in dry climates than in hot-humid climates (Jamei et al., 2021). The same applies to different urban form typologies—the higher cooling potential is captured in compact high-density urban areas than in mid-rise and low-rise neighbourhoods (Zuo et al., 2022). Similarly, the reduction in building energy consumption varies across different climates (Bevilacqua, 2021). The suitability of buildings for green roof installation is influenced by several local factors, including roof size, load capacity, building age, and design considerations. The findings from various studies suggest that a comprehensive evaluation of all of these factors is necessary to optimize the benefits of green roofs in specific urban contexts. It is evident that there is need for more accurate and comprehensive studies of green roof suitability that take into account required ecosystem services and local conditions.

The climate in Nordic countries has been largely unaffected by cooling needs in the summer. However, recent extreme weather events, like the 2012 Copenhagen cloudburst, which resulted in costs of approximately EUR 1.6 billion (Evaluation, 2012), the Norwegian Hans or the heavy snow during last winter in Oslo, underscore the urgency for adopting more resilient urban planning and design. These recent events call for more focus on green infrastructure strategies in the Scandinavian context, including the more widespread implementation of urban green roofs, in particular for more effective water management (Nordh and Olafsson, 2021). The reported retention of stormwater is even up to 58% of the annual precipitation in the more warm and dry locations (Amorim et al., 2021). Implementing green roofs in these climatic conditions, however, comes with many risks and limitations, related to e.g. to low vegetation survival rate and cover (Lönnqvist et al., 2021).

In Norway, there are no explicit national legislation and regulations dedicated to green roofs. They are often implemented for aesthetic purposes, but there is an urgent need to consider actual spatial and infrastructural conditions and limitations more carefully to leverage their potential environmental benefits. Several parameters of green roof adoption and implementation fall under the broader legislative frameworks related to urban planning, building codes and environment protection and biodiversity conservation. The national standards NS-3840 and NS-3845 set guidelines on green roofs and the Blue green factor (BGF) calculation method (NS-3845, 2020). According to the NS3840 standard, the biggest driver for normalization of green roofs in Norway is its stormwater retention capability, rather than insulation, cooling or green space provision. In addition, Byggforskserien includes technical recommendations regarding Sedum roof and Terraces with plants on load-bearing concrete decks (Byggforsk, 2009, 2013).

While the existing legal and regulatory framework provides avenues for potential integration of green roofs into urban landscapes, there is limited guidance on specific technical aspects on these parameters related to green roofs construction and adoption, thus the on-going efforts to refine and expand relevant national regulations at the local level is needed. Oslo first had green roofs as part of their objectives in their municipal plan strategy towards 2030 to strengthen Oslo's blue-green character (Oslo-Municipality, 2015). An action plan for green roofs and facades towards 2030 was approved in 2023 with three focus areas; Learning, Sharing and Incentives, accompanied by 11 measures (Planning and Building Agency, 2024). According to Helene Egeland, Climate Leader at the Planning and Building Agency (PBA), half of the buildings in Oslo that are larger than 250 square meters have the potential suitability for green roofs (Planning and Building Agency, 2024) but more careful analysis is needed to validate this assumption.

This work aims to assess and enhance the effectiveness of green infrastructure, particularly green roofs, planning in Oslo, towards achieving climate resilience and combating the impacts of extreme weather events. By analysing the existing green roofs and developing evidence-based approach for further development strategies, the study seeks to supplement existing policies and provide actionable insights for policymakers, urban planners, and the research community. Through interviews with key stakeholders and the use of Geographical Information System (GIS) tools, the research identifies suitable locations for more green roofs, prioritising locations with more favourable spatial and environmental conditions.

2. METHODOLOGY

2.1 Interviews

Semi-structured interviews conducted with experts working with green roof designing, researching, and planning which provided practical experience and knowledge that is relevant to Oslo´s GI strategy. These interviews aimed at gathering nuanced insights into the practical experiences, challenges, and opportunities associated with green roof implementation, both for Oslo, Norway, and other comparative Nordic contexts. The selection criteria for interviewees focused on professionals with significant contributions and experiences to GI, ensuring a diverse range of perspectives. The interview process was structured into three parts, with a predetermined set of 9 questions to facilitate in-depth discussion on key topics such as their own background, green roof design considerations and regulation guidelines, and the future trend of green roof development. Ethical considerations, including informed consent and confidentiality in accordance with the guidelines of the Norwegian Agency for Shared Services in Education and Research (Sikt), were strictly adhered to during the entire interview process. Five stakeholders were selected and interviewed to gain insights into the implementation of green roofs in Oslo and its benefits and challenges, the related maintenance and costs, and limitations were also emphasized during the in-depth interviews. The panel of interviewees included experts from academia, public sector and industries as follows: i) Athenna Grindaker (AFRY Norway, Landscape Architect, Private sector), ii) Bent Chrisitan (Water and sewage agency, Chief Engineer, Municipal planning), iii) David Barton (Norwegian Institute for Natural Research, Senior Research Scientist, Nature research), iv) David V. Brasfield (Norwegian Association for GI, Chairperson, Policy Advocacy), and v) Tore Mauseth (Planning and Building Agency, Environmental Consultant, Municipal planning). Interview insights strengthen the empirical basis of the study and ensures that the conclusions drawn provide insight into the theoretical and practical considerations of green roof design and implementation.

