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Evaluating Nature-based Solutions as urban resilience and climate adaptation tools: A meta-analysis of their benefits on heatwaves and floods

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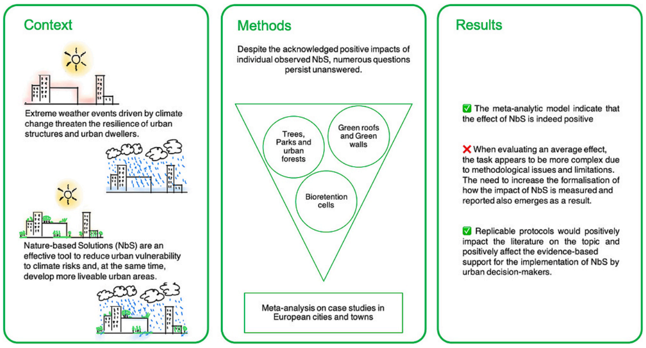
HIGHLIGHTS

- Evaluation and quantification of the impact of NBS on urban areas.
- A meta-analytic model was used to address available studies at the European level.
- NbS mitigate extreme heat and flooding in different climates and urban setups.
- The impact on temperature and runoff reduction is higher in towns than in cities.
- Urban decision-makers must focus on replicable protocols and NbS' combined effect.

GRAPHICAL ABSTRACT



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Meta-analysis on case studies in European cities and towns

✅ The meta-analytic model indicate that the effect of NbS is indeed positive

❌ When evaluating an average effect, the task appears to be more complex due to methodological issues and limitations. The need to increase the formalisation of how the impact of NbS is measured and reported also emerges as a result.

✅ Replicable protocols would positively impact the literature on the topic and positively affect the evidence-based support for the implementation of NbS by urban decision-makers.

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ABSTRACT

Extreme weather events driven by climate change threaten the resilience of urban structures and urban dwellers. Nature-based Solutions (NbS) are an effective tool to reduce urban vulnerability to climate risks and, at the same time, develop more liveable urban areas. Despite the acknowledged positive impacts of individual observed NbS, numerous questions persist unanswered. While existing research supports NbS' positive influence on urban climate adaptation, the extent of their impact remains insufficiently studied. Understanding the magnitude of NbS impact is crucial for justifying their preference over non-NbS alternatives and, consequently, for securing public investment. Via a meta-analysis, this paper aims to contribute to research and practice by providing a more systematic assessment of NbS effects, offering urban planners and decision-makers a robust justification for their incorporation in climate change adaptation, urban resilience, and enhanced liveability.

The results of the meta-analytic model indicate that the effect of NbS is indeed positive. When assessing the impact on temperature and flood protection, there is a general positive effect across the studied NbS. However, when evaluating an average effect, the task appears to be more complex due to methodological issues and

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limitations. The need to increase the formalisation of how the impact of NbS is measured and reported also emerges as a result. Replicable protocols would positively impact the formalisation of the literature on the topic and positively affect the evidence-based support for the implementation of NbS by urban decision-makers.

1. Introduction

Nature-based Solutions (NbS) are increasingly valued as an innovative and efficient approach to climate change adaptation in urban areas with multiple positive synergies (Seddon et al., 2020). The 2023 IPCC Sixth Assessment Report identifies NbS as a core component of adaptation pathways to address climate-related risks threatening the livelihood and health of urban dwellers, in particular temperature regulation and flood protection. As for the main highlighted urban hazards: the impact of heatwaves and urban heat island effect, is foreseen to worsen, and extreme precipitation events are expected to have record increases in frequency and intensity in many parts of the world (IPCC, 2023). However, implementation-wise, NbS face several barriers linked to unawareness of their role, limited technical knowledge, and limited dedicated financial resources (Voskamp et al., 2021). Notwithstanding, several authors foresee NbS as a potentially strategic tool for increasing urban resilience (Frantzeskaki et al., 2019).

Urban NbS definition and implementation is highly challenging, as urban development is a path-dependent process (Collier, 2017) subject to interacting socio-economic and natural variables, lock-in scenarios, and feedback effects. Urban Planners face a multitude of complex and intertwined challenges, ranging from land use, population dynamics, water management and wastewater treatment (Tan et al., 2018), to social equality, health, pollution, and so forth (Voigtländer et al., 2008). Looming in the background, climate change, climate hazards and extreme weather events must be factored in as an overarching challenge that deeply affects human and social well-being (Brundrit and Cartwright, 2012; Harris et al., 2012; Orsetti et al., 2022).

Against this background, in 2015, a European Commission (EC) Horizon 2020 report (Sowińska-Świerkosz and García, 2022) outlined NbS as a tool to support urban areas' resilience to climate change. The EC defined NbS as 'actions inspired by, supported by or copied from nature' that aim to innovatively reduce the negative impacts of extreme weather events on human well-being (EC, 2015). Albert et al. (2019) indicate that urban challenges can be addressed by specific ecosystem services; their identification can guide to the implementation of specific NbS that by restoring, creating or enhancing an ecosystem led to the minimisation of challenges, specifically those linked to climate change. NbS innovation lies within (i) the understanding of the natural processes and their interaction with human activities, (ii) the internalisation of ecological limitations, and (iii) the tailoring of solutions based on local conditions (EC, 2015).

Recent assessments of standalone case studies confirm that the ecosystem services generated by NbS (Cortinovis et al., 2022) provide benefits for urban areas, including the mitigation of Urban Heat Island (UHI) effect (Marando et al., 2022) and the reduction of the intensity of stormwater runoff (Fioretti et al., 2010; Stratigea and Makropoulos, 2015).

Climate change causes more frequent and intense heatwaves, which, at the urban level, tend to increase in length and magnitude due to the presence of heat-storing surfaces that generate UHI (Knight et al., 2021). For the impacts on local environment and dwellers' health, measuring the effect of the studied NbS on air and surface temperature was deemed critical. Similarly, urban areas are sensitive to the increased intensity and frequency of extreme rain events, whose negative impact is magnified by the high share of sealed surfaces; for this, NbS are relevant to reducing the negative impacts on the population and local economy (Emilsson and Ode Sang, 2017).

On the one hand, temperature extremes and the phenomenon of the urban heat islands (UHI) are one of the most relevant stressors for urban areas, urban dwellers' livelihood and health (IPCC, 2023, 2022). The UHI effect can be defined as a higher temperature registered in urban areas, compared to rural areas, on a regular basis. Modern urban areas have a high share of surfaces with low albedo that tend to store heat and energy during the day and release it at night (Marando et al., 2022). Dark surfaces like concrete, asphalt, and steel, among others, can reach relatively high temperatures, especially during summer. The high amount of heat stored in these surfaces leads to an increase in air temperature, both during the day and at night (Noro and Lazzarin, 2015). Due to the different physical behaviours of building materials and air, this work focuses on measuring air and surface temperature.

