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Cost-benefit and equity analysis of nature-based solutions in Haiti, India, Indonesia and Uganda

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ABSTRACT

This study performs an economic efficiency and equity analysis of four recent Ecosystem-based Disaster Risk Reduction (Eco-DRR) interventions in Haiti, India, Indonesia, and Uganda. Our analysis aims at contributing to the development of methodological best practices for assessing both the economic-effectiveness and the distributional impacts of nature-based solutions, with a particular focus on marginalized or underserved communities. Nature-based solutions (NbS) are emerging as possible strategies to mitigate disaster risk while providing additional benefits to biodiversity and sustainable economic growth. However, there is limited scientific evidence about the cost-effectiveness and equity outcomes of NbS. For each ecosystem-based intervention examined we performed an economic efficiency assessment through a quantitative cost-benefit analysis (CBA). Our estimates show that at the 5th year since the project implementation, the interventions in Haiti and India generated positive net benefits, assuming hazard-related yearly losses in properties and GDP per capita in the project areas as low as 0.5 %. We observe the same outcomes in Indonesia and Uganda at the 10th year since the project implementation, assuming yearly losses equivalent to 1 % or higher and adopting a 3 % discount rate. When we include additional benefits from carbon capture and sequestration and pollution reduction the CBA net benefits estimates are positive at the 10th year mark for every discount rate adopted. Extensive qualitative interviews of local stakeholders corroborate the CBA results and provide insights on the numerous additional benefits experienced, which in the future could be measured and monetized if monitored over time. A qualitative analysis of the distributional effects of the interventions was performed to complement the economic efficiency assessment. This equity analysis indicates an enhancement in inclusivity, economic equality, participation, and capacity building among local stakeholders. In particular, the Eco-DRR interventions implemented resulted in significant education, health, safety and economic improvements for women, children, and economically vulnerable members of the local communities.

1. Introduction

Disasters resulting from natural hazards pose an increasing threat to human health and safety, livelihoods, and economies. The consequences of disasters are expected to rise, as the impacts of climate change worsen [1]. Ecosystem-based Disaster Risk Reduction (Eco-DRR) strategies have emerged as "*the sustainable management, conservation and restoration of ecosystems to reduce disaster risk, with the aim to achieve sustainable and resilient development*" [2]. Eco-DRR strategies are one type of Nature-based Solution (NbS), an umbrella concept which also includes Ecosystem-based Adaptation (EbA) and Ecosystem-based Mitigation strategies. This study performs an economic efficiency and equity analysis of four recent Eco-DRR interventions in Haiti, India, Indonesia, and Uganda. Our analysis aims at contributing to the development of methodological best practices for assessing both the economic-effectiveness and the distributional impacts of nature-based solutions, with a particular focus on marginalized or underserved communities.

NbS can provide many socio-economic and environmental benefits. There is growing global scientific evidence that ecosystems conservation and restoration contribute to mitigate hazards through ecosystem protective services [3]. There is also evidence that NbS generate positive

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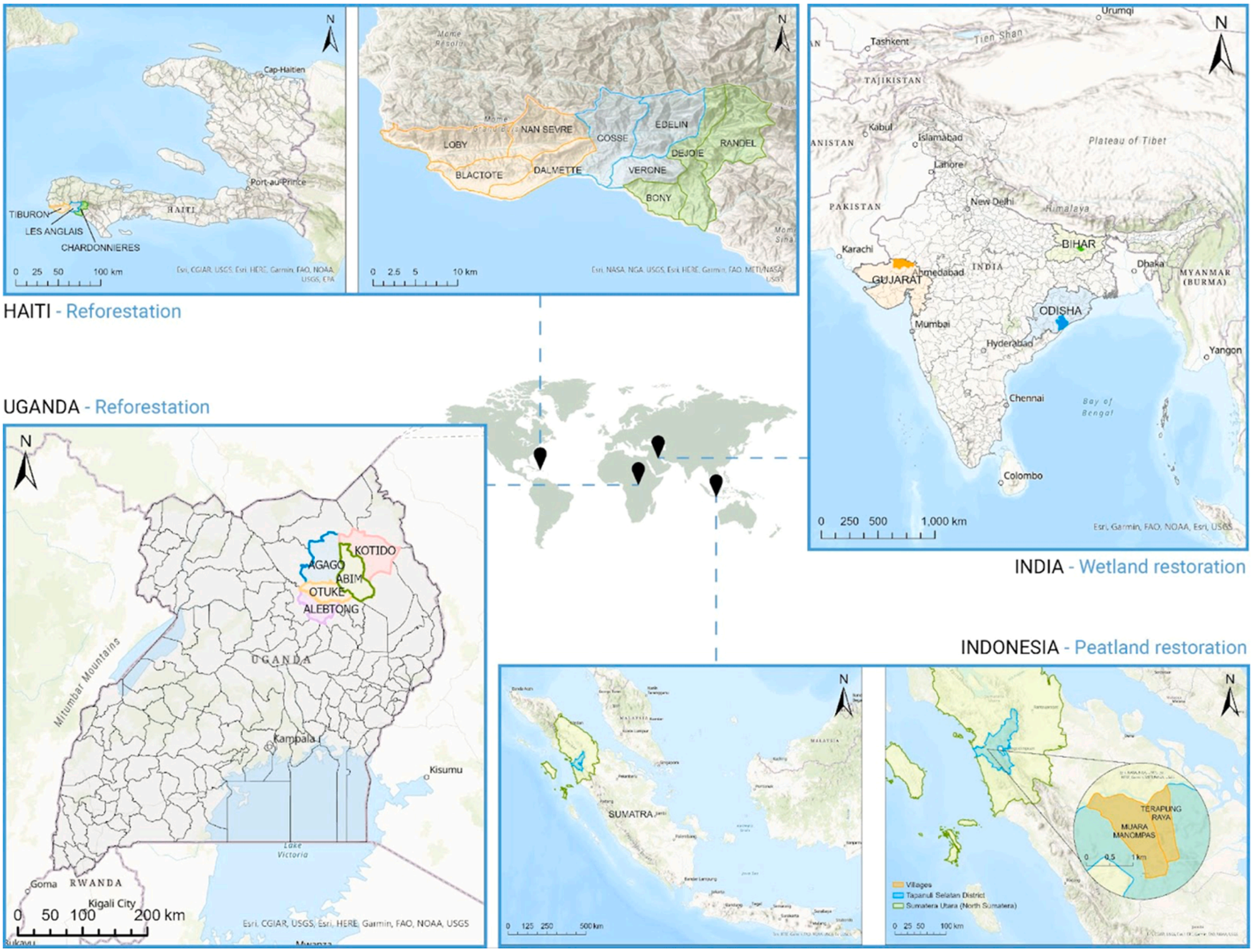

Fig. 1. Location of the project areas in the South District of Haiti, the Indian states of Odisha and Bihar, north-eastern Uganda, and the Island of Sumatra in Indonesia.

synergies between reduced disaster risk, reduced climate impacts and broader ecological, social, and climate change mitigation outcomes [4]. For instance, when they are grounded in sound biodiversity science, NbS can simultaneously enhance biodiversity and contribute to climate adaptation and mitigation [5,6]. Indeed, the biodiversity and climate crisis are strongly interconnected [7] and biodiversity loss reduces global terrestrial carbon storage [8]. Supported by the expanding scientific evidence about the benefits of NbS, a growing number of international policy frameworks and agreements recognizes the potential of NbS for disaster risk reduction, biodiversity enhancement, climate change adaptation, and climate change mitigation (e.g., Sharm el-Sheikh Implementation Plan [9–11]; Sendai Framework for Disaster Risk Reduction (SFDRR) 2015–2030 [12]).

Nature-based solutions have also the potential to transform society and provide benefits to underserved and marginalized communities. The Fifth Session of the United Nations Environment Assembly (UNEA-5) [13] resolution formally adopted the definition of NbS 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"*. Strengthening actions for nature is recognized as a necessary step towards the achievement of the Sustainable Development Goals and UNEA-5 emphasizes the importance of supporting the implementation of NbS *"in partnership with local communities, women and youth as well as with indigenous peoples"* [14].