2.2 ArcGIS mapping strategy

The latest aerial photo mapping of existing green roofs area in Oslo was conducted by Oslo PBE in 2017, accessing the mapped geodata layer can give a realistic picture on the status of green roofs in Oslo. Within the developed zone of Oslo, the city's first green roofs strategy proposal identified 14 million m^2 of existing flat roof space can potentially be suited for green roofs retrofitting. Oslo's current built zone has 47% green space cover, with 60 m^2 of regulated green space per inhabitant. Based on surveys conducted by Oslo PBA, there is not strong enough evidence to estimate the extent of existing green roofs in square meters without incurring a large margin of error (Planning and Building Agency, 2022a). The goal of measuring green roofs implementation were therefore identified as on the number of roofs suitable for greening, while the results of total roof area was also presented. Oslo Municipality locates in Eastern Norway on the Oslo fjord. The city is the capital and the most populated city of Norway with a city area of 454 km^2. Oslo's population is projected to grow by more than 100,000 people by 2050, reaching just under 813,000 people. As of January 1, 2024, the city of Oslo had 717710 inhabitants (see (SSB, 2024)).

Oslo presents a unique urban environment for exploring sustainable urban planning solutions. Oslo´s climate is classified as Dfb under the Köppen system, characterized by warm summers and cold winters, a classification often referred to as a Humid Continental Climate. This climate type is relevant for the study of green roofs, as it encompasses high temperatures variations and change in precipitation patterns, thereby influencing the design, functionality, and benefits of GI. The Marka peri-urban forest greenbelt in Oslo serves as an ecological corridor connecting various green spaces and habitats. We aim to assess the suitability of green roofs across the city, with a particular emphasis on developed areas. The methodology for ArcGIS mapping leverages Oslo's publicly accessible geodata repositories, which include detailed urban planning records, highway traffic volume, main drainage lines, and other important environmental data. The geodata layers related to building attributes, roof attributes and urban environments are obtained from Geonorge, Oslo municipality and (Riksantikvaren, 2024). These geodata layers were interpolated to analyze green roofs' spatial distribution and environmental impacts. Each step of the ArcGIS workflow is designed to support the paper's objectives by providing a systematic approach to analyzing the suitability of roofs areas for green roof implementation. The workflow steps are i) Data collection, ii) Data processing, iii) Spatial analysis, iv) Visualisation, v) Output creation and vi) Sharing. This showcases the analytical process which is suitable for reproducibility and validity of the research findings.

2.3 The criteria for green roof suitability, urban parameters and tree density per person mapping

As identified in the literature review, green roofs are suitable for roofs that are large enough and flat enough, as well as those with good enough structural integrity. Based on the available geodata layers, the following criteria were chosen to represent the spatial suitability for green roofs (see Table 1). There is also no reliable data on the bearing load capacity of mapped roofs in Oslo, and many other factors like building technique and roofing material could also come into play to determine the actual load capacity of roof surfaces. Buildings built after 01/07/2017 must follow (TEK17, 2017) which specifies the requirement of 20-25 cm of insulation in the wall and 30-35 cm in the ceiling. These are generally considered to be enough to withstand the weight of extensive sedum roofs in addition to snow load, thus the consideration for load capacity is simplified by assuming only buildings built after when TEK17 come into effect can be easily retrofitted for green roof implementation.

This study initially considered a comprehensive set of urban environmental parameters to assess their correlation with the mapping and management of green roofs in Oslo. These parameters included population density, tree density, highway traffic, and public drainage lines. The focus on tree density in this study was chosen due to its strong relevance to various urban environmental parameters and its comprehensive benefits for urban resilience. While other forms of GI, such as grass fields, parks, and green facades, also contribute to urban resilience, trees play a critical role in improving air quality, providing shade and green area, and regulating local urban temperature, thereby mitigating the UHI effect. Additionally, trees enhance urban greenery and contribute to residents' well-being. The definition of forest areas in Norway are defined as area with at least 6 trees per hectare that are or can grow 5 meters high, and these should be evenly distributed over the area. Proximity to greenery can be difficult to measure qualitatively without quantifiable metrics. Incorporation of tree density layer can potentially provide a more reliable and objective assessment of urban greenery quality.

