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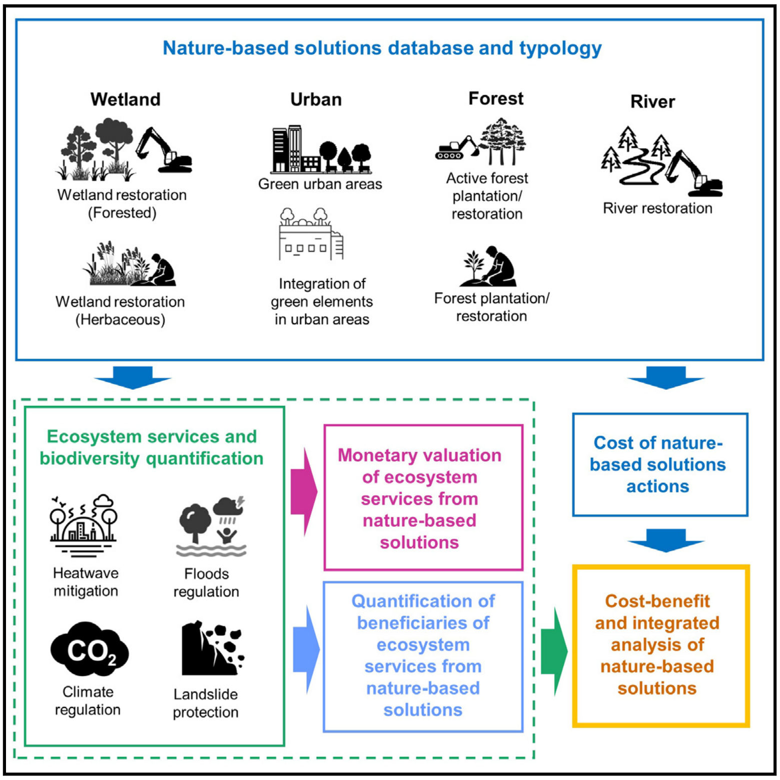
Co-benefits of nature-based solutions exceed the costs of implementation

Graphical abstract



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In brief

González-García et al. evaluate 83 nature-based solutions in the Alps, quantifying biodiversity and ecosystem service benefits. They reveal a 2.8:1 return on investment and highlight how biodiversity outcomes and the number of beneficiaries vary by solution type. Their findings emphasize the need for integrated, landscape-scale planning to maximize co-benefits for ecosystems and societies.

Highlights

- Nature-based solutions yield a 2.8:1 return on investment across diverse actions
- Single-focus strategies risk missing broader nature-based solution co-benefits
- Ecosystem service value and biodiversity vary significantly by solution type
- Integrated, landscape-scale planning can maximize ecosystem and biodiversity benefits

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Co-benefits of nature-based solutions exceed the costs of implementation

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SCIENCE FOR SOCIETY Nature-based solutions are a promising strategy for mitigating and adapting to climate change, as they provide multiple benefits to society and biodiversity. However, detailed quantitative analyses of these benefits and the cost effectiveness of such initiatives are limited. In this study, we present an analysis of 83 nature-based solutions in the Alps, where we quantified heatwave mitigation, flood regulation, carbon sequestration, and landslide protection. We also assessed the number of people who benefited, the monetary value of these benefits, and the associated costs.

Our results highlight the need for an integrated approach to planning nature-based solutions. Forest nature-based solutions offer a wide range of benefits, while river and wetland nature-based solutions are more beneficial for biodiversity. Urban nature-based solutions, despite their high cost effectiveness, contribute less to biodiversity but are located where people can enjoy their benefits. Overall, the analyzed solutions show a return on investment of 2.8 EUR per EUR invested.

SUMMARY

Nature-based solutions offer multiple benefits for ecosystems and societies, supporting their inclusion in policy and practice. This study contributes to closing the gap in quantifying the multiple outcomes of nature-based solutions by assessing 83 nature-based solutions in the Alps. We assessed biodiversity co-benefits and the monetary value of four ecosystem services (heatwave mitigation, flood regulation, climate regulation, and landslide protection) provided by these nature-based solutions to their respective beneficiaries. Forest nature-based solutions showed high values for the four ecosystem services, river and wetland nature-based solutions showed high values for biodiversity, and urban nature-based solutions contributed a lower biodiversity value but were highly cost effective, benefiting a larger population. We estimated a 2.8:1 return on investment benefiting a total of 91,324 persons. We highlight the need for integrating biodiversity and multiple ecosystem services for future nature-based solutions funding and implementation, together with their role to mitigate and adapt to climate change.

INTRODUCTION

Nature-based solutions are a promising strategy for mitigating and adapting to climate change, offering multiple benefits to society.[1] Nature-based solutions encompass a range of actions aimed at protecting, sustainably managing, or restoring nature, effectively addressing societal challenges while simultaneously benefiting both people and the environment.[2–4] For instance, the restoration of degraded riparian forests not only enhances biodiversity but also provides a wide array of ecosystem services to society, including climate regulation, flood regulation, landslide protection, water retention, and heatwave mitigation.[5] Additionally, when properly co-designed and implemented, nature-based solutions can deliver transformative change toward sustainability.[6]

Research on the effectiveness of nature-based solutions in climate change adaptation is critical for implementation worldwide.[7] Indeed, ecosystem services benefits are multiple: forest

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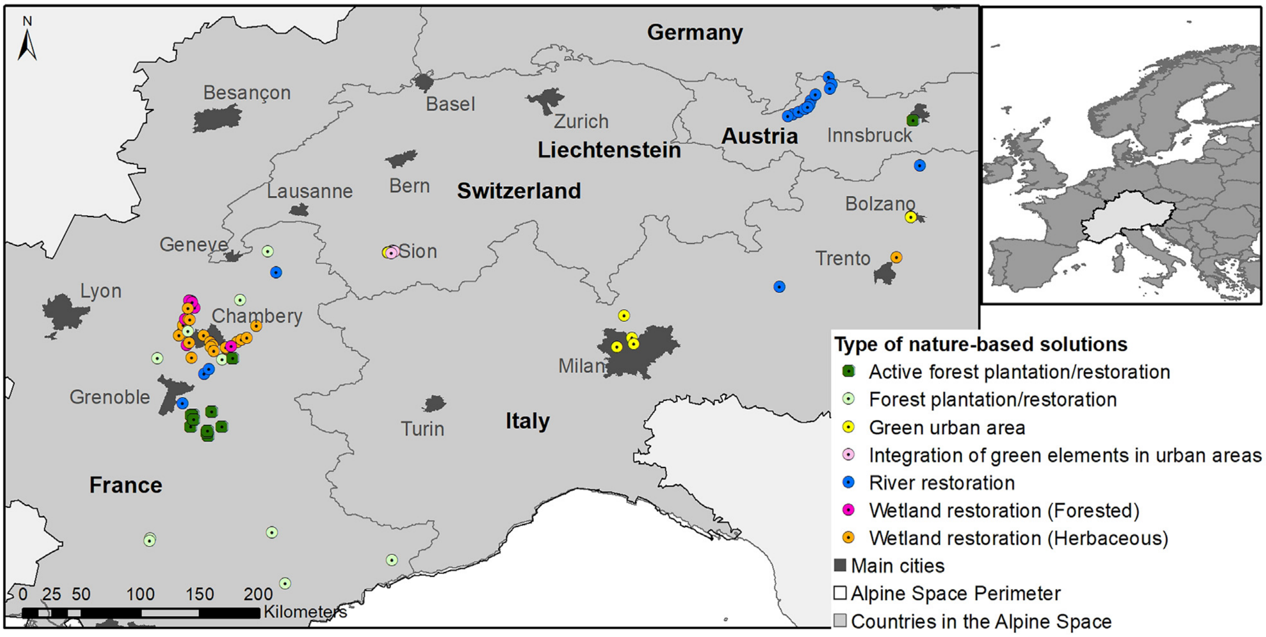

Figure 1. Geographical distribution of the 83 identified nature-based solutions based on their typology
These types are (1) AFP (n = 11), (2) FP (n = 10), (3) GUAs (n = 8), (4) IGEUAs (n = 6), (5) RR (n = 17), (6) wetland restoration (herbaceous) (n = 21), and (7) wetland restoration (forested) (n = 10). Further details regarding the database description, typologies, types of interventions associated, and ecosystems are presented in supplemental methods I.

restoration often improves hydrological services by enhancing water infiltration rates,[8] and agroforestry, permaculture, or organic farming are crucial to safeguard and rebuild soil carbon stocks.[9] Nature-based solutions in river ecosystems can improve resilience to flooding, control the transport of substances through natural filtering, and enhance their ecological status.[10] Some qualitative case reviews have also highlighted nature-based solutions' benefits to various ecosystem services, showing the potential of nature-based solutions as a cost-effective approach for hydrological risk reduction and land degradation.[5] A growing body of literature delves into how urban nature-based solutions can tackle specific urban challenges, such as hydrometeorological hazards[11] or improving health.[12] Regarding biodiversity, certain studies have explored the positive side effects of conserving biodiversity through land conservation practices, demonstrating that by preserving specific species' habitats, it is possible to simultaneously reduce CO_2 emissions[13] and mitigate climate change.[14] However, many of these studies take a qualitative approach[7] or do not quantitatively assess multiple ecosystem services resulting from land use/land cover changes involved in nature-based solutions, despite their substantial influence on biodiversity and ecosystem services.[15,16]

Cost-effectiveness analyses, considering the economic cost of the implementation of nature-based solutions and their benefits, are crucial for assessing how relevant nature-based solutions could be for climate change adaptation.[17] Such analyses are rare because they require an interdisciplinary perspective, large datasets, and complex quantification.[1,4] Ecosystem services modeling is a valuable approach in this regard, as it allows for the quantification and understanding of multiple benefits, their economic value, and identifies who benefits from them.[18] However, while some studies quantify ecosystem services provided by one or a few nature-based solutions case studies,[19] and syntheses have summarized their results across multiple benefits,[7,20] no direct analysis to date has simultaneously quantified the benefits and beneficiaries of multiple ecosystem services, along with biodiversity co-benefits through empirical analysis of a large dataset of nature-based solutions. Addressing this knowledge gap is critical for placing nature-based solutions at the core of a strategy to jointly tackle biodiversity loss and climate change.