On the other hand, in urban areas, impermeable surfaces like roads, pavements, and structures result in a consistent share of precipitation which cannot infiltrate the soil leading to surface runoff. Water excess and overflow are hazardous to urban dwellers, to their livelihood and the overall stability of built-up areas. More frequent and extreme rain events translate into more frequent masses of excess water flow through built up areas leading to floods, erosion, and compromised water quality (Cullmann et al., 2021; IPCC, 2022). NbS are expected to reduce the negative impact of extreme rain events. Bioretention cells, green roofs, parks, and trees reduce the overall amount of urban impermeable surfaces, slow down the stormwater runoff and contribute to the creation of stormwater collection areas (IPCC, 2023).

Beyond heat and flood related risks, NbS positively impact noise reduction, GHGs concentration, water pollution (Piro et al., 2018; Santos et al., 2023), whilst enhancing urban aesthetics and providing recreational value (Rost et al., 2020; Takács et al., 2016).

With such a multiplicity of NbS solutions comes a need for greater formalisation and conceptual clarity. To this effect, Sowińska-Świerkosz and García (2022) indicate that NbS feature four conceptual pillars defining their practical application. NbS should: (i) provide multiple benefits; (ii) be based on natural processes, (iii) should address societal challenges and (iv) should be effective and efficient, thus economically viable.

However, and despite the array of NbS' positive impacts and definitions, multiple questions remain unanswered. If existing research validates the fact that NbS have a positive effect on urban climate adaptation efforts, the degree in which they do remains under-systematised. In this study, the literature is central to mapping a wide array of empirical studies analysing specific cases in order to systematise and aggregate their key findings. Determining the degree of impact of NBS is critical to inform its choice over non-NBS options and, therefore, justify public investment.

This is the core rationale behind the contribution to research and practice that this paper can provide. Greater systematisation of NbS effects will provide urban planners and decision-makers with a sturdier justification for their use under the umbrella of climate change adaptation, and urban resilience and liveability increase.

Concurrently, the impact of NbS as urban resilience and climate-change adaptation tools can be assessed either via the analysis of individual case studies or through a systematic comprehensive review of the case studies found in the literature. This paper attempts to assess NbS as tools for urban resilience and climate adaptation, conducting a meta-analysis of their benefits in mitigating the impacts of heatwaves and floods.

With a geographical focus on European Cities, NbS have been grouped in six categories (i.e., green roofs, green walls, parks and urban forests, tree(s), urban green spaces, and bioretention cells; for further details see Appendix A) whose effects on urban resilience were measured in peer-reviewed studies.

To manage a literature characterised by a high degree of heterogeneity a set of key research questions were used to set up a common denominator across all studied examples. This will also allow a comparison of different case studies across European urban areas in a quantitative, transparent and replicable way. The key research questions are:

1. Is the contribution of NbS to urban microclimate positive and quantifiable?
2. What is the average effect of NbS measures on the urban microclimate?
3. Are there NbS solutions that are working better than others?

Analysing the answers to these questions will help to systematise the literature on the role and contribution of NbS measures to climate change adaptation strategies and urban resilience and liveability in the European context.

2. Methods

2.1. Study design and search strategy

Extreme temperature and flood risks are the main climate stressors at the urban level (IPCC, 2023). This evidence presented above justifies the choice of meta-analysis' focus on these two risks. Within each stream of analysis, there will be a focus on which of the identified NbS have the most effective mitigating response to these risks.

To develop the meta-analysis model the choice of indicators was based on their relevance for urban areas.

When reviewing the literature for case studies, the search criteria was designed to guarantee reliability and reduce biases. The methodology followed at this stage of the literature analysis is based on the existing guidelines for systematic reviews and meta-analysis (Koricheva et al., 2013; O'Dea et al., 2021; Pullin et al., 2022), which links the PRISMA methodology to ecology and environmental policy. When testing for effectiveness, Koricheva et al. (2013) suggest a case study-selection based on the PICO approach. The latter is articulated over four main pillars: (i) population, (ii) intervention, (iii) comparator, and (iv) outcome. Therefore, to measure the effect of NbS on urban resilience, selected publications had to meet the following criteria:

1. Population: Targeted case studies were geographically located in European urban areas (not necessarily in EU countries) fitting with the thresholds identified under the GHSL Settlement model (City: population density greater than 1.500 pop/km2 and population above 50.000 inhabitants – Town: population density greater than 300 pop/km2 and population above 5.000 inhabitants) (Kemper et al., 2022).
2. Intervention: This study focuses on the implementation of urban NbS. To help narrow down the starting sample, inorganic NbS (i.e., based on inorganic materials like concrete) were discarded while organic NbS (i.e., based on organic compounds) were considered as the main object of the analysis.
3. Comparator: Implemented, experimental or modelled NbS were to be compared with "as is" or do-nothing scenarios (e.g., a green roof was to be compared with a comparable traditional black roof, the model of a green requalification of an urban area was to be compared with the current, or do nothing, scenario).
4. Outcome: To test if NbS lead to increased urban resilience to extreme events, included studies had to present a quantitative assessment of the impact of the studied solutions on extreme temperature or stormwater runoff. These data were stored in two separate databases, one for temperature and one for floods.

The included studies had to be written in English and include primary data from either an empirical case or a model developed for that publication. The analysis includes studies based on experimental and modelled data. The underlying rationale, as shown in the literature (Burszta-Adamiak and Mrowiec, 2013; Heusinger et al., 2018; Medina Camarena et al., 2022), is that the models (e.g., the hydrological model Landscape and vegetation-dependent Flood Model) and the software used (e.g., ENVI-met is a 3D modelling software simulating the microclimatic processes) project dynamics quite close to the actual fluctuation of the studied indicators. Additionally, this choice has been observed in other meta-analysis addressing similar variables (Liu and Niyogi, 2019; Schinasi et al., 2018). Hence, modelled results were not excluded In both databases, about 70 % of observations result from experimental studies, while 30 % result from modelling and use of environmental software. Details on the experimental and modelled studies are presented in Tables F.7 and F.8 (Appendix F).

The data presented in the selected studies had to describe the effect of the implemented NbS on temperature or stormwater runoff, and studies had to contain sufficient data to calculate the average effect, range, and standard deviation. As most of the studies were not designed to report on the behaviour of a sample, but rather to present the implementation of a specific NbS, few studies reported on standard deviation. Therefore, the standard deviation, required by the meta-analytic model used in this paper, was manually calculated when possible.

A search query was used in the online database Web of Science (Clarivate, 2022) to identify the studies. The underpinning rationale was based on a two steps process. First, similar examples in the literature were examined to understand that the use of a plurality of databases was the most common solution to guarantee maximum topic coverage. Second, during the query design stage, extensive trail tests were run on both Scopus and Web of Science (WoS). WoS repeatedly provided more coherent results that closely aligned with our query criteria. In other words, WoS provided a better fit of papers for our review. With this in mind, we thus opted to focus on WoS only.

