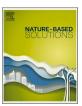
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Nature-based solutions for climate change adaptation and resilience in urban informal settlements: Insights from kibera, kenya and Villa 20, Argentina

Caroline Kibii¹, Flávia Guerra¹, Philip Bonera Bananayo, Simone Sandholz * o

United Nations University- Institute for Environment and Human Security, UN Campus, Platz der Vereinten Nationen 1, 53113 Bonn, Germany

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ABSTRACT

Nature-based Solutions (NbS) are gaining much recognition for their contribution to addressing climate change impacts and overall environmental challenges in urban areas. NbS in urban areas have been associated with varied benefits and ecosystem services such as flood management, cooling effects and recreational values. However, implementation and effectiveness are influenced by various factors, such as space availability. In urban informal urban settlements with limited space, and high exposure to climate risks, NbS implementation is particularly challenging, despite their proven benefits. Noting the heterogeneity of informal settlements, understanding the existing NbS and how they are perceived locally is crucial for their uptake. Based on surveys and interviews in the informal settlements of in Kibera (Nairobi, Kenya) and Villa 20 (Buenos Aires, Argentina), implemented NbS, their particular benefits and perception as well as key factors influencing their implementation, effectiveness and acceptance were identified. Lastly, the extent to which the identified NbS can be considered transformative was assessed. A key conclusion of the paper is that despite differences in geographies and upgrading and planning processes in the two settlements, somewhat similar NbS enablers and barriers could be identified. NbS effectiveness and sustainability in urban informal settlements seem realizable with active multi-stakeholder engagements and consistent integration of NbS initiatives into participatory urban planning programs and policies. Looking into NbS dimensions beyond environmental benefits can be particularly helpful to identify barriers, enablers but also transformative potentials, thereby supporting sustainable livelihoods, capacitation and participation of dwellers.

1. Introduction: NbS in informal urban settlements

The city landscape, particularly in the global south, is rapidly changing due to interconnected factors, but with rapid urbanization at the center. Currently, an estimated 55 % of the global population lives in urban areas, and this is expected to increase to 68 % by 2050 [57]. While urbanization can spur cities as drivers of development and innovation, unplanned urbanization can exacerbate a myriad of multifaceted challenges. These include socioeconomic tensions [45], congestion ([10,40], pollution [10], environmental degradation ([28,43,22], unsustainable resource use and scarcity (Rashed 2023; [40]), urban heat islands [56, 51] flooding [63], and other hazards.

Nature-based solutions (NbS) such as river or watershed restoration activities [16], green spaces, green roofs or tree planting [25,64] are

increasingly advocated as a viable approach to address these numerous and interconnected urban challenges [64,25,16]. They contribute to building resilience and adaptive capacities of affected communities. Next to reducing disaster and climate risks, urban NbS have been shown to provide numerous potential ecological and human well-being benefits [30], including for mental and physical health [27], social cohesion, biodiversity and improved habitat quality [14].

Global reviews have shown and proven the effectiveness of NbS for disaster risk reduction [53], climate adaptation [6] and overall sustainability [21] in urban areas. Despite the transformative potential increasingly attributed to NbS in making cities more sustainable and resilient [4,12], their realization hinges upon addressing co-benefits and fostering co-production of interventions with affected communities [23, 11,61]. Key hurdles in this context are a particular lack of engagement of

E-mail address: sandholz@ehs.unu.edu (S. Sandholz).

^{*} Corresponding author.

¹ These authors have contributed equally to this work and share first authorship.

the urban poor and vulnerable [67], coupled with a crucial gap in studies and related knowledge from Global South countries [3]. Thus, the development and implementation of NbS strategies and measures is still challenging [23]. This is particularly true for informal urban settlements, despite the urgent need for action as dwellers are particularly vulnerable and increasingly suffering from disaster and climate impacts.

Informal settlements are often located in places highly vulnerable to natural hazards such as on flood planies or steep slopes ([17,49]. Furthermore, since informal settlements are mostly excluded from formal urban planning processes, they typically lack basic services and infrastructure [54]. In addition, coping and adaptive capacities to handle climate change impacts are comparably low [44,48], especially in informal settlements in the Global South [65]..

Research has only recently started to explore the applications of NbS in such settings, including for enhancing water security in Colombian cities [60] and as climate mitigation and adaptation strategies in the Pacific region [55] and Southeast Asia [25]. Funding and implementation challenges for NbS have also been assessed in informal settlements in Southeast Asian and Pacific countries [65]. A few studies have demonstrated the importance of community engagement and participatory approaches in the design and implementation of NbS, for example in the Pacific [37,64] or East Africa [15]. However, there is still limited academic literature regarding NbS in informal settlements, particularly in Africa [1,19]. This gap raises concerns regarding the development of urban NbS in regions with growing populations living in informal settlements, including many African and Latin American countries. Furthermore, there is a notable absence of comparative approaches between similar settings that transcend the traditional North-South comparisons.

In response to these research gaps, this paper examines NbS implementation in two urban informal settlements in Africa and Latin America, namely Kibera in Nairobi, Kenya, and Villa 20 in Buenos Aires, Argentina, two of the largest and most underserved informal settlements in their respective countries [2,18].

NbS are being applied in both settlements, however usually that comes from external donors and little is known about how residents interact with and benefit from these interventions. However, such knowledge is crucial to assess whether these NbS solutions are effectively addressing the specific climate and environmental risks faced by the communities [38].

Informal settlements are often overlooked in urban planning processes, that is the case for Kenya and Argentina as well. Consequently, it is important to understand the local context—including institutional, social and environmental factors—that pose barriers and enablers to implementation, and that determine influence the success or failure of NbS in these areas [13]. A particular focus is on community perceptions, effectiveness and transformative potential, as local knowledge about the feasibility and effectiveness of NbS interventions is still underdeveloped, in both researched settlements and in informal settlements in general [62].