Here, we present a comprehensive analysis of 83 nature-based solutions actions in the Alps, encompassing 28 distinct projects (Figure 1). We considered nature-based solutions as "actions to protect, conserve, restore, sustainably use, and manage natural or modified terrestrial, freshwater, coastal, and marine ecosystems, which address social, economic, and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services, and resilience and biodiversity benefits."[21] The actions encompass the creation of green urban areas, the integration of green elements such as green roofs, forest plantation and restoration, river restoration (including riparian vegetation and river margins), and wetland restoration, among others. Our analysis considers independent actions derived from an assessment of aerial images and project information, based on two criteria: actions stemming from the same project but occurring in separate geographical areas are considered as distinct actions (i.e., the restoration of the same river in two distinct areas or the restoration of two non-contiguous wetlands) and interventions

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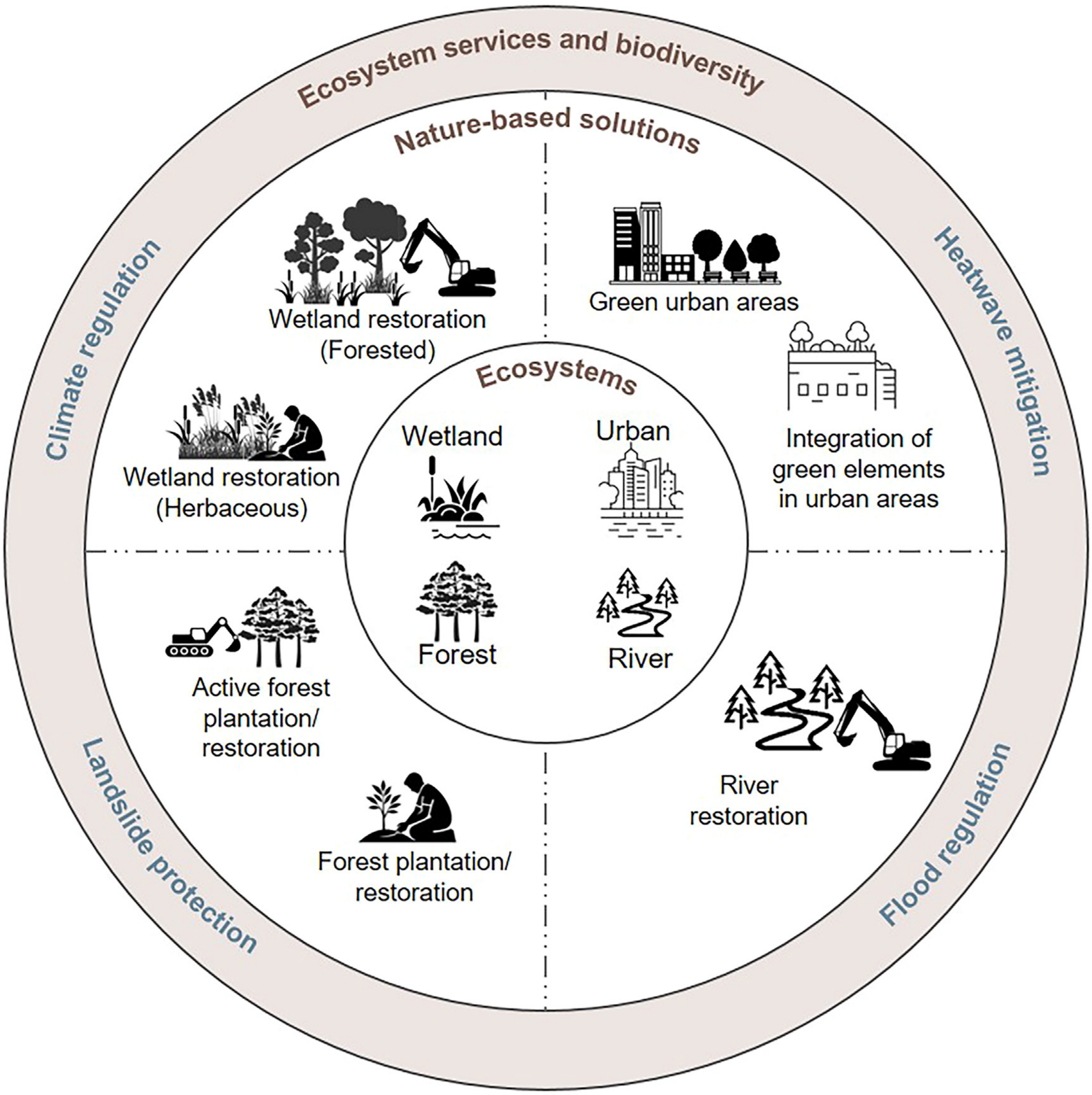

Figure 2. The relationship between ecosystems, nature-based solutions typology, and the provision of various ecosystem services analyzed in this research

Ecosystem services are not exclusively linked to one or more types of nature-based solutions but to several of them and are often included as primary objectives of the initiatives. For instance, while active forest plantations directly contribute to landslide protection, forest plantations actions may focus on other services such as carbon sequestration while improving at the same time landslide protection. Similarly, green urban areas often address heatwave mitigation but may also aim to generate multiple ecosystem services. The figure illustrates how the ecosystem services provided by nature-based solutions are connected to all types of nature-based solutions, highlighting the multifunctional nature of these solutions.

physically separated but very proximate are considered as being part of the same action (i.e., constructing vegetated dikes on two sides of the same river within the same area). We provide the description of the seven types of nature-based solutions used for the analysis (Figure 2), the 22 specific interventions identified, and other relevant information in the supplemental methods Ia (Figure S1 and Table S1).

We analyzed how these actions enhance biodiversity, benefit people through ecosystem services, and evaluated their cost effectiveness based on action costs and the estimated monetary value of the ecosystem services provided. The study relied on photointerpretation of land use/land cover changes before and after the implementation of nature-based solutions (see Figure S2 in supplemental methods Ib), using aerial imagery. We modeled four key ecosystem services: heatwave mitigation, flood regulation, climate regulation (using Integrated Valuation of Ecosystem Services and Trade-Offs [InVEST][22]), and landslide protection (using Slidefornet). These services were selected for their relevance to climate change adaptation and mitigation. For instance, Europe is projected to experience more frequent heatwaves,[23] more severe and widespread flooding,[24] and an increase in landslide frequency and the number of people at risk.[25] Additionally, assessing the carbon sequestration and storage capacity of nature-based solutions allowed us to quantify their mitigation potential. Cultural ecosystem services were excluded due to the challenges of assigning monetary value[26] (e.g., the monetary value of outdoor recreation depends on factors such as actual usage and visitor numbers). Similarly, other services, such as pollutant removal, water supply, and biodiversity-related benefits (i.e., biological control), were not included due to a lack of specific modeling data.

The monetary value of the four ecosystem services was quantified based on the value of energy consumption reduction, the value of infrastructure protected, and the market price of carbon. Biodiversity was analyzed by identifying, in the nature-based solutions project descriptions, mentions of different species, how they are related to priority habitats for conservation, and the number of these habitats targeted by nature-based solutions actions. To determine the beneficiaries of the ecosystem services, we analyzed the number of inhabitants within different distance buffers surrounding the actions, drawing from available literature and the flow dynamics of each ecosystem service. Additionally, we analyzed the differences in GDP for the regions where the nature-based solutions are implemented, aiming to understand how they benefit different socio-economic groups. Through a comprehensive evaluation of costs and nature-based solutions multifunctionality, including biodiversity co-benefits and ecosystem services monetary value and beneficiaries, we hope to provide evidence on the role of nature-based solutions for jointly addressing biodiversity loss and climate change.

RESULTS

Ecosystem services and biodiversity before and after nature-based solutions implementation

The implementation of nature-based solutions generally leads to an overall increase in the supply of ecosystem services (Figure 3). For a detailed description of changes in land use/land cover used in the analysis, refer to supplemental methods Ib. Active forest plantation/restoration actions deliver the most significant median increase for heatwave mitigation (99%), ranking second for flood regulation (71%), fifth for climate regulation (128%), and showing the highest median reduction in landslide probability (−20.5%). Forest plantation/restoration actions generally show lower median increases across all four ecosystem services: 62% for heatwave mitigation, 65% for flood regulation, 81% for climate regulation, and a decrease of −12% for landslide protection.

Green urban areas deliver a median increase of 66% for heatwave mitigation, 49% for flood regulation, and the second-highest median increase for climate regulation (536%), primarily due to pre-action low values. Similarly, integration of green elements in urban areas shows median increases of 66% for heatwave mitigation and the highest median increases for flood regulation (253%) and climate regulation (23,867%). These exceptionally high increases are attributed to very low pre-action values, starting from almost zero for all three ecosystem services. River restoration actions result in a median reduction of −2% in heatwave mitigation. However, they show median increases of 52% in flood regulation and 131% in climate regulation, despite seven out of ten actions showing a decrease in carbon stored. Forested wetland restoration actions yield a median increase of 5% for heatwave mitigation, a −14% median decrease for flood regulation, and a median increase of 96% for climate regulation. Finally, herbaceous wetland restoration actions show a median increase of 10% in heatwave mitigation, a −34% median decrease for flood regulation, and a median increase of 133% for climate regulation.

Biodiversity analysis was conducted at the ecosystem level rather than the nature-based solution typology due to insufficient data for individual actions. Most projects reporting specific biodiversity data presented it at the project level, with a few exceptions reporting at the action level (refer to Data S1 for details). Concerning the number of species used in the actions (Figure 4A), urban nature-based solutions show the highest median value (11 species), followed by wetland nature-based solutions (8 species). However, regarding the number of these species related to priority habitats (Figure 4B), wetland nature-based solutions show the highest median values (4 species), followed by river nature-based solutions (2 species). Nonetheless, urban nature-based solutions show a median value of 0 species. This discrepancy between the number of species mentioned and the number of species related to priority habitats illustrates how urban nature-based solutions, despite showing the highest median number of species, are mostly associated with species not linked to conservation priorities or relevant habitats.

Regarding the number of priority habitats related to the mentioned species (Figure 4C), wetland nature-based solutions show the highest median value (2 species), followed by forest nature-based solutions (1 species). However, considering the number of priority habitats targeted by nature-based solutions (Figure 4D), river nature-based solutions show the highest median value (3.5 habitats), followed by wetland nature-based solutions (2 habitats). Finally, species listed in the International Union for Conservation of Nature Red List as threatened or worse are rarely targeted by the reviewed nature-based solutions projects (4 present in river, 1 in wetland, and 1 in urban).