The PICO approach was used to apply conceptual building blocks to group keywords and design the search query. After multiple adjustment and validation stages, the search query was run in December 2022 and March 2023, for the extreme temperature and the flooding resilience search, respectively. The design of the developed query was highly influenced by the work of Knight et al. (2021). Once the query was set, a few tests were run to see if the already identified key literature would be signalled via the query design. For this validation purpose, studies from Aram et al. (2019), Skoulika et al. (2014), Bochenek and Klemm (2021), Santos et al. (2023), Fioretti et al. (2010), Cipolla et al. (2016) were used.

In practice, the search query was designed around five conceptual building blocks, to identify case studies that were simultaneously (i) in urban settings, (ii) measured the impact of NbS, (iii) on climate-related issues, (iv) acknowledged the interaction between urban and climate dynamics and (v) located within Europe (see Appendix B). The building blocks were kept as similar as possible to guarantee similar outcomes except for the targeted issues.

Strategically, keywords directly referring to NbS (e.g., "nature-based*") were actively avoided. NbS terminology is relatively recent, while the use of green infrastructures in urban areas predates its coding under the NbS category (Pauleit et al., 2017). Therefore, the search strategy targeted these actions without referring to their naming convention, as the opposite strategy would have substantially reduced the number of available records. However, this paper strictly focuses on NbS with the specificities indicated under "Intervention" of the PICO methodology presented above. All fields produced by the Web of Science export were kept in the output of the two databases.

2.2. Study selection, data coding and data extraction

According to the PRISMA methodology (Page et al., 2021), the study-selection process was fourfold. A first stage aimed to exclude duplicates, a second focused on analysing studies' titles, a third honing on pre-selected studies' abstracts and a fourth, and last, stage entailing the review of the complete texts. The latter checked coherency with the selection criteria highlighted in the PICO approach, and highlighted quantitative information that could be fed into the meta-analytic model.

The PRISMA flowchart (Page et al., 2021) (Appendix C) outlines the performed screening and selection processes which were initially undertaken by one reviewer (the first author). At a second stage, the second and fourth authors validated the selection by each focusing on circa 30 papers related to a risk (second author: temperature, fourth author: floods). Additionally, some safety-checks were put in place. At each stage, if there were any doubts regarding the coherency of the study with the research objectives, a deeper, more detailed evaluation would be performed.

To populate the meta-analysis and assess the effect of NbS, the data collection process consisted of analysing studies' text and recording selected data on a dedicated database. Only studies that quantitatively assessed the impact of NbS in European urban areas were included (both modelled and experimental NbS). Many studies had no clear indication of quantitative data and were thus excluded. Further, all selected studies had to have an in-text indication of the effect of the implemented NbS and the possibility of calculating measures of variation (i.e., the standard deviation). This requirement is central to the inclusion of the observation In the meta-analytic model. Finally, when different papers reporting on the same experiment were identified only one was considered.

However, if data were presented with the support of tables and charts, the studies were kept, and the information was extracted via the online version of WebPlotDigitizer (Rohatgi, 2022). This method allowed the reviewer to extract data series and manipulate them to obtain the average and the standard deviation of NbS' effects.

Some studies with minimal data availability were included as long as the simplified formula for the approximated standard deviation could be calculated. According to Taylor (2019), the standard deviation can be approximated as the difference between the max and the min of the population, divided by four. The use of an approximation aims to maximise the number of studies included in the NbS impact assessment. A dichotomous control variable was introduced to control for distortion related to any interpolation. If the study under review reported the average impact of NbS and the standard deviation in text, then the variable would get the result 1. If any interpolation was performed, the value was set to 0 – this included the use of WebPlotDigitizer, calculations or any proxies for the standard deviation.

From each study, information was extracted regarding (i) the geographic location (i.e., City, Coordinates, and Type of urban area); (ii) the NbS implemented (i.e., Type of green space, green areas' characteristics, Surface, Soil type, Slope, Vegetation type); (iii) information regarding the measurement of the identified outcomes (i.e., type of measurement, time and month, position of the measurement, dimension of the analysis); and (iv) other qualitative observation that could be of use in guiding the analysis like the mention of spillover effect deriving from the implementation of the presented NbS. Some of the mentioned independent variables were not used for the meta-analytical model due to a lack of consistency of their presentation in the analysed studies. Table 1, presents the list of variables used while the one in Appendix F presents all the extracted independent variables. The outcomes (dependent variables) measured for the meta-analytic models included air and surface temperature (°C or K), runoff reduction (%), rainfall reduction (%) and peak flow reduction (%) – these variables are defined in the Tables 1 and 2 below.

Finally, each paper was assessed based on bias risk, following the methodology implemented by Knight et al. (2021). After considering selection, detection, and performance bias, every paper in the two databases was marked with a risk grade. The assessment focussed on the studies design, with specific attention to the choice of the experimental study (randomised or non-randomised) and the presence, risk or acknowledgement of selection, detection, or performance bias, as well as confounding factors.

Table 1
Variables addressing the temperature section (note: for variables collected from the literature review but not used in the meta-analysis, see Appendix F).

Dependent variables	Definition	Analysis used
Air temperature	Measurement of the temperature of the air at a given height	Meta-analysis
Surface temperature	Measurement of the temperature of a surface (e.g., pavement, wall)	Meta-analysis
Independent variables	**Definition**	**Analysis used**
Location	Coordinates	Descriptive statistics
Type of data	Experimental or modelled	Descriptive statistics
Risk of bias	Scale from low to very high	Descriptive statistics
Type of urban area	City or town	Meta-analysis
Type of green space	Green roof, Green wall, Park, Tree(s), Urban forest, Urban green space	Meta-analysis
Type of control	The type of control in each study in order to measure the impact of the considered NbS. Observed options could be: i: non-NbS traditional, ii: non-NbS innovative, iii: other NbS	Meta-analysis
Type of measurement	Air or Surface	Meta-analysis
Climate zones	Climate zones based on the Köppen-Geiger climate classification system (Peel et al., 2007).	Meta-analysis

2.3. Effect measures and model

Two separate meta-analyses were conducted in R Studio (rStudio Team, 2022). The model applied the rma function from the metafor package to create random and mixed-effects models (Viechtbauer, 2010). The choice of the models was based on the heterogeneity among studies. The random effect model allows for this variability to be accounted for in the assessment of the effect size. Similarly, the mixed-effect model was used to understand the reasons for heterogeneity by including categorical predictors (Viechtbauer, 2010; Borenstein et al., 2010).

The analysis was split between temperature and flood protection to assess the influence of moderators on the effects of NbS on the respective parameters. The meta-analytical models for temperature were developed as a mixed-effects model, allowing for the interaction between the type of measurement and all other categorical predictors. For the flood analysis, the effect of each level of analysis on the flood variables was assessed in the meta-analysis using random effects models in the first level and mixed-effects models in the subsequent levels. The choice of these models was based on the literature on meta-analysis (e.g., Viechtbauer, 2010; Viechtbauer and Cheung, 2010; Borenstein et al., 2010). Categorical predictors specified as moderators in the meta-regression models representing different levels of analysis are shown in Table D.1 (Appendix D).

