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RESEARCH ARTICLE

Nature-based solutions potential for flood risk reduction under extreme rainfall events

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Abstract Climate change will substantially increase extreme rainfall events, especially in the Tropics, enhancing flood risks. Such imminent risks require climate adaptation strategies to endure extreme rainfall and increase drainage systems. Here, we evaluate the potential of nature-based solutions by using an ecosystem service modeling approach, evaluating the impact of extreme rainfall events on flood risks in a large urban area and with a real-world land recovery plan. We evaluate the cost-effectiveness of four different land recovery scenarios and associated co-benefits, based on a gradient increase in area recovered and cost of implementation. Although the scenarios reveal increasing flood risk reduction and co-benefits along with greater proportion of land recovery, the most cost-effective scenario was the one with an intermediate land recovery where 30% of the study area would be reforested. We emphasize the striking benefits of nature-based solutions for flood risk reduction in cities, considering landscape scale and stakeholders' needs.

Keywords Forest restoration · InVEST urban flood risk mitigation model · Land recovery · Natural regeneration · Rio de Janeiro · Urban ecology

INTRODUCTION

Climate change is predicted to be the biggest threat to the planet in the foreseeable future, affecting both natural and human systems (IPCC 2021; Pörtner et al. 2022). If unchecked, an average increase of > 4 °C in temperature, coupled with changes in precipitation patterns, and extreme climatic events are expected by the end of the century, with strong negative impacts on biodiversity and the ecosystem services they provide (IPCC 2021; Manes and Vale 2022; Manes et al. 2022b; Pörtner et al. 2022). Recent estimates suggest that extreme rainfall events can double in frequency for each degree increase in the planet's temperature—and precisely the ones with heavier rainfall will happen more often (Myhre et al. 2019). Worrisomely, extreme events can lead to severe negative impacts on human well-being and socioeconomic systems, as their unpredictable nature hampers preparedness, especially in the Global South (IPCC 2012; Myhre et al. 2019). Extreme rainfall events often lead to floods and landslides, with profound and often tragic consequences for people, and these are also predicted to increase along with increase in global temperature (Dodman et al. 2022). Urban centers are among the most vulnerable to the impacts of climate change, due to the high concentration of exposed people and their reduced adaptation capacity (Rosenzweig et al. 2019). Notably, people living in flood-prone areas usually have lower incomes and access to sanitation, mostly occupying slopes subjected to landslides, riverbanks and floodplains subjected to flooding (Dias et al. 2018). Climate adaptation actions, i.e., actions to reduce or avoid the negative impacts of climate change, are thus urgently needed to ensure societal resilience to flood events.

Because extreme events are hard to anticipate and cope with, adaptation strategies must be implemented immediately to avoid sudden future loss and damage (Pörtner et al. 2022). Effective adaptation strategies should not only yield immediate benefits but also fortify ecosystem resilience to

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reduce future impacts (i.e., usually known as a ‘no-regrets’ strategy; IPCC 2012). Nature-based solutions (NbS) are strategies with the greatest ‘no-regrets’ potential for climate adaptation and are especially promising for flood risk reduction in urban areas (Alves et al. 2019; Kadaverugu et al. 2020; Dushkova and Haase 2020; Chen et al. 2021; Turkelboom et al. 2021; Kabisch et al. 2022). NbS are actions that protect and restore natural ecosystems to solve global and social problems, promoting benefits for humans and nature alike (Cohen-Shacham et al. 2016). One well-established NbS strategy is land recovery (Manes et al. 2022c) through active restoration and natural regeneration strategies. The numerous land recovery initiatives worldwide reflect the international recognition of their potential (Bustamante et al. 2019) (e.g., the Bonn Challenge, United Nations Decade on Ecosystem Restoration and the Trillion Trees by 2050 goals from Plant for the Planet). Such recovery of neglected or degraded land can promote benefits to people including disaster risk reduction for floods (Dushkova and Haase 2020; Manes et al. 2022b, 2022c), with notable co-benefits for climate mitigation through carbon sequestration in forest biomass. Additional noteworthy co-benefits are evident for biodiversity conservation and connectivity, among others, since habitat loss and climate change are among the main threats to the biodiversity crisis (Manes et al. 2022c; Soares et al. 2023).

Floods induced by extreme rainfall events will become a recurring problem compromising the environmental, social and economic spheres of society (IPCC 2012, 2021; Dodman et al. 2022). The occurrence of floods is imminent in urban areas due to the low soil permeability in extensive impervious cemented areas and insufficient drainage systems characteristic of cities, especially in developing countries (Carter 2018). Despite the high social risk and pronounced economic consequences, the impact of extreme events is still poorly studied compared to other by-products of climate change (IPCC 2012). Such a systemic threat requires urgent and effective ‘no-regret’ solutions to ensure societal resilience, harnessing nature’s potential to design resilient cities (Pires et al. 2021). Several studies suggest that the recovery of forest cover close to or within cities can reduce flood risk because it enhances water permeability and retention by the soil, acting as a natural drainage system (Kadaverugu et al. 2020; Quagliolo et al. 2021). Thus, NbS is a promising strategy to reduce current flood risk and simultaneously promote adaptation to ongoing climate change (Egerer et al. 2021; IPCC 2021). However, the effectiveness of implementing NbS strategies to lessen flood risks under extreme events in urban areas is still under-recognized, especially in the Global South (Dodman et al. 2022).

