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MOMO-NBS

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Scope of this Document

Project definition and comprehensive science requirements analysis including a systematic literature review - This task develops comprehensive science requirements analysis of the proposed key scientific questions. It consists of an analysis and systematic literature review of the context, state-of-the-art, and knowledge gaps as well as stakeholder feedback for the key scientific questions to be addressed in the project.

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1. List of acronyms

Acronym	Definition
AOD	Aerosol Optical Depth
BGI	Blue-Green Infrastructure
DEM	Digital Elevation Model
DLR	German Aerospace Center
EO	Earth Observation
ECV	Essential Climate Variable
GHG	Greenhouse Gases
GIS	Geographic Information System
GSI	Green Stormwater Infrastructure
ISPRA	Italian Institute for Environmental Protection and Research
KTH	KTH Royal Institute of Technology
LST	Land Surface Temperature
LCZ	Local Climate Zones
MRT	Mean Radiant Temperature
NBS	Nature-Based Solutions
PCI	Park Cool Island
PET	Potential Evapotranspiration
RF	Random Forest
SMHI	Swedish Meteorological and Hydrological Institute
SRTM	Shuttle Radar Topography Mission
SUHI	Surface Urban Heat Island
UBA	German Environment Agency
UNIPV	University of Pavia

Acronym	Definition
WUI	Wildland–Urban Interface
XGBoost	Gradient Boosting

2. Introduction

2.1. Overview of the MOMO-NBS Project

The MOnitoring the impact of the ever-changing urban 2D/3D MOrphology on Nature-Based Solutions for urban resilience to climate change (MOMO-NBS) project is a response to the European Space Agency (ESA) Invitation to Tender (ITT) AO/1-12660/25/I/LR under the *CLIMATE SPACE: CLIMATE CHANGE AND CITIES ACTIVITY*. The project aims to enhance urban climate resilience by systematically investigating the link between urban morphological characteristics (2D spatial configuration and 3D geometry) and the effectiveness of Nature-Based Solutions (NBS).

2.2. Scope of this document

This report presents the consolidated findings and outcomes of the initial work package, primarily driven by the comprehensive literature review tasks. The synthesis of this knowledge is crucial, as it directly informs and establishes the groundwork for the development of the MOMO-NBS methodological framework. This framework is intended to be a robust and evidence-based structure that guides the subsequent research, implementation, and evaluation phases of the project. The literature review not only identified key concepts, existing methodologies, and knowledge gaps relevant to MOMO-NBS, but also provided the necessary context to define the scope and specific objectives of the project's methodological approach. In parallel, a structured survey was carried out with key stakeholders to complement the scientific review with operational insights, ensuring that the defined framework reflects both state-of-the-art research and user-driven requirements.

3. Background

Climate change significantly impacts cities, and the analysis of long time series of geospatial and climate variables, particularly leveraging EO data, has been crucial for understanding how urban structure relates to resilience. For instance, urban morphology is known to affect the UHI effect, air pollution, and CO2 emissions [1], [2], [3]. While this work improves the understanding and monitoring of climate impacts at the city level, a more detailed integration of 2D/3D city structure data (increasingly available from advanced EO data) is essential to better differentiate local drivers and enhance the significance of the findings. The temporal effects of climate change and urban resilience are often analyzed using data like the ESA Essential Climate Variables (ECVs) on climatological scales. However, there remains a substantial need to integrate spatially detailed geo- and sensor-data to accurately describe small-scale urban morphology and surface types. NBS are recognized as highly effective measures for enhancing urban climate resilience [4]. While their local-level effects are typically modeled using detailed geospatial information, their city-wide impact, which is inherently linked to the surrounding urban morphology (e.g., building height, vegetation, impervious surfaces), is not yet fully understood. A major challenge in this area is the coarse spatial resolution of existing ECVs, which limits their applicability for intra-city analysis outside of very large urban areas.

4. Literature Review Overview

The review addresses the fragmented nature of quantitative evidence regarding how urban morphology shapes various climate-related hazards. It synthesizes peer-reviewed studies that connect features of the built environment to a range of hazards, including urban heat, air pollution, extreme rainfall, sea-level rise, landslides, wildfires, and compound risks.

The literature review for the MOMO-NBS project was conducted following a systematic methodology to define the scope and research. The review focused on scientific publications spanning the last decade, complemented by highly cited earlier works, and employed a multi-database search strategy that included Scopus, Web of Science, and Google Scholar. The scope was explicitly defined around four core thematic areas:

- Urban Morphologies (2D/3D structure, Local Climate Zones (LCZ), and Building-Based Indicators);
- Climate Impacts (specifically heatwaves, droughts, air quality, wildfires, floods, landslides, and sea level rise);
- Nature-Based Solutions (NBS) Types (green and blue infrastructure)
- Essential Climate Variables (ECVs) and Earth Observation (EO) datasets in urban-climate studies.

The full literature reviews, prepared as a scientific paper and detailed reports, are submitted as Deliverable 1.1. Hereafter, we briefly report a summary for each of the core thematic areas focusing on the major findings and scientific gaps that have guided us to the refinement of the project scientific requirements.

