

Nature-Based Solutions for Resilient Cities : A Methodological Approach to Prioritization and Thermal Regulation Assessment.

Solutions fondées sur la nature pour des villes résilientes : une approche méthodologique pour la hiérarchisation des priorités et l'évaluation de la régulation thermique.

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RÉSUMÉ

Cette recherche propose une méthodologie pour hiérarchiser les zones urbaines et mettre en œuvre des solutions fondées sur la nature visant à améliorer et à quantifier le service écosystémique de régulation thermique et à atténuer les îlots de chaleur urbains. La méthodologie combine trois composantes : des variables biophysiques dérivées de la télédétection pour mesurer les caractéristiques de la végétation ; la perception des citoyens quant aux besoins en services écosystémiques sur le territoire ; et des outils informatiques basés sur des modèles d'apprentissage automatique pour quantifier la relation entre la végétation, la configuration urbaine et la température de surface du sol. Les contextes urbains à évaluer sont la zone « El Reencuentro » à Bogotá, en Colombie, où aucune SfN n'a encore été mise en œuvre, et le campus de l'université Javeriana à Cali, en Colombie, où ces interventions sont bien établies. Compte tenu de ce contraste entre les études de cas, la méthodologie offre des outils analytiques applicables dans les deux cas. Les résultats montrent qu'une faible couverture végétale limite la capacité de régulation thermique et que les scénarios avec des SfN vertes réduisent efficacement la LST. L'ampleur de cette réduction dépendra de la configuration spatiale, du type d'intervention, de l'adaptation à l'environnement urbain et de l'entretien. En conclusion, la structure, la continuité et la santé de la végétation urbaine déterminent les avantages climatiques, fournissant ainsi des preuves solides pour la conception de stratégies d'atténuation des îlots de chaleur urbains.

ABSTRACT

This research proposes a methodology for prioritizing urban areas and implementing nature-based solutions (NbS) aimed at improving and quantifying the thermal regulation ecosystem service and mitigating urban heat islands (UHIs). The methodology combines three components: biophysical variables derived from remote sensing to measure vegetation characteristics; citizen perception of ecosystem service (ES) needs in the territory; and computational tools based on machine learning (ML) models to quantify the relationship between vegetation, urban configuration, and land surface temperature (LST). The urban contexts to be evaluated are the “El Reencuentro” area in Bogotá, Colombia, where no NbS have yet been implemented, and the campus of the Javeriana University in Cali, Colombia, where these interventions are well established. Given this contrast in case studies, methodology offers analytical tools that are applicable in both cases. The results show that low vegetation cover limits thermal regulation capacity and that scenarios with green NbS (i.e. urban forests and green spaces) effectively reduce LST. The magnitude of this reduction will depend on the spatial configuration, the type of intervention, adaptation to the urban environment, and maintenance. In conclusion, the structure, continuity, and health of urban vegetation determine the magnitude of the benefit, providing solid and applicable evidence for different urban contexts seeking to design UHI mitigation strategies through NbS focused on vegetation.

KEYWORDS

Citizen perception, Machine learning, Nature-based solutions, Thermal regulation, Urban heat island

1. INTRODUCTION

Cities have established themselves as strategic spaces for human development. One of the main effects of this development is population growth, which has led to the uncontrolled proliferation of impervious surfaces in urban areas, along with the reduction of green infrastructure in cities (UN-Habitat, 2022). This combination has given rise to the phenomenon of urban heat islands (UHI). Identifying heat islands is key to building healthy and sustainable cities. Fortunately, tools for detecting them already exist, as do studies proposing mitigation strategies. Among these, Nature-Based Solutions (NbS) stand out as an innovative approach that leverages ecosystems and their services to address different challenges (Cobo, 2017). Although studies on mitigation strategies using Nature-Based Solutions (NbS) are becoming increasingly extensive, there is a gap in the literature focused on quantifying this mitigation through the ecosystem services generated. Therefore, the objective and novelty of this research is to quantify this mitigation through the thermal regulation service. This is done through historical data evaluation, simulation of various scenarios, and critical analysis of citizen perception as a relevant factor in evaluating the priority of strategies to be implemented and their efficiency.

1 METHODOLOGY

The methodology consists of four main phases, adapted from previous work by Uribe-Aguado et al. (2022) and Uribe-Aguado et al. (2025), focusing on the analysis of thermal regulation. The methodology begins with a baseline analysis in which the main priority concerns are identified and the available local information on surface temperature is reviewed (phase 1). Subsequently, in phases 2 and 3, the location and preliminary selection of NbS are carried out to define urban planning assessment scenarios with different NbS configurations. Finally, in phase 4, the thermal regulation potential in each assessment scenario is evaluated to identify the most effective option. If the case study has already implemented NbS and there is no interest in assessing future planning scenarios, but only in evaluating current thermal regulation, it is only necessary to carry out Phase 4.