Beneficiaries of nature-based solutions outcomes

The various types of nature-based solutions benefit different numbers of people, with urban nature-based solutions benefiting considerably more people than river, forest, or wetland initiatives (see Figure 5; supplemental methods Ie; Tables S6, S7, and S8). For the mitigation of heatwaves (Figure 5A), green urban areas benefit the highest number of people on average per nature-based solution (4,397 ± 3,851 inhabitants within 450 m; 35,176 inhabitants in total). Similarly, for flood regulation (Figure 5B), green urban areas again demonstrate the highest benefits (1,636 ± 1,954 inhabitants within 200 m; 13,089 inhabitants in total). Active forest plantation/restoration actions benefit slightly more people (14 ± 39) compared with forest plantation actions (11 ± 14) in the 200 m buffer, suggesting that active forest plantation/restoration actions are located closer to beneficiaries. However, forest nature-based solutions are often located far from potential beneficiaries compared with urban, river, or wetland nature-based solutions.

In terms of total GDP per km^2 (Figure 5D), integration of green elements in urban areas actions are located within the highest median GDP (31 million EUR), followed by green urban areas with 21 million EUR and river restoration initiatives (1.5 million

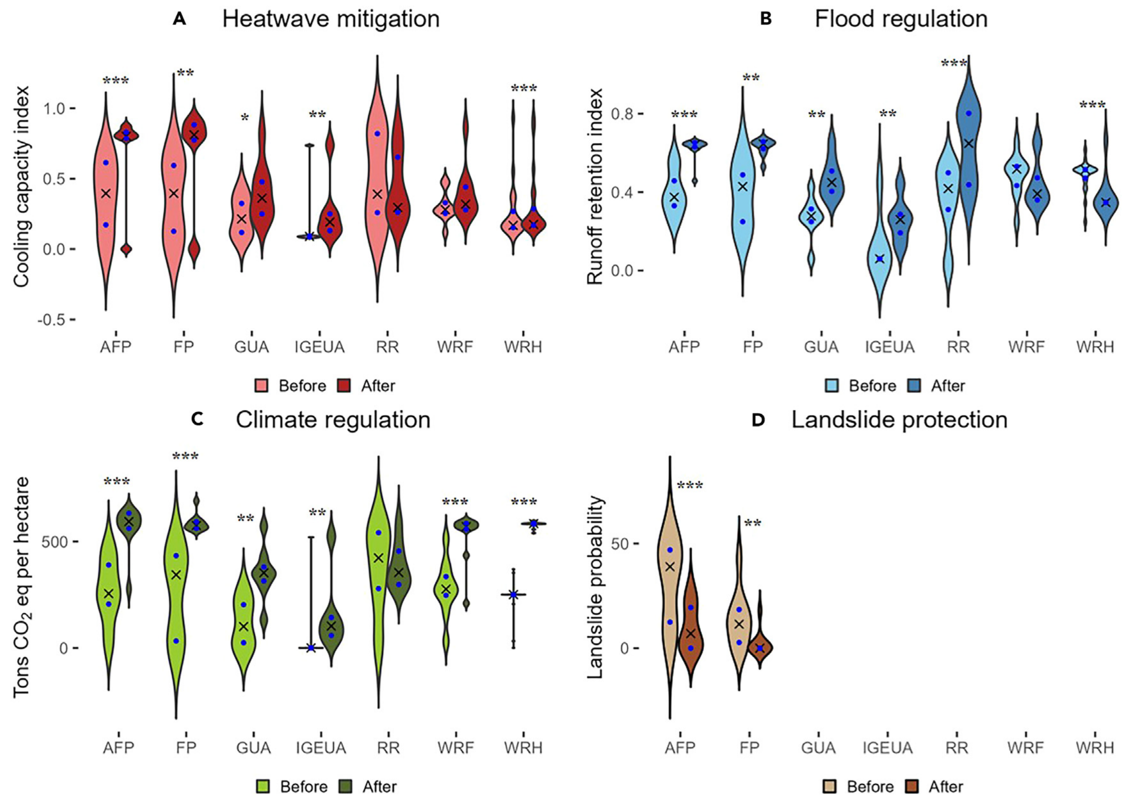

Figure 3. Ecosystem services supply before (light colors) and after (dark colors) the implementation of nature-based solutions projects by typology

(A–D) AFP, active forest plantation/restoration; FP, forest plantation/restoration; GUA, green urban areas; IGEUA, integration of green elements in urban areas; RR, river restoration; WRF, wetland restoration (forested); WRH, wetland restoration (herbaceous). The indicators presented here assess various aspects of nature-based solutions' effectiveness: (A) heatwave mitigation evaluates the cooling capacity, indicating the solutions' ability to reduce temperatures based on model results. (B) Flood regulation measures the runoff retention index, reflecting the potential of nature-based solutions to retain water and prevent runoff based on model variables. (C) Climate regulation quantifies the CO_2 stored per hectare of nature-based solutions, based on the potential stock that would accumulate once the action is stable. (D) Landslide protection assesses landslide probability, considering various vegetation parameters that reduce this risk. Asterisks show the significance of the results of the Wilcox test for paired samples (see supplemental methods Ic and Tables S2, S3, S4, and S5 for details). The "X" inside the plots represents the median value. Blue dots represent Q1 (bottom) and Q3 (top). The value of each indicator within each nature-based solution is the average of all the pixels inside the nature-based solutions before and after nature-based solutions implementation.

EUR). Forested wetland restoration and herbaceous wetland restoration actions show lower GDP with 154,687 EUR and 172,575 EUR, respectively. Nature-based solutions related to forest ecosystems show the lowest GDP, with active forest plantation/restoration actions showing three times less value than forest plantation/restoration actions with 25,453 EUR and 65,974 EUR, respectively. This is consistent with the fact that they are located in areas with fewer beneficiaries.

Monetary value of ecosystem services delivered by nature-based solutions and cost effectiveness

The monetary value of the four assessed ecosystem services per hectare is 402,584 EUR with a total value of 639 million EUR (Table 1). Active forest plantation/restoration actions have the highest median value per hectare (1.06 million EUR/ha), which is almost two times bigger than the integration of green elements in urban areas actions (527,685 EUR/ha). Forest plantation/restoration actions are the third with the highest median value (362,179 EUR/ha), followed by green urban areas (200,059 EUR/ha) and forested wetland restoration actions (115,684 EUR/ha). Herbaceous wetland restoration actions show 16 times less median value than active forest plantation/restoration actions (62,971 EUR/ha). River restoration actions show the lowest median value (7,037 EUR/ha).

Flood regulation constitutes 92% of the total ecosystem services value provided by all nature-based solutions (590 million EUR), followed by heatwave mitigation (2.4%), climate regulation (4.2%), and landslide protection (1%). In terms of value per hectare of individual ecosystem services, the most valuable ecosystem service delivered by nature-based solutions is flood mitigation (371,498 EUR/ha), followed by climate regulation (17,298 EUR/ha), heatwave mitigation (9,861 EUR/ha), and landslide protection (3,928 EUR/ha).

The high standard deviation in monetary value across nature-based solutions is linked to numerous zero values for certain ecosystem services (Figure 6A). For instance, heatwave mitigation is only observed in areas affected by the heat island effect, primarily in urban settings, with rural areas showing no heat

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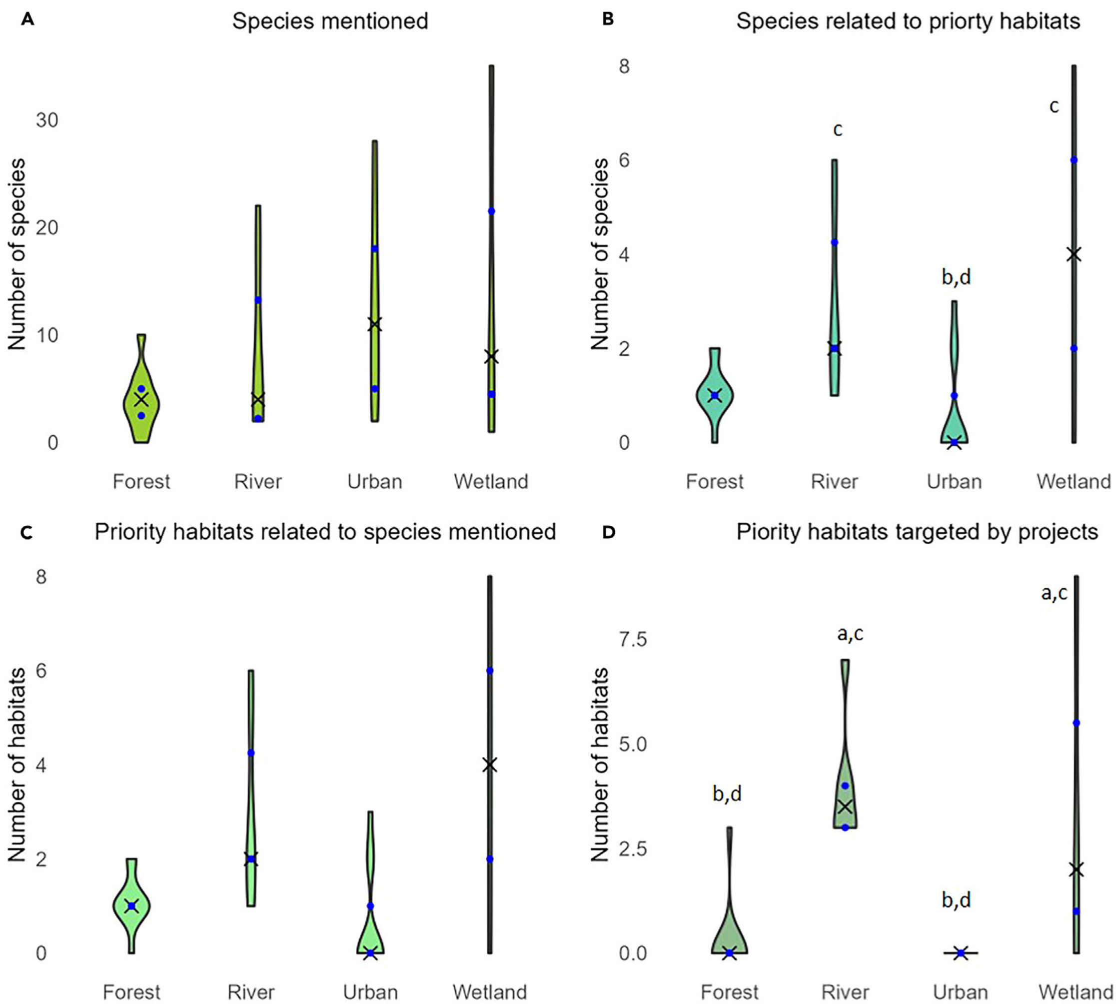

Figure 4. Biodiversity analysis based on information provided by each project

We compiled all mentioned species (see Data S1 to view the species) and assessed their inclusion in the European Habitat Directive[27] and the International Union for Conservation of Nature (IUCN) Red List.[28] Forest projects (n = 12), river projects (n = 6), urban projects (n = 14), and wetland projects (n = 4).