Based on the point layer on nature info on trees, there are totally 177055 trees in Oslo, divided by the total

Table 1. Spatial analysis of green roofs suitability

Parameters	PRIOGRA (Priority green roof area)	PGRA (Potential green roof area)	URA (Unsuitable roof area)
Roof area	Over 250 m^2		
Dominating roof angle	Under 5°	Between 5° and 30°	Over 30°
Building constraints	Non-SEFRAK buildings		
Building age	After 01/07/2017		

population of Oslo (717710), this resulted the average tree density per person in Oslo to be 0.25 tree per person. The population density of Oslo was distributed onto a 250 by 250 meter grid layer (see (SSB, 2023) This grid layer was then imported into ArcGIS as the base for further analysis. By combining this population density layer with points layer data on tree distribution, the study aimed to highlight areas where tree density per person was the lowest as an indicator for the need for green area compensation, providing a new perspective on urban greenery and resilience. To achieve this, the nature info of all trees in Oslo was retrieved and mapped onto the same grid. For each grid cell, the total number of trees was divided by the population within that grid cell, creating a new layer that showed tree density per person. The high correlation of ES deficits with population density is a pattern observed in other cities as reported in (Langemeyer et al., 2020). Previous studies have also explored the presence of three trees within a 15-meter distance of a building as an indicator of access to greenery in urban environments (see (Venter et al., 2020)). Incorporating population density into tree density within the grid allows for a more detailed model of tree replacement. This layer considers the population density factor, which provides a more nuanced understanding of urban resilience by emphasizing areas where green roofs could have the most significant impact.

3. RESULTS AND DISCUSSION

3.1 Interview insights

The outcome of the interviews essentially reveals the common themes concerning the environmental, social, and economic aspects of green roofs. Interviewees unanimously agreed on the benefits of green roofs, including mitigating public health issues linked to rising urban temperatures, improving air quality, reducing carbon footprints, and enhancing biodiversity. These findings align well with the previous literature reviews. However, despite of Oslo's public green roof strategy, stakeholders still encounter constraints in both the qualitative and quantitative implementation of green roofs. Regarding the spatial suitability of roof areas, *Bent Chrisitan* mentioned that even small roof areas contribute to urban sustainability. *Athenna Grindaker* addressed the pressure to compensate for lack of green surfaces on the ground with green roofs at first. However, according to her, budgetary constraints often lead to the elimination of green roofs during later construction phases completely. The critical role of green roofs in effective water management, especially during extreme weather events, was emphasized. The three-step strategy for storm-water management as well as BGF were mentioned as some prevailing guidelines that requires both stringent enforcement and updates in terms of Scandinavian climates. In this aspect, *David Barton* suggests their work (see (Barton et al., 2021)) on storm-water fees as financial mechanisms in supporting climate readiness through local storm-water management that could potentially motivate property owners to adopt GI solutions like green roofs and other GIs towards enhancing urban resilience.

Apart from environmental benefits, adoption of green roofs have increased land values for certain residential projects. The interviews also revealed the common concerns such as the cost and maintenance of green roofs, and the need for clearer guidelines and supportive policies for their adoption in both new constructions and retrofits. On the other hand, for social side, enhanced aesthetics, improved livability, and recreational spaces were highlighted as the primary benefits. Note that long-term cost savings through energy efficiency and potential increases in property values can be realized as economic benefits. However, there is a need to balance public and private costs, as often residents bear the installation and maintenance costs without realizing potential added land value as mentioned by *David V. Brasfield*.

Furthermore, added costs for retrofitting and unprofessional conduct by builders could also be of concern. For example, air-tightness should be checked via pressure tests for a building before any installation of green roof. As mentioned by *Bent Chrisitan*, it may become very uneconomical and difficult to deal with if roof leakages are discovered after the installation of a green roof. Careful consideration of keeping the prescribed temperature under control during transportation and storage is necessary to avoid irreversible damages (leading dead plant layers) of green roof layers. Interviewees mentioned, stakeholders often come in too late in the building process and thereby incurs additional costs. According to *Tore Mauseth*, "There currently lacks a sufficient method or system for determine and accounting for the benefits for green roofs for not only builders and users of the building but also the public goods comes with it, the architectural implications of green roof accounting has been underestimated." Raising public awareness and developing incentive programs are identified as key strategies to encourage the adoption of green roofs. *David V. Brasfield* also highlighted the need for biophilic design aspects in urban environments for the broader perspective on improving citizens health and well-being.

Another concern is the competition for roof space with other renewable solutions such as solar panels. Evidently the combination of green roofs and solar panels improves the environmental performance. Several interviewees mentioned about the same successful pilot projects in Oslo, those may be considered as well documented examples regarding this. Although these projects are valuable, there

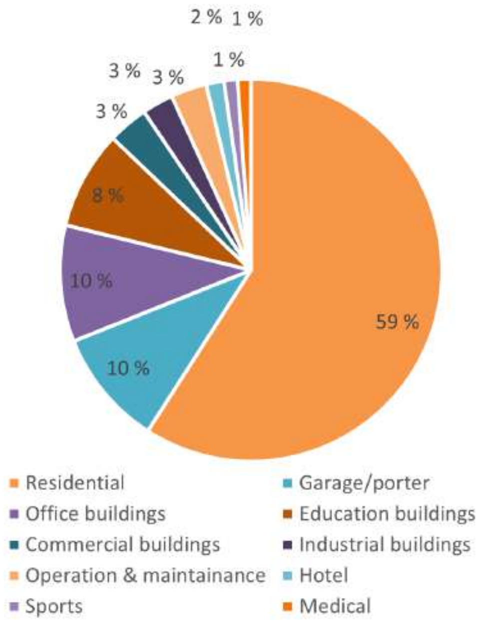

Fig 1. Existing green roofs by building type.

may be a lack of diversity in green roof implementations to consider those as benchmarks.