Because of the many potential environmental and socio-economic benefits of NbS, numerous global, national, and local organizations and governments are now mobilizing large public investments in ecosystem-based approaches and supporting the expansion of the use of Nature-based Solutions [15–19]. For this reason, it is key to gather scientific evidence also on the economic effectiveness and social justice dimensions of NbS.

There is now growing evidence of the cost-effectiveness of NbS for disaster risk reduction [20,21]. However, there are still several limitations in the literature performing economic assessments of NbS. Indeed, in their global review of studies performing an economic evaluation of NbS for disaster risk reduction, Vicarelli et al. [21] found that the benefits of NbS appear to be underestimated; many benefits are not acknowledged, let alone quantified; and methodologies adopted to perform Cost-Benefit Analysis seldom follow best practices. In addition, there is a paucity of peer-reviewed literature performing economic assessments of NbS interventions in the Global South [4,21]. This is an unfortunate limitation because poor countries and individuals are more vulnerable to climate change impacts [22] and global warming has very likely exacerbated global economic inequality [23].

Our study contributes to address these different limitations: we adopted a stakeholder-driven participatory research approach and developed an economic assessment of four NbS interventions in four countries in the Global South, by diligently cataloging all the benefits

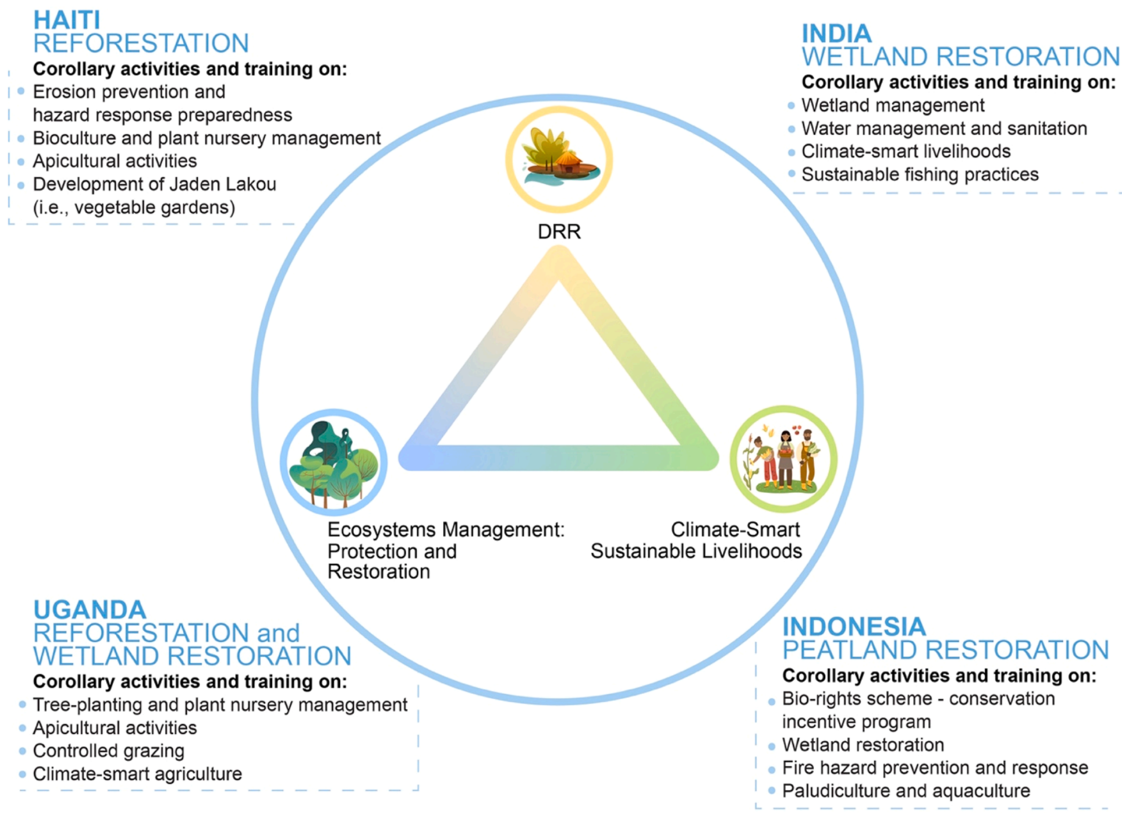

Fig. 2. The Eco-DRR Resilience Triangle Framework (center) was employed to set goals and measure progress of the Eco-DRR interventions and corollary activities developed in each country. The framework includes three dimensions: Disaster Risk Reduction (DRR); Ecosystems Management, Protection and Restoration; and Climate Change Adaptation through Sustainable Livelihood Practices. This study uses this framework to analyze and catalog the benefits of the Eco-DRR interventions.

observed by local stakeholders, and by performing a Cost-Benefit Analysis that follows best practices (e.g., by including numerous robustness checks).

Another limitation of the existing socio-economic literature on NbS is that social justice dimensions are rarely studied. International and national assessments and guidelines have highlighted the importance of rigorously assessing the benefits and distributional outcomes of disaster risk reduction and adaptation strategies aiming at inclusive and just implementations [24–30]. However, there is still limited knowledge about the equity and distributional impacts of these interventions [21] and issues of social and environmental justice remain peripheral in the literature [21,31]. Our study attempts to address these limitations by proposing a participatory research approach where the economic efficiency analysis of NbS is complemented by an equity analysis examining the social justice and distributional impacts of the interventions.

The four interventions examined in this study are part of the global project "*Up-scaling Community Resilience through Ecosystem-based Disaster Risk Reduction*" implemented by the United Nations Environment Programme (UNEP) in collaboration with Partners for Resilience (PfR), a global coalition between the Netherlands Red Cross, the Red Cross/Red Crescent Climate Center, Cordaid, Wetlands International, and CARE. Funded by the European Commission, the project started in 2018 and was completed in June 2022.

One objective of this global project was to develop scalable models for upscaling Eco-DRR in different ecosystem and hazard types in Haiti, India, Indonesia, Uganda and Ethiopia (although this study was not able to include Ethiopia due to the conflict situation there at the time of our data collection). The four interventions were tailored to each location's unique ecosystems and responded to the specific disaster risks faced by participating communities. Eco-DRR activities included reforestation, afforestation, wetland restoration, peatland restoration and Integrated Water Resources Management (IWRM).

This study evaluated the economic efficiency of Eco-DRR interventions in Haiti, India, Indonesia, and Uganda using a Cost-Benefit Analysis (CBA) by comparing implementation costs with observed and future benefits of the protective ecosystem services generated. Through extensive qualitative interviews, local stakeholders reported additional non-monetary benefits related to provisioning, regulatory, supporting, and cultural ecosystem services. These additional benefits were examined in a qualitative assessment that complemented the CBA.

Despite being frequently used to assess policies, CBAs do not consider distributional, and equity impacts of policies and programs [32]. For this reason, an additional qualitative analysis of the social justice and distributional effects of the NbS interventions among local populations was performed, with a particular focus on equity outcomes on women, children, and vulnerable socio-economic groups. This equity assessment was possible thanks to detailed information collected during extensive stakeholder interviews. The remainder of the article is organized as follows: Section 1 describes the key features of the Eco-DRR intervention in each country; Section 2 outlines the data and methodology used in the Cost-Benefit and equity assessments; Section 3 presents the results; and Section 4 discusses the results, outlines the project limitations, and concludes.