Finally, NbS are often praised for their transformative potential to go beyond short-term fixes, contributing to long-term resilience and systemic change. However, there is very little research about such potentials in the urban development of informal settlements, such as contributions to improving living conditions and empowering communities and being enablers of larger and socially just societal transformations [4,12].

Consequently, the study aims to answer the following research questions:

- 1. What NbS are implemented in these two informal settlements, by whom, and how are they perceived and utilized by residents?
- 2. What are the key factors influencing the implementation, effectiveness and acceptance of these NbS from the perspective of the inhabitants of these informal settlements?

3. To what extent can the identified NbS be considered transformative, contributing to broader and systemic change in informal settlements?

The analysis is guided by a framework developed by [31] and adapted by [15], which distinguishes between four dimensions of NbS: (i) NbS and society relations (ii) design (iii) implementation, and (iv) effectiveness. 'NbS & society relations' examines how NbS projects influence human-nature interactions and alter residents' perceptions; 'design' focuses on the integration of various forms of knowledge and the local needs articulated by community members when designing NbS; 'implementation' highlights the technical, legal and administrative requirements underlying NbS deployment; and 'effectiveness' assesses the long-term performance of NbS, including co-benefits, local ownership and knowledge transfer. The framework has been adapted (see Fig. 1) to identify the four dimensions and their transformative potentials.

2. Methods

2.1. Data collection and analysis

The paper adopts a theory-informed, qualitative case study design to examine the potential of NbS in climate adaptation and disaster risk reduction, focusing on two urban informal settlements. The study specifically targets community perceptions, assessing how residents of these settlements understand and engage with NbS. Given the focus on complex social dynamics and individual experiences, qualitative methods were selected as they allow for a richer, more nuanced understanding of community members' perspectives and experiences with NbS. The case study approach enables contextual analysis and comparison of two distinct urban settings, highlighting localized challenges and opportunities within each community

In, Villa 20 (Buenos Aires), qualitative data was collected as part of the of the Transformative Urban Coalitions project (TUC) under the International Climate Initiative. Semi-structured interviews were conducted with nine community leaders (6 women, 3 men), all members of an Urban Lab established by the TUC projectin Villa 20 in late 2021. These individuals were selected for interviews based on their active involvement in Urban Lab activities and availability at the time of data collection. The interviews took place in two rounds: the first round in March 2022 and then the second in March-April 2023, allowing an assessment of changes in respondents' opinions over time regarding . different climate action measures, including NbS.

For Kibera (Nairobi), qualitative data was collected through a survey encompassing a mix of open and closed-ended questions administered to 137 household heads in January 2023, as part of an International Climate Protection Fellowship supported by Alexander von Humboldt Foundation. Households were selected through systematic random sampling and respondents included 52 females, 84 males and 1 preferred not to specify their gender. The survey design was informed by the TUC survey applied in Buenos Aires and focused on community perceptions of climate risks, climate and disaster impacts based on their lived experiences, as well as perceived vulnerabilities and existing climate adaptation approaches. A section of the survey specifically addressed NbS as a climate adaptation and disaster risk mitigation measure. The open-ended responses from this survey, along with qualitative interviews from Villa 20, form the core data used in this paper.

Qualitative data from both case studies was analyzed using content, thematic and narrative analysis methods [33,32]. This analysis allowed for he extraction of dominant themes and narratives related to NbS, as expressed by community members, including perceptions and opinions. Direct quotes from the open-ended survey questions (Kibera) and the interviews (Villa 20) are used to illustrate key themes identified (see demographic overview in Table 1).

In an next step, the data was categorized according to the four themes outlined in the analytical framework. Subsequently, the

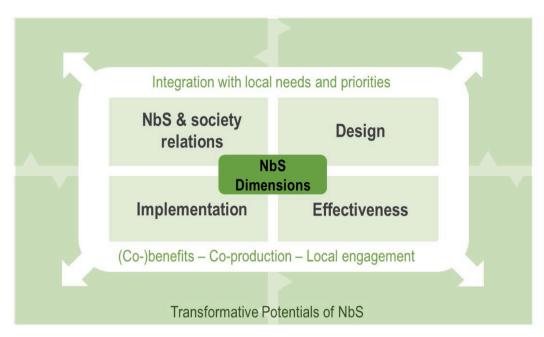


Fig. 1. Analytical framework, adapted from [31] and [15].

Table 1
Overview of coded community members quoted in Section 3.

Code	Gender	Age bracket	Educational level (completed)	Data collection type
Kibera,	Nairobi			
K1	Male	46–55	Primary	Survey / open questions
K2	Female	56–65	Primary	Survey / open questions
К3	Female	46–55	Tertiary	Survey / open questions
K4	Male	46–55	Tertiary	Survey / open questions
K5	Male	26–35	Primary	Survey / open questions
K6	Male	46–55	Tertiary	Survey / open questions
Villa 20), Buenos A	ires		
V1	f	36–45	Tertiary	Interview (both rounds)
V2	Male	36–45	Secondary	Interview (both rounds)
V3	Male	46–55	Secondary	Interview (both rounds)
V4	Female	26–35	Secondary	Interview (2nd round)
V5	Female	16–25	NA	Interview (2nd round)

Note: Table 1 includes demographic information for community members whose quotes appear in Section 3. In Kibera, a subset of six respondents (from 137 surveyed household heads) was quoted to represent key themes. In Villa 20, the smaller interview sample (of nine community representatives) allowed for quotes from five interviewees over two rounds, capturing changes in perceptions over time.

comparison of key findings allowed for drawing conclusions regarding commonalities and differences, as well as on the transformative potential that NbS already show or could have in the two locations, based on a range of benefits and co-benefits created, the integration with local needs and priorities as well as the levels of co-production and local engagement [23,61,64].