As described in Viechtbauer (2010), the following equations are at the core of the Random-effects and Mixed-effects models:

- Random-effects model equation:

$$\widehat{\theta}_k = \mu + \epsilon_k + \varsigma_k$$

Table 2

Variables addressing the flood section (note: the variables that have not been used for the meta-analysis, but that were collected in the study of the literature, are mentioned in Appendix F).

Dependent variables	Definition	Analysis used
Run off reduction	Measurement of the amount of runoff water in case of presence of a NBS and in case of absence	Meta-analysis
Rainfall reduction	Measurement of the amount of rainfall that is retained by trees and does not reach the soil. Rainfall partitioning is a phenomenon that implies that the tree canopies reduce the amount of stormwater reaching the soil. Part of the rainfall is intercepted by the canopy, part is released through the stem (i.e., Stemfall) which contributes to the delay of the peak and part reaches the ground during the rain event (i.e., throughfall) (Zabret and Šraj, 2019).	Meta-analysis
Peak flow reduction	Measurement of the highest discharge of water during a flood event. It represents the maximum rate at which water flows through a particular urban area, river or channel during a flooding event. This measure is key to understanding the severity of a flooding event and its potential impact on the built environment.	Meta-analysis
Independent variables	**Definition**	**Analysis used**
Location	Coordinates	Descriptive statistics
Type of data	Experimental or modelled	Descriptive statistics
Risk of bias	Scale from low to very high	Descriptive statistics
Type of urban area	City or town	Meta-analysis
Type of green space	Green roof, Green wall, Park, Tree(s), Urban forest, Urban green space	Meta-analysis
Type of control	The type of control in each study in order to measure the impact of the considered NbS. Observed options could be: i: non-NbS traditional, ii: non-NbS innovative, iii: other NbS	Meta-analysis
Climate zones	Climate zones based on the Köppen-Geiger climate classification system (Peel et al., 2007).	Meta-analysis

, where $\widehat{\theta}_k$ is the unknown effect size for the k_{th} study, μ is the overall average true effect across all studies, ϵ_k is the within-study error for study k and $\varsigma_k$is the between-study error for study k. This model assumes that the true effect sizes of the studies being analysed in the meta-analysis are not all the same.

- Mixed-effects model equation:

$$\theta_i = \beta_0 + \beta_1 x_{i1} + \ldots + \beta_p x_{ip} + u_i + e_i$$

, where θ_i is the observed effect size for study i, $\beta_1, \ldots, \beta_p$ are the fixed effects parameters, $x_{i1}, \ldots, x_{ip}$ are the covariates for study i, $u_i \sim N(0, \tau^2)$ is the random effects term for study i and $e_i \sim N(0, v_i)$ is the within-study error for study i. Mixed-effects models in meta-analysis allows for the inclusion of study-level covariates and accounts for both within-study and between-study variability.

The Restricted maximum-likelihood estimator (REML) approach was applied to deal with the variability across the studies, which was indicated as method = ““REM”“in the models (Viechtbauer, 2005). To get the confidence interval of the estimated effects from the random and mixed-effects models, the Knapp-Hartung correction was applied by setting the argument test = “knh” (Knapp and Hartung, 2003). The meta-estimates were obtained using effect sizes weighted with the inverse of their respective variances, by setting the argument weighted = TRUE in the meta-analytical models.

In the meta-analysis, the raw mean was employed as an effect size measure. The rationale behind this choice was structured around the fact that the outcome in all studies are reported on uniform scales – degrees, millimetres, percentages. Therefore, the study mean difference was defined as D = X_1-X_2, where X_1 and X_2 were the means of the two independent groups. This approach allowed us to directly compare the results of the individual studies without the need for additional standardisation (Anvari and Lakens, 2021).

To assess the impact of outliers on the meta-analysis outcomes, a sensitivity analysis was performed. The cooks.distance function was selected from the metafor package to estimate the influence of each data point (Viechtbauer, 2010; Viechtbauer and Cheung, 2010). Data points with a Cook's distance greater than 0.5 were deemed outliers and were removed (Cook and Weisberg, 1982). Afterwards, the model was fitted without the outliers which resulted to be minimum. With regards to extreme temperature five outliers were identified, while within the flood protection analysis only one outlier was identified and excluded.

No studies were excluded based on the assessment of biases. The studies that presented a low risk of bias indicate that the authors chose a randomised experimental study (i.e., selection bias), applied the same data collection method between the case study and the control and used similar equipment and measurement conditions (i.e., detection bias). Finally, each event registered is linked to one NbS only, without the risk of potential contamination of effect (i.e., performance bias).

3. Results

3.1. Evidence from the literature and studies characteristics

The analysis of the case studies presented in the literature, driven by the data selection based on the PRISMA method, led to two databases containing 60 studies concerning temperature and 29 concerning stormwater management (Appendix C). The included studies comprised 90 and 124 useful NbS observations for stormwater management and temperature, respectively. These NbS were tested over several events, counted as rainy days and days of temperature measurement–- totalling 1.205 rainy days and 1.139 days of temperature measurements, in 29 and 43 urban areas respectively. There is an evident concentration of temperature-related studies in the southern European countries (Appendix E).

In general terms, the studies included in the analysis are non-randomised. The selection process of the NbS is mainly based on the availability of information and the available NbS to test. Furthermore, in the case of temperature studies, it is observed that the methodology frequently assesses temperature at various points along a traverse, which leads to potential detection biases. There is little reference to the risk of bias in the selected studies. However, many studies indicate their data collection tools, the methods and the description of the studied NbS. This information has helped in the categorisation of the risk of bias. Tables F.3 and F.4 (Appendix F) present the distribution of the studies based on the risk assessment as laid out in the previous section.

The breakdown per publication date (Appendix F, Fig. F.1) illustrates the relatively recent quantitative assessment of NbS as a way to test instruments aiming to increase urban resilience. In addition, the EC publication-year marks a change of pace concerning the release of NbS publications. Studies' characteristics are presented according to the implemented coding system (see Appendix F, Tables F.1 and F.2).

The distribution of observations per type of NbS is presented in Appendix F, Tables F.5 and F.6. In general, temperature holds a more balanced number of records per type of NbS, reflecting how different NbS are perceived as bringing similar contributions to UHI and extreme temperatures mitigation at the urban level. Regarding stormwater management, the situation differs as there is a strong predominance of green roofs, representing 74 % of the observations. The different split may reflect the fact that experimenting with green roofs is relatively more straightforward, and setting up pilots to test their capacity to reduce extreme stormwater runoff is convenient and allows for advancement in steering green roof design.

Finally, the cities included in the analysis were classified according to the Köppen climate classification zones to understand the relationship between this independent variable and the impact of NbS on temperature and runoff reduction. The cities in the analysis were located in the following climate zones: Cfa (Humid Subtropical climate characterised by hot summers, mild winters, and no dry season), Cfb (Oceanic climate having mild temperatures year-round and no dry season), Csa (Mediterranean climate with hot and dry summer and mild, wet winters), Dfb (Humid continental climate with warm summers, cold winters and no dry season), Dfc (characterised by subarctic climate with severe winters, short, cool summers and long, severe winters), and Dsb (continental climates Mediterranean-influenced with warm and humid summer, and wet winters) (Peel et al., 2007).