4.1. Earth observation data for Urban Morphology and Local Climate Zones

This review examines EO-based studies on urban morphology and LCZs to understand urban environmental processes. We systematically searched Web of Science and Google Scholar for peer-reviewed studies using EO-derived datasets, 3D building data, and impervious surface mapping. Results show widespread use of Sentinel, Landsat, LiDAR, and global 3D building datasets, with growing application of AI and deep learning for LCZ classification and urban morphology modeling [5], [6], [7]. Key gaps include limited representation of the Global South, inconsistent 3D datasets, and challenges in harmonizing multi-source data. Future work should focus on globally consistent, multi-scale, and AI-enabled urban datasets.

The analysis of EO based urban morphology and LCZ studies reveals several key trends in data sources, geographic scope, data types, and methodologies. Regarding EO sources, there is a widespread reliance on Sentinel-1/2 and Landsat-based impervious datasets (such as GISA and GISD30), coupled with the increasing integration of radar, optical, and ancillary data. A significant shift is observed toward the use of 3D datasets, with global and continental-scale building height and volume maps (like 3D-GloBFP and GUS-3D) being extensively applied in studies concerning morphology, the Urban Heat Island (UHI) effect, and vertical urbanization.

Geographically, the availability of numerous global datasets (e.g., WSF3D, GUS-3D, Global LCZ map) facilitates planetary-scale analyses. While there is strong regional coverage in Europe, the US, and China, substantial data gaps persist in the Global South, particularly in Africa and rapidly urbanizing secondary cities.

In terms of data types, the research utilizes a range of spatial indicators, including building models, impervious surface dynamics (GISD30, GISA), land cover classification, block-scale patterns, and settlement boundary delineation. Building-based metrics are crucial, encompassing building footprint, height, volume, vertical density, and 3D built-up patterns, with multi-source fusion improving global consistency. LCZ classifications range from detailed single-city maps to broader global products for climate modeling.

Finally, the methodological landscape is diverse. Traditional classification approaches like RF, XGBoost, and ensemble regression models are commonly employed for LCZ classification, 3D structure estimation, and impervious surface mapping. However, there is a growing application of advanced AI and deep learning methods, including Transformer-based architectures and self-supervised models, for fine-scale urban land cover and dense urban segmentation. A notable trend is the increasing integration of 2D impervious data with 3D building structure data to improve environmental modeling, heat exposure assessment, climate adaptation strategies, and the analysis of vertical urbanization.

Major Findings:

- Multi-source and multi-scale data now better capture urban form, with medium-resolution (~100 m) datasets providing global 3D morphology metrics such as building height and volume [5].
- New AI-derived datasets (e.g., Google Open Buildings, Microsoft ML Footprints, Overture) offer detailed global building footprints for improved urban mapping [5].
- Recent Global Building Atlas (TUM) offers more comprehensive 3D urban structure information with global coverage, compared to other datasets such as WSF3D, GHSL building height product and Google’s 2.5D temporal dataset.
- LCZ maps classify urban landscapes into 10 built and 7 natural types using a consistent global scheme, allowing comparison across regions, useful for urban climate modeling and planning [8], [9].

Knowledge Gaps:

- No current methods or datasets enable large-scale, muti-temporal monitoring of 3D urban development (“4D mapping”).
- Google’s 2.5D temporal dataset and Global Building Atlas are promising but limited in coverage, time or consistency [10].
- There is a lack of harmonized and multi-temporal global 3D urban morphology data beyond height/volume
- LCZ’s coarse resolution (~100 m), variable accuracy, lack of time-series data, and need for local validation limit detailed or dynamic applications.

4.2. Assessing Climate Hazards and Urban Morphology

Urban climate risks result from the interaction between climate-related hazards and the built environment, yet quantitative evidence on how urban morphology shapes different types of hazards remain fragmented. This review synthesizes around 150 peer reviewed studies that relate features of urban form, such as density, compactness, Local Climate Zones, street configuration and the wildland urban interface, to hazards including urban heat, air pollution, extreme rainfall, sea level rise, landslides, wildfires and compound risks.

To ensure the relevance of the included literature, a clear set of criteria was applied. Only studies that explicitly analyzed the *quantitative* relationship between urban morphology and one or more climate-related hazards were retained. Conversely, papers that only mapped hazards without a quantitative descriptor of urban form or discussed urban structure in merely qualitative terms were excluded. A strong preference was given to works using EO data or EO-derived products, such as land cover maps, LST, DEMs, and building footprints.

The selected studies published from 2015 to 2025 show a clear acceleration in research on the relationship between urban form and climate-related hazards. This increase has been especially notable since 2020, demonstrating a rapid rise in scientific focus on this topic. While the field has historically been dominated by empirical analyses conducted at the scale of individual cities, the literature shows a gradual but steady shift toward multi-city and global comparative datasets, indicating a move toward more generalizable approaches.

Eligible studies use spatially explicit information, including Earth Observation products, digital elevation models, morphology metrics and in some cases regional or urban climate models. The distribution of hazard studies across regions (**Fig. 2**) indicates that heat-related risks dominate research efforts globally, particularly in Asia. Secondary focuses show regional specificity, with landslides and wildfires receiving stronger emphasis in Europe and North America. In regions with fewer studies, such as Africa and Latin America, the scope is largely limited to floods and landslides.