A potential limitation of the study is the different data collection methods and timelines across the two case study locations. However, these variations cater to different projects and local contexts o maximize the quality of data collected. Despite these differences, the study's comparison is structured using a consistent analytical framework, which facilitates robust cross-site analysis. Thereby, the collected data allow a comparison, especially since this comparison was made along a proven analytical framework.

2.2. Case studies

2.2.1. Kibera, nairobi (Kenya)

Nairobi, the capital city of Kenya, is home to approximately 4.4 million people [34], with an estimated 60 per cent living in informal settlements. Kibera, one of the largest informal settlements in Africa and the most populous in Kenya, is geographically positioned 7 km southwest of Nairobi's central business district. It covers about 2.1 km², with a population density of approximately 55,994 persons per square Kilometer [34]. The settlement is largely excluded from formal access to basic urban services, functioning infrastructure, and access to proper and affordable housing and land rights [36].

Kibera lies along Ngong and Nairobi Rivers, some of the major rivers in Nairobi and a vital resource to Kibera's residents [42]. Residents are vulnerable to climate risks such as flooding, a situation facilitated and accelerated by their proximity to the river as well as open sewers [42]. Nairobi's informal settlements, including Kibera, also show warmer temperatures compared to other parts of the city [50]. Over the years, Kibera has experienced varying temperatures and changing rainfall patterns, leading to disasters with increasingly detrimental implications and mortality [20].

As a result, mechanisms to cope with climate change and natural hazards have been established. NbS are one of the measures introduced and adopted in the Kibera settlement to reduce climate- and disaster-associated impacts, particularly flooding. The Green Storm Infrastructure project, designed through a partnership between Kibera's residents, the Kounkuey Design Initiative, and the architecture studio of the University of Arizona, are a few examples of NbS initiatives in Kibera [13]. Other efforts to build resilience and reduce vulnerability to social, economic and environmental challenges among the residents of Kibera have been introduced over the years. For instance, the Kenya Slum Upgrading Programme (KENSUP), piloted in Kibera, the Nairobi Railway Relocation Action Plan and the National Youth Service (NYS)-led Kibera Slum

Upgrade Initiative [39]. The KENSUP focused mainly on affordable housing, while the NYS project was a multi-tier initiative involving solid waste management, improved sewage systems and water provision, among others [58]. Green, grey and blue infrastructure solutions aimed at solving socio-environmental challenges in Kibera have also been established [41,15]. For instance, the Kibera Public Space Project, implemented by Kounkuey Design Initiative and supported by the World Resources Institute, is intended to establish a network of community-designed and managed public spaces to address drainage and sanitation challenges and for flood protection [66].

2.2.2. Villa 20, buenos aires (Argentina)

Argentina's capital city, Buenos Aires, covers approximately 200km² and is home to >3 million residents [29]. Socio-economic challenges are pronounced in the more southern of the 15 communes, including higher unemployment rates and lower household incomes [8]. Moreover, the southern region faces heightened vulnerabilities due to high flood risk, exacerbating existing issues of inadequate infrastructure and services [52,5]. Climate change further compounds these risks, as rising temperatures and increased precipitation lead to more frequent and severe heatwaves and floods [7].

The prevalent housing deficit contributes to overcrowding in the south [9,35] which houses most of the city's informal settlements, known as *villas*. In 2022, at least 237,000 people were estimated to be living in the around 50 informal settlements within the city of Buenos Aires, representing almost 8 % of its total population [29,46]. Several of the *villas* that have witnessed significant expansion in recent decades are located in Comuna 8 in the south, including Villa 20 – one of the largest informal settlements in Buenos Aires.

Villa 20 spans 37 hectares and accommodates 13,750 families living in 12,500 houses [46], many of them constructed poorly. In 2022, Villa 20 and several other informal settlements in Commune 8 had, on average, one tree per 282 inhabitants, a striking contrast to the citywide average of 6.7 inhabitants per tree [59]. This disparity underscores issues of unequal green space distribution, particularly in marginalized communities.

Efforts to address local challenges include the Buenos Aires City's Law 5705/2016, which initiated the participatory upgrading process of Villa 20 aiming to build new housing units, improve existing houses, enhance and consolidate public spaces, and provide adequate infrastructure and services, among others. Villa 20's upgrading process is coordinated by the Housing Institute of Buenos Aires (IVC), through participatory mechanisms such as the Participatory Management Board, the Technical Board of Participatory Management and the Environmental Board [2]. In 2022, largely as a response to a growing number of projects from international donors implemented in Villa 20, the Environmental Board broadened its mandate to incorporate environmental sustainability and climate change [26,47]. As a result, the upgrading process of Villa 20 has increasingly integrated nature-based solutions into its goals and activities [24,2].

3. Results

3.1. NbS in kibera

Kibera has undergone many upgrading processes mostly with a focus on infrastructure. Currently, there is an increasing uptake of NbS although in varying shapes, proportions and designs. Our survey identified various NbS in Kibera, most of which are utilized as coping mechanisms to climate change impacts and to minimize the effects of other environmental challenges. However, the residents perceived that highly specialized and innovative NbS are generally complex to implement due to limited technical knowledge.

Guided by the intensive use and benefits associated with the rivers flowing through the settlement, river restoration and protection is one of the NbS that have been highly prioritized by residents and communitybased organizations in Kibera. Planting grass and trees along the riverbank, river cleaning through the removal of solid wastes, and erection of small bridges across the river are some of the related activities. Survey respondents linked the restoration of Ngong and Nairobi Rivers to reduced riverine flooding. Healthwise, river restoration was perceived to have minimized the prevalence of malaria caused by mosquitoes breeding within polluted waters. Mosquito prevalence was associated with increasing warming within the informal settlement.