(A) Total number of mentioned species.

(B) Number of these species associated with priority habitats listed in the European Habitat Directive.

(C) Number of priority habitats linked to the mentioned species (note: one species may be associated with multiple priority habitats).

(D) Number of priority habitats indirectly targeted by the project (i.e., alpine rivers are linked to various priority habitats). See supplemental methods Id for list of habitats. In total, there are 36 projects/actions, with six not providing specific data on the species used (2 in forest ecosystems, 3 in urban ecosystems, and 1 in wetland ecosystems). We separated the actions from the same project in cases where the provided information was sufficient. The "X" inside the plots represents the median value. Blue dots represent Q1 (bottom) and Q3 (top).

island effect (66 actions have zero values). Similarly, flood regulation monetary value depends on the presence of infrastructure and the nature-based solutions' ability to retain water, resulting in 38 actions with zero values (see Table S11 in the supplemental methods Ig for details).

The total cost of all actions is 225 million EUR, with a median cost per action of 46,928 EUR (Figure 6B). Active forest plantation/restoration actions show the highest median cost per action (829,200 EUR), followed by river restoration actions (592,839 EUR), which are more than 20 times bigger than the lowest median cost observed (herbaceous wetland restoration actions; 23,998 EUR). On the other hand, the rest of the nature-based solutions show lower median costs, with forested wetland restoration actions at 39,086 EUR, followed by green urban areas (37,353 EUR), forest plantation/restoration actions (35,942 EUR), and integration of green elements in urban areas actions (24,626 EUR). Table S12 in the supplemental methods Ih shows the details of costs by action.

In terms of cost effectiveness, forest plantation/restoration actions show the highest benefits/cost ratio at 9.1 (Figure 6C), followed by integration of green elements in urban areas actions (6), green urban areas (3.2), and river restoration actions (3). In comparison, herbaceous wetland restoration actions (1.7) and forested wetland restoration actions (1.4) were less cost

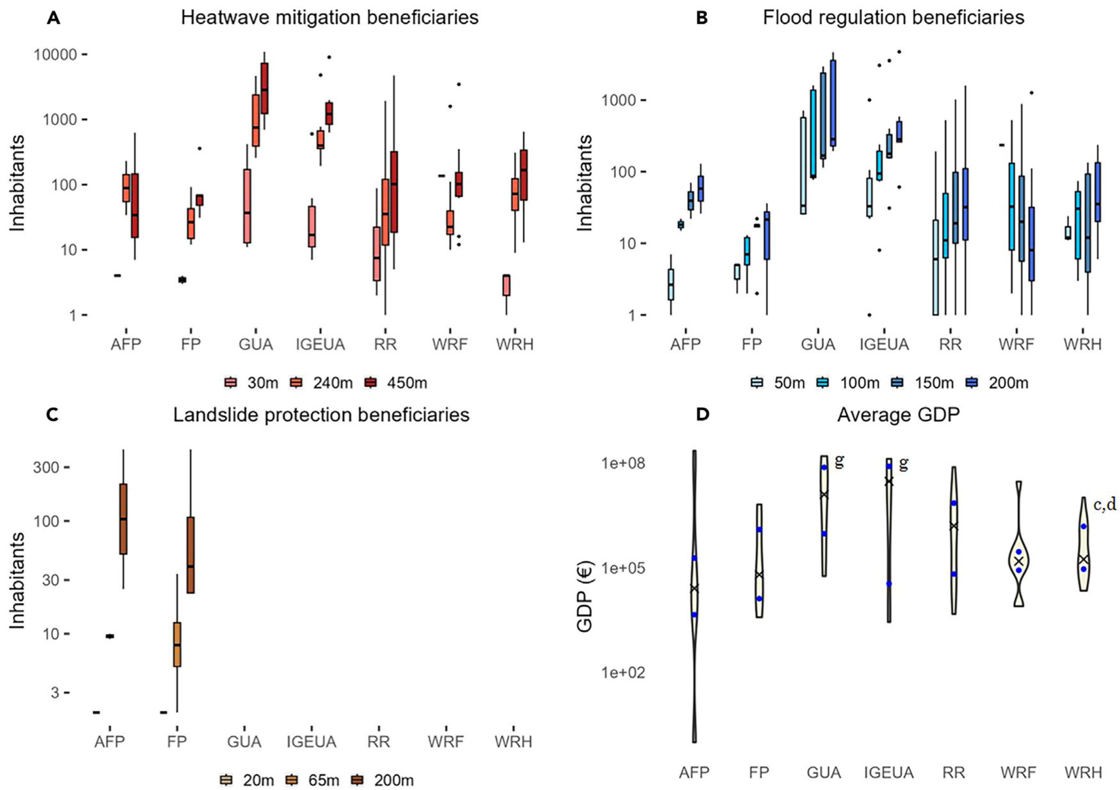

Figure 5. Number of beneficiaries by nature-based solution type

Number of beneficiaries within different distances from the nature-based solutions actions by typology (A–C) and GDP values of the regions benefited (D). Results are presented by type of nature-based solution. AFP, active forest plantation/restoration; FP, forest plantation/restoration; GUA, green urban areas; IGEUA, integration of green elements in urban areas; RR, river restoration; WRF, wetland restoration (forested); WRH, wetland restoration (herbaceous). (A) Inhabitants benefited by heatwave mitigation within three different distances, assuming that the ecosystem service is provided in all directions. (B) Inhabitants benefited by flood regulation within four different distances, assuming that nature-based solutions with less than 5% slope provide ecosystem services in all directions, and nature-based solutions with more than 5% slope only in the direction of flow (gravitational effect). (C) Inhabitants benefited from landslide protection only in the direction of the flow (see supplemental methods Ie for details). (D) Average GDP value per km^2 for the year 2021 obtained from Wang and Sun[27] (see supplemental methods Ie and If and Tables S9 and S10 for details). The "X" inside the plots represents the median value. Graphs are presented on a logarithmic scale; therefore, zero values are not represented. The letters indicate differences between groups, with letters close to the bars representing groups that are different. (g) WRH is different from (c) GUA and (d) IGEUA. Details of the statistical analysis are provided in Table S10 in supplemental methods If.

effective (while maintaining a ratio > 1). Only active forest plantation/restoration actions showed a ratio < 1, which means that the total costs are bigger than the monetary value of the four analyzed ecosystem services.

When considering all types of nature-based solutions, the cumulative value exceeds the total cost by a factor of 2.8:1. The median cost-effectiveness ratio considering all the actions is 3.1. However, cost-effectiveness per action shows considerable variability (Figure 6D) with a median cost effectiveness of 10.1 for integration of green elements in urban areas actions, 7.5 for forest plantation/restoration actions, 6.3 for green urban areas, 3.3 for forested and herbaceous wetland restoration actions, 1.9 for active forest plantation/restoration actions, and 0.008 for RR actions, which show a high standard deviation (an average of 147 ± 607 cost-effectiveness ratio).

Integrated analysis of nature-based solutions

Integrating biodiversity co-benefits, ecosystem services delivery to beneficiaries, and cost effectiveness reveals clear distinctions among nature-based solution types. Green urban areas and integration of green elements in urban areas actions provide high to medium values for heatwave mitigation, climate regulation, and flood regulation in terms of ecosystem services supply (Figure 7A). However, the integration of green elements in urban areas actions show higher cost effectiveness, particularly due to the monetary value of heatwave mitigation (Figure 7B) and the large number of beneficiaries for this ecosystem service (Figure 7C). Nevertheless, both types of nature-based solutions, linked to urban ecosystems, have limited relevance for biodiversity (Figure 4).

River restoration nature-based solutions excel primarily in flood regulation but with comparatively lower values for other ecosystem services (Figure 7A). They have remarkable monetary value, especially for flood regulation, along with high values for heatwave mitigation and climate regulation (Figure 7B). These actions rank second in terms of the number of beneficiaries, largely due to settlements and agriculture near rivers (Figure 7C), and are particularly significant for biodiversity improvement (Figure 4).

Table 1. Monetary value of ecosystem services by nature-based solution type in EUR

Nature-based solution type	Heatwave mitigation monetary value		Flood regulation monetary value		Climate regulation monetary value		Landslide protection* monetary value		Total ecosystem services monetary value	
	Total	Ha	Total	Ha	Total	Ha	Total	Ha	Total	Ha
Active forest plantation/restoration	0	0	0	0	19,064,066	23,662	2,311,718	2,869	21,375,784	26,531
Forest plantation/restoration	2,337,538	2,901	1,079	5	2,868,811	13,549	3,929,022	18,556	9,136,449	43,149
Green urban area	4,928,265	6,117	77,204,124	1,151,613	910,599	13,583	0	0	83,042,988	1,238,708
Integration of green elements in urban areas	6,519,948	8,092	0	0	27,012	8,770	0	0	6,546,960	2,125,636
River restoration	1,883,872	2,338	513,362,402	1,751,373	1,152,433	3,932	0	0	516,398,707	1,761,731
Wetland restoration (forested)	0	0	−112,790	−765	1,689,784	11,455	0	0	1,576,995	10,691
Wetland restoration (herbaceous)	0	0	−152,602	−2,510	1,773,367	29,167	0	0	1,620,766	26,657
Total	15,669,622	9,861	590,302,214	371,498	27,486,072	17,298	6,240,740	3,928	639,698,647	402,584

This table provides insights into the total value (sum of the monetary value of all the actions) and value per hectare (total ecosystem service value divided by the nature-based solutions type's total area). (*) Landslide protection value for the 20 m buffer. The total value for all types is the sum of the total values across ecosystem services. The total value per hectare for all ecosystem services is calculated by dividing the total value of all ecosystem services by the total number of hectares per nature-based solution type.