2. Background

The four countries targeted by the Eco-DRR and resilience enhancement interventions are characterized by low Human Development Index values and high exposure to natural hazards, exacerbated by anthropogenic environmental degradation. The locations of the case studies are presented in Fig. 1. UNEP and PfR developed the Eco-DRR Triangle Framework to set Eco-DRR goals and measure progress of their Eco-DRR interventions toward vulnerability reduction and community resilience building (Fig. 2). The portfolio of Eco-DRR activities examined in this study were structured around the three Eco-DRR components: (i) Ecosystems Management (e.g., reforestation, afforestation, wetland restoration, peatland restoration and Integrated Water Resources Management - IWRM), (ii) DRR activities (e.g., early warning systems, DRR awareness and capacity-building), and (iii) sustainable, climate-smart livelihoods (e.g., agroforestry, honey production). Whereas typically Eco-DRR activities mainly focus on reducing disaster risk through the protection and restoration of ecosystems, in addition, components (ii) and (iii), sought to include a more intentional focus on resilience-building [2]. Here, resilience was considered in terms of "bouncing forward" [33], rather than the more standard reference to "bouncing back" to the normal state [34].

The activities developed in each country are listed in Fig. 2 and reflect the intervention progress as of April 1, 2022. A more detailed catalog of the interventions adopted, based on the three dimensions of the Eco-DRR Triangle Framework is available in the Supplementary Materials (Tables 1A, 1B, 1C, 1D). This study uses the Eco-DRR Triangle Framework to analyze and catalog the benefits of the Eco-DRR interventions.

Haiti – In 2021, Haiti ranked 163 out of the 191 countries, with a Human Development Index of 0.535 [35]. Haiti's economy is primarily agriculture-based, with 70 % of Haitians earning a livelihood through small-scale subsistence farming [36]. Haiti's geological, topographical, and climatic conditions expose it to a wide range of hazards, including cyclones (e.g., storms and hurricanes), floods, landslides, and earthquakes [37,38]. Floods represent the greatest threat, aggravated by widespread deforestation and soil erosion due to charcoal production, and poor drainage infrastructure [39,40]. The frequency and level of vulnerability to disaster risk has a high cost for Haiti, with average annual losses from disasters estimated to be between 8 % (between 2000 and 2019) [41] to 17.5 % of GDP annually [42]. Haiti's disaster risk associated with extreme precipitation is expected to intensify with climate change [43].

Eco-DRR activities in Haiti focused on reducing risks of floods and landslides to ecosystems and surrounding communities through reforestation. Ecosystem restoration was complemented by an integrated risk-management approach including training on erosion prevention, and hazard response (Supplementary Materials Table 1A). The project sought to enhance community resilience by supporting local economic development through the adoption of sustainable livelihood practices. This portfolio of activities included training and support for sustainable and climate-smart agricultural practices; apiculture; and development of *jaden lakou* (i.e., vegetable gardens) and *petit commerce* (small trade) for local women. In addition to the Eco-DRR activities listed above, which frame the scope of our efficiency assessment, communities engaged in capacity-building activities working with local and district authorities through bottom-up planning, awareness raising, and sensitization of youth to disaster risk and climate change. These stakeholder engagement and capacity-building strategies were examined in the equity assessment portion of our analysis.

India – In 2020, India had a population of approximately 1.366 billion people, and its Human Development Index value stood at 0.633, ranking it in the 131st position out of 191 countries [35]. A peninsula surrounded by two large bodies of water, India has a diversity of climates and experiences monsoons from May to September. Floods are one of the main environmental risks to the country with >220 million people exposed [44]. Between 1980 and 2020, India experienced 263 floods that affected approximately 779 million people and caused approximately $109 billion USD (adjusted) in damage [45]. In 2015, annual losses and damage associated with floods in Odisha and Bihar (i.e., regions under exam in this study) were estimated to be between 2.5 % and 3.5 % of their state Gross Domestic Product (GDP) ([46]; communication from country team).

Wetlands have an important role in mitigating flood risk. According to the Indian National Wetland Inventory and Assessment, an estimated 757,000 wetlands are spread over 15 Mha or approximately 4.7 % of the country's total land area (Indian Space Research Organisation [47] - Space Applications Center, 2011). Despite their important role in lessening the impacts of hydrological hazards, Indian wetlands are under threat of degradation and shrinkage due to increasing urbanization and changing land use, agricultural and industrial pollution, and impacts of climate change [48].

Eco-DRR activities in India focused on community-driven ecosystem restoration and protection of 3312 hectares (ha) of land (as of April 2022) in the Kanwar Jheel wetlands in the eastern state of Bihar and Lake Tampara wetlands in the eastern state of Odisha (UNEP and PfR implemented Eco-DRR interventions in Suigam Taluka drylands in the western state of Gujarat too. However, they were not included in this study due to lack of data). The habitat restoration intervention included afforestation of nearly 270 ha of land with fruit-bearing, soil binding, wind-speed attenuating plants The goal was to reduce flood risk in an Integrated Water Resources Management (IWRM) framework. In addition to landscape restoration of wetlands, Eco-DRR activities included promotion of sustainable water management and sanitation practices; and creation of new economic opportunities through community training on sustainably managed agriculture, climate smart livelihoods, and sustainable fishing practices (Supplementary Materials Table 1B).

Indonesia – In 2021, Indonesia's Human Development Index value stood at 0.705, ranking it 114th out of 191 indexed countries [35]. Peatlands and peat forests account for about 21 M ha of Indonesia land and correspond to 36 % of all tropical peatlands globally [49,50]. They store 57 gigatonnes of carbon, which corresponds to 65 % of the world's tropical peatland carbon pool [50]. In addition to carbon storage, peatlands provide many other ecosystem services including water regulation, biodiversity protection, protection and risk mitigation from natural hazards, and support for local livelihoods [51]. Since the 1980s Indonesia's peatland ecosystems have been consistently impacted by deforestation, draining and conversion into industrial and smallholder agricultural plantations for the production of palm oil, pulp, and paper products [52]. As a result of these changes, peatland ecosystems have become highly susceptible to fire, with large peatland fires (which rarely occurred prior to the late 1990s) emerging as a regular occurrence in recent decades [53]. Indonesia cyclically suffers the effects of El Niño, which reduces average rainfall and water storage capacity, thus further increasing the risk of drought and fire over large regions. Carbon emissions from these recurring fires, along with carbon emissions from peatland drainage and cultivation, make Indonesia one of the world's top greenhouse gas emitters [54].

Recurrent peatland fires in Indonesia carry substantial social and economic costs. The six largest fire events between 2004 and 2015, caused a total of $93.9 billion USD in economic losses and thousands of deaths. In 2015 total losses and damage from fire (associated with El Niño) were equivalent to 3.3 % of Indonesian Gross Domestic Product (GDP). In other years, loss and damage were equivalent to 1.1 %–2.4 % of Indonesian GDP, making Indonesia's economy one of the most heavily impacted by peatland fire [53]. Peatland degradation and resulting fires also have negative impacts on local biodiversity which, while difficult to quantify monetarily, has significant repercussions on ecosystem health and ecosystem services [55,56].

Eco-DRR activities in Indonesia focused on reducing peatland fires through community-driven peatland ecosystem restoration and protection of about 50 hectares (ha) of peatland ecosystem in Muara Batang Soru sub-district in Northern Sumatra. Ecosystem restoration was supported through Eco-DRR training, and the implementation of a biorights funding scheme to incentivize participatory ecosystem restoration and protection (detailed in Supplementary Materials Tables 1C and 1C.2). Ecosystem restoration was complemented by awareness building activities in local communities to reduce vulnerability to fire risk, including peat monitoring; water level monitoring, and canal blocking; training of two community fire brigades; and fire-awareness and