One of the respondents commented that, "There are health benefits when routine river clean-ups are done. It helps our kids not to get infected with malaria or any other waterborne disease that is so costly in hospital." (K1, January 2023)

There is a strong certainty among the respondents that river restoration promotes biological and livelihood diversity. It was expressed that since the restoration of Ngong River, some fish and water plants have been sighted at various points within the river course. This positive outcome is supposedly true only in sections of the river where serious cleaning and growing of trees and other vegetation has taken place. As a result, some of the Kibera residents can now fish in the same river and use the fish for consumption within their households. Therefore, survey respondents recognize that the regular clean-up activities in and along Ngong River and the planting of grasses and trees along the river have improved its state. These activities are mainly done by the community members, particularly young people, through community-based organizations and groups.

Greening the settlement through green roofs, green walls and green spaces through trees, flowers and grass planting (see Fig. 2) were mentioned as Kibera's easiest and most practiced activities. Most of these activities are spontaneous while others are planned by communitybased and non-governmental organizations. The residents perceived these activities to require no technical skills since they are informed by the prevailing conditions and resources within a household, neighborhood or settlement. Nonetheless, perceived limited technical and practical knowledge was reported. The respondents cited fresh air, cooling effects during hot periods of the year and shade as some of the benefits associated with greening the settlements. Another benefit mentioned is that trees reduce the strength and intensity of the winds that previously destroyed weaker roofs in parts of the informal settlement. The residents associate the presence of nearby forests, such as the Ngong Road Forest, with the reduced impact of windstorms, especially in areas close to the forest. This was perceived in reference to the increased forest protection and awareness creation within the informal settlement on the significance of forests in mitigating climate impacts and for human wellbeing.

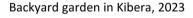
Interviewees explained: "We can have parks in the slum at the same time we will have the trees as wind breakers," (K2, January 2023); K3 said they now have places to relax, "Socially we have places to relax," (K3, January 2023), while K4 talked of trees providing a cooling effect, "Trees have made our area to be cooler," (K4, January 2023).

Despite the greening efforts in Kibera, several residents indicated increased flooding due to destroyed or cleared vegetation and grasses. Clearance or destruction is said to have been perpetrated by increased land use. Some residents highlighted that they experienced stronger winds due to the clearing of trees in surrounding or nearby forests.

Several kitchens and community gardens have been established in Kibera, although they are of varying sizes, shapes, and designs. Some residents have established sack gardens stationed by the wall of their houses, while others use plastic containers to grow vegetables and flowers. Often, the containers are placed on the roofs of the houses, while others place the containers with climbing plants against the house walls, creating some form of green walls. These actions are perceived to have contributed to the greening of the settlement and diversification of food sources. Some residents now harvest kales, famously known in Kenya as "Sukuma Wiki", tomatoes and onions for their own household consumption from their kitchen gardens.

Rainwater harvesting is a common NbS among some households in Kibera that was said to solve water challenges, although on a short-term A B







Recycled flower pots in Kibera, 2023

C



Trees and grasses planted in spaces between houses in Kibera, 2023

Fig. 2. Examples of NbS initiatives implemented in Kibera.

basis. Even if the residents wanted to collect large volumes of water, they needed more space and containers to store it. Water scarcity is a major challenge in Kibera that worsens during dry periods.

The introduction and existence of NbS-related activities in Kibera are perceived to have generated benefits beyond the ecological ones to include strengthening social cohesion within villages in Kibera. Most

respondents cited job creation, sensitization, awareness of climate change and environmental protection, and infrastructural development. It was perceived that NbS activities have strengthened community engagement, peace and encouraged people to work together towards a common goal as stated by different interviewees.

"These activities make people to come together communally for a better course to build a better future for the coming generation." (K5, January

"Socially, the community has come to understand much more about nature. Economically, it leads to construction of infrastructure, and it restores the calendar of the weather and seasons." (K6, January 2023)

Although there is a growing number of NbS initiatives, most residents believed that vegetation and tree cover in their settlements would decrease within the next 5-10 years, mostly due to population increase, limited space and increased infrastructural development. At the same time, some residents perceived an incremental likelihood of more NbS, pointing to the increased awareness on their significance and the governmental initiative to plant more trees across the country, including within the informal settlements, and implemented measures to curb the destruction of environmental resources.

Community stewardship is an art applied in Kibera and believed to motivate community members to actively participate in environmental conservation initiatives and take responsibility for their actions. For instance, the youth in Kianda village have formed micro and macro groups that champion digging trenches to channel excess water and sewers, unclogging sewer lines and engaging in greening initiatives. Survey respondents see these groups as avenues for more people to be accountable for their actions and be more aware of the vitality of protecting the natural resources within their neighborhoods.

Finally, the survey revealed that while non-governmental and community-based organizations spearhead most Nbs activities, diverse entities, including also government agencies and non-organized individuals are involved in NbS implementation in Kibera. Most respondents had participated in at least one NbS-related activity in the informal settlement. Table 2 summarizes the findings regarding NbS dimensions in Kibera.

3.2. NbS in villa 20

Until recently, the upgrading process of Villa 20 prioritized housing, land tenure security, infrastructure and quality public space, only rarely linking it to NbS. However, data collected from surveys and interviews in 2021 and 2022 confirmed that the lack of green spaces is among the most pressing problems for dwellers. One community leader explained:

"We have limited green space, especially within the macizo [densest area of Villa 20 where families live under more vulnerable conditions], where it's most needed. It's predominantly concrete, grey, with houses tightly clustered together. Now, with the upgrading process, passages are opening up, streets are widening; it would be wonderful to see green there, like those found elsewhere in the city." (V3, March 2022)

Initial understanding of NbS seemed exclusively linked to trees and plants, which were perceived by some as easy but superficial solutions to much larger issues. Consequently, a few interviewees emphasized the need to integrate environmental considerations into the provision of basic services like sewage and waste management, and access to clean water, even if it may seem complex to start with and take time.