Active forest plantation/restoration and forest plantation/restoration nature-based solutions demonstrate the highest values for landslide protection and heatwave mitigation (considering the potential cooling capacity, Figure 7A). However, when considering monetary value (Figure 7B), only forest plantation/restoration actions reach high values, as these projects are generally located in areas with more pronounced heat island effects. Consequently, active forest plantation/restoration actions show low cost effectiveness. Regarding biodiversity, both these types of nature-based solutions focus on species of rapid growth or others not related to priority habitats, limiting their relevance for biodiversity improvement (Figure 4).

Wetland nature-based solutions (forested and herbaceous) demonstrate high values for climate regulation (Figure 7A) but low values for landslide protection and flood regulation. However, they are highly relevant for providing biodiversity co-benefits (Figure 4). Their monetary value is largely determined by the value of carbon stored (Figure 4B), as the rest of the ecosystem services have low values despite both being located in areas with medium population densities (Figure 7C). Nevertheless, their low cost results in relatively high cost effectiveness.

DISCUSSION

Cost effectiveness of nature-based solutions to tackle climate change

Here, we present an integrated analysis of the cost effectiveness of nature-based solutions, addressing the knowledge gap in how these solutions tackle the climate-biodiversity-society nexus.[28] Our study shows that the 83 nature-based solutions identified in the Alps (covering 1,588 ha) generate ecosystem services valued at 639 million EUR, with implementation costs of 225 million EUR. These findings align with prior evaluations of nature conservation's economic benefits, such as a 100:1 benefit-to-cost ratio for protected areas in 2005[29] and a 2.7:1 ratio for marine protected areas.[30] While our results appear conservative compared with a recent non-peer-reviewed report using benefit transfer methods (8:1 ratio),[31] they highlight that even conservative estimates demonstrate the potential of nature-based solutions as a key strategy for climate change adaptation and mitigation, particularly when biodiversity co-benefits are prioritized.

Previous peer-reviewed studies have mostly focused on either single ecosystem services or single nature-based solutions. Many have modeled the potential delivery of ecosystem services from future nature-based solution projects rather than evaluating the benefits of implemented ones. For example, studies have explored future scenarios for carbon storage, nitrogen retention, and outdoor recreation.[19] Others have quantified individual services for various urban nature-based solutions, such as the positive impact of land use on flood regulation, including pond creation combined with sustainable urban drainage systems.[32] Some studies have analyzed multiple ecosystem services for a single type of nature-based solution. For instance, bamboo forests have been assessed for flood mitigation, soil conservation, nitrogen retention, and habitat quality in trade-off analyses,[33] while urban forests have been modeled to understand ecosystem service supply and demand dynamics.[34] Qualitative assessments have also been conducted, such as for water purification outcomes.[35] By contrast, our study broadens the scope by examining a diverse range of nature-based solutions and ecosystem services, including biodiversity co-benefits, to provide a comprehensive understanding of these solutions. For instance, quantifying changes before and after implementation revealed a bimodal distribution of benefits, reflecting varying starting conditions. Actions like green roofs target previously

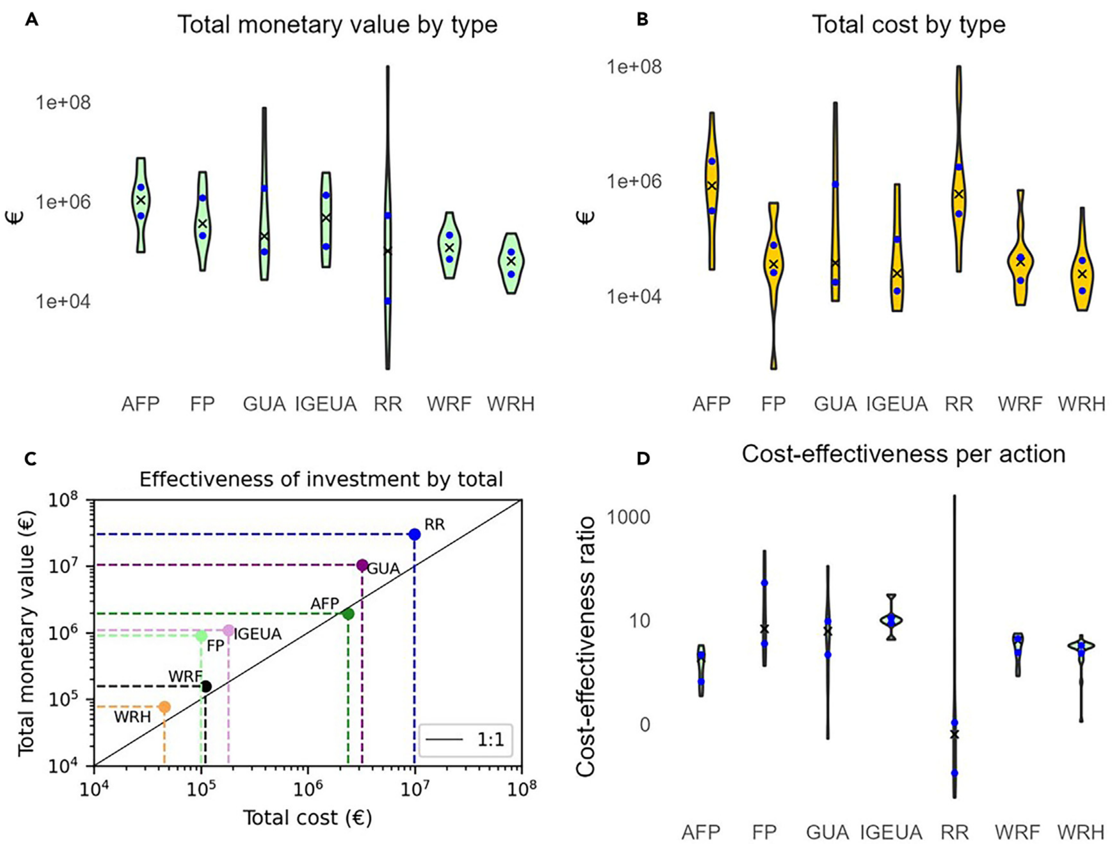

Figure 6. Monetary value and cost effectiveness of the four analyzed ecosystem services by type of nature-based solution

AFP, active forest plantation/restoration; FP, forest plantation/restoration; GUA, green urban areas; IGEUA, integration of green elements in urban areas; RR, river restoration; WRF, wetland restoration (forested); WRH, wetland restoration (herbaceous). (A) Average value per action, representing the sum of all monetary values of the four ecosystem services assessed by nature-based solution type. (B) Average cost per action for each nature-based solution type. (C) Cost-effectiveness analysis, considering the total monetary value and cost per nature-based solution type. (D) Average cost-effectiveness ratio per action (total monetary value in the action in relation to cost). The "X" inside the plots represents the median value. Blue dots represent Q1 (bottom) and Q3 (top).

non-natural areas, while measures such as forest restoration on slopes enhance existing ecosystem services by increasing tree cover.

A report from the European Investment Bank has highlighted the need for economic arguments to support investments in climate adaptation through nature-based solutions, particularly benefit-cost analyses, to engage the private sector.[36] In this context, addressing the funding-implementation gap has called for at least a 3-fold increase in current public funding levels for adaptation worldwide.[37] In 2019, nature-based solutions globally received 113 billion EUR in public-sector financing, of which 27 billion EUR were allocated in the European Union.[38] This is yet insufficient, as by one estimation, to conserve the natural environment, 845 billion dollars are needed on an annual basis worldwide.[39] We hope that our results encourage the development of diverse financial mechanisms for nature-based solutions beyond public funding, including those involving asset managers, banks, insurance companies, and risk capital investments.[36] In light of the forthcoming EU Nature Restoration Law and the proposed allocation of 100 billion EUR for ecological restoration,[40] our results show that investments in nature-based solutions could present an opportunity, if not for direct economic returns, to avoid economic losses linked to climate hazards.

Previous research has assessed the value of ecosystem services across various ecosystem types, showing the high monetary value of certain ecosystems, such as wetlands and coral reefs.[41] They reported an average value for river biomes, for example, at $12,512/ha/year, while urban biomes had a value of $6,661/ha/year globally. The results of our study differ mainly for two reasons: first, we use a single value instead of an annual value, and second, the monetary value is directly linked to the specific context of each nature-based solution, rather than being based on a transfer value. For example, considering the beneficiaries around river nature-based solutions, we obtained a value of 1.76 million EUR per hectare, which, compared with Costanza et al.,[41] would require around 135 years to reach the same value. This difference is mainly because nature-based solutions address specific problems, which results in higher monetary values when related to the infrastructure they protect. In the case of river nature-based solutions, urbanization is often observed near the river margins, justifying the remarkable differences with other studies. Similarly, we obtained a value of 1.2