Phase 1: Baseline Analysis: The baseline analysis is developed using established methods for assessing urban conditions and public perception, as described in Uribe-Aguado et al. (2025). The objectives of this phase are (i) to assess the current conditions of the selected urban area before implementing any NBS and (ii) to identify stakeholder priorities to inform planning decisions. Phase 1 begins with the identification of key stakeholders, including local authorities, NGOs, private investors, and public institutions. Subsequently, a set of contextual indicators is applied to assess the site using a multidimensional framework structured into five categories: environmental, urban, social, economic, and public health and well-being. In parallel, a citizen perception analysis is conducted to complement the technical assessment. This analysis seeks to identify which locations within the site residents considered to be the highest priority for NBS interventions and to explore perceptions of the availability or absence of ecosystem services. A key component in developing a robust and consistent index of priority locations is the integration of thermal regulation data. This information enables the construction of a thermal history for areas of interest, which can be compared with stakeholder opinions gathered during this phase.

Phase 2: Identification of potential NbS locations: The main objective of this phase is to determine the most suitable locations for implementing NbS. This is achieved through the development of a priority index that combines technical assessments of ecosystem services with the priorities expressed by citizens in the perception analysis phase, based on Uribe-Aguado et al. (2025). The priority index reflects the relationship between the current state of key regulatory ecosystem services (water regulation, air quality maintenance, climate regulation, and wastewater treatment) and the priority assigned by citizens to specific locations.

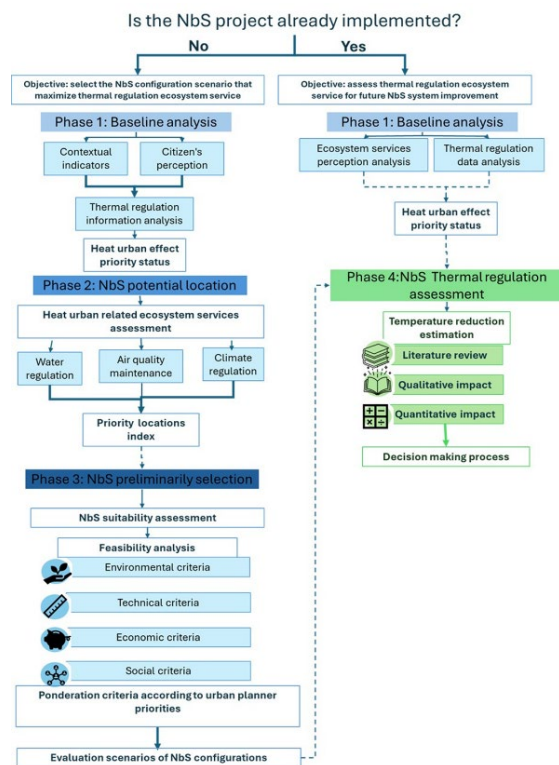


Figure 1. Methodology.

Phase 3: Preliminary Selection and Feasibility Analysis: This phase focuses on identifying the most effective, feasible, and contextually appropriate NbS interventions to improve thermal regulation in prioritized areas, based on the methodology Uribe-Aguado et al. (2025). The phase integrates citizen perception data, the priority index, and technical, environmental, and economic analyses to guide urban planners in defining appropriate NbS scenarios. The first step is the suitability assessment of NbS, which begins with the identifying of the most appropriate types of NbS for the site using the euPOLIS NbS selection tool (Baki, 2023). Following the suitability assessment, a feasibility analysis is carried out to determine which NbS are realistic and can be implemented in each priority area. The feasibility analysis integrates a multi-criteria analysis of environmental, technical, social, and economic factors. The outcome of this phase is a set of urban planning scenarios, including a baseline scenario of alternatives for the implementation of NbS.

Phase 4: Assessment of the Impact of Thermal Regulation: The main objective of this phase is to assess the quantitative and qualitative effectiveness of the NbS selected in the previous phase. To do this, future scenarios are simulated using pre-trained machine learning models that teach the statistical relationships between land surface temperature (LST) and relevant biophysical and urban variables. The machine learning models used are Random Forest and XGBoost. These models have demonstrated good predictive performance as well as flexibility when adjusting the parameters necessary to optimize them (Toscan et al., 2025). The models are trained with a history of multitemporal variables (e.g. 2000–2024) composed of biophysical variables NDVI (Normalized Difference Vegetation Index), NDWI (Normalized Difference Water Index), TCC (Tree Cover Canopy), HC (Height Canopy), Albedo, DEM (Digital Elevation Model) and Tree biomass and urban variables (i.e. Land use, Impervious surfaces, NDBI (Normalized Difference Built-up Index), Green–blue infrastructure presence, Building height). It should be noted that all variables were evaluated, with statistical methods like Pearson's correlation coefficient, to determine their relevance in predicting LST; otherwise, they were discarded. Finally, these models enable the prediction of LST under modified conditions by incorporating the changes generated by NbS in each of the variables. The impact of these interventions is then quantified using the methodology proposed by Gobatti et al. (2023). This methodology estimates the expected Cooling Establishment Time (CET) by modeling the NDVI and the LST relationship before and after the intervention using satellite images. This facilitates an evaluation of each alternative and the selection of the most appropriate nature-based solutions.