"When we are approached to work on environmental issues, I understand it as 'let's work on trees and vegetable gardens.' And we, from the neighborhood or territorial experience, automatically say 'but wait, the environmental part for us has to do with having sewers and potable water and garbage collection.' [...] I hope we will discuss where to put more trees, pots with plants, vines on the walls, more green. But I also expect support with our struggle to have basic services." (V2, March 2022)

It was challenging for interviewees at the time to envision how NbS could be leveraged to address higher priority goals, rather than competing with or being overshadowed by them. While there was some recognition that more and varied NbS initiatives could be beneficial, a perceived lack of knowledge and financial resources as well as

Table 2

NbS dimensions	Findings
NbS-Society relations	Growing general awareness of the link between environmental degradation, urbanization and growing hazard levels, such as the link between stronger winds or increased flooding and cleared vegetation, or further decrease of vegetation and tree cover due to population increase and infrastructural development NbS are perceived as complex and challenging to implement Although several NbS are implemented in Kibera, they are perceived to be done without precision and adequate technical and practical knowledge, which limits their effectiveness Need for educational programs on the causes and impacts of climate change and how to adapt, as well as a better understanding of NbS was recognized Willingness to participate in activities focused on
Design	 implementing NbS Lack of knowledge on NbS and their significance and inadequate know-how to design viable and effective NbS i Kibera emerged as a considerable design obstacle. A demonstrated need for creative and innovative designs for kitchen or backyard farming and green spaces within the informal settlement was raised. Designs of many NbS are determined by space availability cost, simplicity, land tenure issues and longevity of an individual's stay within the informal settlement
Implementation	 Majority of the existing NbS in Kibera are low-scale and designed without a sustainability element. Active participatory designing of NbS are evident in household-led and community-led initiatives. There is a growing recognition of integrating environments concerns in the design of slum upgrading processes in Kibera Financial constraints, land tenure and limited space were perceived as the major factors limiting designing and establishment of public green spaces within Kibera Most residents have participated in one or more NbS-relate activities The need to continuously implement NbS within Kibera an surrounding areas is valued by most residents, for instance regularly and progressively growing trees and river clean ups. NbS implementation is gender inclusive, involving men, women, and youth in various initiatives, including
Effectiveness	leadership roles There is multi-stakeholder collaboration in NbS introduction and implementation between the government (local and national), non-government organizations, community based organizations, households and individuals. Most of the initiatives are spearheaded by the CBOs and the residents. Social and economic barriers including lack of finances, insufficient knowledge to implement NbS, lack of tenure security, poor leadership, and prioritization of basic needs over environmental concerns were identified. Limited space, population density and infrastructural development are core hindrances to the introduction of new NbS and expansion of the existing ones in Kibera. NbS effectiveness is widely recognized among citizens. Some socio-economic benefits stimulated by NbS initiative were mentioned and include job creation, income generation, new partnerships, infrastructural improvement, awareness-raising and learning opportunities on environmental conservation Ecosystem benefits mentioned include biodiversity restoration (fish have been observed in restored rivers) Climate action and risk reduction benefits including prevention of flood occurrence, reduced spread of water-and vector-borne diseases Health benefits including improved air quality, creation o

regulatory constraints imposed by basic service providers hindered their implementation. Interviewees stated that without proper understanding and tools, it was challenging to advocate for or implement NbS effectively. They thus highlighted the importance of community engagement, including through formal environmental education and professional training, as well as field visits and other hands-on activities to promote wider socioeconomic benefits, raise awareness, build trust and mobilize the community for NbS implementation.

"If you ask me what the problem is, I'll tell you that we lack trees, but I won't be able to tell you why or what the benefit is, or what type of tree. And I think we're all in the same boat. What we would like, and what has happened to us when working with other universities or educational partners, is for them to provide us with those tools and knowledge, so that we can fight and raise awareness for that specific issue." (V1, March 2022)

Throughout 2022 and 2023, a plethora of NbS were implemented in



Flowerbeds, trees and shrubs, along with a pergola, installed on Teresa Rodriguez Street in the Papa Francisco new housing complex, 2023. © UNU-EHS



Recycled home gardens to be distributed across Villa 20, 2022.

© IIED-AL



Vertical gardens, shrubs and permeable soil incorporated into the newly opened Eva Estela Carrizo Street in Block 19, 2023. o IIED-AL



Pergolas and flowerbeds installed in the courtyard of the local school no. 11, 2023. © IIED-AL

Fig. 3. Examples of NbS initiatives implemented in Villa 20.

Villa 20, including the introduction of trees, shrubs and flowerbeds using native species as well as permeable pavements instead of concrete or other grey infrastructure. Pergolas adorned with creepers have created natural canopies and, vertical gardens have been installed. In public areas with more space, including a local school, various NbS such as rain gardens and hydroponic systems are being installed along with pergolas and flowerbeds. Community leaders in collaboration with the local school have also promoted a program for the creation and distribution of recycled home gardens across Villa 20 (see Fig. 3).

Although there are exceptions, the majority of NbS initiatives in Villa 20 are pilot projects implemented by community-based organizations, typically in collaboration with municipal government agencies, and with support from international donors. They benefitted from workshops and capacity development activities provided by urban planning experts and landscape architects and were defined through consensus. These initiatives are serving to co-produce knowledge among diverse local stakeholders and generate data often lacking in informal settlements (e.g. temperature and humidity), contributing to developing new capacities within the community.

These endeavors are also helping to shift perceptions of NbS and their benefits. Consequently, community representatives showed more favorable views and newly gained knowledge regarding NbS in the second round of interviews, and emphasized the interconnectedness of NbS, community development and quality of life.