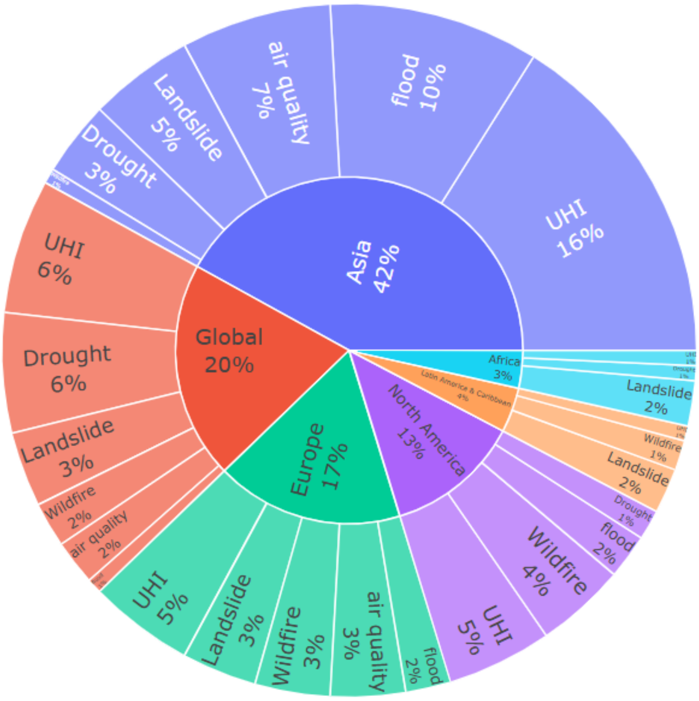

Fig. 2 Geographical distribution of reviewed studies by hazard

This low volume and limited diversity of studies reveal a critical research gap, particularly in informal settlements and rapidly urbanizing countries where urban morphology may strongly condition future climate risk. Evidence is geographically biased towards Europe, North America and East Asia, and only a few studies integrate social vulnerability, health indicators or nature-based solutions as explicit elements of urban form. These patterns highlight clear priorities for future Earth Observation based research on climate risk and urban morphology.

Across the considered studies, EO data and EO-derived products are used in some form in a clear majority of cases, although the degree of reliance varies. Several studies use EO data directly as primary inputs, for example satellite-derived land surface temperature, land-cover products, impervious surface datasets, or DEMs such as SRTM and Coastal DEM [11], [12], [13]. Several others use EO-based information more indirectly, for instance to derive urban extent or greenness, to delineate the WUI, or to validate model outputs [14], [15], [16]. The remaining papers rely mainly on non-EO inputs, including climate model outputs, socio-environmental indicators, exposure databases, and in-situ morphology or health data[13], [17], [18].

Urban morphology datasets (LCZ classes, building footprints, density metrics, WUI boundaries, street-canyon geometry, landscape metrics) appear in most studies, making them one of the most consistent data sources across the set. Climate and weather models are explicitly used in several studies, especially those dealing with extreme events, compound hot–dry extremes and future landslide risk or climate–health interactions (e.g. urban climate simulations and compound extremes, and global indicator modelling).

Major Findings:

- Urban morphology strongly influences local climate and hazards: compact, high-rise, and impervious forms trap heat, worsen air pollution, and amplify drought and flood risks, while green, permeable, and ventilated layouts enhance resilience.
- Nature-based and adaptive designs - such as ventilation corridors, green infrastructure, fire-resistant materials, and preserved coastal buffers - help mitigate multiple risks including heatwaves, air pollution, floods, and wildfires.
- Urban cores with little green infrastructure intensify heat–pollution feedback; heat boosts ozone formation, and street canyons trap pollutants, causing nighttime buildup.
- Expansion of the Wildland–Urban Interface increases exposure to wildfire smoke, which becomes trapped in dense urban areas with poor ventilation.
- Wildfires increase fuel aridity and degrade soil, raising runoff and post-fire landslide risk during intense rainfall.

Knowledge Gaps:

- Integrated frameworks linking 3D urban form with multi-hazard risk remain limited.
- Temporal data to monitor evolving urban morphology and its compound climate impacts are still lacking.
- Limited understanding of combined heat, pollution, and wildfire interactions in dense urban morphologies.
- Insufficient multi-hazard models linking wildfire effects, rainfall extremes, and post-fire landslide dynamics at city scale.

4.3. NBS effectiveness and climate resilience across city forms

The review systematically assessed quantitative evidence on the relationship between urban morphology and NBS performance assessing urban form through complementary 2D spatial configuration and 3D geometry, prioritizing metrics over simple coverage; determining how the built/open space structure influences NBS (e.g., green roofs, parks) across climatic, hydrological, and ecological functions; analyzing how NBS effectiveness is conditioned by green-blue connectivity/continuity, compact vs. open morphology's association with hybrid/engineered vs. process-based NBS, and the comprehensive use of 2D and 3D descriptors; and using the Local Climate Zone (LCZ) classification to standardize urban form description and enable systematic comparison of NBS across case studies. In essence, the goal was to establish that urban form is a critical determinant for NBS success in enhancing urban climate resilience [4].

