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

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# Abstract

Nature-based Solutions' (NbS) potential for multiple benefits across ecosystems and societies justify their uptake in policy and implementation. This study contributes to closing the gap in quantifying the multiple outcomes of NbS by evaluating the multifunctionality of 85 NbS actions in the Alps. We assessed biodiversity co-benefits, the economic value of four Ecosystem Services (ES) provided by these NbS, and their respective beneficiaries: heatwave mitigation, flood regulation, climate regulation, and landslide protection. Our results show the diversity of NbS, with forest NbS having high values for all ES, river and wetland NbS showing high values for biodiversity, and urban NbS, presenting lower biodiversity value but being highly cost-effective and benefiting a larger population. We estimated an average ES economic value per hectare of NbS of 424,662 Euros, with a three to one return on investment. We discuss the need for integrating biodiversity and multiple ES for future NbS funding and implementation together with their role to mitigate and adapt to climate change.

# 1. Introduction

Nature-based Solutions (NbS) are a promising strategy for mitigating and adapting to climate change, offering multiple benefits to society[1]. NbS 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[2,3,4]. For instance, the restoration of degraded riparian forests not only enhances biodiversity but also provides a wide array of Ecosystem Services (ES) to society, including climate regulation, flood regulation, landslides protection, water retention, and heatwave mitigation[5]. Additionally, when properly co-designed and implemented, NbS can deliver transformative change towards sustainability[6].

Research on the effectiveness of NbS in climate change adaptation is critical for implementation worldwide[7]. Indeed, ES benefits are multiple: forest restoration often lead to an improvement in hydrological services by enhancing water infiltration rate[8]; and agroforestry, permaculture or organic farming are crucial to safeguard and rebuild soil carbon stocks[9]. Additionally, NbS in river ecosystems can improve resilience to flooding, control the transport of substance through natural filtering and enhance the ecological status[10]. Some qualitative case reviews have also highlighted NbS' effects on enhancing various ES, showing the potential of NbS as a cost-effective solution for hydrological risk reduction and land degradation[5]. A growing body of literature delves into how urban NbS can tackle specific urban challenges, such as hydrometeorological hazards[11] or impacting positively on 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 ES resulting from NbS-related Land Use/Land Cover (LULC) changes, despite their substantial influence on biodiversity and ES[15,16].

Cost-effectiveness analyses, considering the economic cost of implementation of NbS and their benefits, are crucial for assessing how useful NbS will be for climate change adaptation[17]. Such analyses are rare because they require an interdisciplinary perspective, large datasets and complex quantification[1,4]. ES modelling 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 ES provided by one or a few NbS case studies[19], and syntheses have summarised their results across multiple benefits[7,20], no direct analysis to date has simultaneously quantified the benefits and beneficiaries of multiple ES, along with biodiversity co-benefits through empirical analysis of a large dataset of NbS. Addressing this knowledge gap is needed for placing NbS at the core of a strategy to jointly tackle biodiversity loss and climate change.

Here, we provide a comprehensive analysis of how 85 NbS actions in the Alps enhance ES, target priority habitats for biodiversity, benefit people, and assess cost-effectiveness based on the economic value of their ES and the cost of the actions. The study is based on the photointerpretation of LULC changes before and after NbS implementation in forest, river, urban, and wetland ecosystems using aerial imagery (Supplementary information I). Four ES were modelled, using InVEST[21] (heatwave mitigation, flood regulation, climate regulation) and Slidefornet (landslide protection). Their economic value was quantified based on the value of temperature reduction, the value of infrastructure protected, and the market price of carbon. Biodiversity was analysed by identifying mentions to priority habitats for conservation in NbS actions. To determine the beneficiaries of these ES, we analysed the number of inhabitants within different distance buffers surrounding the actions, drawing from available literature and the nature of each ES. Additionally, we estimated the differences in GDP for the regions benefited by NbS. Through a comprehensive evaluation of ES beneficiaries, economic value, costs and the multifunctionality in terms of ES of NbS, we hope to provide valuable insights and evidence for jointly addressing biodiversity loss and climate change through NbS implementation.

# 2. Results

### a. Ecosystem services and biodiversity before and after NbS implementation

The overall supply of ES increases after the implementation of NbS (refer to Supplementary Information II for details of the LULC changes analysis and detailed results). For heatwave mitigation (Fig. 1A), urban NbS show the highest median increase (53%), followed by forest (39%), wetland (9%), and river (-2%). In terms of flood regulation (Fig. 1B), urban NbS again show the highest median increase (89%), followed by forest (68%), river (52%), and wetland (-32%). Similarly, for climate regulation (Fig. 1C), urban NbS demonstrate the highest median increase (1,658%), followed by wetland (132%), forest (105%), and river (10%). Landslide protection (Fig. 1D) is exclusively provided by forest ecosystems with slopes exceeding 15%, resulting in a substantial median decrease in landslide probability (-52%). Regarding biodiversity (Supplementary Information II-g), wetland NbS target the restoration of an average of 7.3 ± 2.6 priority habitats according to the EU Habitats Directive per project, followed by river (5.5 ± 2 habitats), forest (1.3 ± 2.9 habitats), and urban (0.2 ± 1 habitats).