In this study, we assessed the potential of NbS for flood risk adaptation to extreme rainfall events. Modeling and quantifying the potential benefits of implementing such actions are essential to guide decision making at the city and regional levels (Hamel et al. 2021). We applied our analysis as a case study to the second most urbanized region in Brazil, the Rio de Janeiro state, where urban flooding, a primary environmental disaster in the region, results in recurrent and high-magnitude social and economic losses. We designed four different scenarios with increasing costs of implementation based on a real-world land recovery proposal from the state’s main environmental agency, with natural regeneration and/or active restoration. Large-scale land recovery is the most appropriate NbS strategy for the case study due to the region’s extensive area of pasturelands and degraded forests ($\sim$ 70% of the state). Active restoration is understood as the effort of hands-on recovery of vegetation (i.e., tree planting), while natural regeneration is a slower process of assisted recovery to allow nature to recover itself by preventing additional disturbances (Benini et al. 2017). We included both types of land recovery strategies with different cost ranges to allow for cost-effectiveness analysis. We reveal the enormous benefits of all NbS scenarios in these policy-established areas for flood risk reduction, through the assessment of implementation cost, flood reduction potential and estimated associated co-benefits.

MATERIALS AND METHODS

Study area

We evaluated the potential of NbS to reduce flood risk in the second most urbanized region of Brazil, within the Atlantic Forest domain. The Atlantic Forest is a biodiversity hotspot with severe historical deforestation, which has thus been presented as a region with very high potential for land recovery and climate mitigation (Rezende et al. 2018; Manes et al. 2022a). Our study area, the Rio de Janeiro state, has historically been extremely prone to flood disasters, resulting in severe economic and social losses and damages (IBGE 2012), with consequences to public health (e.g., associated disease outbreaks, Barcellos and Sabroza 2000). The region has endured strong land-cover conversion from native Atlantic Forest to pasture and agriculture (especially in the northeastern portion), with a dense metropolitan region with large urban areas (in the southern portion, Fig. 1). Indeed, although Rio de Janeiro state has 92 cities, most of the 17 million people (39%) live in the metropolitan region. In the metropolitan region, the Rio de Janeiro city itself is the second most at-risk nationally with $>$ 450 thousand people living in flood-prone areas (IBGE 2012). In 2011, for example, the economic losses caused by floods in only a few cities of the study area already reached

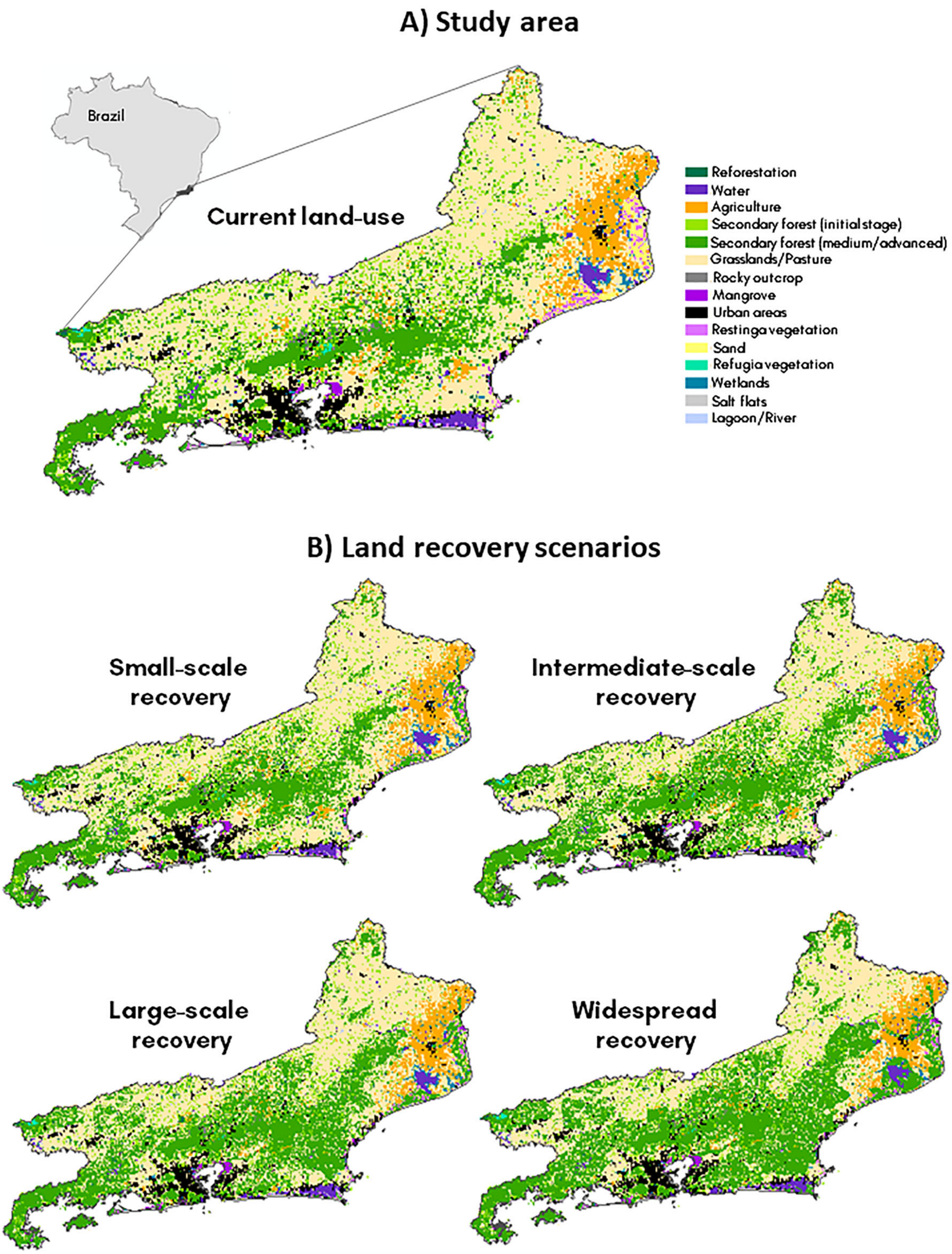

Fig. 1 Current land use in the study area and spatial arrangement of reforested areas in each land recovery scenario. **A** The study area is characterized by a current land use mainly structured with grasslands and pasturelands. The current land use has endured strong conversion from native Atlantic Forest to pastureland and agricultural fields (especially in the northeastern portion, in orange), with a dense metropolitan region with large urban areas (in the southern portion, in black). **B** We show four land recovery scenarios that show an increasing increment in forest area in comparison to current land use. The characterization, amount of recovered area and implementation cost of each scenario are shown in Table 1