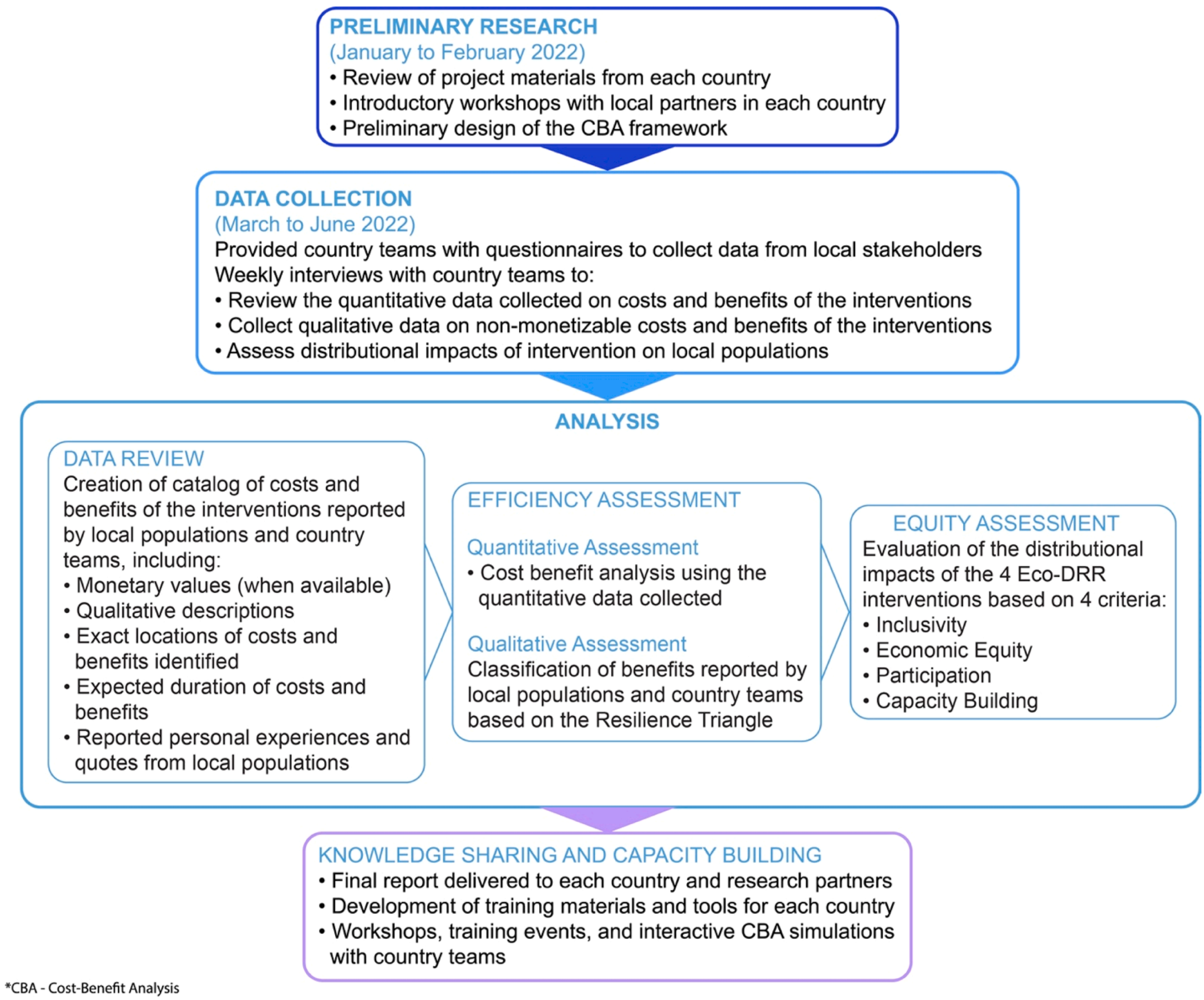

Fig. 3. Methodological approach adopted outlining the components of the efficiency and equity assessments. CBA stands for Cost Benefit Analysis.

preparedness community trainings. The project sought to increase community resilience by supporting local economic development through the adoption of sustainable livelihood options compatible with sustainable peatland management practices, including paludiculture, aquaculture, and maggot-culture. Because of the projected increase in fire risk associated with climate change, the Eco-DRR peatland restoration intervention implemented in this project has the potential to also decrease the impacts of climate change.

Uganda – A landlocked country located along the equator in the eastern part of Africa, Uganda has one of the highest population growth rates in the world at 3 % [38]. In 2021, its Human Development Index value stood at 0.525, ranking Uganda in 166th position out of 191 countries [35]. Agricultural activity is a key national economic pillar, with 70 % of the workforce working in agriculture [57]. Uganda's land cover classification includes 71.2 % agricultural land, 14.5 % forest, and 11 % wetlands; wetlands make a critical contribution to Uganda's economy by providing numerous ecosystem services [58]. Key environmental threats faced by Uganda include wetland draining for agricultural activities, deforestation, soil erosion, decline in soil fertility, water insecurity, and reduction in biodiversity [59]. Environmental degradation exacerbates hazard risk associated with flooding and hydrological droughts. World Bank estimates indicate that each year, floods impact nearly 50,000 people with over $62 million in GDP losses [60]. Another major risk is represented by droughts which affected close to 2.4 million people between 2004 and 2013; drought conditions in 2010 and 2011 caused an estimated loss and damage value of $1.2 billion, equivalent to 7.5 % of Uganda's 2010 GDP [60].

Eco-DRR activities in Uganda focused on drought and flood risk mitigation through community-based restoration of local wetlands, forests and sustainable riverine ecosystems management in the Aswa River Catchment area of Northern Uganda. Ecosystem restoration of >29,000 ha of land was implemented considering an Integrated Water Resources Management (IWRM) framework, with a portfolio of activities aimed at enhancing sustainable water resource management practices and promote water security. Other Eco-DRR activities included community-centered education of local stakeholders to support ecosystem-restoration practices (e.g., farmer-managed natural tree regeneration practices); training in sustainable livelihood activities (e.g., apiculture, climate-smart agriculture); and direct support to and expansion of sustainable livelihood development (e.g., tree nursery management for reforestation, apiculture, sustainable grazing practices, climate-smart agriculture) (Supplementary Materials Table 1D).

3. Data and methodology

NbS costs and benefits are location specific and local stakeholders are the actors best placed to identify them. For this reason, one of the priorities of our study was to engage stakeholders to scope locally relevant costs and benefits of the NbS interventions. The World Bank guidelines for assessing the benefits and costs of Nature-Based Solutions for climate resilience [30] highlight the critical importance of consulting and engaging "stakeholders to identify the relevant benefits to consider in project identification", which also fosters community buy-in and participation.

The methodology adopted in this study is therefore defined by a stakeholder-driven, participatory scientific approach. The steps implemented are described in detail below and include (i) preliminary research, (ii) data collection for each intervention, (iii) analysis, and (iv) knowledge sharing and capacity building (Fig. 3).

3.1. Preliminary research

Introductory workshops with project coordinators for each country, and in-depth review of the project materials provided by the project partners led to a preliminary itemization of the costs and benefits of the interventions and the initial development of the Cost-Benefit Analysis (CBA) framework. Documents reviewed during this initial research phase included budgets, progress summaries, narratives, notes, reports and project archives. Their review was particularly helpful to start cataloging costs. Quantifiable benefits were not as easily identifiable at this stage. Preliminary research also included analysis of reports by governmental and intergovernmental organizations detailing historical data on disaster risk and socio-economic impacts in the regions under exam.

3.2. Data collection

After the preliminary review of project documents and historical data, we refined, verified, and expanded our costs and benefits data set by interviewing local stakeholders. Our final dataset includes both quantitative and qualitative data.

The quantitative data, collected thanks to both preliminary research and interviews, was used to perform the *Quantitative Economic Efficiency Assessment* (i.e., Cost-Benefit Analysis (CBA)) (Sections 3.3.1 and 4.1). The qualitative data collected through interviews was employed for both the *Qualitative Economic Efficiency Assessment* (Sections 3.3.2 and 4.2) and the *Equity Assessment* (Sections 3.3.3 and 4.3).

Snowball sampling techniques were employed to collect qualitative data. A purposeful qualitative sampling method, snowball sampling is effective in providing community-based data when the sample is not easily accessible [61].