One interviewee explained: "When the upgrading process started 8 years ago, we [...] didn't realize that we also needed to build parks with trees. Perhaps we should have made the buildings a bit taller and then manage them better internally, leaving more space for parks and trees [...]. That kind of information, which we didn't have before but have now, helps us develop better projects and better ideas." (V2, March 2023)

Interviewees emphasized a greater variety of (co-)benefits associated with NbS beyond aesthetics, such as improving air quality and health, providing shade, reducing urban heat, attracting biodiversity, and creating communal areas that enhance safety and well-being. Residents stated a sense of ownership and pride in enhancing their neighborhoods, leading to increased community cohesion. Encouraging participation from residents of all ages, during the design and implementation of NbS, was seen as crucial for its effectiveness and sustainability.

"Now, everyone proudly tends to their plants [...]. The neighbors seem happier in nature, and their enthusiasm is contagious. When they gather below, sharing tereré or mate, there's a stronger sense of community and more reasons to come downstairs, as previously, everything was grey. Additionally, the air quality has improved and, each summer, we'll endure less heat. I hope this initiative is replicated; it won't just ease the heat in this passage but throughout the neighborhood." (V5, March 2023)

Compared to the first round of interviews, community members showed growing recognition of NbS contribution to climate change adaptation and disaster risk reduction, particularly as regarding heatwaves and extreme temperatures. They also acknowledged the disproportionate impact of climate change on informal settlements like Villa 20.

"The heatwaves we've been experiencing this summer, with their relentless intensity over more days, are the result of climate change and the lack of trees and plants, and the garbage that is thrown away." (V4, March 2023)

Interviews highlighted the importance of NbS projects to build on existing local initiatives and people already doing NbS at some level, mostly women. However, female interviewees frequently mentioned the high time demands associated with the upkeep of NbS and related community dissemination and awareness raising activities. Taking care of the plants is perceived to be one of the most basic or few things that people without much knowledge can do to contribute to protecting

nature and the environment.

Interviewees underlined the need for policy and regulatory changes to enable more widespread NbS implementation in Villa20 and other informal settlements. Some advocated for new laws or regulations to ensure equity and consistent action, especially within upgrading processes of informal settlements:

"When environmental issues first came up, I wasn't really interested. But then, I realized that any effort we put in will influence the legal framework governing construction in informal settlements. [...] it won't be the State saying we have to go green, we will be the ones demanding environmentally conscious interventions." (V1, March 2023)

While the need for state involvement was acknowledged, there was also criticism. Some interviewees claimed that economic and other interests often sideline environmental concerns, leading to inadequate infrastructure and services in marginalized communities, further exacerbating inequalities within the city:

"We've planted 100 trees because we discovered that Villa 20 has the fewest trees in the entire city. [...] In other parts of the city, you see a park: there are paid caretakers who prune and water. Why can't we have green spaces here in the villa where people come and take care of the trees and plants?" (V3, March 2023)

Most interviewees agree that prioritizing NbS in urban planning and development in informal settlements is easier when integrated into an ongoing upgrading process. This is evidenced by the fact that IVC has been able to incorporate many of the NbS tested previously as pilot projects, such as rain gardens, vertical gardens and other permeable soil alternatives, into their new procurement processes for the upgrading works of Villa 20. A collaborative learning process involving both community leaders and government technical teams has emerged, with both groups recognizing that, in the daily rush to address immediate emergencies, they had not previously stopped to think about climate change. However, some interviewees still noted that linking environmental and climate goals with the upgrading process after it had already started, left little room for deeper NbS interventions beyond vegetation additions. Table 3 summarizes the findings regarding NbS dimensions in Villa 20.

Generally, there is a sense that more holistic, creative and long-term approaches involving NbS are needed in informal settlements. These approaches should address not only environmental and climate issues but also socioeconomic concerns, particularly the lack of income and job opportunities. Interviewees advocate for embedding environmental aspects into all local development projects to ensure sustainable solutions with multiple benefits, including economic ones, thereby enhancing the functionality and relevance of NbS within the community.

4. Discussion

The results from Kibera in Nairobi and Villa 20 in Buenos Aires, exhibit some similarities in the existing NbS, their intended purposes, effectiveness and attributed co-benefits. Fig. 4 Differences were noted regarding the nature of implementation, sizes and designs.

NbS is assumed to refer primarily to tree planting, a popular activity in both informal settlements due to its simplicity and minimal technical requirements. However, advocacy efforts, especially through community-based organizations, have gradually expanded residents' understanding to include aftercare and the establishment of green spaces. Although previous studies [64,25] acknowledge the growing advocacy for tree planting in the Global South, our research reveals a mindset shift from merely 'planting' to embracing the 'growing' of trees. Growing trees includes nurturing them until maturity, ensuring greater effectiveness and sustainability.

NbS holds significant value for residents of both informal settlements, particularly those who regularly interact with them. Respondents confidently linked the existing NbS initiatives to numerous co-benefits

NbS dimensions

NbS-Society

relations

Table 3 Summary of findings in Villa 20, Buenos Aires.