3.2 ArcGIS mapping and anslysis

From an aerial photo mapping done by Oslo municipality PBA in 2017, there were 957 green roofs in Oslo with the majority being turf roofs or sedum roofs, many of the 400 green roofs in Vestre Aker district, as well as around 70 roofs from the folk museum on Bygdøy are traditional turf roofs in this mapping. Of the existing green roofs mapped in 2017, 270 were over 250 m^2 with 49% of those being categorized for low utilization for utilizing less than 30% of available roof area. When it comes to building types, 59% of the green roofs were implemented on residential buildings and building blocks (see Fig. 1).

The adoption of green roofs in Oslo has shown promising growth trends over the past decade. Notably, from 2013 to 2017, the city experienced an increase of 75 new green roofs annually, (Planning and Building Agency, 2022b). Continuing from the period from 2017 to today (2024) has likely witnessed another batch of growth in green roof installations. While specific annual growth data from this period are pending, it is reasonable to assume a positive annual development trend over the past seven years well beyond the initial numbers mentioned here. Interviews with stakeholders also revealed that some successful pilot projects like Vega Scene was not captured in our mapping or analysis results, indicating that green roof projects has been proactively implemented in Oslo without considering spatial suitability or ES needs.

In the initial phase of our analysis, we examined the distribution of roof areas across Oslo. Using the dataset of 189,601 roofs, the distribution of roof area size and suitable roof area percentage for all mapped buildings were studied. As depicted, a significant majority of the roofs have an area of less than 250 square meters, this indicates that while there is a substantial number of larger roofs, they represent a smaller proportion (17077 or 9.01%) of the total number of roofs in Oslo. Consequently, this highlights potential challenges in implementing widespread green roof installations, as smaller roofs may have limited capacity to support green roofs both structurally and economically. Around 46% of the roofs have 100 percent of their existing roof area available for green roofs retrofitting, although this is highly unlikely due to various structural and practical constraints. Additionally, it is important to recognize that this estimation includes a significant margin of error, as there is insufficient evidence to fully support the suitability of all these roofs for green roof installation.

The spatial distribution of potential green roofs in Oslo was analyzed using a series of filter parameters and steps to determine the suitability of roofs for green roof installation. The suitability analysis identified a limited number of roofs in Oslo that fulfill all criteria for potential green roof installations. The filtering process effectively narrowed down the pool of potential roofs, emphasizing the critical parameters that influence suitability. These results, as summarized in Table 2, offer a comprehensive overview of the spatial distribution of potential green roofs in Oslo by outline the area most amenable to green roof installations and the inherent challenges associated with their implementation. Figure 2 illustrates the process of filtering down roofs in Oslo to identify Priority green roof area (PRIOGRA) and Potential green roof area (PGRA). The figures depict the sequential results by filtering criteria applied to determine roof suitability, with PRIOGRA shaded in dark green and PGRA in light green. This series of figures visually demonstrates the step-by-step process of narrowing down the suitable roofs, providing a clear understanding of the criteria and their impact on the spatial distribution of potential green roof areas in Oslo.

The method involved in analyzing tree density per person in 250m × 250m grids across Oslo were done by combining two ArcGIS layers through spatial joining and intersect and arcade code filtering. The results, as depicted in Fig. 3, highlight the areas with the greatest need for GI. The city's average tree density per person is 0.25 tree per person. By categorizing the grids and applying a threshold of less than 0.1 tree per person, the analysis filtered out 90% of the grids with higher tree densities than 0.1, identifying grids with the highest ES needs, where the environmental benefits are the greatest. Figure 3 illustrates the tree density per person across Oslo, depicted by 250m ×250m grids. This analysis categorizes grids based on the number of trees per person, providing a clear spatial representation of urban areas with varying levels of tree density. The categorization into grids with less than 0.1 tree per person was chosen as the critically low tree density area since 90% of the grids in Oslo have less than 1 tree per person. The symbology was achieved through arcade coding filtering the tree density per person per grid. This threshold was used to filter out 90% of the grids, thereby identifying the areas with the highest ES needs, where green roof installations would have the most significant impact. The results of the spatial suitability analysis for potential green roofs in Oslo provide a comprehensive understanding of the area most amenable to green roof installations. The evaluation of these results

Table 2. Summary of results for suitable green roof area

	PRIOGRA	PGRA (Percentage of total roofs)	Total
Filtered after roof area	27485 (14.5%)	73047 (38.5%)	100532 (53%)
Filter after roof dominating area and slope criteria	6278 (3.3%)	5383 (2.8%)	11661 (6.1%)
Filter after cultural heritage buildings and existing green roofs	6033 (3.2%)	1208 (0.6%)	7241 (3.8%)
Filter after tree density per person deficit	1208 (0.6%)	836 (0.4%)	2044 (1%)
Filter after building age	91 (0.05%)	13 (0.007%)	104 (0.057%)