Qualitative sampling commenced with extensive, weekly or biweekly interviews with members of the implementing agency (i.e., country teams), in each country, over the span of three months (questionnaires are available in Supplementary Materials 11). Country teams in turn reached out and interviewed other local stakeholders to acquire the information needed for the analyses using the questionnaires provided by our research team. To minimize the risk of bias, country teams were asked to reach out to a large array of local stakeholders including local government, NGOs, community organizations and civil society members. When needed, project partners visited project sites and collected additional data through in-person interviews with community members. This snowball sampling approach was especially important to identify and catalog qualitative data on benefits that could not be easily monetized. The data collected was digitally stored on a cloud platform shared by the country teams and the research team. The data was iteratively reviewed, discussed and verified during meetings between members of the country teams and the research team. This intensive remote collaboration allowed the research team to generate a comprehensive and detailed catalog of costs and benefits data and to progressively review and refine the analytical framework.

Implementation costs - In cataloging the costs of the NbS analyzed we considered both the capital expenditures of the NbS (e.g., design, planning, construction) and the operating expenses (e.g., monitoring, maintenance, operation) to sustain the services provided by the NbS over time [30]. In addition to capital expenditures (i.e., CAPEX) and operating expenses (i.e., OPEX) we also explored possible transaction costs, opportunity costs, and costs associated with negative externalities and disservices. The scope of our analysis focused on the costs directly associated with the Eco-DRR implementation, including ecosystem restoration and protection, and sustainable livelihood development (costs are detailed in Supplementary Materials 2). No maintenance costs were reported after the end of the project implementation (i.e., June 2022). The local stakeholders interviewed did not report additional costs or damages to local populations due to negative externalities and disservices. Incidental administrative and planning expenses related to non-indispensable meetings (e.g., meetings with state and local public officials, workshops on general themes related to resilience) were considered non-indispensable transaction costs for the Eco-DRR implementation. The rationale for this approach is that in order to identify and quantify the net environmental and socio-economic benefits resulting from the Eco-DRR interventions, considered costs should be limited to costs required for the implementation of the interventions.

Benefits of the Eco-DRR interventions - Benefits considered in the CBA calculations included reduction in hazard risk and consequent reduction of properties losses (e.g., mitigation of damages to farmland and dwelling places) and income losses (i.e., GDP per capita). The country team members in each location provided background information about the number of households (and total number of people) benefiting directly or indirectly from the project. The estimated total values of properties in the project areas were obtained from local partners in each country (with the exception of Uganda where this data was not available). Annual income in each case study area was estimated by using GDP per capita [44] multiplied by the number of people benefiting from the Eco-DRR interventions, as reported by the country teams (details are available in Supplementary Materials 3).

The extensive interviews with country team members over the span of three months, allowed us to also collect abundant qualitative information on a large array of environmental and socio-economic benefits that, despite not being quantifiable in monetary terms, are still pertinent to the project efficiency and equity analysis (e.g., more reliable access to education, empowerment of women and girls, increase in biodiversity). Some of these benefits could potentially be estimated in the future if more time and resources are available for long-term monitoring and data collection. Qualitative benefits were not employed for CBA calculations but were used in the qualitative components of our analysis: *Qualitative Economic Efficiency Assessment* and *Equity Assessment.*

Country team members confirmed the exact locations associated with each cost and benefit in our database, and estimated their respective time horizons (i.e., time when costs/benefits began and their expected duration into the future). Testimonials and quotes from beneficiaries provided an additional layer to our analytical framework. Supplementary materials 9 and 10 catalog in detail the benefits reported by local stakeholders during the interviews. The analysis of these abundant qualitative data is an important part of this study, as it enriches and complements the quantitative cost-benefit assessment.

3.3. Data analysis

After a careful review of the data collected, and the finalization of a detailed catalogue of costs and benefits for each country, the analysis was performed in three phases: a *Quantitative Economic Efficiency Assessment*; a *Qualitative Economic Efficiency Assessment*, including additional benefits from provisioning, regulatory and cultural ecosystem services; and an *Equity Assessment,* analyzing the social justice and distributional effects of the NbS interventions among local populations.

3.3.1. Quantitative economic efficiency assessment: cost-benefit analysis

The economic efficiency of the Eco-DRR interventions was assessed by completing a forward-looking CBA, combining data on hazard and vulnerability to risk and reduced risk [62,63]. This approach allows the estimation and comparison of the future *net benefits* (expressed in monetary values) of different policy scenarios. *Net benefits* are the difference between benefits and costs (available in monetary terms) and represent a measure of *efficiency*. Discounting techniques allow to aggregate costs and benefits occurring at different times into the future. The present value of net benefits is referred to as *Net Present Value* (NPV). When comparing two policy scenarios, the most efficient policy is identified as the one with the highest present value of net benefits (NPV) over a given time period.

The CBA framework adopted in this study examines the net benefits of the Eco-DRR interventions over 20 years into the future, compared to a baseline scenario where there is no Eco-DRR intervention. All the costs cataloged during the data collection were considered in the CBA. Numerous benefits could not be estimated quantitatively and monetized at this time. The benefits-side of the CBA model adopted, therefore, focuses exclusively on the protective ecosystem services that could be estimated and monetized. These "estimates" of future benefits are built using historical data from the regions (i.e. observed economic impacts of hazards). The benefits that could not be monetized are considered in the *Qualitative Economic Efficiency Assessment* and in the *Equity Assessment*.

The net benefits of the baseline scenario, which corresponds to no Eco-DRR intervention, are compared to two alternative Eco-DRR scenarios (i.e., Model 1 and Model 2) that differ for the benefits considered:

- Baseline Scenario with no Eco-DRR interventions
- Model 1 with Eco-DRR interventions:
  - Benefits include reduction in property damages and income losses.
  - Benefits **do not** include carbon capture and pollution reduction.
- Model 2 with Eco-DRR interventions:
  - Benefits include reduction in property damages and income losses.
  - Benefits also include carbon capture and pollution reduction.

Model 1 - Reduction in property damages and income losses achieved thanks to Eco-DRR is a key benefit considered in our main model (i.e., Model 1); we refer to this benefit as *"Estimated yearly avoided losses"*. These estimates are based on an approximation of the frequency and magnitude of weather hazards (i.e., hurricanes, storms, floods, fires) in the regions under exam. We performed the analysis using different percentages of yearly loss in properties and GDP per capita in the project areas due to local hazards (i.e., 0.5 %, 1 %, 2 % and 5 % yearly losses). Data provided by each country team and historical trends estimated in the literature for each case study area indicate yearly losses close to about 2 % in each country [41,42,44,46,53]. Nevertheless, we performed the analysis using also lower values of yearly losses (i.e., 0.5 %, 1 %) for robustness checks. Weather extremes are expected to worsen with climate change; therefore, our CBA may be underestimating the benefits of ecosystem restoration in the future. This would make an even stronger case in support of the Eco-DRR intervention. We performed additional robustness checks applying a 5 % yearly loss in properties and GDP per capita in the project area (available upon request).

Model 2 - Model 2 expands the main CBA framework (Model 1) by considering additional regulatory services produced by the vegetation of restored ecosystem (i.e., carbon capture and sequestration and pollution reduction), in addition to the benefits associated with protective ecosystem services (i.e., estimated yearly avoided losses). The *carbon capture and sequestration and pollution mitigation* produced by the Eco-DRR intervention in each case study area were estimated using the software iTree and included as benefits in Model 2 CBA estimates. The software iTree is a global forestry analysis and benefits assessment tool from the United States Department of Agriculture's (USDA) Forest Service [64] that estimates ecosystem services of both the urban and the rural forest. iTree allows to estimate carbon storage (tons) and yearly carbon sequestration (tons) as well as pollution reduction from satellite images of a given vegetation area. Pollutants considered include Carbon Monoxide, Nitrogen Dioxide, Ozone, Sulfur Dioxide, Particulate Matter <2.5 μm, Particulate Matter greater than 2.5 μm and <10 μm. iTree provides estimates of the corresponding monetary values too, and they were used in the CBA calculations. iTree estimates for each country are reported in the Supplementary Materials 4.