2 CASE OF STUDY

El Reencuentro - Bogotá, Colombia: The problem of heat islands is becoming increasingly common in the city of Bogotá, Colombia. However, as it is in a temperate climate zone, these effects are not perceived to the same extent by the public. In this case, the “El Reencuentro” area was chosen as the epicenter of the study because is an important component of the Bogota's urban renewal plan, which identifies the area as a strategic action within the so-called “extended center.” This analysis will therefore generate additional information that can support planning processes. “El Reencuentro” does not currently have any implemented; instead, it contains a set of infrastructure such as parks and individual trees.

Javeriana University - Cali, Colombia: The campus of Javeriana University in Cali, Colombia, has implemented and/or features various green NbS on its premises due to its strategic location in the city's green corridor. This makes it easier to assess the impact of these solutions on reducing surface temperatures in the immediate environment. Furthermore, as it is in a warm climate, the temperature-buffering effects are evident, which facilitates the validation of the results.

3 RESULTS & ANALYSIS

El Reencuentro - Bogotá, Colombia: Firstly, a slight downward trend was observed in Δ LST, especially after 2013, suggesting a moderate cooling effect associated with the lack of green infrastructure in the area represented by parks. However, the average NDVI values remain low, in the range of [0.01–0.25], indicating that vegetation cover has not increased significantly. This implies that the observed thermal effect is limited and not

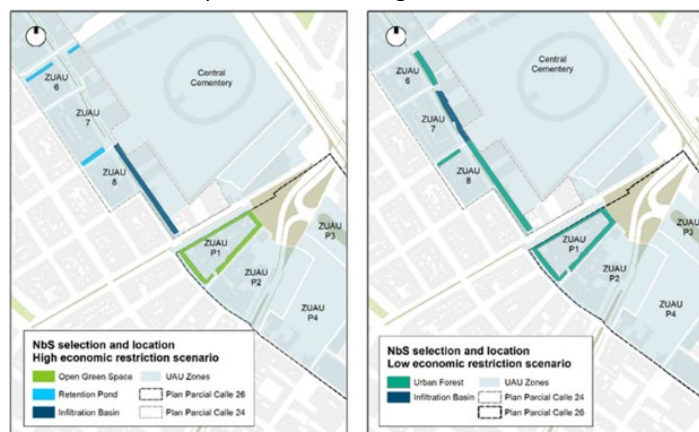


Figure 2. NbS potential location in the El Reencuentro case study.

strongly driven by increased vegetation. Therefore, the need for additional interventions is evident. Second, microclimate and water regulation ecosystem services were identified as the most valued by the community in most of the territory.

Figure 2 shows the results of the possible location of SbN according to priority areas for implementation and the technical, geometric, and physical analysis of site characteristics in scenarios with high and low economic constraints. In summary, with low economic constraints, green infrastructure will always be the most recommended option due to all the thermal benefits it provides. Based on this result, a sensitivity analysis was generated from different scenarios that incorporate social perceptions and adjust the weighting assigned to technical, environmental, and socioeconomic variables to carry out phase 4.

Finally, after modeling, it was found that scenarios prioritizing open green spaces and urban forests show the greatest thermal regulation, with a temperature decrease of between 5 and 6 °C when full adaptation of the area is achieved. However, combination with other solutions should be considered to improve infrastructure diversity and strengthen connectivity.

Javeriana University - Cali, Colombia: The results show that there is a reduction in Δ LST after the NBS intervention for the year 2010, which coincides with an increase in NDVI. This suggests that the green infrastructure implemented in the area has had a significant effect on reducing surface temperature.

Based on these data, an analysis of the spatial distribution of Δ LST was performed in an area of 900 meters around the university campus. In general, a concentration of cooling is observed around the NbS area, suggesting a positive or localized buffering effect. However, this effect is not completely homogeneous, as it depends on other variables such as urban configuration and land use, among others.

Finally, the modeling showed that the area is expected to continue to exhibit climate regulation effect, but to maximize this effect, it is necessary to perform maintenance and periodically monitor the NbS, in addition to diversifying the type of interventions to improve ecological connectivity.

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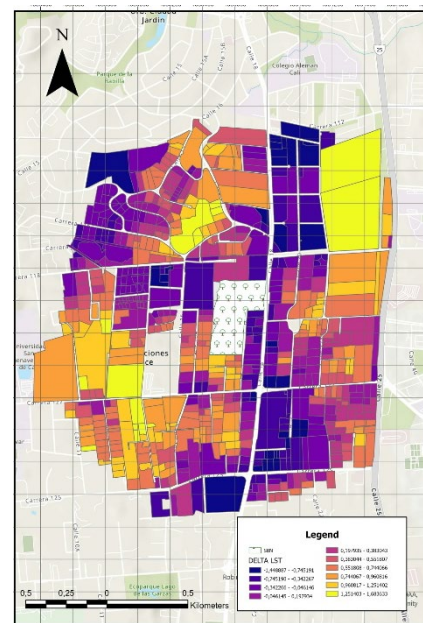


Figure 3. Spatial distribution of LST.