The *paper search* phase involved a two-step selection process. Initially, 43 documents were selected through title and abstract screening. The primary criteria for inclusion were that the studies must be original research articles (excluding reviews or commentaries), written in English, and demonstrate clear thematic relevance to urban morphology, its descriptive indicators, or optimization approaches. Furthermore, only full-text articles were retained for comprehensive assessment. The literature review ultimately selected a final sample of 21 studies for synthesis. While many initial papers were purely theoretical, the final 21 studies offer a wide geographical scope, encompassing both global-scale analyses and highly specific, localized case studies. The cases are distributed across varied climatic, cultural, and morphological environments, with a notable concentration in high-density Asian cities like Guangzhou, Hong Kong, Changchun, and Kolkata, which are areas experiencing rapid urbanization and significant climate challenges. European cities such as Vienna and London are less represented but contribute to broadening the research scale. Regarding geographical focus, there is a preference for site-specific morphological conditions over whole-city analyses, often concentrating on areas like street or canyon microclimates, clusters of parks or ponds, and functional zones.

The selected studies employ a wide, interdisciplinary array of methods, grouped into four main categories. GIS-based Spatial Analysis is heavily utilized in combination with satellite data to analyze LST, vegetation indices, land cover, and spatial configuration metrics, predominantly for city-scale or neighbourhood-scale assessments of NBS cooling effects and network morphology [19], [20]. Statistical and Machine Learning Approaches quantify the relationships between morphology, climate, and NBS performance, utilizing techniques such as Random Forest regression, correlation analyses, multi-criteria evaluation, and innovative applications like Generative Adversarial Networks (GANs) [21, 22] for creating morphology-adaptive scenarios. Physical Microclimatic Modelling relies on process-based models like ENVI-met to analyze pedestrian-level conditions, such as air temperature, MRT, and PET, which is crucial for detailed scenario analysis of different morphological typologies and their cooling efficiency. Finally, Conceptual or Scoring-based Frameworks, though non-quantitative, build essential context through methods like scoring systems for evaluating biophilic design suitability, pattern-based NBS–urban form matrices, and frameworks classifying morphology (e.g., using the LCZ system) [23]. Collectively, these methods advance both theoretical and applied understanding, providing transferable approaches for establishing the critical relationship between urban morphology and the successful implementation of NBS .

Major Findings:

- Urban form matters more than quantity: spatial configuration (2D) and geometry (3D) strongly condition the effectiveness of NBS
- Connectivity and continuity of green-blue elements consistently enhance performance
- Compact morphologies can still host NBS, but typically as hybrid or engineered forms (e.g., roofs, facades)
- Open morphologies support process-based NBS (forests, wetlands)

Knowledge Gaps:

- Integration of 2D + 3D urban morphologies need further investigation to quantify NBS–morphology interactions.
- Architectural and planning interpretation remains crucial to translate these metrics into design strategies

4.4. Essential Climate Variables in climate-change and urban-climate studies

The literature review summarizes how different ECVs are used in climate-change and urban-climate applications, with a focus on remote sensing. The goal is to understand which ECVs are most commonly employed, at which spatial/temporal scales, with which types of datasets and methods, and for what kinds of questions relevant to MOMO-NBS (e.g., urban heat, exposure, mitigation and adaptation planning). The review concentrates on six ECV groups that are particularly relevant for MOMO-NBS:

- Land Surface Temperature (LST)
- Soil moisture
- Aerosol Optical Depth (AOD) / atmospheric aerosols
- Greenhouse gases (GHG, mainly CO_2/CH_4 in cities)
- Land cover / land use
- Surface albedo and surface radiation budget

The core of the literature review was built using the Scopus database focusing on studies published over the last 10 years. Searches combined generic terms related to urban environments and climate change (e.g., *urban*, *city*, *urbanization*, *climate change*, *urban heat island*) with ECV-specific terms (e.g., *land surface temperature*, *soil moisture*, *aerosol optical depth*, *surface albedo*, *urban* CO_2 *emissions*). Remote-sensing terms (e.g., *remote sensing* and *satellite*) were added to focus on observation-based studies.

In total, 28 studies were analyzed. Most of them use satellite remote sensing directly, often in combination within situ data or model products. The sample includes both global/continental analyses and local case studies in individual cities or city clusters.

Across the 28-paper sample, LST (7 papers) and Land Cover (5 papers) stand out as the most frequently used ECVs, forming the backbone of many urban-climate analyses. Soil moisture, AOD, Above-ground biomass, GHG and surface albedo/radiation appear in 3–4 papers each, often as complementary variables that contextualize heat, emissions, or air quality. Wind speed/direction is less frequently treated, but the example show that can be important for a meteorological modulation of UHI.

Remote sensing is clearly central: 24 of 28 papers explicitly use satellite or EO data, and only two do not. MODIS and Landsat dominate across several ECV categories; SMAP, Sentinel-2 and AERONET appear in more specialized roles (soil moisture, biomass, aerosol validation). Spatial resolutions range from coarse ECV-like grids (5–10 km) for soil moisture and some GHG products, down to 30 m for Landsat-based land cover, LST and biomass. This selection mirrors the tension that MOMO-NBS has identified: ECV products are powerful but often too coarse for intra-city analysis, while high-resolution EO provides rich local detail but lacks the long, consistent climate records of ECV datasets.