CBA assumptions and empirical specifications - The CBA framework employed for Model 1 and Model 2 adopts the following assumptions and specifications:

- The present value of net benefits (i.e., NPV) is estimated over a time horizon of 20 years from the end of the project implementation.
- The full costs of the project implementation are paid only once in year 0, which corresponds to the end of the implementation.
- There are no maintenance costs after year 0.
- The ecosystem associated with the Eco-DRR intervention reaches maturity after 5 years (per discussion with country teams in each country).
- Until year 5, while the ecosystem is maturing and/or getting restored, there is a progressive increase in benefits (i.e., 10 % of benefits the first year, 20 % the second year, 40 % the 3rd year, 60 % the 4th year, and 80 % the 5th year).
- The ecosystem restored/protected by the Eco-DRR intervention provides full benefits starting in year 6.

Discount rates – Following CBA best practices [63], the CBA estimations were performed using three discount rates (i.e., 3 %, 7 %, and 10 %) to allow for robustness checks and comparisons across outcomes. Higher discount rate values lead to a lower weight of future benefits and costs in the CBA estimations. Ecosystem-based interventions may generate long-term benefits that would be underestimated with high discount rates. For this reason, it is important to perform sensitivity tests by adopting a range of discount rates. Three percent and seven percent are the discount rates generally recommended by the US Office of Management and Budget (OMB) [65]. The 7 % rate captures the return paid by private capital, it reflects effects on investment and business. The 3 % rate represents the return received by consumers, with the difference due largely to taxes [66]. Conservatively, we performed additional robustness checks with a 10 % discount rate (selected estimates are available in Supplementary Materials 7 and 8, more detailed estimates are available upon request).

3.3.2. Qualitative economic efficiency assessment

The quantitative efficiency assessment is complemented by the analysis of the abundant qualitative data on environmental and socio-economic benefits gathered from extensive interviews with field-staff and feedback from local stakeholders. The qualitative data collected provides valuable insights into the vast array of positive externalities generated by the interventions, including, for instance, an increase in wages and revenues, water security, gender equality, and access to health, and education. After cataloging all the benefits reported by local stakeholders (available in Supplementary Materials 9 and 10) we analyzed them based on the three dimensions of the Eco-DRR Triangle Framework (presented in Fig. 2): enhanced Ecosystems Management, increase in DRR, and development of Climate-smart Sustainable Livelihoods.

3.3.3. Economic equity assessment

The efficiency assessment of a policy or program provides insights on the aggregate value of net benefits generated by the intervention but not on how the benefits are distributed among different socio-economic groups in a population. For this reason, we complemented our economic efficiency assessment with an equity assessment aimed at providing insights into the distribution of benefits among community members and into the impacts of the interventions on vulnerable groups.

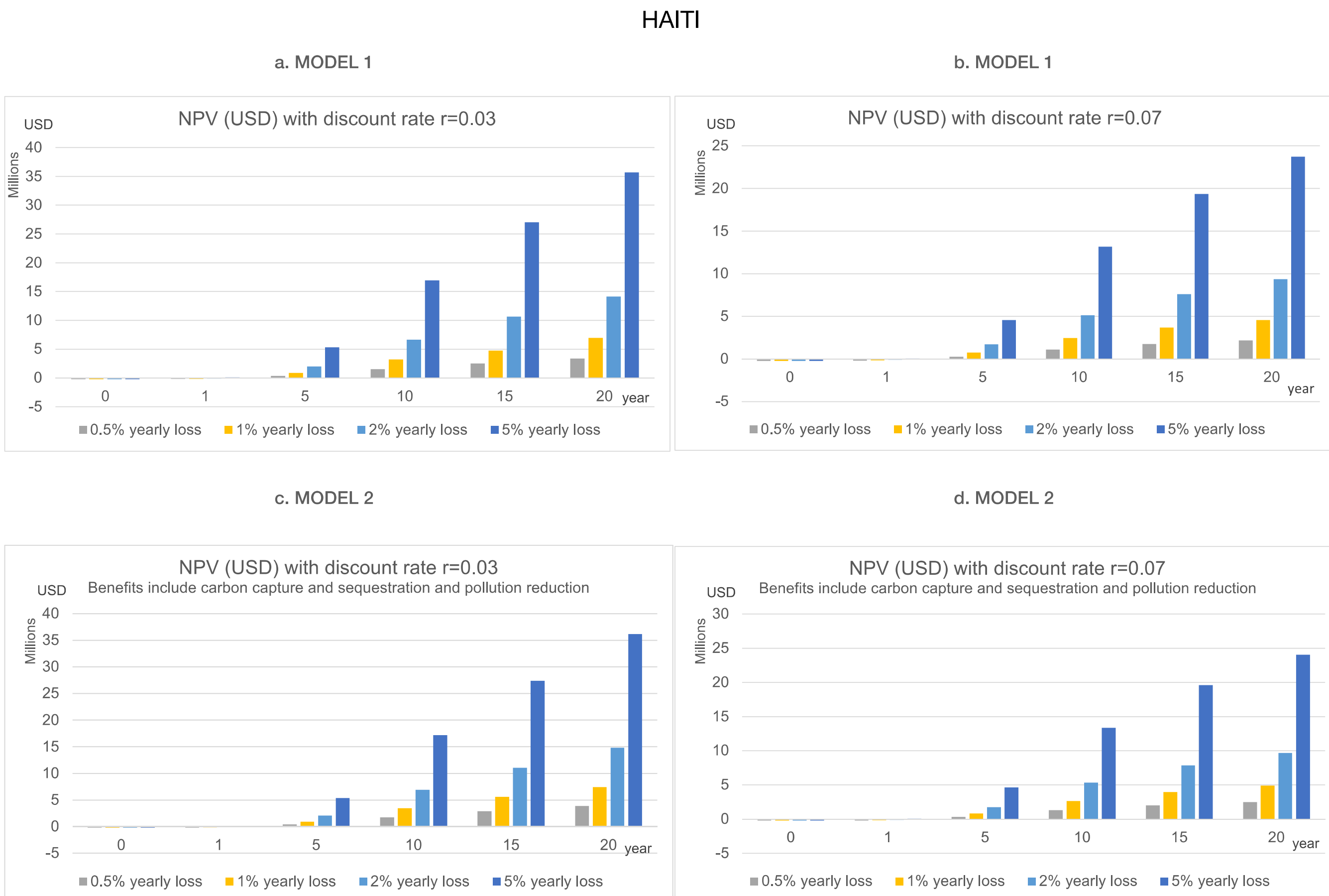

Fig. 4. Results of the cost benefit analysis (CBA) of Eco-DRR interventions in Haiti. Each graph presents the Net Present Value (NPV) (i.e., present value of net benefits) up to 20 years post implementation of the Eco-DRR interventions. Estimates are calculated for four different percentages of annual losses (0.5 %, 1 %, 2 % and 5 %) for two discount rates (3 % and 7 %). **a. b.** The images at the top correspond to Model 1, considers as benefits only the protective services of the Eco-DRR interventions and does not include additional benefits from reforestation-induced carbon capture and sequestration and pollution reduction. **c. d.** Results from Model 2 are below, this scenario takes into account possible benefits from carbon capture and sequestration and pollution reduction.

During weekly and biweekly interviews with local stakeholders we gathered data on the distributional impacts of the interventions on the different socio-economic groups in the areas under exam. The four Eco-DRR interventions were then examined along the following equity dimensions: inclusivity, economic equality, participation, and capacity building. Special attention was paid to the impacts of the interventions on vulnerable groups, in particular women, children, and ethnic and racial minorities.

3.4. *Knowledge sharing and capacity building*

The stakeholder driven scientific approach adopted in the study aimed at producing actionable science, guided by local needs. After the analyses were completed, learning materials, data, and CBA simulation tools were shared with the project partners and with local stakeholders. Knowledge transfer was facilitated by workshops and learning events. The goal was to help country teams and local stakeholders to become familiarized with the CBA methodology, to enable them to continue monitoring costs and benefits over time, and ultimately to be able to independently reproduce the analyses for the current Eco-DRR interventions and for future projects.

4. Analyses and results

The results of the efficiency assessment are provided below, followed by the results of the equity assessment.