### b. Beneficiaries of NbS outcomes

Different types of NbS have varying impacts on the number of beneficiaries, with urban NbS benefiting considerably more people than river, forest or wetland NbS (Fig. 2; Supplementary information III Tables S2-S4 for details). For the mitigation of heatwaves, urban NbS demonstrate the highest benefits (Fig. 2A), benefitting 1,492 ± 1,605 to 3,567 ± 3,479 inhabitants within 240 to 450 meters on average per NbS (21,436 to 53,510 inhabitants in total). For flood regulation (Fig. 2B), urban NbS demonstrate the highest benefits, with 598 ± 1,239 to 1,370 ± 1,782 inhabitants within 100 to 200 meters (13,954 to 20,553 inhabitants in total). Regarding forest landslide protection, an average of 39 ± 117 inhabitants benefit within 200 meters (1,010 inhabitants in total). This indicates that forest NbS are often located far from potential beneficiaries. In terms of GDP per km$^2$ (Fig. 2D), urban NbS are situated in areas with the highest median GDP per km$^2$ (20 million Eur), followed by river (1.5 million Eur), wetland (172,575 Eur) and forest (53,970 Eur).

### c. Economic value of ecosystem services delivered by NbS and cost-effectiveness

The economic value of the the four assessed ES per hectare is 424,662 Eur with a total value of 676 million Eur (Table 1). Urban NbS have the highest median value per hectare (2.5 million Eur/ha), followed by forest (34,413 Eur/ha), wetland (29,213 Eur/ha) and river (4,638 Eur/ha). The flood regulation ES constitute 87% of the total ES value provided by all NbS (590 million Eur), followed by heatwave mitigation (8%), climate regulation (4%) and landslide protection (1%). In terms of value per hectare of individual ES, the most valuable ES delivered by NbS are flood mitigation (370,318 Eur/ha), followed by heatwave mitigation (33,143 Eur/ha), climate regulation (17,286 Eur/ha) and landslide protection (12,296 Eur/ha). The high standard deviation in economic value across NbS is linked to numerous zero values for certain ES (Fig. 3A-D). For instance, heatwave mitigation is only observed in areas affected by the heat island effect, primarily in urban settings, with rural areas showing no impact (64 NbS present zero values). Similarly, flood regulation economic value depends on the presence of infrastructure and the NbS's ability to retain water, resulting in 38 instances with zero values (see Supplementary Information IV Table S6 for details).

The total cost of all actions is 217 million Eur, with a median cost of 20,094 Eur/ha. River NbS show the highest median costs (265,847 Eur/ha), followed by urban (89,752 Eur/ha), wetland (20,094 Eur/ha) and forest (3,232 Eur/ha). Regarding the median cost of the individual actions (Fig. 3E), the highest values are for river NbS (592,839 Eur), followed by wetland (40,188 Eur), urban (21,000 Eur) and forest (19,348 Eur).

Considering the economic value of ES and the costs per ecosystem, the cost-effectiveness ratio is notably higher for urban, at 4.2 times, river at 3.1 times, forest at 1.6 times and wetland NbS at 0.6 times (excluding biodiversity considerations) (Fig. 3F). Considering all ecosystem types, the cumulative value of NbS surpasses the total cost by a factor of 3 to 1. For additional details on the economic assessment and cost-effectiveness, refer to Supplementary Information IV.

Table 1

Results of economic value of Ecosystem Services (ES) by Nature-based Solution (NbS) type in Eur. This table provides insights into the total value, value per per hectare (total ES value divided by the NbS type's total area). (*) Landslide protection value corresponds to the 20 m buffer. The total value for all ecosyste total value per hectare for all ES is calculated by dividing the total value of all ES by the total number of hectares per ecosystem type. The average value per h ES per NbS, dividing by each NbS's area, and calculating the average of these values (± Standard Deviation).

| | **Heatwave mitigation** | | | **Flood regulation** | | | **Climate regulation** | | | **Landslide protection*** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Total ES value | Avg. ES value per action | ES value per ha | Total ES value | ES value per action | ES value per ha | Total value | ES value per action | ES value per ha | Total ES value | ES value per action | ES va pe |
| **FOR** | 2,095,345 | 682 ± 2,887 | 2,030 | 1,078 | 41 ± 166 | 1 | 22,398,683 | 861,488 ± 1,727,840 | 21,696 | 6,240,739 | 520,062 ± 1,057,604 | 12 |
| **RIV** | 23,747,246 | 11,833 ± 33,300 | 81,015 | 513,362,401 | 30,197,788 ± 124,517,788 | 1,751,373 | 1,152,433 | 67,790 ± 213,819 | 3,932 | 0 | 0 | 0 |
| **URB** | 26,988,046 | 15,241 ± 21,342 | 370,511 | 77,204,124 | 5,146,942 ± 19,375,248 | 1,059,914 | 1,006,560 | 67,104 ± 138,561 | 13,819 | 0 | 0 | 0 |
| **WET** | 0 | 0 | 0 | -265,391 | -9,829 ± 43,712 | -1,356 | 2,996,630 | 110,986 ± 126,407 | 15,315 | 0 | 0 | 0 |
| **Total** | 52,830,637 | | 33,143 | 590,302,213 | | 370,318 | 27,554,308 | | 17,286 | 6,240,739 | | 12 |

### d. Integrated analysis of NbS

A comparative assessment of NbS per ecosystem type considering their benefits, beneficiaries and costs-effectiveness shows clear differences among them. Concerning ES supply and biodiversity (Fig. 4A), urban NbS supply substantial flood regulation and heatwave mitigation. However, their weakness lies in their limited biodiversity co-benefits. Despite this, urban actions have the highest cost-effectiveness (Fig. 4B) reflecting their placement in valuable infrastructure areas. For the same reason, these projects benefit a larger number of beneficiaries in flood regulation and heatwave mitigation than wetlands (Fig. 4C).