3.2. *NbS effects and impacts on risk of flooding and on the UHI effect*

The following Sections (3.2.1 and 3.2.2) present results in several tables containing the general metanalytical effect, in the bottom row, and the specific effect per each type of NbS. The tables in Appendix D present the effect (estimate), including the standard error (se), the t-statistics (tval), the data frame (df), the *p*-value (pval), the confidence intervals (ci.lb. and ci.ub), and the number of observations (k). The related forest plots are introduced in Section 4 to better guide the discussion.

3.2.1. *NBS and extreme temperature*

Due to the different physical behaviours of building materials and air, this work focuses on measuring air and surface temperature. Included observations totalled 116, of which 75 addressing air temperature and 41 focusing on surface temperature.

The overall impact of NbS on air temperature in urban areas brings about an average reduction of 1.1 °C – differentiated between cities (0.9 °C reduction) and towns (1.8 °C reduction), again towns appear to be more impacted by NbS. As previously indicated, the test on dichotomous control variables aimed at verifying that the interpolation did not have any negative impact. As for temperature analysis, most observations (99 %) were subject to interpolation allowing for a methodologically sound comparison.

The impact of different NbS on air temperature appears to be relatively homogenous, around a 1 °C reduction (Table D.2, Appendix D). Not all effect estimates have statistical significance due to a lack of a consistent number of observations. However, the direction of the effect appears to be clear: all NbS reduce air temperature, especially in the case of parks and urban forests, which present the highest reduction.

Contrastingly, urban green spaces present a positive yet low effect. The result of urban regeneration initiatives, the latter bring about a greening process that transforms grey urban spaces, without necessarily creating a park or an urban forest. Urban green spaces are not entirely natural areas but feature more greenery than the usual impermeable urban surfaces. Hence the impact on air temperature. Similarly, the impact of trees is aligned with the overall NbS score.

When assessing NbS impact on surface temperature (see Table D.3, Appendix D), two main differences stand out: (i) the absolute value of change is much higher than the one identified for air temperature; (ii) there is an additional NbS, green walls, which was not part of the analysis addressing air temperature. The latter concerns the conformation of green walls and their predisposition to have an impact on the temperature of the building itself – both on the building envelope and internally.

The overall impact of NbS on surface temperature is a noteworthy reduction of 4.4 °C, a statistically significant outcome derived from 41 observations. The substantial disparity in absolute value concerning the alteration in surface temperature is attributed to the distinct physical characteristics of the materials under observation, diverging significantly from the properties inherent to air itself.

Among the different NbS studied for their impact, trees show the most substantial effect with the highest absolute value of surface temperature reduction of 8.0 °C. Urban forests also showcase a significant cooling effect of 5.5 °C. Parks, urban green spaces, and green roofs display moderate yet noticeable decreases in surface temperature, 3.1 °C and 3.4 °C, respectively. Green roofs contribute to cooling effects with an absolute value of temperature reduction of 3.0 °C. Finally, green walls display the lowest value, standing at a 2.1 °C reduction (see Table D.3, Appendix D).

The high standard error observed for the effect of certain NbS, can be attributed to the extensive diversity within the sample, which contains observations of solutions implemented in different geographical locations and measured in different ways. This diversity contributes to substantial variability in the data points around the mean, typical of a heterogeneous sample. Despite varying population sizes, the statistical significance observed across all NbS proves their surface temperature reduction potential. Notably, their impact is statistically robust even with a smaller number of observations in urban forests and urban green spaces. Furthermore, NbS effectiveness in surface temperature reduction is not solely contingent upon population size but rather the inherent characteristics of these green interventions in urban settings.

The findings of the impact of NbS on temperature reduction (see fig. D.1, Annex D), which encompassed cities across various climate zones, including Cfa (21 cities), Cfb (39 cities), Csa (42 cities), Dfb (3 cities), Dfc (1 city), and Dsb (3 cities), have significant implications. Fig. D.1 in Appendix D indicates that temperature reduction consistently exceeded 2° Celsius in cities within the Csa and Cfa climate zones. In contrast, cities in the Csb and Cfb zones saw reductions above 1° Celsius. However, the temperature reduction was notably lower for cities in the Dfc and Dsb zones.

3.2.2. *NBS and stormwater management*

To quantitatively assess flooding impacts, the first level of analysis investigates the effect of NbS on the amount of runoff affecting urban areas. A total of sixty-nine observations were included. The first level of analysis does not differentiate the type of NbS but considers the overall impact of NbS on runoff. Evidence from the meta-analysis indicates that the overall studied NbS retain more than half of the rainfall, reducing runoff by about 58 % of overall excess water. When evaluating how NbS behave in different setups, the differentiation follows the thresholds identified under the GHSL Settlement model presented in Section 1. Runoff reduction appeared to be higher in the case of towns. Out of the 69 observed NbS, 21 were in towns where the runoff reduction reached 62 % of the overall excess water. The same indicator for cities registered a 56 % reduction.

Besides the overall impact of NbS, the analysis considers how different NbS contribute to increasing urban resilience (see Table D.4, Appendix D). The largest runoff reduction (77 %) is achieved through bioretention cells. Green roofs and parks achieve 60 % and 57 %, respectively. Single trees have a more marginal impact on runoff reduction (14 %).

All results are statistically significant, except for the impact of single trees. However, the direction of the effect is nonetheless relevant as the interception of rainfall by tree canopies and increased water absorption in the soil have a positive effect on reducing the overall urban runoff.

The case of green roofs is interesting as these NbS can be either intensive or extensive (see Appendix A). Almost all cases included in this analysis were extensive green roofs (up to 60 % runoff reduction); contrastingly, the one case of an intensive green roof showed a very high reduction (84 %) of overall excess water. This split does not provide an indication with statistical significance but it strongly hints at an unexplored potential when it comes to intensive green roofs.

Finally, as indicated in the methods section, in order to verify that the interpolation did not have any negative impact on the generation of unbiased results, a dichotomous control variable was put in place. In the case of the runoff analysis, this control variable does not suggest any indication of changes worth mentioning.

The analysis of the impact of NbS on runoff reduction includes cities across different climate zones (see fig. D.2, Annex D), these zones are Cfa (17 cities), Cfb (17 cities), Csa (24 cities), Dfb (2 cities), and Dfc (4 cities). In general, the study revealed a consistent reduction in runoff of over 50 %, with one notable exception: cities within the Cfb climate zone experienced only a 24 % reduction. In Cfb climate zones, precipitations are more frequent and evenly distributed throughout the year; these high moisture levels challenge the effectiveness of NbS runoff reduction measures.

Finally, the analysis included two other depended variables linked to the risk of flooding in urban areas: rainfall reduction and peak flow reduction (as defined in Table 2).