4.1. *Quantitative economic efficiency assessment: cost-benefit analysis*

For each of the 4 projects we performed an efficiency assessment by computing the present value of net benefits (i.e., NPV) at various time horizons up to 20 years since the project implementation (Figs. 4–7). In the graphs, the horizontal axis represents the time horizons, and the vertical axis represents the NPV. We estimated the NPV using both Model 1 and Model 2, and for each model we performed calculations using both the 3 % and 7 % discount rate. A positive NPV indicates that the project benefits exceed its costs and that the project is more efficient compared to a scenario where there is no Eco-DRR intervention. As mentioned above, for robustness checks, we performed the analysis using different percentages of yearly loss in properties and GDP per capita in the project areas due to local hazards (i.e., 0.5 %, 1 %, 2 % and 5 % yearly losses). In the graphics, different yearly losses are represented by bars of different color.

Model 1 considers as benefits only the protective services of the Eco-DRR interventions and does not include additional benefits from reforestation-induced carbon capture and sequestration and pollution reduction (Figs. 4a-b, 5a-b, 6a-b and 7a-b; detailed quantitative values are presented in Supplementary Materials 5).

Results from Model 1 indicate that by the 5th year since the Eco-DRR implementation, the NPV of the interventions in Haiti and India is positive irrespective of the percentage of yearly loss adopted (0.5 % to 5 %) for both the 3 % and 7 % discount rate (Figs. 4 and 5).

The NPV of the Indonesia intervention is positive at the 10th year since implementation for both the 3 % and 7 % discount rate, adopting a

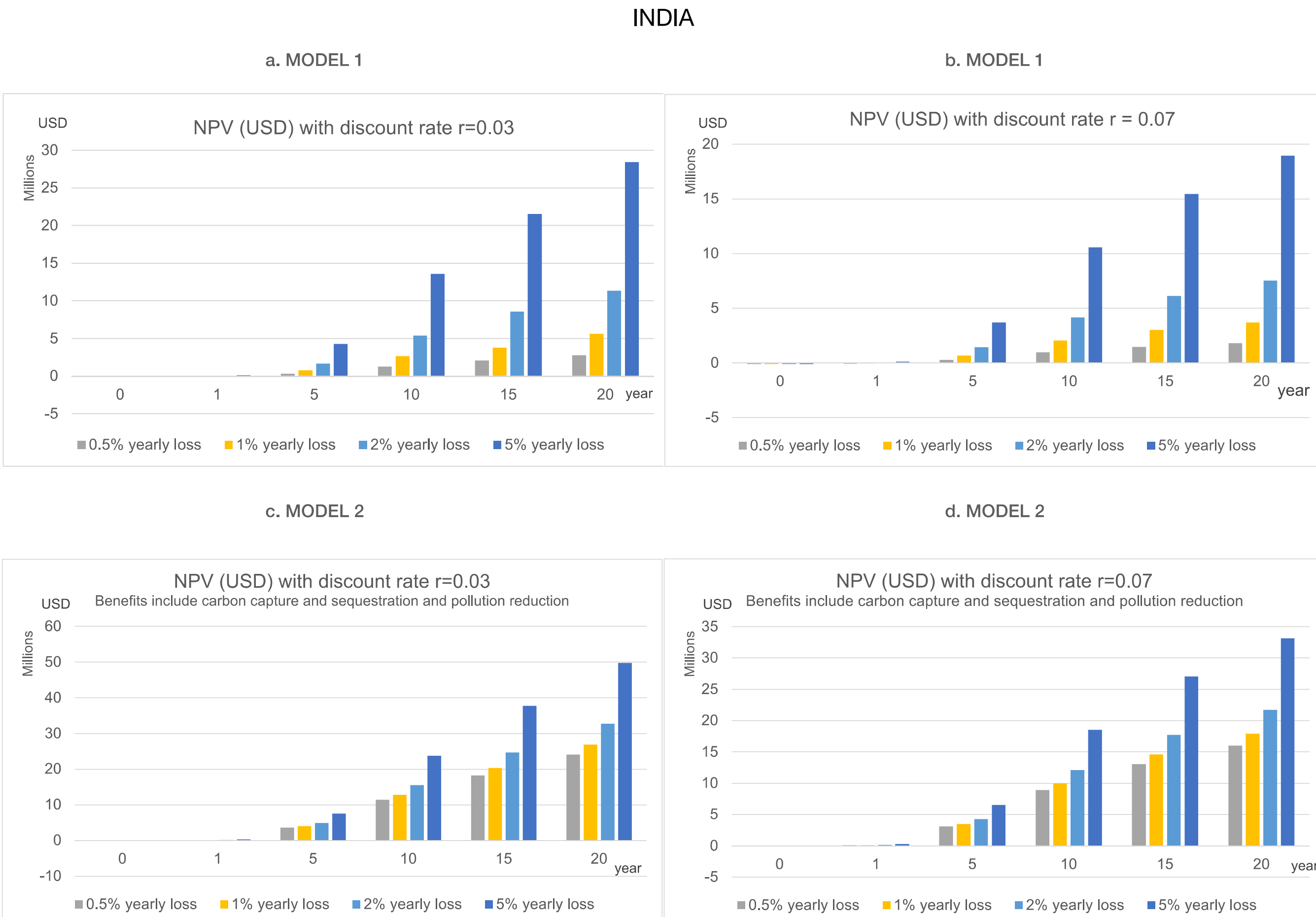

Fig. 5. Results of the cost benefit analysis (CBA) of Eco-DRR interventions in India. Each graph presents the Net Present Value (NPV) (i.e., present value of net benefits) up to 20 years post implementation of the Eco-DRR interventions. Estimates are calculated for four different percentages of annual losses (0.5 %, 1 %, 2 % and 5 %) for two discount rates (3 % and 7 %). **a. b.** The images at the top correspond to Model 1, considers as benefits only the protective services of the Eco-DRR interventions and does not include additional benefits from reforestation-induced carbon capture and sequestration and pollution reduction. **c. d.** Results from Model 2 are below, this scenario takes into account possible benefits from carbon capture and sequestration and pollution reduction.

1 %, 2 % and 5 % yearly loss. The value becomes positive independently from the percentage of yearly loss adopted (0.5 % to 5 %) at 20 years from implementation.

The NPV associated to the Uganda intervention is positive at the 10th year since the implementation for both the 3 % and 7 % discount rate, adopting a 2 % and 5 % yearly loss. The NPV become positive at 15 years, for both discount rates, when adopting a 1 % yearly loss.

Overall, the NPVs for Indonesia are lower than the values for the other countries due to the smaller project size.

As discussed above, a 2 % yearly loss is the most likely amount based on existing literature [41,42,44,46,53]. With this assumption, adopting a conservative 7 % discount rate, at the 10th year since the Eco-DRR implementation, the NPV value is above 100,000 USD in Indonesia and Uganda. The NPV is above 4 M USD in Haiti and India, which corresponds to >40 times the original implementation costs. At the 5th year since the Eco-DRR implementation, in Haiti and India, the NPV is positive and above 1 M USD using the 7 % discount rate, which corresponds to >10 times the original implementation costs. The NPV values are even higher when using a less conservative 3 % discount rate. Detailed yearly outcomes of Model 1 for every country, for every discount rate, assuming a 2 % yearly loss, are available in the Supplementary Materials 7.

Model 2 expands the main CBA analysis (Model 1) by considering in the NPV calculations additional regulatory services produced by the vegetation of restored ecosystem (i.e., carbon capture and sequestration and pollution reduction), in addition to the benefits associated with protective ecosystem services (i.e., yearly avoided losses). The *carbon capture and sequestration and pollution mitigation* benefits were estimated obtained using iTree. The NPV estimates of Model 2 (Figs. 4c-d, 5c-, 6c-d and 7c-d; detailed quantitative values are presented in Supplementary Materials 6) are therefore even higher than the values obtained from Model 1.