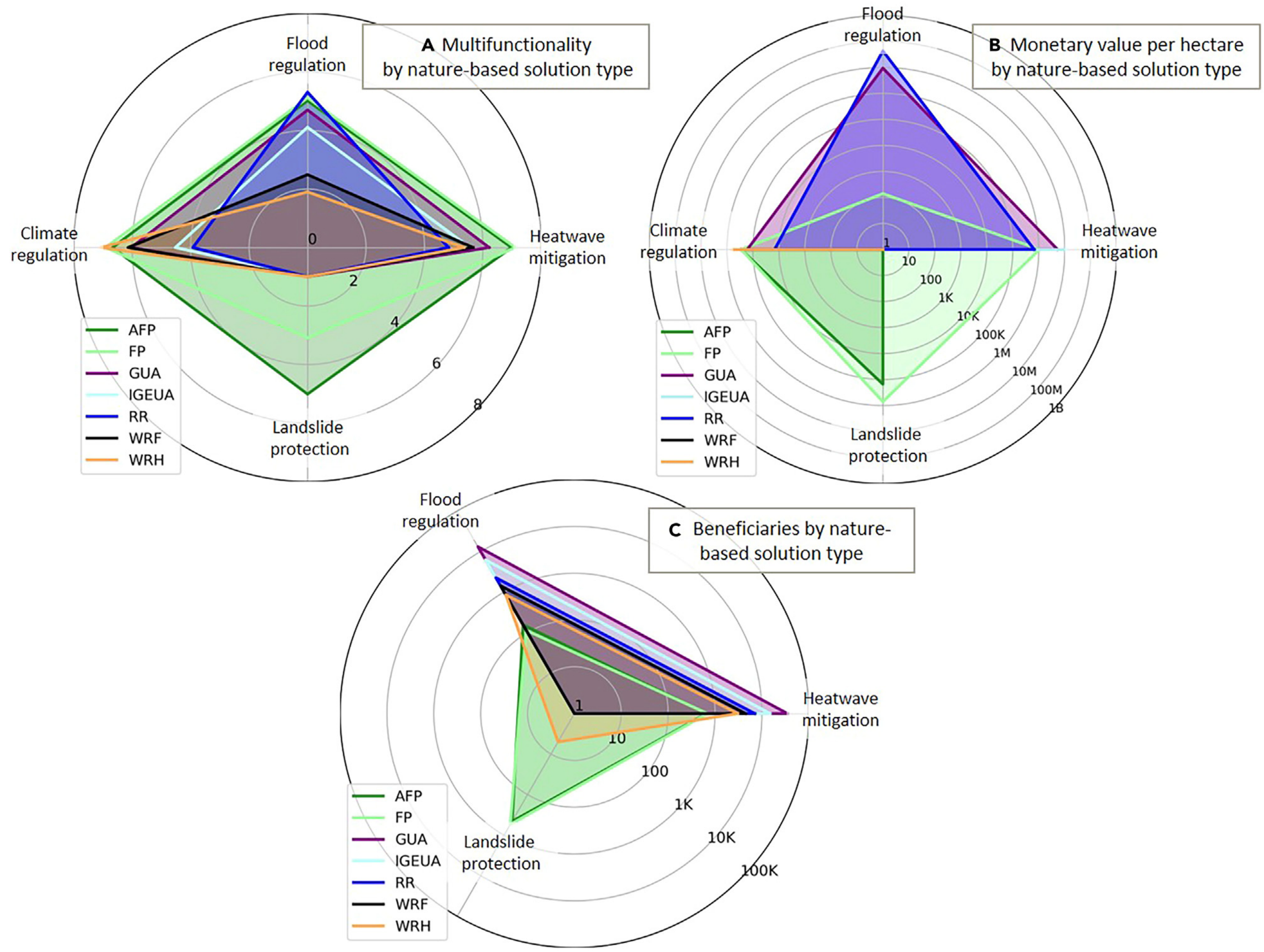

Figure 7. Integrated analysis of nature-based solutions

(A) Ecosystem services (the graph shows the standardized values from 1 to 10 of the four analyzed ecosystem services).

(B) Monetary value.

(C) Beneficiaries.

AFP, active forest plantation/restoration; FP, forest plantation/restoration; GUA, green urban areas; IGEUA, integration of green elements in urban areas; RR, river restoration; WRF, wetland restoration (forested); WRH, wetland restoration (herbaceous).

million EUR per hectare for green urban areas, which, compared with Costanza et al.[41] and their urban biomes value, would need around 180 years to reach the same value. Again, since we based the monetary value on the direct value to the beneficiaries and the specific climatic conditions of each location where nature-based solutions are implemented (e.g., avoided energy costs for residents regarding heatwave mitigation), we better captured the context of each solution. However, this also means that some of the nature-based solutions presented here show no or very low value. This aligns with previous findings showing that the monetary value of ecosystem services depends on the methods used for assessment,[26] as well as the specific context of the ecosystem or nature-based solution. Consequently, our results demonstrate that the monetary value of ecosystem services provided by nature-based solutions is expected to yield significantly higher returns than regular estimates of ecosystem services. Additionally, we selected ecosystem services closely linked to climate change mitigation and adaptation, which may result in different patterns compared with broader-scale valuations.

In our study, integration of green elements in urban areas actions provides the highest monetary value per ha since they benefit a larger number of inhabitants and protect critical infrastructure such as roads and buildings. A concentrated emphasis on urban nature-based solutions may yield a return of 6:1 EUR for the integration of green elements in urban areas actions or 3:1 EUR for green urban areas but might disregard biodiversity objectives due to urban pressures and lower biodiversity co-benefits.[42] Similarly, when examining forest plantation/restoration nature-based solutions exclusively, the return on investment is 9.1 EUR per EUR invested. However, this may underestimate their critical importance for priority habitats for biodiversity and multiple other ecosystem services, including outdoor recreation or timber and fuelwood production where relevant. These results highlight the complementarity of different nature-based solutions and the need to place future nature-based solutions where certain ecosystem services are most needed.[43] For mountain systems such as the Alps, this means considering future climate change impacts on ecosystem services supply and demand and future potential adaptation services.[44,45]

Ecosystem service multifunctionality, biodiversity co-benefits, and scaling

Assessing multiple ecosystem services is crucial to unravel the cost effectiveness of nature-based solutions and their capacity to provide societal benefits, as demonstrated in our study and supported by others.[19,46] We show that focusing solely on one or a few ecosystem services may lead to an undervaluation of nature-based solutions, limiting their amplification and their future integration as a core strategy on the political agenda. Ideally, nature-based solutions implementation costs should not only be covered by a single planning department but also be distributed among different sectors (i.e., conservation, tourism, risk prevention, health, and landscape planning).[47]

Forest nature-based solutions rarely referenced biodiversity-priority habitats, although sometimes referred to species, with ten actions mentioning species associated with priority biodiversity habitats (a median value of 1 species per action). Similarly, urban actions, primarily centered on integration of green elements and urban parks, tend to overlook the restoration of priority habitats and species, even when focusing on urban wetlands or water bodies, where we found just three actions targeting priority biodiversity habitats. Urban nature-based solutions also show limitations in providing a wide range of ecosystem services compared with other ecosystems. By contrast, river nature-based solutions stand out as high-cost-effective options generating biodiversity co-benefits and providing a wide range of ecosystem services. Wetland nature-based solutions, while less cost effective and distant from beneficiaries, frequently target biodiversity-priority habitats. The global outcome of wetland nature-based solutions carries immense importance by enhancing nature-based solutions resilience through biodiversity improvement,[48–50] such as reducing invasive species and enhancing ecological conditions. For example, Meli et al.[49] demonstrated that biodiversity significantly improves following ecological restoration in wetlands, with a corresponding 36% increase in other ecosystem services. Moreover, wetlands are crucial for climate change mitigation, as they store large amounts of carbon in their soils.

Trade-offs within single types of nature-based solutions can be addressed through integrated landscape approaches that combine different types of nature-based solutions for multifunctional outcomes at local and regional scales. However, these approaches must consider the ecological dimension, focusing not only on societal benefits but also on overall biodiversity gains.[51] Balancing ecosystem services and biodiversity objectives is particularly challenging in the context of climate change, especially with urgent adaptation needs such as mitigating heatwaves. For example, heat-related deaths in Europe during 2022 exceeded 60,000.[52] As a result, urban nature-based solutions may sometimes take priority to address pressing issues, even if they provide fewer biodiversity benefits compared with restoring priority habitats or supporting targeted species. Conversely, an overemphasis on urban nature-based solutions risks neglecting broader biodiversity conservation. Therefore, decisions on the allocation of nature-based solutions should involve participatory processes that ensure equitable distribution. Such an approach can deliver economic and social benefits while supporting biodiversity conservation and climate change mitigation goals.[53]

Improving nature-based solutions assessment and monitoring

Interdisciplinary assessments of nature-based solutions face challenges, especially regarding the robustness of data used to model ecosystem services. Our photointerpretation process captures changes before and after implementation but does not account for potential failures or degradation over time. Most restoration projects are monitored for only 1 to 15 years, with few extending beyond 35 years,[54] and uncertainties are further heightened by factors such as extreme weather events and drought. Additionally, limited interviews restricted access to precise location and cost data for some projects, requiring extrapolations from similar initiatives. More sophisticated models could better capture the contributions of complex ecosystems like wetlands. For example, our model shows a median reduction in flood regulation in wetlands, assuming water-saturated conditions limit further water retention. Additional limitations are detailed in supplemental methods IIa.

Despite its limitations, the methodological approach presented here provides valuable support for regional strategies to locate nature-based solutions in the alpine region. It emphasizes not only the specific ecosystem services provided but also how these services are distributed in terms of GDP. Future analyses could enhance decision-making by incorporating specialized models tailored to specific ecosystem types (e.g., wetlands vs. river floods). In a context where landslides and floods are projected to increase,[24,25] our methodological approach and results highlight the need to integrate biodiversity considerations into nature-based solutions planning (i.e., wetlands and rivers show better co-benefits for biodiversity). However, it also underscores the need for better methods to assess biodiversity benefits and values in nature-based solutions projects.

Monetary valuation presented another challenge as it involved combining values associated with single events (such as floods or landslides) with those linked to more frequent occurrences, like heatwaves, predicted from the number of heatwave days per year, or like carbon sequestration occurring between two time periods. Selecting specific time periods to evaluate cost effectiveness will likely be unavoidable. However, certain benefits will be associated with specific events, and calculating an annual value may prove challenging (for example, an ecosystem protecting from floods can mitigate the impact of floods several days per year, but only one of those catastrophic events would result in a very high economic impact). Similarly, an ecosystem safeguarding an agricultural area not only protects the current value of the land but also the potential monetary value of its current production. We acknowledge the need for more studies on which socio-economic groups benefit from the ecosystem services of nature-based solutions. While we used GDP as a proxy in this study, better indicators and approaches are needed, especially to assess how vulnerable groups in cities benefit.[55]

We also did not assess other ecosystem services provided by nature-based solutions, such as cultural ecosystem services. Similarly, we excluded the monetary valuation of biodiversity, which is particularly challenging to quantify,[56] especially given that the method used in this research focuses on existence value (i.e., the intrinsic worth of biodiversity regardless of direct use) rather than instrumental value (i.e., the market value of derived products). Further, our study of 83 nature-based solutions actions reveals that a few actions generate the majority of monetary value. For example, three actions account for 99% of the monetary value of flood reduction, while four actions contribute to 65% of the monetary value of heatwave mitigation. Therefore, understanding the full potential of nature-based solutions requires the incorporation of multiple and diverse nature-based solutions, as certain nature-based solutions may not be cost effective. Addressing these challenges demands improved data availability, transparency, monitoring practices, and scenario modeling to enhance our understanding of nature-based solutions outcomes.