River NbS excel in their primary purpose of flood regulation, while their location on flat terrain explains low effectiveness in landslide protection. Importantly, they play a significant role in enhancing priority habitats for biodiversity (Fig. 4A). Their economic value is remarkable, with the highest value for flood regulation, and high values for heatwave mitigation and climate regulation (Fig. 4B). River NbS actions score second in terms of number of beneficiaries due to the presence of settlements close to rivers (Fig. 4C).

Forest NbS demonstrate the highest values for landslide protection and heatwave mitigation. However, as they primarily consist of native species plantations their biodiversity co-benefits are limited. Remarkably, among 26 forest actions, only seven incorporate species linked with priority habitats outlined in the EU Habitats Directive. The cost-effectiveness reflects a moderated economic value for climate regulation and landslide protection (Fig. 4B). However, forest NbS actions are usually located far from beneficiaries (Fig. 4C).

Wetland NbS demonstrate high values for various ES (Fig. 4A), except for landslide protection, due to their location in low-slope areas and flood regulation. However, they are the most relevant in providing biodiversity co-benefits. In spite of their good performance for carbon sequestration (Fig. 4B), wetlands achieve a lesser economic value due to their lesser value for other ES given their location away from densely populated areas (Fig. 4C), and even though they impact more people than forest NbS for flood regulation and heatwave mitigation.

## 3. Discussion

### a. Cost-effectiveness of NbS to tackle climate change

Here, we present a comprehensive and interdisciplinary analysis of the cost-effectiveness of NbS which contributes to reduce the knowledge gap in how NbS currently address the climate-biodiversity-society nexus[23]. Our study reveals that the 85 NbS identified in the Alps (covering 1,594 ha), generate an economic value of ES of 676 million Eur and had implementation costs amounting to 217 million Eur. This results in an average return on investment of 3 to 1 Eur. This result is consistent with previous evaluations of the economic benefits of conserving nature, as for example regarding the benefits and costs of protected areas[24,25].

Previous studies have predominantly taken disciplinary approaches when investigating NbS outcomes, focused on single ES or single NbS, or have modelled potential ES delivery of future NbS projects instead of benefits of already implemented NbS. Such studies include the potential for ES like carbon storage, nitrogen retention, and outdoor recreation in future scenarios of NbS implementation[19]. Other studies have quantified single ES for a range of urban NbS, like flood regulation[26], while others have examined multiple ES for a single forest NbS[27] or a single urban NbS[28]. Others have presented qualitative assessments of outcomes for specific ES, such as water purification[29]. In contrast, our study expands its scope beyond well-researched urban NbS and embraces a diverse array of NbS types and ES, providing a more comprehensive understanding of NbS benefits. Our results show a bimodal distribution primarily because certain NbS initiatives focus on previously non-natural areas, such as the implementation of green roofs. In contrast, others start from ecosystems that already provide some ES, for example, a forest on a slope that has increased tree cover through restoration.

Previous studies have underscored the need for economic arguments to favour investments in climate adaptation[30]. In the context of NbS, addressing the funding-implementation gap has called for at least a threefold increase in current public funding levels for adaptation worldwide[31]. In 2019, NbS globally received 113 billion Euros in public-sector financing, of which 27 billion Euros were allocated in the European Union[32]. This is yet insufficient as by one estimation, in order to conserve the natural environment, 845 billion dollars are needed on an annual basis worldwide[33]. We hope that our results encourage the development of diverse financial mechanisms for NbS beyond public funding, including those involving asset managers, banks, insurance companies, and risk capital investments[30]. In light of the forthcoming EU Nature Restoration Law and the proposed allocation of 100 billion euros for ecological restoration[34], our results show that investments in NbS 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 ES across various ecosystem types, showing the high economic value of certain ecosystems such as wetlands and coral reefs[35]. In our study, urban NbS amount for the highest economic value per ha since they benefit a larger number of inhabitants and protect critical infrastructure such as roads and buildings (see Supplementary Information V for additional discussion on ES economic valuation). A concentrated emphasis on urban NbS may yield a return of 4.2 Euros per euro invested but might disregard biodiversity concerns due to urban pressures and diminished biodiversity co-benefits[36]. Similarly, when examining NbS in forests exclusively, the return on investment is 1.6 Euros per euro invested. However, this may underestimate their critical importance for priority habitats for biodiversity. These results highlight the complementarity of different NbS and the need to place future NbS where certain ES are most needed[37]. For mountain systems as the Alps, this means considering future climate change impacts on ES supply and demand and future potential adaptation services[38,39].