A second cross-cutting pattern is the tendency to combine ECVs with information on land cover and basic descriptors of urban structure. In many cases, the main ECV of interest is analyzed together with land-cover classes, simple indices or other surface and meteorological variables, so that spatial variability and trends can be better explained. However, truly multi-ECV frameworks (where several ECVs are treated on an equal footing and analyzed in a consistent way across multiple cities) are not apparent in the current sample.

In terms of scale, the sample includes several global or very large multi-city studies (e.g., LST trends, land cover in 196 cities, albedo/radiation in 3037 cities), but most analyses remain single-city or small multi-city case studies. Moreover, cross-city comparisons often focus on a single primary ECV plus land cover, rather than multi-ECV integration. This suggests that truly multi-ECV, multi-city analyses remain relatively rare, especially when intra-urban detail and morphological descriptors are required.

Major Findings:

- Spatial resolution requirements vary with the process scale: Thermal and hydrological effects typically require 30–100 m resolution (Landsat, ASTER, Sentinel-1/2); Structural Nature-Based Solution (NBS) features need high resolution, 1–10 m; Atmospheric pollutants are usually recorded at >1 km resolution, which is acceptable for city-scale evaluation when fused with higher-resolution land/vegetation data.
- Temporal resolution is dependent on the phenomenon being monitored: Floods and storms necessitate event-based revisits (hours–days); Heat and vegetation monitoring require multi-season or multi-year composites; Air quality, due to short-lived peaks, needs daily or hourly products.
- Data integration is crucial: Most studies rely on multi-sensor fusion (e.g., thermal + high-resolution optical; Synthetic Aperture Radar (SAR) + optical; Earth Observation (EO) + hydrology models); Interpolation primarily involves temporal compositing or spatial resampling to model grids, not fine-scale gap filling.

Knowledge Gaps:

- Mixed pixels and shadowing arise from heterogeneous surfaces and 3-D geometry.
- Longer revisit times restrict the observation of short-duration hazards (e.g., floods, heat peaks).
- Proxy variables (e.g., Land Surface Temperature (LST) for heat stress, NO_2/AOD column for exposure) require calibration using ground data.
- Attributing observed change specifically to NBS interventions versus meteorology or general urban dynamics remains challenging without controlled experimental setups.

5. Stakeholder Interaction

5.1. Overview of Stakeholder Involvement

Stakeholder engagement activities within the MOMO-NBS project aimed to capture perspectives from both municipal authorities and national agencies involved in climate adaptation, urban planning, and environmental monitoring. A structured questionnaire was discussed with and distributed to selected stakeholders to collect information on climate challenges, urban vulnerability, experience with Nature-Based Solutions (NBS), data and monitoring practices, and expectations regarding project outputs.

Responses were received from five organisations operating at different governance levels and geographic contexts: **the Municipality of Milan**, **the Municipality of Stockholm**, **the Italian Institute for Environmental Protection and Research (ISPRA)**, **the Swedish Meteorological and Hydrological Institute (SMHI)**, and **the German Environment Agency (UBA)**. This mix ensured coverage of both operational, city-level challenges and strategic, national-level perspectives.

5.2. Climate Challenges and Urban Vulnerability

Stakeholders consistently report increasing exposure to climate-related hazards, although the relative importance of specific risks varies by location. Heatwaves and urban heat stress are widely recognised as critical challenges, particularly in dense urban environments and areas characterised by older building stock. Extreme precipitation and flooding are also prominent concerns, affecting cities and regions through pluvial flooding, river overflow, and stormwater management pressures. Air pollution is highlighted mainly in large metropolitan areas, while sea-level rise and coastal flooding are particularly relevant for northern and coastal contexts. Wildfires are identified primarily at national scale, reflecting broader landscape-level risks.

In terms of urban vulnerability, compact low- and mid-rise neighbourhoods are frequently identified as particularly exposed, especially where they coincide with ageing infrastructure and limited capacity for retrofitting. Low-elevation and coastal areas are seen as highly vulnerable to flooding and sea-level rise, while river-adjacent zones are recognised as critical interfaces between urban development and hydrological processes. Some stakeholders also underline the heightened vulnerability of low-income neighbourhoods, where climate risks may be compounded by social factors. National agencies emphasise that adaptation efforts must prioritise existing urban fabric, as opportunities for climate-responsive design are more constrained than in new developments.

5.3. Experience with Nature-Based Solutions

All stakeholders report experience with the implementation or support of Nature-Based Solutions, although the scale, objectives, and maturity of these initiatives vary. Commonly implemented measures include urban trees and forests, parks and green or blue-green corridors, green roofs and walls, wetlands and water retention areas, and Sustainable Drainage Systems (SuDS). Municipal authorities tend to integrate NBS within urban regeneration, public space design, and local climate adaptation plans, whereas national agencies address NBS within broader frameworks for ecological restoration, hydrological management, and climate policy support.

Despite widespread implementation, stakeholders report that the effectiveness of NBS is rarely assessed in a systematic or standardised manner. In many cases, NBS performance has not been formally evaluated, or assessments are limited to project-level monitoring. Where evaluation is undertaken, it typically relies on field inspections, ad hoc data collection, or modelling approaches, rather than harmonised indicators or long-term monitoring frameworks. This limits the ability to compare NBS outcomes across locations and to build a robust evidence base for decision-making.