3.2.2.1. Rainfall reduction and peak flow reduction. Due to a limited number of observations, this subsection does not present results with statistical significance. This issue is addressed in the limitations section, nonetheless, the direction of the effect is interesting to mention. The impact of NbS on rainfall reduction is measured with regards to the trees and urban forests – a total of eight observations, of which five are related to urban trees and three to urban forests. The overall impact of NbS in reducing the amount of rainwater that does not reach the soil is about 31 % - urban trees are estimated to have a reduction effect of about 42 % and urban forests of about 13 %. The limited number of observations does not allow to extend the analysis to other factors (see Appendix G, Table G.1).

When analysing the impact on peak flow reduction, the pool of results addressing this specific indicator is even slimmer: three observations all of which contain studies of the impact of extensive green roofs in cities. The measured effect indicates a reduction of the peak flow of about 88 % (see Appendix G, Table G.2). Considering the limited population analysed, the absolute value of the reduction does not provide results characterised by a solid statistical significance (Appendix G). Nevertheless, it is possible to observe that extensive green roofs have a positive impact on the reduction of stormwater peak flow, in the studied European cities.

4. Discussion

The literature on NbS is characterised by numerous studies focusing on the definitions of Nature-based Solutions (NbS), their identification and on single case studies' positive impacts. While existing research confirms that NbS positively affect urban climate adaptation efforts, the extent of this impact is not yet well-systematised. As similarly done by other authors focusing on different combination of variables (e.g., Knight et al. (2021) focus on the impact on pollutants and UHI effect), our study aims to map a wide array of empirical studies by analysing specific cases to systematise and aggregate their key findings. Understanding the degree of NbS impact is crucial for selecting NbS over non-NbS options and justifying public investment. Given the fragmentation of the literature and the predominant focus on single-impact case studies and recognizing both the multiple positive impacts of NbS and the efforts of previous research to systematise existing findings, we have chosen to concentrate on the benefits of NbS for temperature reduction and flood risk reduction.

This is the core rationale for the research contribution of this paper. Better systematisation of NbS effects will provide urban planners and decision-makers with stronger justification for their use in climate change adaptation and enhancing urban resilience and liveability. The impact of NbS as tools for urban resilience and climate-change adaptation can be assessed either through individual case studies or a systematic comprehensive review of case studies in the literature.

To ensure a coherent integration of NbS within local urban policy-ecosystems and budgetary constraints, it is crucial to evaluate NbS impact, particularly in mitigating extreme weather events. This analysis set out to assess if NbS contribution to urban microclimates was positive and quantifiable.

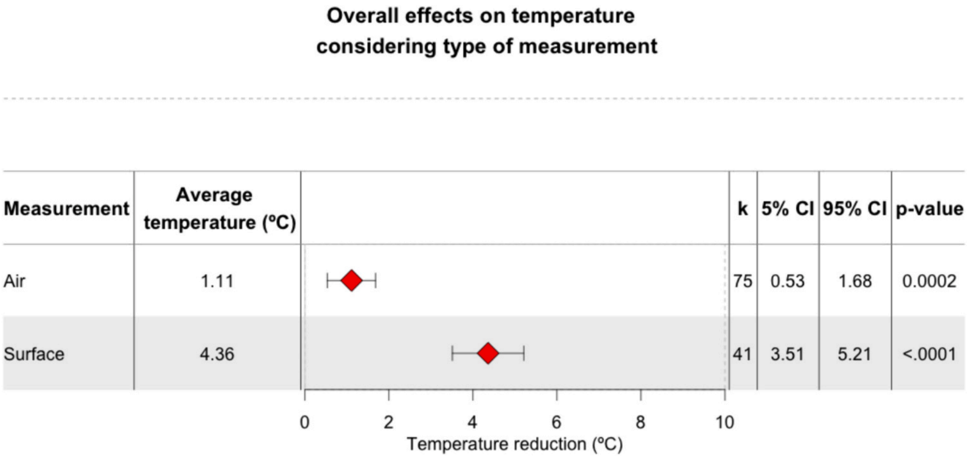
As presented in the forest plots below (Figs. 1 and 2), evidence from the meta-analysis confirms NbS positive impact on urban resilience. Extreme heat and risk of flooding linked to extreme rainfall events appear mitigated by NbS across different climates and urban setups. These forest plots visually display the evidence derived from the meta-analysis. The meta-analysis provides clear indication that there is a reduction of runoff and temperature (air and surface) associated with the implementation of NbS.

Likewise, the type of urban area affects the benefits derived from the implementation of NbS measures. In fact, Figs. 3 and 4 inform that the impact on air temperature and runoff reduction is higher in towns than in cities (Figs. 3 and 4). Thus, it is possible to infer that, based on the sample of observations at hand, NbS appear to be more effective in smaller and less densely populated urban settings. This can be explained by the fact that in larger urban areas, there is a wider set of dynamics both related to climate and to the urban architecture, interacting simultaneously. The feedback effects resulting from these interactions appear to have a lessening impact on the absolute value of effect of NbS.

The same NbS can positively impact more than one indicator (e.g., temperature reduction, runoff reduction). The effects measured for green roofs and parks clearly indicate their positive impact in mitigating runoff, curbing air temperature, and lowering surface temperatures concurrently. While neither solution singularly excels across all indicators, their overall effect presents a relevant case for their contribution to urban resilience. This underlines the importance of evaluating combined effects, potentially offering a strategic approach for decision-makers in selecting the most suitable solution for their city. By considering the overall effect and benefits, city planners can opt for a more holistic approach to urban sustainability. Accordingly, the versatility of these solutions not only highlights their strength and importance in urban contexts but also validates the EC's definition and the established hypothesis regarding the positive impact of NbS on urban resilience.

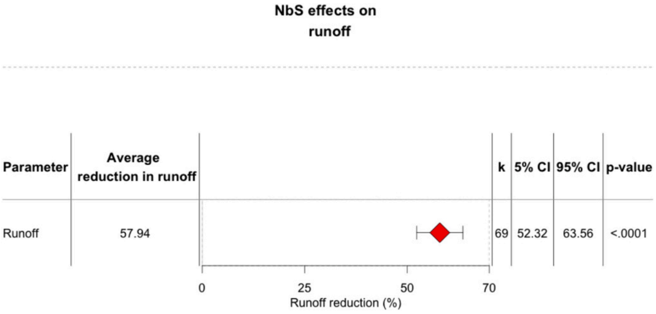
Regarding the quantification of the NbS impacts on temperature and flood risk reduction, the meta-analysis confirms the possibility of estimating impacts on the urban microclimate. Results indicate that the studied NbS positively impacts temperature and flood-related indicators. Average impacts are presented in the forest plots below (Fig. D.3 and D.4., Appendix D). The confidence intervals of some of the effects of the studied NbS overlap zero (e.g., the case of trees in the runoff analysis and of green roof for air temperature), mirroring a lack of statistical significance of the studied effect explained by the limited pool of observations. A wider population may provide better indication that the observed effects are not due to random variation but actually driven by implemented NbS as in the cases of green roofs impact on runoff reduction.