Table 1 Extent of area recovered and cost of implementation of each land recovery scenario. The four scenarios, small-scale, intermediate-scale, large-scale and widespread recovery scenarios, are designed with an increasing gradient of area recovered and implementation costs. The total forest area (medium/advanced secondary vegetation) after recovery of each scenario was compared with the original forest area in the current scenario, indicating the percentage increase in relation to current forest cover (% increase in forest cover) and absolute values for the study area as a whole after recovery (study area's final forested area)

Land recovery scenarios		Recovered area (hectares)			Cost	Increase in forest cover (%)	Study area's final forested area (%)
		Regeneration	Restoration	Total			
Small-scale recovery	Natural regeneration of high priority areas	380 809	0	380 809	$228 485 529	8	25
Intermediate-scale recovery	Natural regeneration of high and medium priority areas	687 192	0	687 192	$412 315 010	35	31
Large-scale recovery	Natural regeneration of high and medium priority areas + Active restoration of high priority areas	687 192	160 753	847 945	$1 055 327 313	50	35
Widespread recovery	Natural regeneration of high and medium priority areas + Active restoration of high and medium priority areas	687 192	461 233	1 148 425	$2 257 247 139	79	41

~ US$950 million, leading to dozens of casualties and more than 35 000 residents losing their homes (IBGE 2012). Several factors aggravate flood risks in the study area, including the high degree of land conversion and deforestation of the Atlantic Forest, the topography with large mountain ranges in between lowland areas, and the largest cities being located very near to the coast and water bodies (e.g., Dias et al. 2018). It is well documented that in the study area, the urban artificial drainage system is not enough to prevent floods (SEA/INEA 2018), and several economic sectors are below critical levels for water security, demanding investments in water infrastructure toward climate adaptation, through short and medium-term initiatives (Prado 2010). Traditionally, such investments focused solely on gray infrastructure, disregarding the potential of NbS, which is the focus of the modeling process described below (WWAP 2018).

Flood risk modeling

We used the Urban Flood Risk Mitigation model of the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) (Kadaverugu et al. 2020; Hamel et al. 2021; Quagliolo et al. 2021). The model assesses the flood risk based on the soil's impermeability to precipitation (excluding river or coastal floods). The model focuses on how natural vegetation can increase the permeability of rainwater in the soil, reducing runoff that leads to floods. Thus, the model calculates the vegetation's ability to decrease runoff volume after a rainfall event, specifically through the amount of water absorbed per pixel compared to the volume of rainwater (Sharp et al. 2020). To do so, the model is based on 'Curve Number' values for each combination of land-use classes and soil type in each pixel. The Curve Numbers estimate the water infiltration capacity after a rainfall event, transforming the volume of rainwater into a volume of surface runoff (Mishra and Singh 2003). Using the intensity of rainfall events and the soil infiltration capacity values (Curve Number) in each pixel, the model produces a flood retention index (increasing gradient of retention between 0 and 1) and a non-retained runoff value (a sum of the value of all pixels, in millimeters) (Sharp et al. 2020). In addition, the model calculates the total volume of water retained in the study area (m^3).

Curve Numbers were established for different combinations of land-use systems and soil types. We used the land-use maps from the database of the State Environmental Institute of Rio de Janeiro (INEA 2018). We used the Global Hydrologic Soil Groups HYSOGs250m map (Ross et al. 2018) to classify the 4 major soil-type groups and their gradual infiltration capacity, developed using rates of water movement on the surface and within the soil (Mishra and Singh 2003). Soils in groups A, B, C and D have high, moderate, low and very low infiltration potential and rainwater movement, respectively (Ross et al. 2018; Fig. S1). Our study area predominantly has soils with very low infiltration capacity (mostly type D soils, followed by type C soils, with the absence of type A soils; Ross et al. 2018), which increases the risk of surface runoff leading to floods.

The soil infiltration capacity values for a rainfall event (Curve Numbers; Table S1) for each of the combinations of land use and soil types were defined using all national values available from the National Water Agency (ANA 2021), and for the remaining combinations we used values suggested by the model developers (USDA 2004; Sharp et al. 2020).

Land recovery scenarios

To assess the potential benefits from NbS, we used large-scale land recovery scenarios, designated by IUCN as nature-based solutions encompassing 'ecological restoration' and 'forest landscape restoration' to restore ecological integrity and functionality in degraded or deforested ecosystems (Cohen-Shacham et al. 2016). Large-scale land recovery is known for its extensive benefits for biodiversity and ecosystem services, especially under strategic spatial planning and scenario design (e.g., Strassburg et al. 2019; Bastin et al. 2019), including in urban contexts (Elmqvist et al. 2015). Here, we use the term 'Land recovery' to refer to both active restoration and natural regeneration. We used the priority areas for land recovery in our study area produced by the State Environmental Institute of Rio de Janeiro (INEA) (INEA 2010). INEA's maps indicate areas with different priorities for natural regeneration and active restoration based on different indices of environmental fragility, ecological functionality, biological importance and connectivity (INEA 2010, Fig. S2). We designed four scenarios using the priorities for land recovery, with a gradient increase in area recovered considering two levels of priorities (high and medium) for natural regeneration and active restoration, and based on a gradual increase in the cost of implementation: small-scale, intermediate-scale, large-scale and widespread recovery scenarios (Table 1, Fig. 1). The cost of implementing natural regeneration and active restoration was estimated at US$600 and US$4000 per hectare (Table 1), with an estimated implementation time of 5 and 3 years, respectively (Benini et al. 2017).