5.4. Data, Monitoring, and Evidence Gaps

Most stakeholders already use satellite or remote-sensing data for environmental and urban monitoring, particularly for land cover and green space mapping. National agencies tend to apply such data more extensively, including for climate and hydrological analyses, while municipalities primarily use them within GIS-based planning workflows. However, several shared challenges are reported. These include insufficient spatial resolution for city-scale applications, limited temporal frequency, and constraints related to technical capacity and expertise.

Beyond technical issues, stakeholders consistently highlight gaps in evidence and knowledge. There is a strong demand for high-resolution urban morphology data that can be directly linked to climate risks and NBS performance. Stakeholders also emphasise the need for quantitative evidence demonstrating the effectiveness of NBS, including cooling potential, flood risk reduction, damage prevention, and co-benefits such as biodiversity enhancement and improved air quality. Economic evidence, including cost–benefit analyses, long-term savings, and maintenance requirements, is considered essential to support planning, prioritisation, and investment decisions.

5.5. Expectations towards the MOMO-NBS Project

Stakeholders express strong interest in engaging with the MOMO-NBS project beyond the questionnaire exercise. Workshops and scientific sessions are widely viewed as valuable mechanisms for knowledge exchange, while joint pilot projects are seen as particularly relevant for testing and validating new datasets and tools. Most organisations indicate willingness, or conditional willingness, to participate in the co-development and testing of MOMO-NBS outputs.

In terms of expected results, stakeholders highlight the importance of climate risk maps tailored to urban morphology, NBS planning and prioritisation tools, and integrated data portals or dashboards that improve access to relevant datasets. Training and capacity-building activities are also considered critical, particularly to support municipalities in operationalising advanced data products and monitoring approaches. Overall, stakeholders perceive MOMO-NBS as an opportunity to strengthen the link between scientific evidence and practical decision-making for climate-resilient urban development.
Table 4.1 provides a comparative overview of the engaged stakeholders, synthesizing governance scale, main climate risks, vulnerable urban forms, experience with Nature-Based Solutions, key data gaps, and level of engagement with MOMO-NBS.

Table 4.1 Stakeholder Comparison Table

Stakeholder	Scale	Main Climate Risks	Key Vulnerable Urban Forms	NBS Experience	Main Data / Knowledge Gaps	Engagement Interest
Milan	City	Heatwaves, flooding, air pollution	Compact low-rise urban areas	Trees, parks, green roofs, SuDS, wetlands	Scientific evidence, cost–benefit data, monitoring tools	Medium-High
Stockholm	City	Flooding, extreme precipitation, sea-level rise	Coastal and low-elevation areas	Trees, parks, green roofs, wetlands	Access to monitoring and evaluation tools	Medium-High
ISPRA	National	Flooding, extreme precipitation, sea-level rise	River-adjacent and low-elevation areas	Wetlands, green corridors, river restoration	Local-scale NBS impact data	High
SMHI	National	Heatwaves, wildfires, air pollution	Dense urban areas, low-income neighbourhoods	Broad range of NBS	High-resolution urban climate and morphology data	High
UBA	National	Heatwaves, extreme precipitation	Compact low- and mid-rise, existing building stock	Trees, green roofs, parks, SuDS	Limited evidence on NBS performance; urban morphology data	High

6. Science Requirements

6.1. Approach to Refining the Science Requirements

The effective use of Earth Observation (EO) to assess climate impacts in urban environments requires a clear understanding of the current scientific landscape, knowledge gaps, methodological practices, and user needs. This section outlines the approach to refine key science requirements for advancing EO-based research and applications in the context of urban morphology, climate change, and resilience planning.

6.1.1. Clarifying the Current Knowledge Base

EO has proven critical for analyzing climate impacts in urban areas. Concerning MOMO-NBS it needed to be analyzed what is already known about how EO is used to study climate impacts with respect to urban morphology. To stipulate any further science requirements, it is important to understand EO datasets and indicators most widely used.

6.1.2. Defining Knowledge Gaps and Underexplored Areas

Despite these advances, several gaps persist. Integration of EO data with socio-economic variables remains limited, hindering the ability to assess climate impacts through an equity lens. Temporal resolution is often inadequate for capturing short-term or extreme events, while spatial resolution may not resolve intra-urban variability, especially in rapidly growing or informal settlements. Methodologically, insufficient differentiation of urban typologies and land use classes restricts the ability to tailor analyses to diverse urban forms and functions.

6.1.3. Evaluating User Requirements

Key user priorities include timely, high-resolution data on heat stress, pluvial and fluvial flooding, and air quality. Information gaps persist regarding the spatial and temporal resolution of ECVs needed to inform actionable climate adaptation strategies. Users differentiate between the adaptation needs of the existing building stock and long-term urban planning for climate-resilient design. Additionally, while nature-based solutions (NBS) are often promoted, robust EO-based evidence of their effectiveness remains scarce.