However, average impact claims must be taken cautiously. In fact, local climates and diverse urban fabrics interact differently, leading to results of different magnitudes. Additionally, the analysis stressed the need for more randomisation and the use of replicable protocols in the measurement of effects, as its absence makes it challenging to present an average impact of NbS. In most observed studies, the choice of the analysed NbS relied on the existing NbS rather than via a proper randomised approach. These solutions are only sometimes used in the most effective location within the urban area, as they tend to occupy historical urban development voids. Additionally, UHI studies typically involve assessing temperature at various points along a path, potentially leading to different results if a different path were to be taken. Consequently, it is more relevant to assess the direction of the effect rather


Overall effects on temperature considering type of measurement

Measurement	Average temperature (°C)	k	5% CI	95% CI	p-value
Air	1.11	75	0.53	1.68	0.0002
Surface	4.36	41	3.51	5.21	<.0001

Fig. 1. Overall effects on temperature reduction considering the different types of measurement. The table presents, the number of studies, the confidence intervals (5 %–95 %) and the significance level (*p*-value).


NbS effects on runoff

Parameter	Average reduction in runoff	k	5% CI	95% CI	p-value
Runoff	57.94	69	52.32	63.56	<.0001

Fig. 2. NbS effects on runoff. The table presents, the number of studies, the confidence intervals (5 %–95 %) and the significance level (p-value).

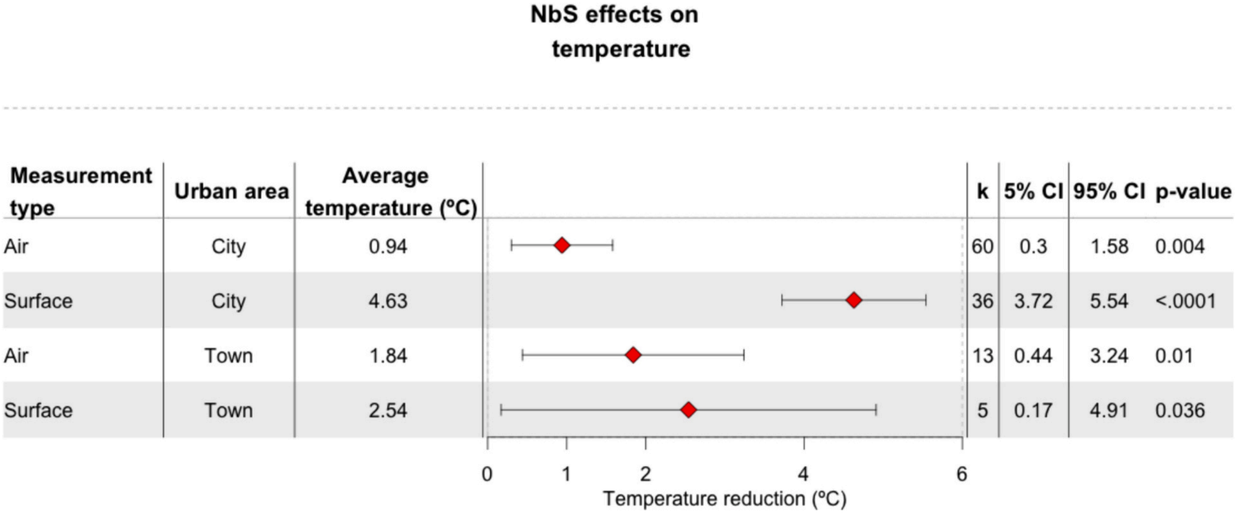
than its absolute value or average.

The last research question aimed to assess if the included observations could help identify optimal solutions. As indicated in the paragraphs above, the identification of an average effect of the impact of NbS on the urban microclimate is not straightforward. Additionally, it may be relevant to re-state several conditions from previous sections:

- The NbS considered have been implement or studied in European urban areas;
- Many of the studies have been flagged as carrying a high to very-high risk of bias; and
- There is a limited relevance of the absolute value of the NbS impacts on temperature and flood risk reduction.

Within the presented framework, green roofs appear to have a medium to high positive impact on runoff and temperature reduction. In the case of runoff, intensive green roofs perform remarkably well. The same type of information could be found for the analysis of temperature. However, given the conformation of intensive green roofs and respective greenery, it can be inferred that intensive green roofs are expected to significantly impact air and surface temperature due to the increased shade they generate. Notwithstanding, a more rigorous quantification of the effects of intensive green roofs on the urban environment, their cost and economic impact is needed to justify the implementation. For one they are difficult to implement in old urban areas because they require a dedicated supporting structure that can rarely be added to existing buildings.

Similarly, parks appear to have a high impact on temperature, both air and surface, but also a positive impact on stormwater runoff. Nevertheless, the urban conformation of many European urban areas is


NbS effects on temperature

Measurement type	Urban area	Average temperature (°C)	k	5% CI	95% CI	p-value
Air	City	0.94	60	0.3	1.58	0.004
Surface	City	4.63	36	3.72	5.54	<.0001
Air	Town	1.84	13	0.44	3.24	0.01
Surface	Town	2.54	5	0.17	4.91	0.036

Fig. 3. City vs Town, effects on temperature reduction considering the different types of measurement. The table presents the average temperature for each type of urban area, the number of studies, the confidence intervals (5 %–95 %) and the significance level (p-value).

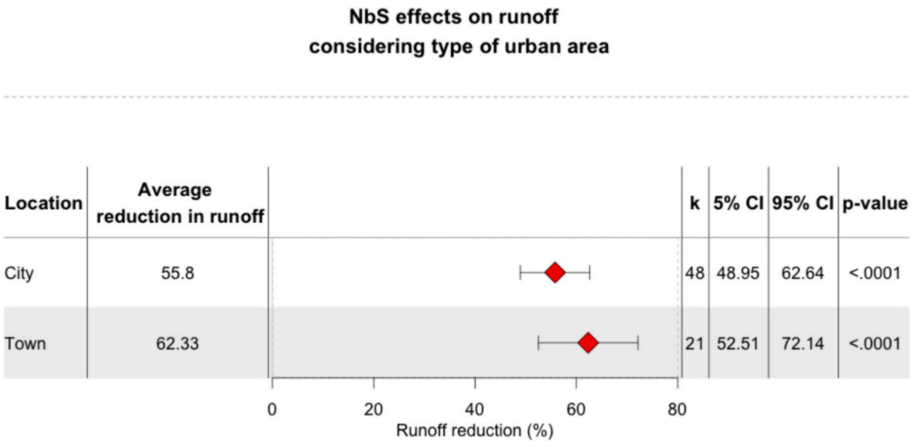


Fig. 4. City vs Town, NbS effects on runoff. The table presents the average effect on runoff for each type of urban area, the number of studies, the confidence intervals (5 %–95 %) and the significance level (p-value).

unsuitable for the proliferation of this type of NbS.