Findings

multifaceted potential

· Expanding initial understanding of NbS beyond only trees

and other forms of vegetation towards embracing their

· NbS are no longer predominantly viewed as secondary to

immediate concerns but are advocated for simultaneously

Design	addressing pressing issues Growing awareness of NbS benefits and links to climate action and risk reduction, including mitigating extreme temperatures and reducing the impact of heatwaves Need for knowledge and tools, with emphasis on improving access to formal environmental education for Villa 20 dwellers but also using creative formats and hands-on activities to engage both adults and children Growing knowledge about NbS associated with greater
Design	perceived importance of better integrating environmental and climate considerations into the upgrading process of Villa 20
	 Participatory design of NbS represents a win-win for communities; residents contribute with their lived experience to the design of more relevant, integrated, sustainable and effective solutions and in turn develop own capacities for leveraging NbS into broader socioeconomic opportunities Limited space availability constraints design options and requires alternatives beyond the community's initial NbS
Implementation	 expertise Most NbS in Villa 20 are pilot projects designed and implemented by the community in collaboration with government agencies and local partners with international
	 funding Limited resources (financial and time), competing political priorities, regulatory constraints and lack of policy support hinder widespread implementation Integrating NbS implementation with ongoing upgrading processes proves advantageous but should go 'deeper' into integrated solutions While some residents advocate for government support and collaboration in raising awareness for, implementing and maintaining NbS, others are skeptical of government motivations and prioritize strengthening community-led efforts
Effectiveness	Gradual evolution in residents' understanding of the effective (co-)benefits of NbS beyond environmental and climate action advantages to include also socioeconomic benefits such as income generation and expanded networks, improved health and well-being, food security, and social cohesion Increasing emphasis on the importance of monitoring and evaluation of NbS effectiveness for bridging data gaps in informal settlements, including opportunity for mobilizing the community with citizen science Perceived importance of community engagement and ownership throughout the NbS project lifecycle but need for recognition of and further support for community achievements like NbS maintenance and dissemination activities, many of which are led by women Growing desire and advocacy for replicating NbS initiatives across the entire neighborhood but this should be approached as an integrative measure within the city, not a further exclusionary factor of informal settlements
attitudes towards the restoration of fishing activities The 'seeing is b	ly and indirectly influenced people's livelihoods and a senvironmental conservation. For instance, in Kibera f the Ngong River has led to the return of fish, enabling that offer both economic and psychological benefits believing' ideologyhas encouraged more community discountability in river restoration. Furthermore

s and ibera. bling nefits. involvement and accountability in river restoration. Furthermore, building cohesion, togetherness and a sense of harmony are values that respondents professed to have strengthened during their participation in joint NbS initiatives. This shows that NbS has a deeper meaning for those who embrace them. Previous studies [27,31] have found similar evidence linking NbS with improved ecological and human well-being, as well asmental and physical health.

Knowledge and understanding of NbS vary but are generally limited

in informal settlements. Residents of Kibera and Villa 20 implemented initiatives such as river restoration and community gardens without really knowing that they were NbS. This lack of awareness is widespread and often stemming from limited access to information rather than education levels. In fact, obstacles more often arise from government agencies and service providers, where highly educated individuals work. In Villa 20, once NbS was included in the agenda of the upgrading process and new actors joined and provided capacity development on NbS, the community quickly grasped and implemented it.

Globally, there is scarce research or practical experience with NbS in informal settlements, and even less on their long-term performance and maintenance. To overcome these limitations and enhance NbS scalability and sustainability, it is essential to provide widespread environmental education and hands-on training open to all individuals and organizations in informal settlements.

The implementation of NbS in Kibera and Villa 20 has facilitated knowledge transfer. Leveraging the already existing knowledge base and tailoring NbS to local contexts and needs is essential for fostering community empowerment and expanding skillsets. For instance, respondents from Villa 20 emphasized the need to engage residents not only as implementers of NbS but also in on-site monitoring of NbS performance. This inclusive approach generates instrumental data to help finance, streamline and integrate NbS into urban planning and informal settlement upgrading processes.

Participatory engagement is vital in both the design and implementation of NbS initiatives. Interviews in Villa 20 highlighted the importance of 'learning by doing', facilitated by existing participation mechanisms. Consequently, Villa 20 residents took a leading role in the NbS projects' design and implementation stages. Consistent with [15] our findings reveal that residents' perceptions of NbS have evolved through co-design and co-implementation processes. In Kibera, although residents specified their extended involvement during NbS implementation, there is no pecific justification for their little participation in the design phase. Factors such as their temporary residency in the informal settlement, their perceived lack of knowledge of NbS and climate change and other pressing needs could have influenced this outcome. Yet, Villa 20's findings support previous studies linking the adoption of NbSco-design approaches in informal settlements with a stronger sense of ownership, effectiveness and meaningful engagement [64]. Despite some criticism towards certain government actors and agendas, community representatives underscore the importance of shared visions, consensus and mutual trust in NbS activities to ensure effectiveness, especially in building resilience to climate change and environmental risks while tackling pressing socioeconomic challenges.

The NbS in Kibera and Villa 20 are transformative by themselves and as triggers of other projects and activities that have improved the outlook of the two informal settlements. Kibera hasbeen transformedfrom a settlement with almost no vegetation covering a highly polluted river to a more appealingneighborhoodwith increased greenery and cleaner sections of the river. The presence of flora and fauna in some sections of the restored Ngong river demonstrates how transformative the NbS initiatives are.In fact, some residents projected an increase in vegetation cover in Kiberawithin the next 5-10 years, citing the progressive and collaborative NbS initiatives within the settlement. The same applies to Villa 20, where the transformability aspect of NbS has been measured over the years and is evident. The increased greening of Villa 20 has given community leaders a sense of environmental justice and inclusion. The perceived socio-ecological and economic benefits attributed to NbS in the two informal settlements illustrate that they can trigger more than just physical transformation.