6.1.4. Assessing Methodological Trends

EO research in urban climate has increasingly adopted advanced techniques such as machine learning (ML), time series analysis (TSA), land cover classification, and EO-informed urban climate modelling. Best practices have emerged in spatial aggregation strategies, urban boundary definitions (e.g., functional urban areas vs. administrative units), and EO downscaling to finer spatial scales. However, harmonization and standardization across studies remain limited, especially when comparing outcomes across cities or regions.

6.1.5. Aligning with Theoretical Frameworks

Scientific questions should be grounded in established theoretical frameworks such as urban metabolism, urban climate zones (LCZ), and resilience theory, which provide conceptual clarity for interpreting EO-derived indicators. Linking EO analysis to these frameworks ensures that research is not only data-driven but also theory-informed, enhancing both interpretability and policy relevance.

6.1.6. Identifying Interdisciplinary Linkages

EO is increasingly used in interdisciplinary settings, including public health (e.g., exposure assessments), urban planning (e.g., spatial zoning, green infrastructure siting), and socio-economic vulnerability mapping. Strengthening these linkages can expand the impact of EO by informing holistic urban resilience strategies that combine physical, social, and institutional dimensions.

6.1.7. Integration of Technological and Data Innovations

Recent advances in artificial intelligence (AI) have enabled more accurate urban feature extraction and enhanced urban climate modelling. New satellite missions (e.g., Copernicus expansion, Landsat Next) and ECV data streams offer opportunities for higher temporal and spatial resolution monitoring. These innovations are crucial for operationalizing EO in local climate adaptation and urban planning workflows.

6.1.8. Strengthening Justification and Impact

Scientific efforts must be aligned with stakeholder requirements and grounded in policy-relevant frameworks. A growing body of literature demonstrates the urgency of EO-informed climate services for cities. Strengthening the scientific justification of EO research through reference to user priorities, climate policy goals (e.g., SDGs, Paris Agreement), and societal needs will help maximize impact and ensure uptake beyond the research community.

6.2. Specific Science Requirements

The MOMO-NBS science requirements translate the literature review findings and stakeholder needs into operational conditions for answering the four project scientific questions. MOMO-NBS must enable both cross-city comparability and intra-urban relevance, by combining ECV records with 2D/3D urban morphology and NBS information, and by explicitly addressing scale and attribution limits.

Multi-scale design (global + local):
The project shall implement (i) a multi-city/global analysis to allow a cross-city comparison, and (ii) city-level pilot analyses to test feasibility for neighborhood scale monitoring of NBS effects.

Cross-city indicator framework:
The project shall define a standardized set of indicators that can be computed for all cities using consistent rules. The framework shall include:

- **Spatial reporting units:** a common city boundary concept for cross-city reporting (e.g., Functional Urban Area / urban extent) and at least one intra-urban stratification scheme (e.g., LCZ or morphology-based classes).

- **Morphology indicators (2D/3D):** Urban form shall be represented using 2D descriptors (e.g., density/compactness, impervious–pervious patterns, green-blue connectivity), and 3D descriptors (e.g., building height/volume/vertical density). Where feasible, changes over time shall be included to separate climate signals from urban development.

- **ECV-based climate indicators:** for example, LST-derived heat indicators and land cover–derived structural indicators; additional ECV-derived indicators where relevant (soil moisture, albedo/radiation, aerosols/AOD, GHG).

- **NBS indicators**: type, area/coverage, spatial configuration (e.g., patch size, connectivity) and, where available, implementation period.

- **NBS effectiveness indicators (ECV-linked)**: change metrics (e.g., ΔLST or cooling intensity around NBS) computed with consistent controls (seasonal baselines, matched morphology classes, or control areas)

The project shall define and document the selection criteria for cities included in the global and local studies. For the global study, the selection shall ensure diversity in urban morphology, population size, climate zones and climate vulnerability, green space coverage, and the presence of NBS policies or projects during the period covered by the ECV records. For the local study, the project shall select a smaller set of cities that enable comparisons within climate zones and shall prioritize locations with stakeholder connections and available local reference data for validation. The final selection shall be co-designed with national and local stakeholders.

ECV use:
A core ECV set shall be used consistently across cities (e.g., Land Surface Temperature and Land Cover/Land Use). Additional ECVs (e.g., soil moisture, aerosols/AOD, albedo/radiation, GHG) shall be included when they support a specific hazard or mechanism, with clear limitations documented for urban settings

Definition of spatial and temporal scale requirements:
For each analysis task, the project shall define required spatial and temporal scales. When ECV resolution or revisit is insufficient for intra-urban questions, the workflow shall integrate higher-resolution EO and/or morphology datasets and report the gain and remaining uncertainties.

Uncertainty and validation plan:
The project shall provide uncertainty characterization for urban EO indicators (mixed pixels, shadowing and 3D effects, revisit limitations, boundary choices) and validate results using available local datasets and stakeholder references when feasible.

Attribution and confounding control:
For NBS effectiveness indicators, the project shall apply a consistent control strategy to reduce confounding attributable to meteorology and broader urban change. This shall include, for example, seasonal baselines and matched comparison areas, and where feasible meteorological normalization and sensitivity analysis to separate NBS signals from background variability.

7. Conclusions

Advances in high-resolution EO global datasets, multi-source fusion, and AI-based methods have enabled unprecedented mapping of urban morphology, LCZs, and climate-relevant indicators.