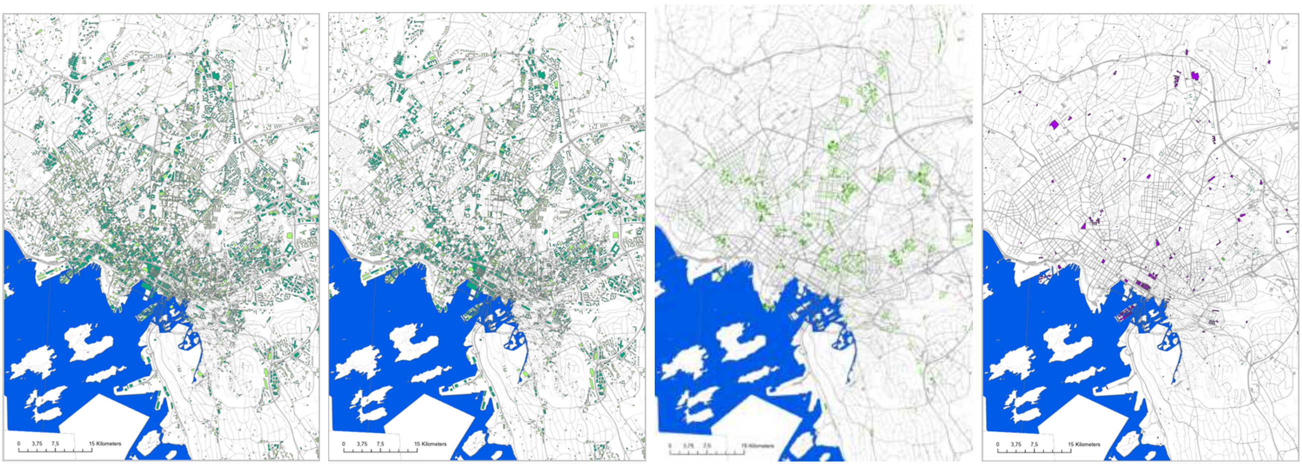

Fig. 2. Spatial distribution of PRIOGRA and PGRA around ring roads in Oslo, PRIOGRA in dark green and PGRA in light green, from left to right: filtered by area and slope requirement, excluding cultural heritage buildings and existing green roofs, tree density per person deficit, and the overall filtered roofs together within existing green roofs in purple.

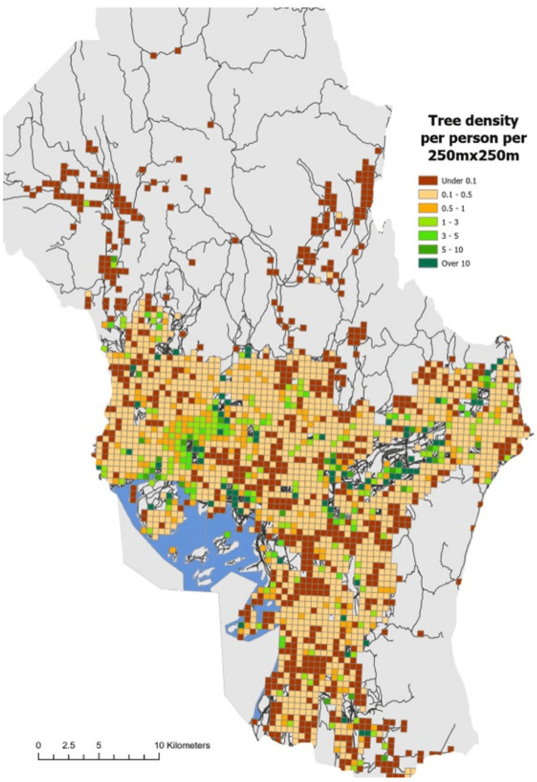

Fig. 3. Tree density per person by 250m×250m grid.

can be broken down into several key observations and implications:

The initial filtering based on roof surface area greater than 250 m^2 and slope criteria identified 27485 roofs (14.5%) as suitable candidates for green roofs. This number indicates a significant potential for green roof installations in terms of available space. However, the subsequent reduction to 6278 PRIOGRA (3.3%) and 5383 PGRA (2.8%) after applying the slope criteria indicates the importance of considering structural feasibility. Roofs with inappropriate slopes are not conducive to effective green roof installations, highlighting a critical constraint.

The exclusion of cultural heritage buildings and existing green roofs refined the pool of suitable roofs to 6033 PRIOGRA (3.2%) and 1208 PGRA (0.6%). This step was necessary because including historical buildings would pose significant challenges, such as low utilization of roof area, extra costs, and complex installation procedures.This step ensured the exclusion of historical buildings and avoided redundant placement of new green roofs over existing ones. Additionally, many non-historical buildings are either too small in roof area or have sloped roof styles, which already are difficult for green roof installation. The relatively small reduction in the number of suitable roofs suggests that most cultural heritage buildings were already excluded by the roof area and slope criteria, indicating that these three factors together are effective in filtering out unsuitable candidates for green roof installation.