Conclusions

Nature-based solutions offer cost-effective climate change solutions, providing diverse ecosystem services and some biodiversity co-benefits. Nature-based solutions analyzed across the Alps yielded a 2.8 return on initial investment when considering the array of ecosystem services delivered across diverse actions. Our results show that given nature-based solutions diversity, an exclusive focus on a single ecosystem service, a single nature-based solution, or a small set of nature-based solutions may lead to a failure to understand the comprehensive co-benefits inherent to these actions. Different nature-based solution types vary substantially in both the monetary value of ecosystem services and implementation costs. Biodiversity outcomes differ significantly, with river and wetland nature-based solutions providing more co-benefits. Nature-based solutions in urban ecosystems, such as green urban areas and integration of green elements in urban areas, while delivering ecosystem services with high monetary value and benefiting a large number of people, provided fewer biodiversity co-benefits. Effective nature-based solutions strategies require a nuanced consideration of beneficiaries and biodiversity co-benefits at landscape scale. Our findings emphasize the need for integrated planning and accounting for landscape-scale effects to ensure the comprehensive inclusion of diverse ecosystem services and biodiversity. Interdisciplinary analyses, coupled with assessments of monetary value of ecosystem services and biodiversity co-benefits, provide essential insights into nature-based solutions potential.

METHODS

Nature-based solutions database and photointerpretation

We developed a database of nature-based solutions focused on climate adaptation in the Alps. Our inclusion criteria targeted projects addressing climate change impacts or those exacerbated by climate change, with a focus on biodiversity utilization. From this, we identified 28 projects leading to land use/land cover changes, comprising 83 nature-based solutions actions. Each action represented an area of land use change. We focused on projects with land use changes or those providing detailed information on soil quality alterations, such as wetland or river restoration. Actions were categorized into four ecosystem types (forest, river, urban, and wetland) and seven solution types based on ecosystem intervention interactions. The seven types identified were (1) active forest plantation/restoration ($n = 11$), (2) forest plantation/restoration ($n = 10$), (3) green urban areas ($n = 8$), (4) integration of green elements in urban areas ($n = 6$), (5) RR ($n = 17$), (6) herbaceous wetland restoration ($n = 21$), and (7) forested wetland restoration ($n = 10$). These encompassed 22 different interventions, such as creating corridors, improving water infiltration, and increasing tree cover (see supplemental methods Ia). We adopted this approach based on existing typologies for nature-based solutions,[57,58] which commonly incorporate attributes such as measures, techniques, ecosystem functions (e.g., type of hazard addressed), and ecosystem type.

To assess the location and extent of these projects and their land use/land cover changes, we used aerial imagery from 2003 to 2020 and additional project data (supplemental methods IIb; Figures S3–S5). The database provided qualitative insights to interpret visible changes, which were classified as completed (e.g., forest restoration in early stages was considered as a forest). We then visually estimated current forest cover for each polygon, updating tree cover in the "after" layer based on project data and changes observed in the imagery. For other variables needed to run the models, we used available geographic databases and literature. References are detailed in the next section and supplemental methods II.

Ecosystem services modeling

We used InVEST software to model heatwave mitigation, flood regulation, and climate regulation.[59] InVEST was chosen for two main reasons: its wide usage and validation within the scientific community and its economic valuation approaches suitable for cost-effectiveness analysis. We applied two specific models designed for urban areas across all nature-based solutions to ensure comparability between results and because the identified model limitations for other ecosystems were acceptable for this research's objective of providing a broad overview of the benefits of various nature-based solutions. For heatwave mitigation, we used the cooling capacity index, based on evapotranspiration coefficients and albedo, which are relevant to all ecosystem types. Similarly, the flood mitigation model used the runoff retention index, reflecting the soil and ecosystem's water retention capacity (Table 2). For flood risk mitigation, we provided specific limitations and how we addressed them in the study's design (see supplemental methods IIa). Additionally, we employed the Slideforнet model developed by the International Association for Natural Hazard Risk Management.[60]

The urban cooling model quantified the cooling capacity index of ecosystems, considering factors such as tree cover (shadow effect), evapotranspiration, and albedo specific to each land use/land cover type.[61] Tree cover values were obtained during the photointerpretation process, while evapotranspiration

Table 2. Ecosystem services models, supply, beneficiaries, and value metrics used in the study

Model name (ecosystem service)	Supply metric (indicator)	Beneficiaries metric	Value metric
Urban cooling (heatwave mitigation)	air temperature reduction (cooling capacity index)	population living in 30, 240, and 450 m buffer ranges	value of Kwh reduced per °C
Urban flood risk mitigation (flood regulation)	extreme weather runoff volume retained (runoff retention index)	population living in 50, 100, 150, and 200 m buffer ranges	avoided cost of stormwater retention
Carbon storage and sequestration (climate regulation)	carbon stored and sequested in Mg CO_2 equiv (Mg CO_2 eq./ha)	global (not measured in this study)	monetary value of carbon sequestered
Slidefornet (landslide protection)	probability of shallow landslide (probability)	population living in 20, 65, and 200 m buffer ranges	monetary value of roads, agriculture, and urban areas in the buffer ranges

coefficients and albedo data were sourced from the literature (refer to Tables S13and S14 in supplemental methods IIc). Climatic variables were acquired from Chelsa,[62] which provides raster layers for different years. Detailed explanations of how we utilized these layers are available in supplemental methods IIc. The model also incorporated variables such as maximum cooling distance and air blending distance, set to 450 and 500 m, respectively, in accordance with the InVEST user guide recommendations. We ran the models using land use/land cover maps from before and after nature-based solutions implementation, processing each model separately based on its specific data requirements. For instance, the heat island effect variable, indicating the difference between urban and rural temperatures, was calculated individually for each action.

The urban flood risk mitigation model evaluated runoff retention using soil properties, curve numbers, and soil hydrologic group[63] for a specific rain event. We applied a reference value of 100 mm precipitation for all the nature-based solutions.[64] The curve number predicts direct runoff or infiltration from rainfall excess, and it is linked to each land use/land cover type. The assumptions and references for obtaining these numbers are detailed in Table S15 in the supplemental methods IId. The soil hydrologic group is obtained from a raster layer that remains constant across all the models. InVEST overlays the location of the nature-based solution action with the corresponding pixel in the raster layer. We used land use/land cover before and after to capture the effect of nature-based solutions actions. For changes related to alterations in soil hydrologic conditions due to nature-based solution interventions, we adjusted the values of those pixels to represent more optimal soil hydrological conditions. For example, river interventions involving the restoration of gravel systems changed the value from 3 (indicating good hydrological condition) to 4 (indicating excellent hydrological condition), demonstrating an improvement in water retention. Further details of the model assumptions are provided in supplemental methods IId.

The carbon storage and sequestration model calculated the total carbon content across the four primary ecosystem pools, comprising above- and below-ground biomass, soil, and dead organic matter.[65] We sourced the values from the literature, including specific data from the Alps and other available references. To incorporate the effect of tree cover, we assumed the values from the literature for tree land use/land cover as 100%, and then we proportionally decreased the above, below, and litter pools based on a linear calculation from the 100% reference value. Details regarding the values of each carbon pool and assumptions for the model are provided in Table S17 in the supplemental Information IIe.

The Slidefornet model integrated slope, soil depth, soil cohesion, stand density, and other forest parameters to estimate landslide probability.[66] Following preliminary analysis, we identified that there were no significant changes in the model results in areas with less than 15% slope. Consequently, we ran the model for only 20 nature-based solutions actions present in the database coincident with forest ecosystems. One of the variables in the model includes specific details on the species that affect slope stability. In this research, we only used the percentage of coniferous species and the percentage of broadleaved species, as we lacked data on the percentage of each specific species in the projects. Details on the assumptions, sources, and data are provided in Table S18 in the supplemental methods IIf.

We provide a detailed analysis of the existing sensitivity analysis and validations for the urban cooling and urban flood mitigation models, along with a sensitivity analysis conducted for the landslide protection model in supplemental methods IIg.

Biodiversity assessment

Nature-based solutions' biodiversity co-benefits often lack standardization, complicating assessments. While studies indicate that most nature-based solution projects mention biodiversity co-benefits, these references are often vague, with few focusing on specific species or habitats.[67] In our study, we sought to analyze specific contributions to biodiversity rather than relying on generalized. Our methodology does not directly measure biodiversity changes following the implementation of nature-based solutions. Instead, it considers specific mentions in the projects, such as habitat restoration or the integration of species directly linked to the interventions. Data collection primarily focused on the project level due to difficulties in differentiating species contributions at the action level. However, action-level data were incorporated when available. The data collection process followed four steps:

(1) We gathered all references to plants, animals, or other living organisms mentioned in the project documentation. Out of all projects reviewed, only six did not provide

specific information. Additionally, two of these projects offered vague statements regarding biodiversity enhancement, such as "enhancing fish and avifauna" or "providing microhabitats for species," without specifying particular species or biodiversity strategies.

(2) Review of species associated with priority habitats or special conservation areas in Europe: We examined references to species listed in the European Habitat Directive.[68] This directive covers habitats linked to one or more species (i.e., *Quercus ilex* and *Quercus rotundifolia* forests), as well as species of community interest regardless of habitat. We documented mentions of both species types. However, species related to habitats in different geographical areas were excluded. For instance, some forest actions mentioned *Picea abies*, which is associated with fennoscandian herb-rich forest habitats in the European Habitat Directive but is not mentioned as relevant in habitats in the Alps, where our research is focused.

(3) Targeted priority habitats based on an ecosystem approach: Recognizing that focusing solely on species linked to priority habitats might oversimplify how nature-based solutions target crucial habitats for biodiversity, we also evaluated the potential habitat associated with the ecosystem targeted by each project. For instance, while a project may mention species relevant to river ecosystems, these species might not be the primary ones defining the priority habitat. In such cases, we identified habitats related to the initiatives, such as alpine rivers, which are associated with at least three different priority habitats. This approach ensures that we acknowledge the potential value of initiatives targeting relevant habitats even if they do not provide specific species information.