The review shows that urban forms play an important role in shaping climate-related risks. Studies consistently find that density, compactness, shape and street configuration influence heat, air pollution, carbon emissions, rainfall patterns, wildfire losses, and coastal exposure. However, many papers still rely on simplified morphology proxies such as land cover or imperviousness. The evidence is also concentrated in Europe, North America, and East Asia, with limited representation of rapidly growing regions in the Global South. Earth Observation is widely used, but often through a narrow set of variables such as land surface temperature and land cover, while the quality of elevation models and the mismatch between coarse and fine spatial scales remain important limitations.

The reviewed literature demonstrates that while EO-derived variables such as land surface temperature and land cover are widely used, they must be complemented by richer representations of urban form, including building footprints, heights, street-canyon geometry, and patterns of urban expansion. The body of research further underscores the critical role of urban morphology in shaping the effectiveness of NBS, with consistent evidence of the superior cooling performance of tall vegetation and the potential of integrated water features. Methodological advances—such as improved modelling approaches, the use of comparable parameters like LCZ classes, and more sophisticated assessment tools—represent important progress. However, major gaps remain, particularly the limited temporal scope of analyses, the lack of standardized morphological metrics, the weak integration of thermal and hydrological performance, and the near absence of studies that explicitly treat NBS as a component of urban form or link EO indicators to the systematic monitoring of NBS performance.
Overall, the analysis confirms that land surface temperature and land cover clearly dominate the current literature, reflecting their role as the primary thermal and structural descriptors of urban climate. A second group of ECVs (soil moisture, greenhouse gases and above-ground biomass) appears regularly enough to show growing interest in hydrological constraints, urban carbon dynamics and the role of vegetation, even if they are still less systematically explored than LST and land cover. In addition, several of these ECV products (especially soil moisture, GHGs and some radiation-related variables) are often available only at coarse spatial resolution, which limits their direct use for intra-urban analyses and highlights the need for downscaling approaches to obtain neighborhood-scale information inside cities.

From a MOMO-NBS perspective, this pattern reinforces the choice of LST and land cover as core ECVs for multi-city analysis, while also highlighting the potential added value of systematically integrating soil moisture, GHGs and biomass to capture both thermal and carbon-related dimensions of urban climate. At the same time, the relatively marginal treatment of AOD, wind and albedo points to clear opportunities for MOMO-NBS to go beyond the existing literature, especially by combining these variables with detailed 2D/3D morphology and NBS information.

Within the reviewed literature, the use of dedicated 2D/3D urban morphology datasets—such as building footprints, heights, or detailed street-canyon parameters—remains limited, with urban structure typically represented only indirectly through land-cover classes or simple proximity to infrastructure. Similarly, the potential of ECVs to serve as indicators for monitoring the effectiveness of nature-based solutions for urban climate-change adaptation has yet to be systematically explored. This represents a clear opportunity for MOMO-NBS to advance the state of the art by explicitly integrating detailed urban morphology and EO-based ECVs into NBS assessment frameworks.

Stakeholders from both municipal and national levels face increasingly complex climate challenges, with heatwaves, flooding, extreme precipitation, air pollution, sea-level rise, and, in some contexts, wildfires emerging as the most significant risks. Vulnerability is strongly linked to urban form, particularly compact low- and mid-rise neighbourhoods, ageing building stock, low-elevation and coastal areas, and river-adjacent zones, with social factors further increasing exposure in some cases. All stakeholders have experience with implementing or supporting Nature-Based Solutions, such as urban trees, parks, green roofs, wetlands, and sustainable drainage systems; however, the effectiveness of these measures is rarely assessed in a systematic or comparable manner. Despite widespread use of satellite and spatial data for environmental monitoring, stakeholders report persistent limitations related to insufficient spatial and temporal resolution, technical capacity constraints, and difficulties in integrating data into planning processes. Across all organisations, there is a strong demand for high-resolution urban morphology data, quantitative and economic evidence of NBS performance, and accessible monitoring and evaluation tools.

Stakeholder interactions within the MOMO-NBS project demonstrate a high level of interest and engagement across both municipal authorities and national agencies, with a clear willingness to contribute beyond the questionnaire exercise through participation in workshops, scientific sessions, joint pilot activities, and the co-development and testing of tools and datasets. Overall, stakeholders view MOMO-NBS as a valuable platform for strengthening collaboration between science and practice, improving the usability of data and evidence, and supporting more informed and effective decision-making on Nature-Based Solutions for climate resilience.

The science requirements in this deliverable define the operational conditions for the next project phases. They confirm a multi scale implementation combining a global multi city analysis with pilot city feasibility studies, and they require a harmonized cross city indicator framework linking ECV records with 2D and 3D urban morphology, explicit NBS descriptors, and ECV linked effectiveness metrics. They also set the key conditions for robustness and comparability, including common spatial reporting units and intra urban stratification, clear spatial and temporal scale requirements, uncertainty characterization and validation, and a consistent strategy to reduce confounding when interpreting NBS effects. Taken together, these science requirements provide the reference for WP2 methodological definition and for evaluating transferability across cities and usefulness in pilot cases.

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