While land recovery bestows immeasurable co-benefits upon biodiversity and ecosystem services, it is possible to estimate the monetary value of some benefits (Grima et al. 2016; Pires et al. 2017; Vale et al. 2021). A decade after forest restoration, the ecosystem services it provides could yield more substantial profits than the typical returns from prior land use (e.g., pasture for livestock, Brancalion et al. 2012). Therefore, to account for the benefits arising from the implementation of the different land recovery scenarios we used estimates for wood production, non-woody products and carbon sequestration: US$250 per hectare per year for wood production; US$2000 per hectare per year for non-timber palm fruit and seed products, considering at least 100 trees per hectare; and 15 tons of carbon dioxide (CO_{2eq}) sequestered per hectare per year, considering the value of US$11 per CO_{2eq} (Brancalion et al. 2012). Estimates were extrapolated to the entire area recovered in each of the scenarios.

We superimposed the map of priority areas for land recovery with the land-use map, and in the areas to be recovered we changed the land-use classes to secondary vegetation in the medium/advanced stage, simulating full forest recovery. All maps were produced using ArcMap 10.5.

Extreme rainfall events

To simulate recurring conditions under future climate change, we used two intensities of extreme rainfall events, following Pires et al. (2016) study design: a standard extreme event of 50 mm per hour and a maximum extreme event of 100 mm per hour. For comparison purposes, we used the value of 10 mm per hour as a normal average rainfall event. These reference values were established based on the historical series for the region (e.g., Rio Alert System http://www.sistema-alerta-rio.com.br), which have already been used in field experiments that sought to reproduce extreme rainfall events in our study area (Pires et al. 2016).

A flowchart summarizing all methodological steps can be found in the supplementary information (Fig. S3).

RESULTS

The results indicate that the increase in flood risk is not directly proportional to the increase in rainfall intensity. Compared to an average rainfall event, a standard extreme event produces five times more rain but amounts to 23 times more runoff (Table 2). Accordingly, although a maximum extreme event produces 10 times more rain than an average rainfall event, it amounts to a 70 times greater runoff (Table 2). Similarly, the water retention index in the soil decreases due to the substantial increase in rainfall volume. The retention index of an average rainfall event is almost at its maximum (> 0.9), while it decreases $> 30\%$ (0.6) and $> 50\%$ (0.4) in standard and maximum extreme events, respectively (Table 2). The agricultural (northeastern) and metropolitan (southern) regions of the study area (Fig. 1) are the most affected by exceeding runoff under standard and maximum extreme events (Fig. 2). Both are characterized by singular land uses with little water infiltration capacity (Table S1): the agricultural region (also with distinct presence of wetlands and water bodies) and the metropolitan region being highly urbanized (Fig. 1).

All land recovery scenarios showed enormous potential for reducing flood risk compared to the current land use of the study area. Notably, the more land recovered, the greater the retention index, the volume retained and the reduction in runoff (Table 3). The reduction in flood risk was not directly proportional to the area recovered, as the small-scale recovery scenario led to smaller reductions, whereas the intermediate to widespread recovery scenarios led to overall similar more prominent reductions in runoff (Fig. 3,

Table 2 Difference between average and extreme rainfall events exacerbated by climate change. The values were modeled for the current land use scenario (without any land recovery strategy)

Different rainfall intensities (per pixel)	Estimated rainfall considering all pixels in study area (mm)	Accumulated runoff considering all pixels in study area (mm)	Retention index
Average rainfall event (10 mm/h)	311.530	26.393	0.938
Standard extreme event (50 mm/h)	1.557.650	609.967	0.624
Difference to average rainfall event	5 times greater	23 times greater	− 34%
Maximum extreme event (100 mm/h)	3.115.300	1.845.018	0.418
Difference to average rainfall event	10 times greater	70 times greater	− 55%

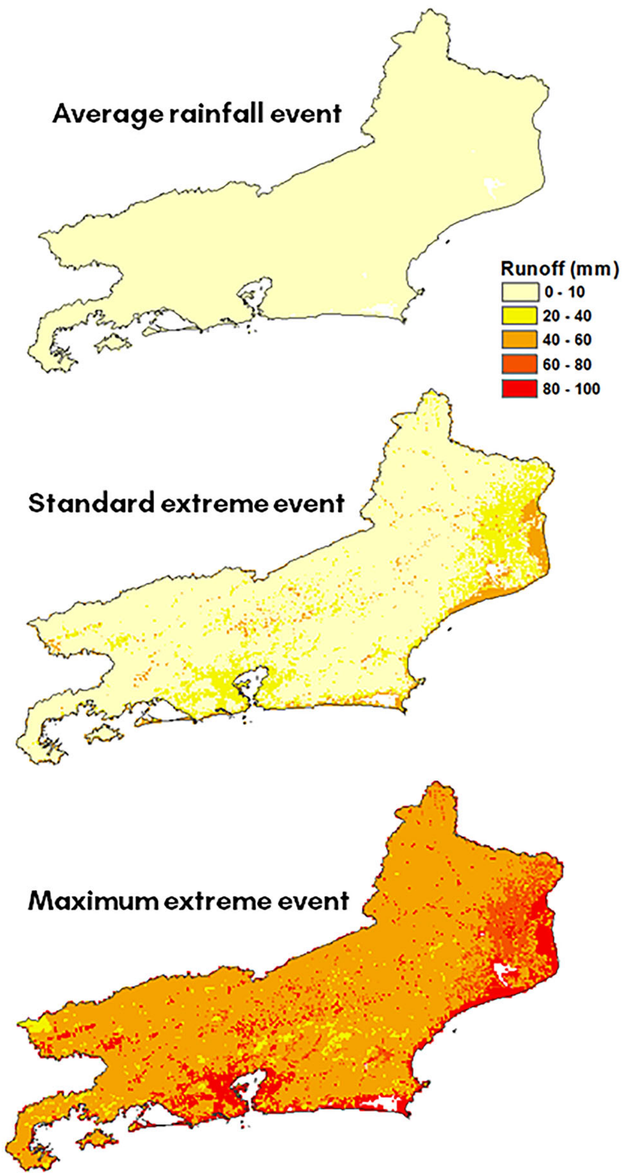

Fig. 2 Runoff in average rainfall events, standard and maximum extreme events under current land use. Average rainfall events, standard and maximum extreme events have rainfall intensities of 10, 50 and 100 mm/h, respectively. The regions with the highest runoff in both standard and maximum extreme events are the metropolitan (southern) and agricultural (northeast) regions