### b. Ecosystem services multifunctionality, biodiversity co-benefits and scaling

Assessing multiple ES is crucial to unravel the cost-effectiveness of NbS and their capacity to provide societal benefits, as demonstrated in our study and supported by others[40]. We show that focusing solely on one or a few ES may lead to an under-valuation of NbS, limiting their amplification and their future integration as a core strategy on the political agenda. Ideally, NbS implementation costs should not only be held by a single planning department, but be distributed among different sectors (i.e. conservation, tourism, risk prevention and health)[37,41].

Our interdisciplinary approach exposes important trade-offs in NbS implementation. We find that urban NbS are highly cost-effective since they are often situated in areas with high infrastructure value and beneficiary density. Forest NbS are also cost-effective given their low average cost per hectare. However, both forest and urban NbS fall short in biodiversity conservation, lacking priority biodiversity habitat restoration[42]. Forest NbS rarely reference biodiversity priority habitats although sometimes referring to species, with seven actions mentioning species associated with priority biodiversity habitats. Similarly, urban actions, primarily centred on green roofs and urban parks, tend to overlook priority habitats and species, even when focusing on urban wetlands or water bodies, where we found just one action targeting priority biodiversity habitats. Urban NbS also show limitations in providing a wide range of ES compared to other ecosystems. In contrast, river NbS stand out as high cost-effective options generating biodiversity co-benefits and providing a wide range of ES. Wetland NbS, while less cost-effective and distant from beneficiaries, frequently target biodiversity priority habitats and are located in areas with lower GDP. The global outcome of wetland NbS carries immense importance by enhancing NbS resilience through biodiversity improvement[43,44,45], such as reducing invasive species and enhancing ecological conditions. Additionally, wetlands play a crucial role in climate change mitigation as they store the highest amounts of carbon in soil.

A balanced approach considering the strengths and weaknesses of each ecosystem type is crucial. We suggest these trade-offs within single types of NbS can be overcome through integrated landscape approaches that combine NbS for multifunctional outcomes at landscape to regional scale[46]. However, it is important to acknowledge the challenges with balancing ES and biodiversity objectives in the context of climate change, particularly regarding heatwaves increase[47]. For example, addressing heatwave mitigation through NbS in urban areas sometimes could prioritise improving the ES rather than biodiversity. Additionally, overemphasizing urban NbS risks neglecting biodiversity conservation. Deciding the future allocation of NbS considering these outcomes has to be accompanied by a participative process ensuring distributional equity considerations. This approach ensures economic and social benefits while contributing to biodiversity conservation and climate change mitigation goals[48].

### c. Improving NbS assessment and monitoring

Interdisciplinary assessments of NbS outcomes pose significant challenges. Among the main limitations is the robustness of the NbS data used to model ES. Our extensive photointerpretation process to capture changes before and after NbS implementation assists in addressing this issue, but we could not account for the possibility that implemented NbS and restoration projects might fail in the near future[49], for instance, due to extreme weather events or drought. Additionally, our inability to conduct interviews for all NbS restricted our access to location data for some NbS (i.e., specific sites where trees are planted) and cost data (i.e., private projects that we extrapolated from similar cost initiatives). Further discussion on the limitations is provided in Supplementary Information VI.

Economic valuation posed another challenge as it involved mixing values related to single events (e.g., floods or landslides) with those tied to more frequent occurrences, like heatwaves, predicted from the number of heatwave days per year. We also did not include all provided ES, like some cultural ES, nor did we incorporate the economic value of biodiversity, which is particularly challenging to assess[50]. Therefore, we believe this study underestimates the economic value of NbS. Finally, our study of 85 NbS actions reveals that a few initiatives generate the majority of economic value. Therefore, understanding the full potential of NbS requires the incorporation of multiple and diverse NbS, as certain NbS may not be cost-effective. Addressing these challenges demands improved data availability, transparency, monitoring practices and scenario modelling to enhance our understanding of NbS outcomes.

## 4. Conclusion

NbS offer cost-effective climate change solutions, providing diverse ES. NbS analysed across the Alps yielded a threefold return on initial investment when considering the array of ES delivered across diverse actions. Our results show that given NbS diversity, exclusive focus on a single ES may lead to a failure to recognize the comprehensive co-benefits inherent to these actions. Different NbS types vary substantially in both economic value of ES and implementation costs. Biodiversity outcomes differ significantly, with river and wetland NbS providing more co-benefits. Urban NbS, while impactful in terms of economic value of the ES they provide and benefitting people, provided fewer biodiversity co-benefits. Effective NbS 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 ES and biodiversity. Interdisciplinary analyses, coupled with assessments of economic value of ES and biodiversity co-benefits, provide essential insights into NbS potential.

## 5. Methods

### a. NbS database and photointerpretation

We developed a database encompassing NbS projects focused on climate adaptation in the Alps. From this database, we identified 29 projects leading to LULC changes, comprising a total of 85 NbS actions. Each action represented an area where LULC changes occurred. These actions were further categorized into four groups corresponding to the targeted ecosystem type: forest, river, urban, and wetland. To assess the location and spatial extent of these projects and their resulting LULC changes, we utilized aerial imagery covering the period from 2003 to 2020 (Supplementary information I). The database provided valuable qualitative information that help to interpret the changes visible in the images. These changes were considering as happened (for example when a forest restoration was in early growing stages, it was considered as a forest). Subsequently, we included information such as tree cover and soil hydrological conditions before and after the project implementation.