The indication is that NbS reduce the negative impacts of extreme climate events on urban areas and dwellers. However, due to the interaction with other variables (e.g. local climate, urban conformation) providing an indication of the average, or absolute value, of the effect of a specific NbS does not appear to be feasible. This result is coherent with climate change adaptation needs, which, by definition, are geographically context dependent.

Therefore, there is not one NbS working better than others. What is needed is to understand how different NbS and climate change adaptation measures jointly impact urban resilience. Cartwright et al. (2012) argue, to this effect, that urban decision makers need to allow room for flexibility when dealing with the multifaceted challenges of resilient urban planning. For this, the analysis presented provides a relevant starting point for urban decision-makers, indicating the benefits of including NbS in their resilience strategies.

The innovative component of NbS highlighted by the EC provides the flexibility necessary when planning in urban areas characterised by spatial and natural constraints, like in the case of most European urban areas.

5. Limitation of the analysis

5.1. Observations

Assessing the average impact of NbS on some of the chosen dependent variables proved unfeasible due to limitations in the number of observations. This was limited by, first, the complex interplay between local climates and diverse urban landscape, resulting in disparate outcomes when measuring NbS impact on rainfall reduction and peak flow reduction; second, the absence of a standardised methodology for reporting on some independent variables, particularly regarding the dimension of NbS or the temporal scale. Therefore, prioritising the evaluation of the impact's direction holds greater significance than focusing solely on its absolute or averaged value.

5.2. Heterogeneity

The second limitation concerns the studies set up. Heterogeneity among selected studies stems from several causes. Despite the absence of a uniform approach to measuring runoff or temperature, methodological differences play a pivotal role, leading each observation to be independently retrieved. Moreover, environmental, geographical and urban conformations variability significantly contribute to the difference in observed effects. And so do the varied temporal and spatial scales across studies, leading to observations being registered during different parts of that day and for different amounts of time. Besides, the spatial measurement component (e.g., different distances at which temperature is measured) also affects reported outcomes. Last but not least, potential measurement errors, including inaccuracies in data collection, instrumentation, or assessment methods, also contribute to data variability, further emphasising the complexity of synthesising findings.

5.3. Bias

As aforementioned, the majority of selected studies have been categorised as showing a high or very high risk of bias. Despite all efforts to guarantee the quality, integrity, and reliability of the data analysis and the creation of the databases, the following sources of bias can arise:

- Selection Bias: the creation of the queries and the formalised process of selection of studies have aimed at generalising and allowing for the sample to be representative of the entire population. However, the selection process was done by one researcher leading to the risk of skewed conclusions, which was mitigated by the validation process supported by the second and fourth authors.
- Confirmation Bias: similarly, to what stated above, the selection process, performed by one reviewer, could have led to favour the confirmation of preconceptions or hypotheses.
- Measurement Bias: in the use of WebPlotDigitizer errors or inaccuracies in the measurement process could have led to misleading or flawed data.

5.4. Scope

In order to address the research questions, it was necessary to review the interaction between NbS, climate variables, and the urban environment. However, NbS implementation not only impacts the risks linked to temperature increases or extreme rain events but also socio-economic variables, e.g. green areas impact real estate value and neighbourhood attractiveness thus impacting equity. This study did not take these dynamics into consideration despite their relevance to urban climate change adaptation strategy-design (McGray et al., 2007). There is a very limited number of studies in the literature that attempts the inclusion of physical and socioeconomic variables in NbS impact evaluation with a high level of detail. As a research-design option it was decided to examine those who focused on physical measurements as these fitted our research goal the best.

5.5. Sources

While planning the meta-analysis, we examined similar examples in the literature. Most used a plurality of databases to guarantee maximum topic coverage. In sync, during the query design stage, we performed extensive tests on both Scopus and Web of Science (WoS). We observed that WoS repeatedly provided more coherent results that closely aligned with our query criteria. In other words, WoS provided a better fit of papers for our review. We thus opted to focus on WoS only. To enhance the robustness of future research the incorporation of additional databases should be considered, however with a set of quality-control measures in place to assure the coherence of query-outputs and research objectives.

6. Conclusions

NbS currently experience a booming interest from researchers and policy-makers alike. This meta-analysis innovates as a contribution to a more systematic evaluation and measurement of the positive impact of NbS on urban microclimates, namely concerning different NbS average impact and comparative effectiveness with respect to extreme temperature and extreme weather events.

However, methodological limitations make measuring the average effect of NbS an ambiguous process. Similarly, there is no specific NbS that works better than other alternatives, but rather the understanding that NbS positively influence multiple indicators simultaneously in urban contexts, also depending on external variables such as climate zones.

This meta-analysis helps urban decision-makers better grasp NbS benefits in addressing critical urban challenges. It underscores the need for context-dependent holistic approaches that integrate diverse solutions to further urban resilience. An effective strategy must articulate grey solutions and NbS and exploit their complementarity.

Furthermore, NbS positive impact on urban resilience needs to be evaluated in the context of urban decision-making. When considering municipal budgets and limited resources consumed by competing priorities, solutions providing multiple benefits are preferable, mainly when their impact expands beyond its immediate application's area. NbS positively impacts urban climate change mitigation whilst having positive social benefits (Pumo et al., 2023).

This meta-analysis provides relevant guidance for urban decision-makers, concerning the multiple benefits of including NbS in urban resilience strategies. When doing so, decision-makers should integrate socio-economic impact evaluations, e.g. green infrastructure investments impact land value and real estate, which in turn defines the type of population that can afford to live in such areas. This stresses the central role of planning when it comes to capturing and redistributing social value, especially when evaluating the implementation and potential impacts of NbS in urban areas (García-Lamarca et al., 2022; García-Lamarca and Ullström, 2022).

Future research should include in-depth case studies to delve deeper into these variables' interactions and their specific influence on observed outcomes. It is necessary to develop an agreed methodology that allows for more replicable approaches. Ideally, this would include the identification of standard indicators per type of targeted measurement and criteria for their measurements. Such methodology should include a definition of instruments, time, place and number of repetitions of each measurement, and type of data to be shared in the connected publication. This standardisation would allow determining average impacts of NbS minimising biased interpretations. Lastly, more studies are needed on intensive green roofs and a rigorous quantification of its effects, together with their cost and economic impact, to justify expanding on their implementation.

Finally, decision-makers need to include socio-economic evaluation when considering the use of NbS. NbS offer innovation in constrained urban settings, their nuanced impacts require tailored and context-specific strategies. Therefore, future research should provide a body of work to support such decisions by further detailing the intricate connections between NbS and socio-ecological and socio-economic urban development dynamics.

CRediT authorship contribution statement

Francesco Ferrario: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **João Morais Mourato:** Writing – review & editing, Supervision, Methodology, Conceptualization, Validation. **Miguel Silva Rodrigues:** Writing – original draft, Methodology, Formal analysis, Conceptualization. **Luís Filipe Dias:** Conceptualization, Methodology, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.175179.

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