Table 3). All land recovery scenarios were more efficient in an average rainfall event, leading to a reduction of up to 57% in the runoff, and there was a proportional decrease in the risk reduction efficiency according to increases in rainfall intensity (Figs. 3 and 4, Fig. S4, Table 3). Locally, the regions in which forest recovery was implemented presented striking runoff reductions, even if implemented in regions previously dominated by extensive pasturelands and agriculture (Fig. 4, Fig. S4). In highly urbanized areas, such as the metropolitan region, where land recovery was nearly impossible due to the lack of adequate areas, reductions in runoff were more modest (Fig. 4, Fig. S4). Indeed, we identified an inverted relationship between the current proportion of urban and forested areas for the retention index under extreme events in the cities evaluated, where higher proportions of urban areas within cities led to smaller retention indexes and the contrary is true for the proportion of forested areas (Fig. S5).

All land recovery scenarios resulted in clear increases in water retention services, with overall increases in total water retained up to ~ 100 and ~ 200 million cubic meters in standard and maximum extreme events, respectively (Table 3). Although these values refer to the whole study area, some cities will particularly benefit from the land recovery strategies (Fig. 5, Fig. S6). For example, from the intermediate-scale recovery scenario onwards, half of the landscape increased total retention by > 1 million cubic meters of stormwater under maximum extreme events (Fig. 5, Table S2). Notably, under maximum extreme events, the agricultural region had pronounced increases in the total volume of water retained (> 3 million cubic meters) regardless of the land recovery scenario (Fig. 5).

Additionally, all land recovery strategies presented co-benefits of potential annual financial returns that outweighed their implementation costs in just 1 year (Fig. 6).

DISCUSSION

Worrisomely, we reveal that climate change imposes astonishing nonlinear risks to society. An increase in

Table 3 Effectiveness of land recovery scenarios for flood risk reduction

Land recovery scenarios	Average rainfall event			Standard extreme event			Maximum extreme event		
	Accumulated runoff in all pixels in study area (mm)	Retention index	Total retention volume in study area (m^3)	Accumulated runoff in all pixels in study area (mm)	Retention index	Total Retention volume in study area (m^3)	Accumulated runoff in all pixels in study area (mm)	Retention index	Total retention area (m^3)
Current land use	26 393	0.938	407 436 512	609 833	0.624	1 354 594 208	1 845 018	0.418	1 815 414 496
Small-scale recovery	23 119	0.950	412 851 800	584 459	0.642	1 394 423 744	1 780 572	0.433	1 881 924 896
Difference to current	− 12%	1.3%	5 415 288	− 4%	2.9%	39 829 536	− 3%	3.6%	66 510 400
Intermediate-scale recovery	12 866	0.959	414 051 048	519 872	0.658	1 419 605 888	1 653 933	0.447	1 928 035 008
Difference to current	− 51%	2.3%	6 614 536	− 15%	5.5%	65 011 680	− 10%	6.9%	112 620 512
Large-scale recovery	12 403	0.961	414 718 496	509 512	0.665	1 434 523 456	1 634 520	0.453	1 955 728 640
Difference to current	− 53%	2.4%	7 281 984	− 16%	6.6%	79 929 248	− 11%	8.4%	140 314 144
Widespread recovery	11 269	0.965	416 350 704	487 896	0.679	1 465 650 240	1 594 835	0.466	2 012 326 272
Difference to current	− 57%	2.8%	8 914 192	− 20%	8.9%	111 056 032	− 14%	11.6%	196 911 776

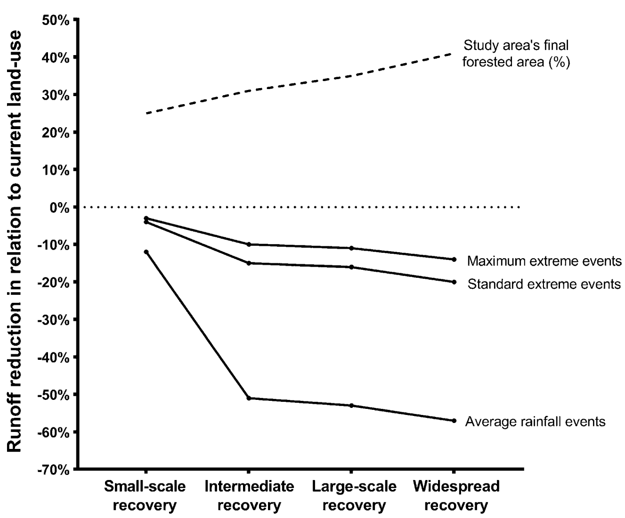

Fig. 3 Runoff reduction effectiveness of each land recovery scenario compared to the current land use

rainfall intensity under extreme events disproportionately increases flood risks. Under no effective adaptation efforts, a 10 times greater rainfall can lead to a 70 times greater flood risk. Such disproportional risk together with the unpredictability of extreme events calls for urgent measures of climate adaptation to safeguard urban populations. All land recovery scenarios showed remarkable potential for disaster risk reduction under extreme events, thus being a relevant urban climate adaptation strategy. Here, we reveal the power of land recovery to reduce the runoff associated with extreme events, retaining hundreds of millions of cubic meters of rainfall more than the current land use. Our results reinforce the role of nature-based solution strategies in providing a cost-effective solution with a series of additional co-benefits to ensure human well-being in the medium and longer term.