### b. Ecosystem services modelling and biodiversity

The InVEST software was used to model urban cooling, urban flood risk mitigation, and carbon storage and sequestration[51]. Additionally, we utilized the Slidefornet model developed by the International Association for Natural Hazard Risk Management[52].

The urban cooling model quantified the cooling capacity index of ecosystems, considering factors such as shadow effect, evapotranspiration, and albedo specific to each LULC type[53]. Climatic variables were obtained from Chelsa[54]. The urban flood risk mitigation model assessed runoff retention based on soil properties and curve numbers associated with each LULC type and soil hydrologic group[55]. The carbon storage and sequestration model calculated the total carbon content across the four primary ecosystem pools, including above and below-ground biomass, soil, and dead organic matter[56]. The Slidefornet model integrated slope, soil depth, soil cohesion, stand density, and other forest parameters to estimate landslide probability[57]. Finally, biodiversity was quantified by analysing the mentions to priority habitats for biodiversity included in the EU habitats directive. For detailed information on the models, including their specific assumptions and details, refer to the Supplementary information VII. The models were applied using the two LULC maps available for each NbS of the database: before and after its implementation (Table 2).

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 (Heatwaves mitigation) | Air temperature reduction (Cooling capacity index) | Population living in 30m, 240m and 450m buffer ranges | Value of each ºC reduced |
| Urban flood risk mitigation (Floods regulation) | Extreme weather runoff volume retained (Runoff retention index) | Population living in 50m, 100m, 150m and 200m buffer ranges | Avoided cost of storm water retention |
| Carbon storage and sequestration (Climate regulation) | Carbon stored and sequestered in Mg $CO_2$ eq. (Mg $CO_2$ eq./ha) | Global (not measured in this study) | Economic value of carbon sequestered |
| Slidefornet (Landslide protection) | Probability of shallow landslide (Probability) | Population living in 20m, 65m and 200m buffer ranges | Economic value of roads, agriculture and urban areas in the buffer ranges |

### c. Benefits and beneficiaries

We determined the number of each ES beneficiaries by creating buffers around the NbS boundaries using ArcGIS 10.7. The buffer size and direction were determined based on the nature of the ES and relevant literature (see Supplementary information VII). For heatwave mitigation, we utilized the maximum cooling distance of 450 meters from the InVEST model[58,59], as well as two additional buffers of 30m and 240m[60]. For flood mitigation, we used buffers of 50, 100, 150, and 200 meters, following previous studies[61]. In actions which happens on flat areas (< 5%) we considered that the flow of the ES could happen in all directions. However, for actions occurring on areas with a slope greater than 5%, we considered as beneficiaries areas and people located in the same direction. For landslide protection, we used buffers of 20, 65, and 200 meters[62]. Similar to flood mitigation, we considered only areas in the flow direction for this ES, limiting it to NbS with slopes of 15% or more since the model results were significant above this threshold.

The analysis of ES benefits relied on the economic value associated with each ES provided by the NbS. For heatwave mitigation, benefits were calculated by estimating the value of each degree Celsius reduced, based on the InVEST model results and values provided in previous studies that used this model[18]. Flood regulation value was obtained directly from the InVEST model results, which quantified the value based on the damage reduction resulting from the presence of ecosystems. The economic values for urban, agricultural, and road sectors were derived from Huizinga et al. (2017)[63]. The value of climate regulation ES was estimated by multiplying the increase in carbon stored by 88€ per ton, based on the average value of the European markets in the first six months of 2023[64]. The value of landslide protection was determined by intersecting the defined buffers with urban, agricultural, and road areas and multiplying by the values provided in Huizinga et al. (2017)[63]. For landslide protection, only the portion of the buffers in which the slope was conducive was considered. Cost-effectiveness analysis for all the NbS was calculated by dividing the total value of all NbS by the total cost of all NbS. Cost-effectiveness for each type of ecosystem was calculated by dividing the total value of NbS in each ecosystem type by the total cost of those actions.