Knowledge acquisition and transfer and related changes in people's mindsets and behaviors also demonstratethetransformative role of NbS in both settlements. Respondents recognized the ability of NbSto address the needs of the communities while changing their settlements, hence their recommendation to strengthen community engagement at the initial stages of NbS initiatives. They perceive that this approach will

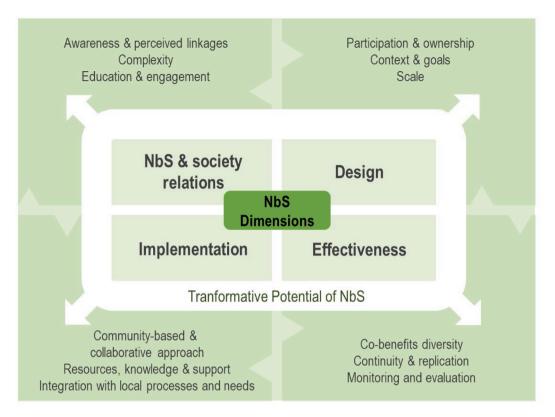


Fig. 4. Summative figure with the common NbS features in the two informal settlements; the dimensions are adapted from [15]).

ensurethemost pressing local socio-ecological challengesare prioritized and that the solutions are contextualized and mainstreamed into upgrading programs. These findings resonate with previous studies that found that traditionalmodes of planning and sectoral approaches are not enough to enhance climate adaptation, build resilience and address other societal challenges [67]. The transformative potential of NbS hinges on localizing the climate agenda and co-creating an understanding rooted in local priorities, knowledge and experiences.

Besides closing a research gap the study also provides practical recommendations:

- In both Kibera and Villa 20, residents have a deep understanding of their environment and local needs, which can be leveraged for more effective NbS implementation. NbS have the potential to drive broader urban upgrading processes, particularly when communities feel ownership and engagement in the planning and implementation stages.
- Although NbS in our study areas are still relatively small-scale and underdeveloped, they are starting to represent a source of jobs and income. Furthermore, backyard or kitchen gardens allow people to harvest their own herbs and vegetables, while restored rivers are safe to fish. These co-benefits can serve as incentives to further engage residents.
- Regulatory challenges and tenure insecurity hindered the full realization of NbS potential, showing that NbS implementation cannot be seen isolated from overall efforts towards sustainable urban development and well-being.
- In both settlements, residents implemented NbS without full awareness of the term or its broader potential. Thus, a targeted, widespread environmental education campaign is needed and could make NbS implementation more sustainable and successful.
- The effectiveness and sustainability of NbS depend on ongoing maintenance and monitoring, which was sometimes lacking in both settlements. The transformative potential of NbS could be undermined if they are not properly nurtured over time. Handing them to

communities and making them the owner can help overcoming these challenges. The ability to measure the success of NbS initiatives will help to make the case for their wider adoption.

The experiences of Kibera and Villa 20 provide valuable lessons for scaling and replicating NbS in other informal settlements worldwide. However, scaling requires adapting models to different contexts, ensuring that they are flexible yet impactful.

5. Conclusions

NbS have an unmatched potential to address various environmental challenges while generating socio-economic benefits in Kibera, Kenya, and Villa 20, Argentina. Despite differences in gepgraphy and upgrading status, the attributed co-benefits and challenges surrounding NbS aresimilar, underscoring the benefits of South-South comparisons and knowledge transfer.

The NbS implemented in the two informal settlements vary in size, nature and design and are defined by the existing local knowledge, needs and pre-existing conditions. Despite the disparity, NbS in both settlements are perceived to be fundamental in addressing various challenges that destabilize residents' lives. For instance, trees, shrubs and flowerbeds offer a cooling effect that mitigates the impact of heatwaves, green spaces provide areas for relaxation and recreation, and restored rivers promote biodiversity. We conclude that most of the NbS in Kibera are spontaneous, isolated and short-term whereas Villa 20 adopts a more strategic and interconnected approach to NbS.

There is multi-stakeholder engagement in the design and implementation of NbS in both informal settlements. However, non-governmental organizations and community-based organizations predominantly lead these efforts. The involvement of government agencies is notably stronger in Villa 20 compared to Kibera. In Villa 20, various projects and organizations collaborate to maximize resources and impact regarding NbS implementation. Conversely, in Kibera, the effectiveness of NbS is limited by siloed activities.

The NbS in Kibera and Villa 20 exhibited cross-cutting transformative potential, which includes transforming people's perceptions and actions towards engagement in NbS-related activities. However, the transformative potential has not yet been fully explored in either case and requires more time to develop. Continued and active involvement of informal dwellers from the design stages of NbS activities, along with the integration of their ideas and knowledge into plans and projects, strengthens this transformative potential. Addressing regulatory, spatial, financial and land tenure constraints could promote more positive changes not only within these two communities but also more systemically in both cities and countries.

This study shows that NbS represents a multifaceted climate adaptation and disaster risk reduction strategy that generates numerous additional benefits for residents of informal settlements. Therefore, NbS should be consistently integrated into participatory urban planning programs and policies, ensuring their continuity and sustainability in informal settlements.

NBS Impacts and Implications of the Study Environmental

This paper provides tangible evidence of the environmental benefits of NbS in informal urban settlements. For instance, tree and vegetation planting increases air quality, health and well-being, reduces surface run-off and, consequently, flood risk, provides a cooling effect that helps to mitigate the effects of heatwaves, and enhances biodiversity.

Social

Our findings show that effective NbS should and can enhance community cohesion, multi-stakeholder collaboration, knowledge coproduction, increased climate change awareness and mindset change. Despite the limited space factor in densely inhabited informal urban settlements, green spaces not only foster recreational activities and relaxation but can also address urgent local needs and support creating more sustainable livelihoods.

Economic

Although NbS in our study areas are still relatively small-scale and underdeveloped, they are starting to represent a source of jobs and income for some people. Furthermore, backyard or kitchen gardens allow people to reduce food expenses since they can harvest their own aromatic herbs and vegetables, and fish from restored rivers.

CRediT authorship contribution statement

Caroline Kibii: Writing – original draft, Visualization, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. Flávia Guerra: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. Philip Bonera Bananayo: Writing – original draft. Simone Sandholz: Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Funding acquisition, Conceptualization.

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.

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Data availability

The data that has been used is confidential.

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