Much of the striking success of nature-based solutions in our study area is due to the extensive conversion of current pastureland into forests in all assessed scenarios. Notably, cities dominated by land uses with very poor infiltration capacities (often together with very little forest cover) were the ones that most benefited from the disaster risk reduction from land recovery. Both the agricultural and metropolitan regions are experiencing the most substantial impact from extreme events due to their predominant land uses with limited infiltration capacity (Fig. 2). Cities in the agricultural region, characterized by croplands, wetlands and waterbodies, greatly benefited from implementing forest recovery strategies across all rainfall intensities (Fig. 4). Importantly, land recovery resulted in substantial benefits in these regions, which lacked any forest cover and, therefore, were the most vulnerable to floods. The striking

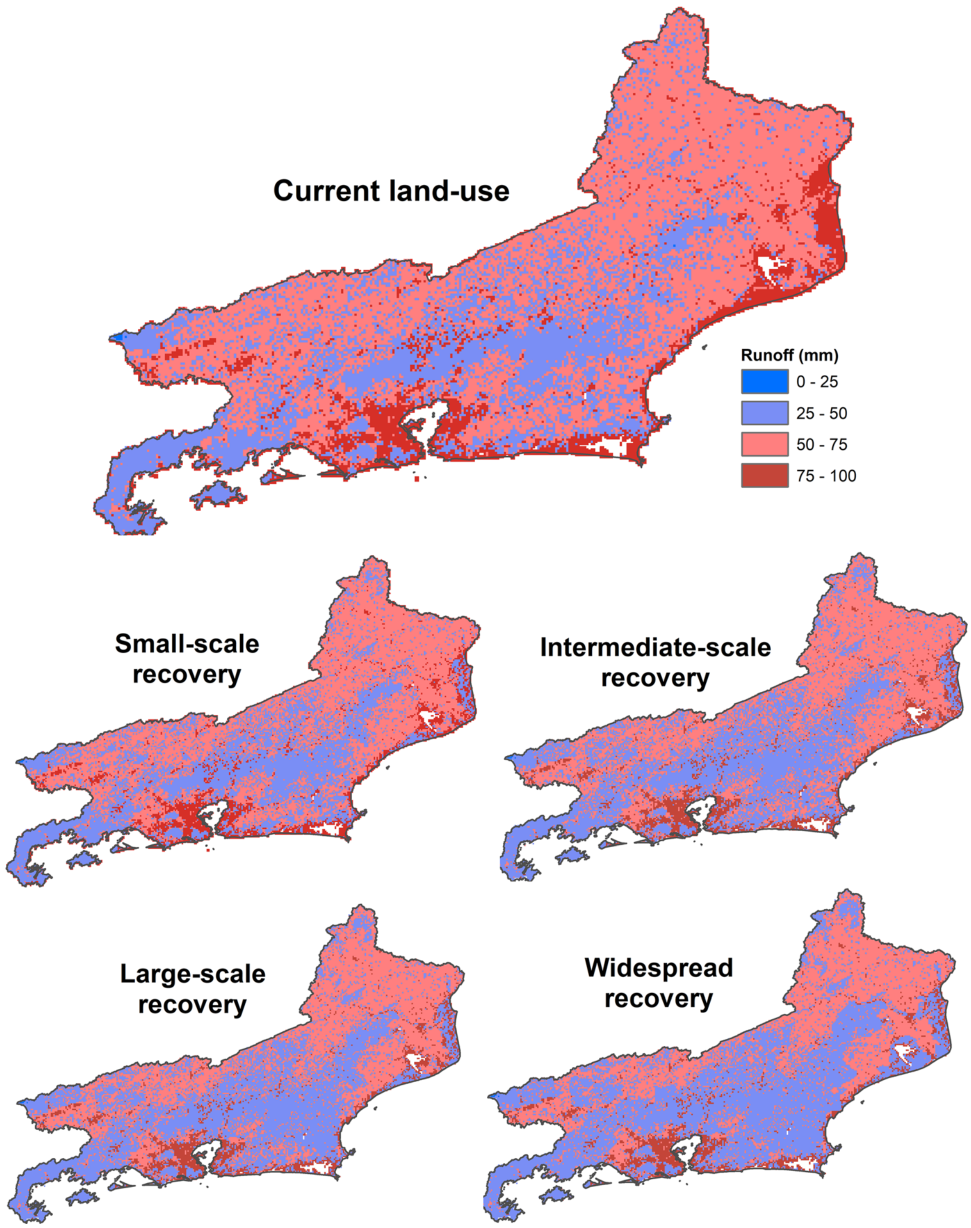

Fig. 4 Runoff in each land recovery scenario under maximum extreme events. Runoff is represented as an estimate per pixel in millimeters with respect to maximum extreme events of 100 mm/h. See Fig. S4 for runoff in these land recovery scenarios under standard extreme events

benefits of land recovery in the most at-risk regions reveal their potential as cost-effective nature-based solutions (Bustamante et al. 2019). Notably, potential trade-offs may arise from such large-scale land recovery, especially involving the reduction of available land in regions with high dependency on economic activities such as agriculture or cattle ranching. Neither of those activities is extensively explored in our study area, which is mostly predicted to be affected by urban sprawl in future years (Kii 2021). Nevertheless, nature-based solutions have already been identified as strategies able to increase agricultural productivity and support livelihoods, while concomitantly producing multiple other ecosystem services (Manes et al. 2022b).

Although the widespread recovery scenario provides the greatest benefits, financial constraints may preclude the recovery of such an extensive area. Noteworthy, actions to be implemented should not only consider their flood reduction potential but also their cost-effectiveness, in consonance with stakeholder and policymaker's needs and constraints (Niemeyer et al. 2019; Turkelboom et al. 2021). Thus, we identified the intermediate-scale recovery scenario as the one with the greatest cost-effectiveness.