## Declarations

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## Figures

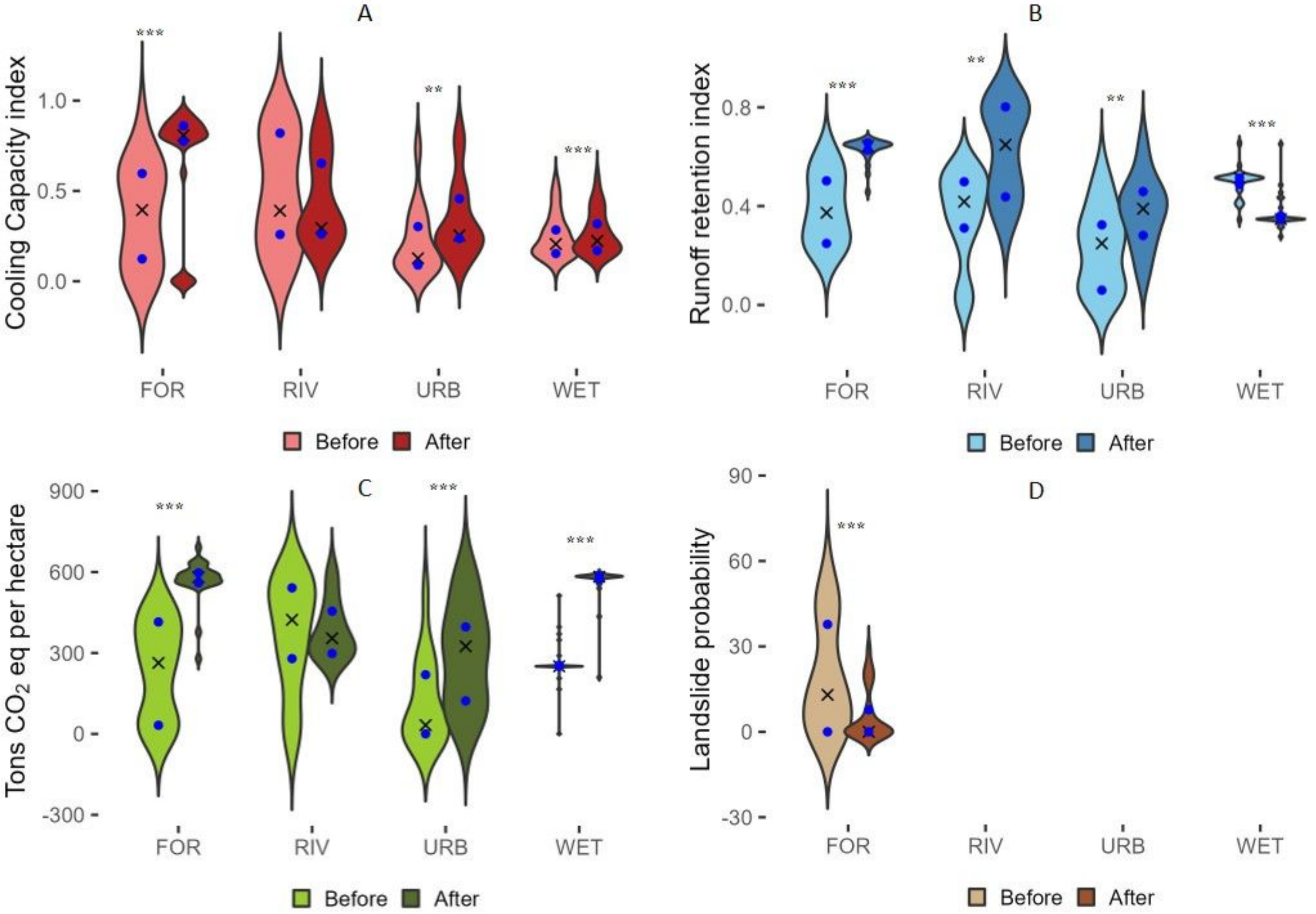

**Figure 1**

*Ecosystem services supply before (light colours) and after (dark colours) the implementation of Nature-based Solutions (NbS) projects by ecosystem type (FOR: Forest; RIV: River, URB: Urban, WET: Wetland). (A) Heatwave mitigation. (B) Flood regulation. (C) Climate regulation. (D) Landslide protection. Asterisks show the significance of the results of the Wilcox test for paired samples (See supplementary information II for details). The 'X' inside the plots represents the median value, which is calculated across all the NbS in each category of ecosystem. Blue dots represent Q1 (bottom) and Q3 (top). The value of each indicator within each NbS is the average of all the pixels inside the NbS before and after NbS implementation.*