Considering tree density per person provided a more focused approach to identifying areas with the highest ES needs. The significant reduction to 1208 PRIOGRA (0.6%) and 836 PGRA (0.4%) after applying this criterion reveals the limited number of roofs in areas with critically low tree density. This criterion is crucial for maximizing the environmental benefits of green roofs, targeting urban areas most in need of GI. The significant reduction in suitable roofs when applying the tree density per person criterion highlights the disparity in greenery across Oslo especially when consider population density. Areas with low tree density per person are typically urban zones with limited green spaces, higher population density, and greater environmental stresses such as poor air quality and higher temperatures due to the UHI effect. Implementing green roofs in these areas can provide greater environmental benefits where they are most needed.

The final criterion, focusing on buildings constructed after July 1, 2017, further narrowed the pool to 91 PRIOGRA (0.05%) and 13 PGRA (0.007%). This significant reduction highlights the challenge of retrofitting older buildings with green roofs. Newer buildings, compliant with newer standards, offer better structural support for green roofs, but the small number indicates that recent construction alone cannot meet the need for wider scale green roofs adoption. While identifying 2044 roofs (1208 PRIOGRA and 836 PGRA) in the earlier steps of the analysis seemed promising, the final reduction to just 104 roofs (91 PRIOGRA and 13 PGRA) was unexpected. This drastic narrowing down indicates that these 104 roofs represent the highest priority areas for green roof installations. These roofs should be able to enjoy the maximum benefits that green roofs provide, making them the ideal candidates for Oslo municipality.

Figure 4 illustrates the distribution of the final 104 roofs (91 PRIOGRA and 13 PGRA) by building type. This categorization helps evaluate the potential and focus areas for green roof installations. The figure reveals that 88 out of the 104 selected roofs are residential. This indicates that residential buildings are likely the primary candidates for retrofitting, but there is a need to encourage other building types to consider green roof installations as well. Ensuring that these residential buildings can structurally support green roofs remains a challenge. While these roofs meet the intended criteria, detailed structural assessments are required to confirm their suitability. The cost of retrofitting and maintaining green roofs on residential buildings may vary significantly based on their size and usage. Securing funding and incentives will be crucial for successful implementation. Ensuring all selected roofs comply with local regulations and building codes is essential. This includes obtaining necessary permits and adhering to any specific guidelines for green roof installations. Encouraging other building types (e.g., commercial, industrial) to adopt green roofs is necessary to diversify and optimize the environmental benefits of green roof installations across different sectors. Figure 4 also depicts the potential utilization rate of green roofs relative to the total roof area for the final 104 selected roofs. This analysis was done by calculating the sum of roof area under 5° and between 5° and 30° as a ratio to the total available roof area, this can help evaluate the efficiency and effectiveness of the selected roofs. Potential high utilization rates for green roofs on these selected roofs means higher chances of maximizing environmental benefits. Smaller roofs may face difficulties in achieving optimal utilization. Implementing green roofs on these selected roofs, especially those with irregular shapes or smaller sizes, poses technical challenges. Customized solutions may be required to address these issues effectively. This includes selecting appropriate plant species and designing systems that support long-term ecological balance.

The findings of this study align with previous research that emphasizes the potential of green roofs to mitigate UHI, improve air quality, and enhance biodiversity. However, the significant reduction in the number of potential green roofs due to stringent suitability criteria is consistent with challenges identified in other studies. Similar findings in other cities highlight structural limitations and regulatory barriers for historical buildings as critical factors affecting green roof feasibility, (Silva et al., 2017).

4. CONCLUSIONS

The study aims to map and identify suitable locations for green roofs in Oslo using GIS analysis. It seeks to develop strategies to optimize the environmental benefits of green roofs, considering local conditions and limitations. Literature reviews highlighted several benefits of green roofs, especially in densely populated areas. The GIS-based suitability analysis identified 1% (1208 PRIOGRA and 836 PGRA) of roofs in Oslo as suitable for green roof installations based on roof area and slope criteria and tree density per person criteria. 104 roofs (91 PRIOGRA and 13 PGRA) were considered as most suitable for green roof installations after applying all relevant criteria. These criteria included factors such as roof area and slope, exclusion of cultural heritage buildings and existing green roofs, tree density per person deficit and building age criteria. While many other roofs did not meet all the criteria, they still hold potential for green roof installations and can offer substantial environmental and social benefits.

Stakeholder interviews highlighted practical challenges such as structural limitations, high installation and maintenance costs, and regulatory issues. Despite these challenges, the environmental benefits of green roofs underscore their value in urban sustainability strategies. The findings of this study provide actionable insights for urban planners and policymakers to optimize the environmental gains from green roofs. The study contributes to the knowledge on GI and offers guidance for future sustainable urban development. Establishing standards for roof insulation and load capacity can aid developers in quantifying the associated costs to implement green roofs. Additionally, financial incentives, potentially subsidies or reductions in tax or lower interest on loans, should be introduced to encourage adoption. Innovative funding mechanisms, such as stormwater fees, could also provide additional support. Integrating green roofs with other sustainable technologies, such as solar panels, will optimize roof space and enhance overall environmental performance. Further research should focus on utilizing spatial data to develop the strategies for developing green roof in conjunction with other forms of GI and mapping their potential spatial distribution. Investigating cost-effective installation and maintenance solutions, as well as financial incentives to overcome identified barriers, is crucial. Further inquiries, including interviews with local architects, planning officers, and engineers, should be conducted to explore practical solutions. Long-term studies should evaluate the impacts of green roofs on urban ecosystems and local climate