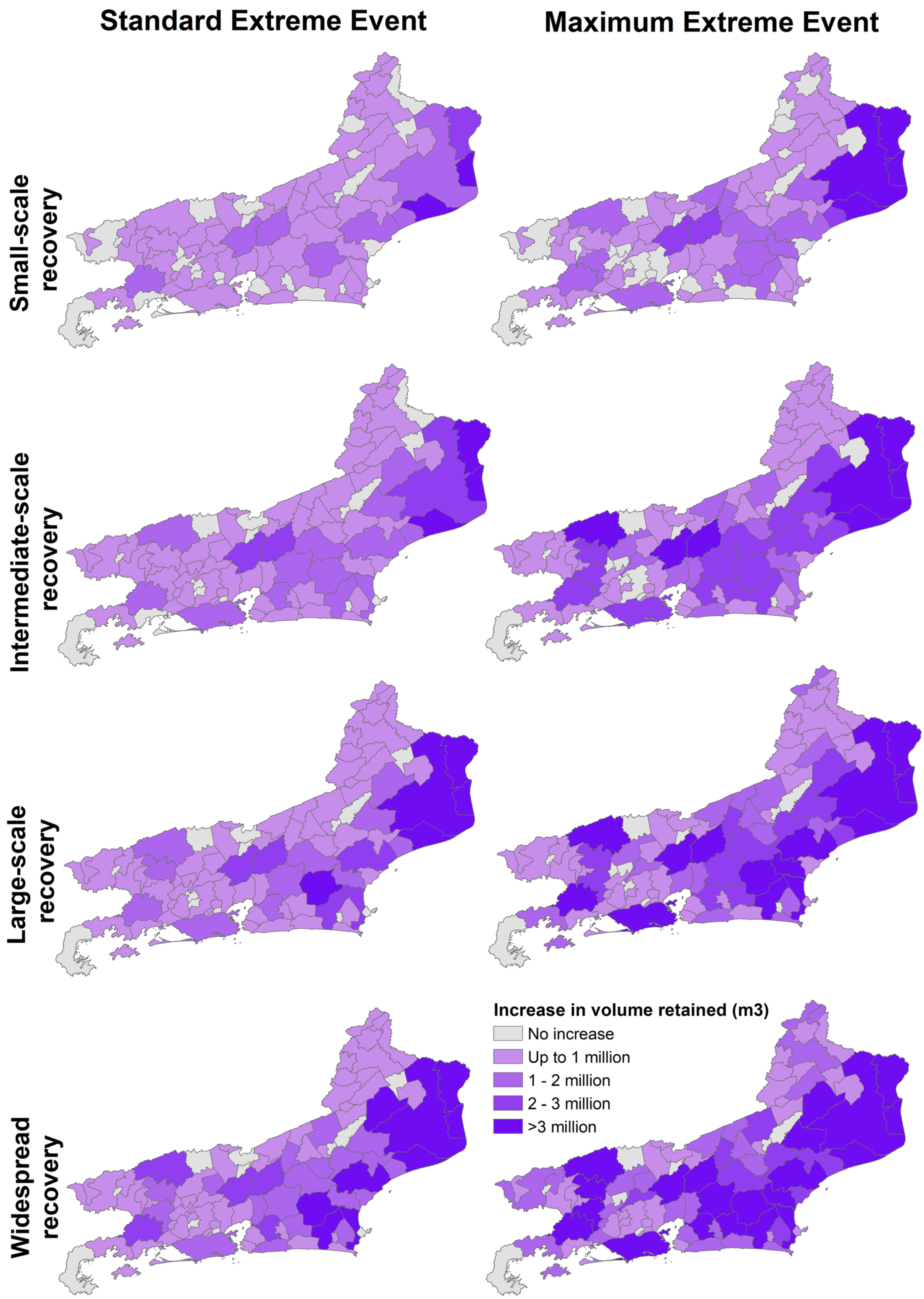

Fig. 5 Increase in rainfall retention in each land recovery scenario compared to the current land use under extreme events. The difference between the total volume retained is shown in cubic meters under standard (left) and maximum extreme events (right). The maps show the impact of the land recovery scenarios in all of the cities in the study area. See raw values in Table S2

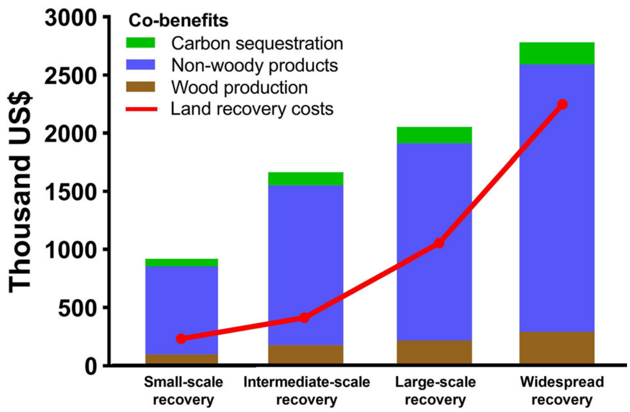

Fig. 6 Estimated cost of implementation and financial co-benefits from each land recovery scenario. Values were calculated multiplying the financial co-benefits per hectare by the extension of land recovered in each scenario (please refer to Table 1 for land recovered and cost of implementation in each scenario). The following values were used for financial co-benefits: US$250 per hectare per year for wood production; US$2000 per hectare per year for non-timber palm fruit and seed products, considering at least 100 individuals per hectare; and sequestration of 15 tons of carbon dioxide (CO_{2eq}) per hectare per year, considering the value of US$11 per CO_{2eq} (Brancalion et al. 2012). Note that although the cost of implementation is fixed, the financial co-benefits are yearly estimates, meaning that the benefits might surpass all the costs of implementation in only 1 year

Benefits from the intermediate recovery scenario are considerably higher than the ones with the lowest forest recovery (small-scale recovery), while still being a low-cost strategy. Because active restorations are costly, strategies with natural regeneration allow for land recovery to be implemented in larger spatial scales (Crouzeilles et al. 2017, 2020). In fact, more than 2.7 million hectares have already been recovered through natural regeneration in the Atlantic Forest, and estimations suggest that regenerated areas could double by 2035 (Crouzeilles et al. 2020).