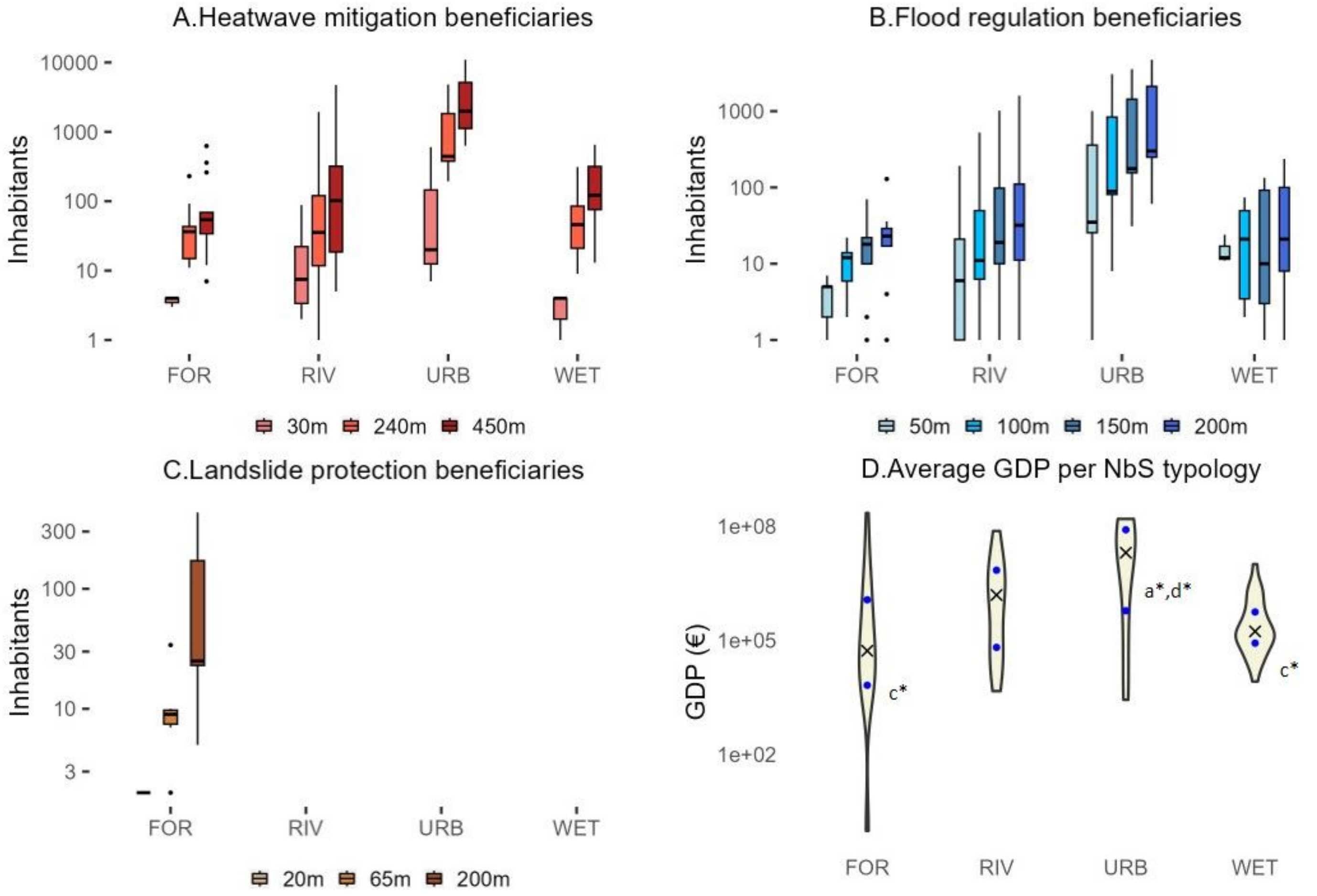

Figure 2

*Number of beneficiaries within different distances from the Nature-based Solutions (NbS) actions based on the type of ecosystem services (A-B-C); and GDP values of the regions benefited (D). Results are presented by ecosystem type (FOR: Forest; RIV: River, URB: Urban, WET: Wetland). (A) Inhabitants benefited by heatwaves mitigation within three different distances assuming that the ES is provided in all directions. (B) Inhabitants benefited by floods regulation within four different distances assuming that NbS with less than 5% slope provide ecosystem services in all directions and NbS with more than 5% slope only in the direction of flow (gravitational effect). (C) Inhabitants benefited by landslide protection only in the direction of the flow (see Supplementary information III for details). (D) Average GDP value per km*$^2$ *for the year 2021 obtained from Wang & Sun, (2022)*[22]*. The 'X' inside the plots represents the median value. Graphs are presented on a logarithmic scale; therefore, zero values are not included in the representation.*