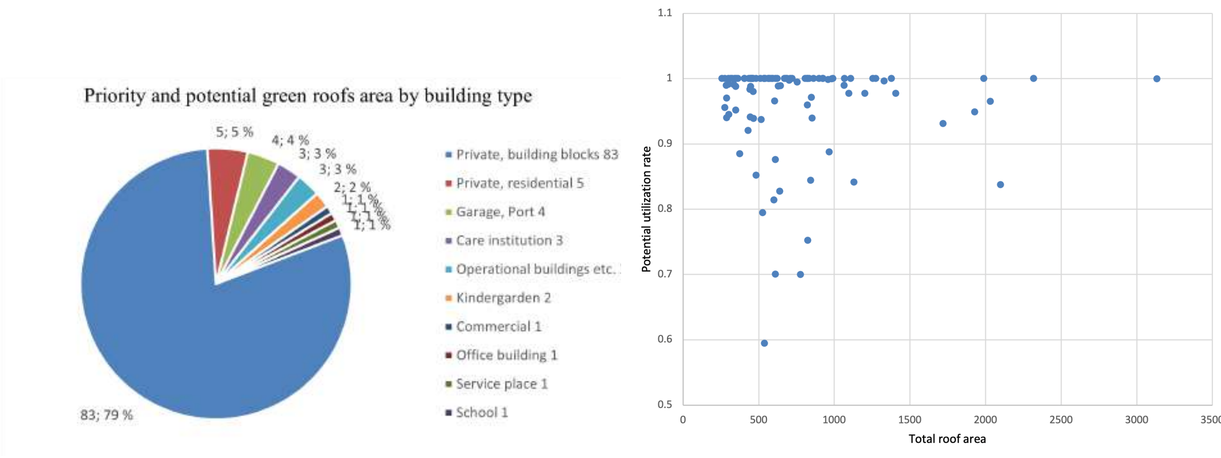

Fig. 4. Priority and potential green roofs area by building type and Potential utilization roof area vs total roof area.

conditions, including their role in mitigating UHI effects, improving stormwater management, and enhancing urban biodiversity. By addressing these areas, future research can provide more evidence-based support and practical solutions to achieve wider scale adoption and effective implementation of green roofs in cities.

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REFERENCES

Affairs, D.o.E. and Social (2019). World urbanization prospects 2018. Report, United Nations.

Amorim, J.H., Engardt, M., Johansson, C., Ribeiro, I., and Sannebro, M. (2021). Regulating and cultural ecosystem services of urban green infrastructure in the nordic countries: A systematic review. *International Journal of Environmental Research and Public Health*, 18(3), 1219. URL `https://www.mdpi.com/1660-4601/18/3/1219`.

Barton, D.N., Venter, Z., Sælthun, N.R., Furuseth, I.S., and Seifert-Dähnn, I. (2021). Brukerfinansiert klimaberedskap? en beregningsmodell for overvannsgebyr i Oslo. *Vann*, 4.

Berardi, U., GhaffarianHoseini, A., and GhaffarianHoseini, A. (2014). State-of-the-art analysis of the environmental benefits of green roofs. *Applied Energy*, 115, 411–428. doi:10.1016/j.apenergy.2013.10.047. URL `https://www.sciencedirect.com/science/article/pii/S0306261913008775`.

Bevilacqua, P. (2021). The effectiveness of green roofs in reducing building energy consumptions across different climates. a summary of literature results. *Renewable and Sustainable Energy Reviews*, 151, 111523. doi:10.1016/j.rser.2021.111523. URL `https://www.sciencedirect.com/science/article/pii/S1364032121008017`.

Bianchini, F. and Hewage, K. (2012). How "green" are the green roofs? lifecycle analysis of green roof materials. *Building and Environment*, 48, 57–65. doi:10.1016/j.buildenv.2011.08.019.

Busker, T., de Moel, H., Haer, T., Schmeits, M., van den Hurk, B., Myers, K., Cirkel, D.G., and Aerts, J. (2022). Blue-green roofs with forecast-based operation to reduce the impact of weather extremes. *Journal of Environmental Management*, 301, 113750. doi:10.1016/j.jenvman.2021.113750. URL `https://www.sciencedirect.com/science/article/pii/S0301479721018120`.

Byggforsk, S. (2009). 525.306 terrasser med beplantning påbærende betongdekker [525.306 terraces with planting on load-bearing concrete decks].

Byggforsk, S. (2013). 544.823 sedumtak [544.823 sedum roofs].

Deilami, K., Kamruzzaman, M., and Liu, Y. (2018). Urban heat island effect: A systematic review of spatio-temporal factors, data, methods, and mitigation measures. *International Journal of Applied Earth Observation and Geoinformation*, 67, 30–42. doi:10.1016/j.jag.2017.12.009. URL `https://www.sciencedirect.com/science/article/pii/S0303243417302994`.