Payment for ecosystem services is one of the instruments that can accelerate the implementation of projects of landscape-scale land recovery (Kasecker et al. 2018). Importantly, although cities may have different financial incentives and/or barriers for land recovery, which would facilitate their implementation in some regions rather than others, we show that the financial benefits of associated ecosystem services certainly largely outweigh the costs of forest restoration, especially the ones associated with non-woody production (Brancalion et al. 2012; Grima et al. 2016; Borgo et al. 2017). Despite the very high potential for co-benefit generation and their economic valuation outweighing implementation costs, our analysis did not incorporate market demand or infrastructure for such goods and services, nor considered the opportunity costs for these lands or the creation of new jobs (e.g., Golub et al. 2009). Without such complex market considerations, our results could be overestimating economic co-benefits. Nonetheless, a cost-effectiveness analysis of any given land recovery project considering the potential co-benefit production is an indispensable first step provide a more holistic dimension of nature's contributions to people (e.g., Bain et al. 2016).

When evaluating land recovery scenarios, it is important to consider the timescale of different strategies. Natural regeneration is a much slower process resulting in delayed benefits, whereas active restoration implies a much faster hands-on process with direct seedling planting and intensive management (Crouzeilles et al. 2017). Indeed, time is a very important determinant of forest recovery success (Crouzeilles et al. 2016), and estimates for obtaining benefits range between 10, 20 and 30 years for species with fast, moderate and slow growth, respectively (Brancalion et al. 2012). Thus, the inclusion of time frames as an additional cost factor in our analysis could have influenced the comparison of cost-effectiveness between natural regeneration and active restoration. That was outside the scope of our study, which nonetheless aimed at evaluating strategies designed for the study area. By evaluating and pondering best-choice scenarios consistent with the existing managing portfolio of environmental agencies, science can help boost the immediate implementation of solutions to the ever-growing problem of floods to people in cities. This is particularly important given that one of the main challenges to the implementation of natural regeneration strategies is the identification of areas where their potential for success is the greatest (Crouzeilles et al. 2020). Not all areas can undergo natural regeneration—often areas need to be near standing forests to guarantee seed rain, which accelerates forest growth (Rodrigues et al. 2009). Recent studies have been striving to provide the needed information to aid the identification and maintenance of these areas (e.g., Crouzeilles et al. 2020 for the Atlantic Forest). The use of pre-determined priority areas for natural regeneration defined by the state environmental agency can foster their immediate implementation in the study area, although the replication of the study in other regions might require a prior viability analysis of which areas are prone to natural regeneration.

Contrastingly, the most urbanized regions had more modest benefits from the land recovery scenarios precisely because the extensive urbanization precludes the establishment of new forests (Fig. 4). For example, Rio de Janeiro city, one of the most populated and affected cities in the study area, has approximately 48% of its land covered by impervious urban surfaces. In our scenarios, ranging from small-scale to widespread recovery, only 3–12% of the city's area was available for land recovery. Such recovery only led to a modest increase of up to 10%

in the total volume retained in all scenarios (Supplementary Table S2). This is an additional challenge that demands alternative nature-based solutions other than large-scale forest recovery, with smaller green areas being integrated within the urban matrix. Several studies reinforce the need to design cities with a mixture of 'green' areas that can increase water infiltration on mostly impervious 'gray' land to safeguard them from floods, known as 'sponge cities' (e.g., Alemaw et al. 2020; Song 2022). Recent studies point to the high effectiveness of such green infrastructure for flood risk reduction in the form of rain gardens (Song 2022), permeable pavements and infiltration trenches in the streets, and water cisterns and green roofs in buildings (Joksimovic and Alam 2014; Chen et al. 2021). Such strategies, however, are still scarce and implemented at very local levels (e.g., streets), and must be upscaled for widespread benefits (Chen et al. 2021). Thus, effective flood risk reduction in densely urbanized cities requires a diverse portfolio of city-wide nature-based solutions.

Our study revealed the great potential of nature-based solutions for flood risk reduction with important co-benefits at landscape scale, which can reduce the impact of climate-induced extreme events even with smaller-scale and low-cost strategies. We used four real-world possible scenarios developed by the environmental agency in our study area to assess their potential benefits and cost-effectiveness. The use of real-world scenarios is an essential strategy to guide decision making and accelerate implementation, as they are viable and applicable. Several legal instruments can guarantee the implementation of these strategies in a timely manner to allow the achievement of global goals (e.g., 2030 Agenda). These include potential partnerships with institutions designed for nature conservation (e.g., such as the Atlantic Forest Restoration Pact, for our study area; Crouzeilles et al. 2019), the establishment of partnerships with the private sectors (e.g., emerging biodiversity credit systems; IIED 2022), and enabling subsidies for strategies of payment for ecosystem services (PES; Grima et al. 2016). Particularly, our study area is especially prone to the increase in floods and other natural disasters in the near future, highlighting the need for decision-making tools such as local and regional adaptation plans depicting nature-based solutions (e.g., Rio de Janeiro Adaptation Plan, SEA/INEA 2018). Assessments of nature-based solutions' potential for implementation based on sound scientific evidence can provide important subsidies for their adoption. Above all, the recognition of nature-based solutions as one of the main strategies to promote resilient and sustainable cities under a changing climate is a great step forward in the integration of social, economic and environmental agendas, especially in the Global South.

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Declarations

Conflict of interest All co-authors have seen and agree with the contents of the manuscript and there are no conflicts of interest to declare.

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