(4) Review of species on the International Union for Conservation of Nature Red List[69]: We assessed whether the species mentioned in the projects were listed on the International Union for Conservation of Nature Red List, which categorizes species based on their vulnerability, ranging from least concern to extinct. We focused on species categorized as at least near threatened to gauge the project's potential impact on biodiversity loss. Six projects referenced species falling into these categories. Additionally, four actions mentioned *Ginkgo biloba*, which is not included in the analysis since it is commonly associated with urban gardens in Europe. Similarly, *Cedrus atlantica* was mentioned in five projects but was not included in the analysis due to its status as an exotic species unrelated to alpine ecosystems but rather associated with reforestation projects.

The biodiversity analysis, involving 36 cases, was conducted at the ecosystem level. This approach aligns with the idea that biodiversity is more closely linked to ecosystems than specific nature-based solution types, allowing for a broader understanding of how typology relates to biodiversity. For example, both urban parks and integration of green elements in urban areas actions are associated with urban ecosystems. We include details of the species mentioned in the projects and all the scores for the aforementioned variables in Data S1 and further justification of the approach followed in supplemental methods IIh.

Benefits and beneficiaries

We determined the number of ecosystem service beneficiaries by creating buffers around the boundaries of the nature-based solutions in ArcGIS 10.7, using the flow potential area as a reference.[70] We considered only direct beneficiaries, following approaches used in studies of ecosystem service flows from protected areas.[71] The buffer size and direction were determined based on the flow dynamics of ecosystem services and relevant literature (see Figure S6 and supplemental methods IIi). For heatwave mitigation, we utilized the maximum cooling distance of 450 m from the InVEST model,[72,73] as well as two additional buffers of 30 and 240 m.[74] We chose these two additional buffer distances to encompass a broad range of distances from 0 to 450 m. The study referenced analyzed the cooling effect within buffers ranging from 5 to 240 m, including various intervals (5, 10, 15, 30, 60, 120, 150, 200, and 240 m) for areas with and without trees. Therefore, we selected these specific values based on the findings regarding the cooling effect. For flood regulation, we used buffers of 50, 100, 150, and 200 m, following previous studies that analyzed the economic impact of natural disasters such as floods in urban areas.[75] However, because the direction of the flood can vary due to slope orientation, for flood regulation and landslide protection, we only considered beneficiaries in areas where the direction of the flow was conducive. For actions taking place in flat areas (<5% slope), we assumed that the flow of the ecosystem service could occur in all directions. However, for actions occurring in areas with a slope greater than 5%, we considered beneficiaries to be areas and people located in the direction of the flow. For landslide protection, we used buffers of 20, 65, and 200 m.[76] We chose these buffers to encompass a broad range of potential landslide effects, even though the model used focuses on shallow landslides. However, for the monetary valuation, we only selected the first buffer, corresponding to 20 m. Similar to flood mitigation, we considered only areas in the flow direction for this ecosystem service, limiting it to nature-based solutions with slopes of 15% or more since the model results were significant above this threshold.

Regarding the analysis of GDP, we examined the distribution of the 83 actions based on GDP to identify the types of beneficiaries for each nature-based solution. We calculated the average GDP per km^2 for the year 2021 using data from Wang and Sun.[27] The purpose of introducing this indicator was to explore whether certain types of nature-based solutions tend to benefit specific socio-economic groups, especially given the need to introduce more holistic frameworks to analyze nature-based solutions.[77] For example, in urban areas, the implementation of green spaces often benefits people with higher socio-economic status.[55] However, our method does not capture variability at the city level. Despite this limitation, it allows us to identify potential typologies that could be planned to benefit more vulnerable populations.

Monetary valuation of ecosystem services

The analysis of ecosystem service benefits focused on the monetary value associated with each service provided by the nature-based solutions. Final monetary values were calculated by subtracting the value before from the value after implementation. We chose a direct monetary value approach over benefit transfer, as the latter has limitations,[78,79] particularly for localized effects like those of nature-based solutions. To estimate direct values, we used the InVEST monetary valuation module for heatwave mitigation and flood regulation, a market value approach for carbon, and infrastructure-based values for landslides. Previous studies have assessed the monetary value of heatwave mitigation using indicators such as labor capacity, differentiating between outdoor and indoor work.[80] For flood and landslide mitigation, the avoided damage and compensation payment schemes are commonly used in the literature.[81,82] Carbon storage and sequestration are often valued from a market perspective,[83] though social value can also be considered.[84] We applied these different approaches based on the available data and methods for each ecosystem service.

To assess the monetary value of heatwave mitigation, we used the energy savings valuation method, which estimates cooling requirements in the absence of nature-based solutions. This method, integrated into the InVEST model, requires data on urban coverage, energy consumption per degree Celsius of cooling, and kWh costs.[85] Instead of distinguishing between different building consumption patterns, we used the average cooling demand for residential and service areas. The model calculates the monetary value per day for a reference heatwave, so we multiplied this by the number of heatwave days in the studied area over the past two decades. Details on kWh savings, assumptions, heatwave day calculation, and kWh reference values are provided in supplemental methods IIj (Tables S20 and S21).

Flood regulation value was obtained from the InVEST model, which quantified the value based on damage reduction due to ecosystem presence. The monetary value for urban, agricultural, and road sectors was derived from Huizinga et al.[86] (see supplemental methods IId and Table S16). This value is correlated with water retention, so nature-based solutions that retain water from precipitation events have higher monetary value, while those with small areas and low infiltration capacities are less effective. The climate regulation value was estimated by multiplying the increase in carbon stored by 88 EUR per ton, based on European market averages in the first half of 2023.[87] The value of landslide protection was calculated by intersecting buffers with urban, agricultural, and road areas, multiplying by values from Huizinga et al.,[86] considering only areas with conducive slopes, as in the beneficiaries' analysis.

Cost and cost-effectiveness analysis

We collected the costs of each project based on the provided information, contacting project managers and public authorities, reviewing available online information, and consulting other references for projects lacking information (i.e., press release). For actions implemented many years ago, as in the case of one urban park created in 2007, project engineers were contacted directly to obtain the exact costs. The cost data for most of the projects primarily pertains to projects rather than individual actions. Therefore, we calculated the cost per hectare based on general cost information and used this value to multiply by the area of each action.

Of all the projects, 18 provided information on the general cost of the project either within the provided information or through contact with project managers. However, 11 projects related to forest plantation for carbon offsetting by private companies did not provide detailed cost information for the actions. For these projects, although they state that the cost per planted tree is approximately 1 EUR, we opted to consider the average cost of forest planting as provided by the EU, based on a review of current literature on the actual costs of such endeavors.[88] This average cost, derived from various public restoration projects conducted in Europe until 2015, amounts to 4,857 EUR/ha.[89] For nine projects related to forest plantations under national authorities, which included specific actions related to slope preparation, we utilized information from two reports on average cost per hectare from existing projects in the Alps, aimed at increasing slope stability through forest use. Both projects presented an average cost of 15,000 EUR/ha. Details regarding the sources of information for economic costs and general data are provided in Data S1.

We conducted the cost-effectiveness analysis in two different ways. First, we used the total value of all the nature-based solutions and divided the value between the total cost to identify the general cost-effectiveness of all the nature-based solutions used. Further, we repeated this analysis per type of nature-based solution to identify cost effectiveness for each typology. Second, we conducted the analysis of the cost effectiveness per action by calculating the cost effectiveness per action and analyzing median and average values per typology.

Our cost-effectiveness approach is based on identifying direct beneficiaries[90]—individuals whose welfare is improved by particular ecosystem services. However, we acknowledge specific limitations regarding this issue in the supplemental methods IIa. For instance, the flow direction approach used to calculate the beneficiaries for landslides can depend on landscape processes, such as a barrier of rocks and trees in the direction of the landslide. Similarly, we did not account for the potential mobility of beneficiaries when assessing the potential benefits of nature-based solutions. Finally, in the case of landslide protection, we considered the infrastructure within the first 20 m buffer. However, expanding the consideration to a 200 m buffer may result in greater monetary value and more beneficiaries.

Statistical analysis

The statistical analysis conducted to analyze the differences between before and after nature-based solutions implementation involved testing the normality of the distribution using the Shapiro test for all ecosystem services before and after the implementation of nature-based solutions (Figure 3). The results indicated a lack of normality, necessitating the use of non-parametric tests. We employed the Wilcoxon test for paired samples using RStudio (function R package coin), and the results were consistent with the adjusted p value.

For biodiversity analysis, we utilized ANOVA with Tukey's test for pairwise comparisons across the four analyses. We did not observe significant differences for the number of species (Figure 4A, p value = 1.1059) or priority habitats related to individual species (Figure 4C, p value = 0.1472). However, we did identify significant differences in the number of species related to priority habitats (Figure 4B, p value = 0.0052) and priority habitats targeted by the projects (Figure 4D, p value = 8.458e−07).

Regarding the analysis of differences in GDP (Figure 5D), we performed ANOVA with Tukey's test for pairwise differences, revealing significant variation between nature-based solution types (p value = 0.00791).

We applied ANOVA tests to assess differences in total monetary value per nature-based solution type, yielding non-significant results. Similarly, we analyzed differences in the costs of actions using ANOVA, with comparable outcomes.

RESOURCE AVAILABILITY

Lead contact

Requests for further information and resources should be directed to and will be fulfilled by the lead contact, Alberto González-García (alberto.gonzalez-garcia@univ-grenoble-alpes.fr).

Materials availability

This study did not generate new, unique reagents.

Data and code availability

- All original code has been deposited at Zenodo at https://doi.org/10.5281/zenodo.14584948 and is publicly available as of the date of publication.
- Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

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AUTHOR CONTRIBUTIONS

A.G.-G.: conceptualization, methodology, validation, formal analysis, investigation, data curation, writing – original draft, and writing – review & editing; I.P.: conceptualization, validation, writing – original draft, writing – review & editing, supervision, project administration, and funding acquisition; A.C.: investigation, data curation, and writing – original draft; M.R.: investigation, data curation, and writing – original draft; T.D.: formal analysis and writing – original draft; A.V.: conceptualization and writing – original draft; S.L.: conceptualization, validation, writing – original draft, writing – review & editing, supervision, and funding acquisition.

DECLARATION OF INTERESTS

The authors declare no competing interests.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work, the author(s) used ChatGPT to improve English and readability. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

SUPPLEMENTAL INFORMATION

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