Evaluation, D.I.f.P. (2012). Redegørelse vedrørende skybruddet i storkøbenhavn lørdag den 2. juli 2011[statement regarding the cloudburst in greater copenhagen on saturday 2 july 2011].

Jamei, E., Chau, H.W., Seyedmahmoudian, M., and Stojcevski, A. (2021). Review on the cooling potential of green roofs in different climates. *Science of The Total Environment*, 791, 148407. doi:10.1016/j.scitotenv.2021.148407. URL `https://www.sciencedirect.com/science/article/pii/S0048969721034781`.

Langemeyer, J., Wedgwood, D., McPhearson, T., Baró, F., Madsen, A.L., and Barton, D.N. (2020). Creating urban green infrastructure where it is needed–a spatial ecosystem service-based decision analysis of green roofs in barcelona. *Science of the total environment*, 707, 135487.

Lönnqvist, J., Hanslin, H.M., Johannessen, B.G., Muthanna, T.M., Viklander, M., and Blecken, G. (2021). Temperatures and precipitation affect vegetation dynamics on scandinavian extensive green roofs. *International Journal of Biometeorology*, 65(6), 837–849. doi:10.1007/s00484-020-02060-2. URL 10.1007/s00484-020-02060-2.

Mentens, J., Raes, D., and Hermy, M. (2006). Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century? *Landscape and Urban Planning*, 77(3), 217–226. doi:10.1016/j.landurbplan.2005.02.010. URL https://www.sciencedirect.com/science/article/pii/S0169204605000496.

Nordh, H. and Olafsson, A.S. (2021). Plans for urban green infrastructure in scandinavia. *Journal of Environmental Planning and Management*, 64(5), 883–904. doi:10.1080/09640568.2020.1787960. URL 10.1080/09640568.2020.1787960. 10.1080/09640568.2020.1787960.

NS-3845 (2020). Ns 3845:2020 blågr ønn faktor - beregningsmetode og vektingsfaktorer [blue-green factor - calculation method and weighting factors].

OpenAI (2024). Chatgpt (version gpt-4). https://www.openai.com. Large language model.

Oslo-Municipality (2015). Kommuneplan 2015, Oslo mot 2030 [municipal plan 2015, Oslo towards 2030].

Planning, T. and Building Agency, O. (2022a). Strategi for grønne tak og fasader [strategy for green roofs and facades].

Planning, T. and Building Agency, O. (2022b). Vedlegg til strategi for grønne tak og fasader [appendix to the strategy for green roofs and facades].

Planning, T. and Building Agency, O. (2024). Handlingsplan for grønne tak og fasader mot 2030 [action plan for green roofs and facades towards 2030].

Riksantikvaren (2024). Kulturminner - sefrakbygninger[cultural monuments - sefrak buildings].

Silva, C.M., Flores-Colen, I., and Antunes, M. (2017). Step-by-step approach to ranking green roof retrofit potential in urban areas: A case study of lisbon, portugal. *Urban forestry & urban greening*, 25, 120–129.

SSB (2023). Befolkning pårutenett 250 m [population on grid 250 m]. URL https://kartkatalog.geonorge.no/metadata/befolkning-paa-rutenett-250-m-2023/89bc9a2c-5cb8-4780-8c24-7965c0829696.

SSB (2024). Municipal facts, Oslo. URL https://www.ss b.no/kommunefakta/oslo.

TEK17 (2017). *Regulation on Technical Requirements for Construction Works (TEK17)*. Directorate for Building Quality (DiBK), Norway, 1st edition. URL https://www.dibk.no/regelverk/byggteknisk-forskrift-tek17/14/14-3.

Venter, Z.S., Krog, N.H., and Barton, D.N. (2020). Linking green infrastructure to urban heat and human health risk mitigation in oslo, norway. *Science of the Total Environment*, 709, 136193.

Viecco, M., Jorquera, H., Sharma, A., Bustamante, W., Fernando, H.J.S., and Vera, S. (2021). Green roofs and green walls layouts for improved urban air quality by mitigating particulate matter. *Building and Environment*, 204, 108120. doi:10.1016/j.buildenv.2021.108120. URL https://www.sciencedirect.com/science/article/pii/S0360132321005217.

Wang, L., Wang, H., Wang, Y., Che, Y., Ge, Z., and Mao, L. (2022). The relationship between green roofs and urban biodiversity: a systematic review. *Biodiversity and Conservation*, 31(7), 1771–1796. doi:10.1007/s10531-022-02436-3. URL 10.1007/s10531-022-02436-3.

Wong, N.H., Tan, C.L., Kolokotsa, D.D., and Takebayashi, H. (2021). Greenery as a mitigation and adaptation strategy to urban heat. *Nature Reviews Earth Environment*, 2(3), 166–181. doi:10.1038/s43017-020-00129-5. URL 10.1038/s43017-020-00129-5.

Zuo, J., Ma, J., Lin, T., Dong, J., Lin, M., and Luo, J. (2022). Quantitative valuation of green roofs' cooling effects under different urban spatial forms in high-density urban areas. *Building and Environment*, 222, 109367. doi:10.1016/j.buildenv.2022.109367. URL https://www.sciencedirect.com/science/article/pii/S036013232200600X.