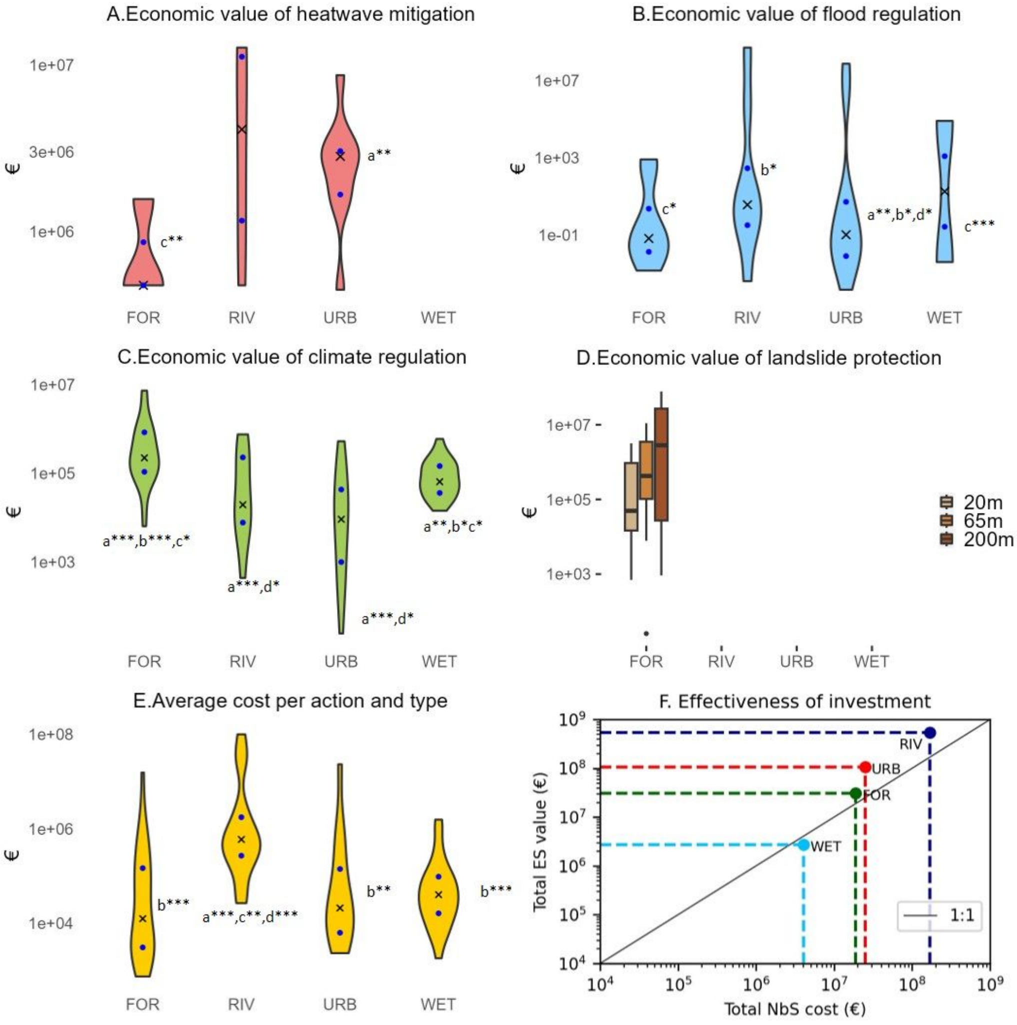

**Figure 3**

*Economic value of the four analysed Ecosystem Services (ES) per type of ecosystem (FOR: Forest; RIV: River, URB: Urban, WET: Wetland) (A-D); Average cost per action (E) and cost-effectiveness of NbS (F). Asterisks show the significance of the results of the Wilcox test for paired samples. Letters show the difference between groups. (A) Heatwave mitigation. (B) Flood regulation. (C) Climate regulation. (D) Landslide protection in the three buffers of distance to the NbS. (E) Shows the average cost per action and type of NbS. (F) Shows the effectiveness of the investment considering the total cost per type of ecosystem and the total value per type of ecosystem. The 'X' inside the plots represents the median value, which is calculated across all the NbS in each category of ecosystem. Blue dots represent Q1 (bottom) and Q3 (top). Graphs are presented on a logarithmic scale; therefore, zero values are not included in the representation, refer to Supplementary Information IV for detailed results on each NbS economic value.*

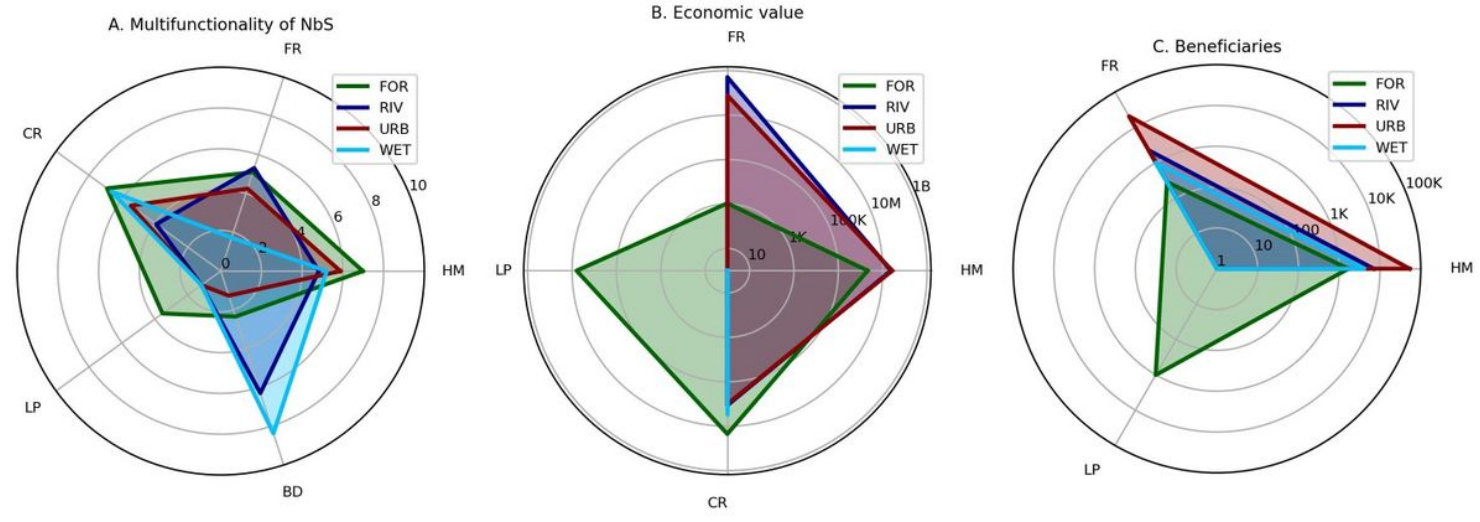

**Figure 4**

*Integrated analysis of Nature-based Solutions (NbS). (A) Ecosystem service and biodiversity (the graph shows the standardised values from 1 to 10 of the four analysed ecosystem services and biodiversity). (B) Economic value. (C) Beneficiaries. FR: Floods regulation; HM: Heatwave mitigation; BD: Biodiversity; CR: Climate regulation; LP: Landslide protection. FOR: Forest; RIV: River, URB: Urban, WET: Wetland.*

## Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- AppendixNS24112023Final.docx