Results from Model 2 show that, in Haiti, India and Uganda, at the 5th year since the Eco-DRR implementation, the NPV is positive for every discount rate (i.e., both 3 % and 7 %), independently from the yearly loss adopted (i.e., 0.5 %, 1 %, 2 % and 5 %).

In Indonesia the NPV is positive for every discount rate and yearly loss adopted by the 10th year. As mentioned above, the small size of the Indonesian project compared to the projects in the other countries is the main reason for the low NPV estimates.

The Uganda Model 2 NPV estimates are very high due to the large *carbon capture and sequestration and pollution mitigation* benefits produced by the vast Eco-DRR reforestation effort (corresponding to >29,000 ha). For a given year, the benefits associated with *carbon capture and sequestration and pollution mitigation* are the same, irrespective of the percentage of yearly loss adopted in the model. Their value is up to two orders of magnitude larger than the disaster risk reduction benefits. In the graphics (Fig. 7c and d), each colored bar (NPV estimates) includes both types of benefits. The NPV estimates for each year differ minimally, reflecting the differences in disaster risk reduction

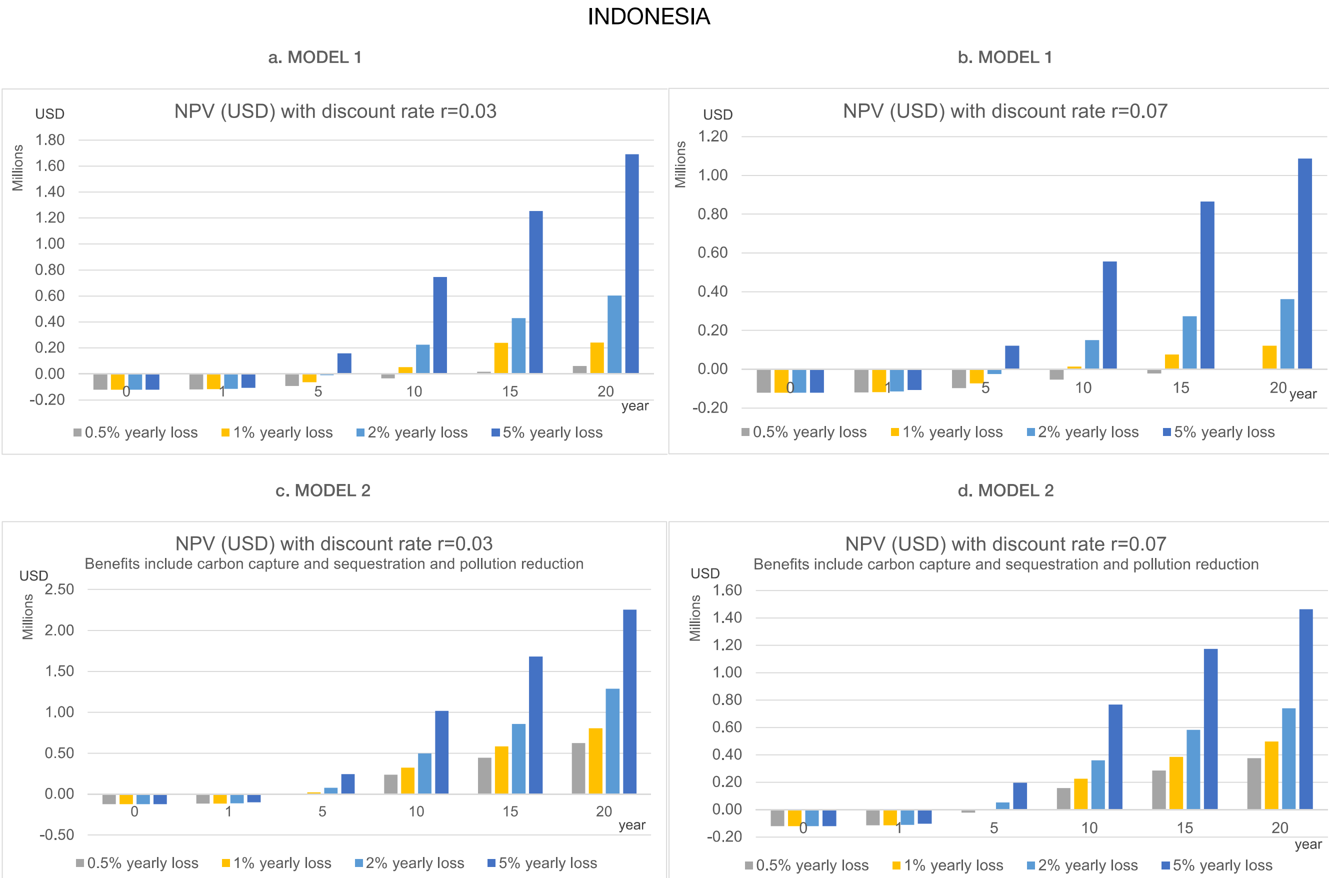

Fig. 6. Results of the cost benefit analysis (CBA) of Eco-DRR interventions in Indonesia. Each graph presents the Net Present Value (NPV) (i.e., present value of net benefits) up to 20 years post implementation of the Eco-DRR interventions. Estimates are calculated for four different percentages of annual losses (0.5 %, 1 %, 2 % and 5 %) for two discount rates (3 % and 7 %). **a. b.** The images at the top correspond to Model 1, considers as benefits only the protective services of the Eco-DRR interventions and does not include additional benefits from reforestation-induced carbon capture and sequestration and pollution reduction. **c. d.** Results from Model 2 are below, this scenario takes into account possible benefits from carbon capture and sequestration and pollution reduction.

benefits.

Detailed yearly outcomes of Model 2 for every country, for every discount rate, assuming a 2 % yearly loss, are available in the Supplementary Materials 8.

4.2. Qualitative economic efficiency assessment

A detailed catalog of benefits, created through interviews with local stakeholders, allows to complement and expand the quantitative efficiency assessment. When needed, country teams collected supplementary data from local populations to be integrated in this analysis. Interviewees indicated benefits observed since 2018, the beginning of the project implementation. Benefits in each location are organized in three broad categories, consistent with the Eco-DRR Triangle Framework: benefits derived from DRR activities; benefits from enhanced ecosystem management; and benefits derived from climate-smart, sustainable livelihoods (Fig. 8). For each case study, we examined the expected evolution of benefits to the local communities over time, as indicated by our local partners (Supplementary Materials 9 and 10). Their expectations were that benefits would successfully extend into the future, also thanks to the capacity building and community participation components of the project. In this study, ecosystem services were categorized based on the Millennium Ecosystem Assessment approach, including regulating, provisioning, supporting, and cultural services [67].

4.2.1. Benefits deriving from disaster risk reduction (DRR)

Economic benefits from ecosystem restoration and conservation are associated with both risk reduction and enhancement of income generating activities following risk-reduction. According to our survey, in every case study, economic benefits from lower vulnerability included reduced property damages and reduced income losses, already accounted for in the CBA calculations.

For instance, in India the Eco-DRR intervention led to reduced crop and livestock loss. The project included both wetland protection (>3000 ha) and restoration (800 ha), obtained through planting of native species and cleaning of canals and waterways. Prior to the project implementation, the villages surrounding the Tampara wetlands would experience stagnant water in crop fields after each cyclone or severe rainstorm, causing drastic crop loss (up to 100 % in some cases). Assessments by the local team indicate that the improved wetland drainage has mitigated agricultural losses and reduced livestock losses from disasters up to 96.1 % (by comparing livestock deaths from the Titli Cyclone in 2018 and the Gulab Cyclone in 2021).

DRR is related to improvements in ecosystem services, which can further reinforce DRR in positive feedback. For instance, in Haiti and Uganda Eco-DRR (i.e., reforestation) led to a progressive increase in soil stabilization, which will contribute to enhanced protection from flash floods, landslides, and high wind events.

Risk reduction is in turn creating additional socio-economic benefits in all case studies. Increased agricultural productivity due to increased soil quality and avoided hazards was reported as an additional benefit in all case studies. In Haiti and Uganda, increased soil stability and lower

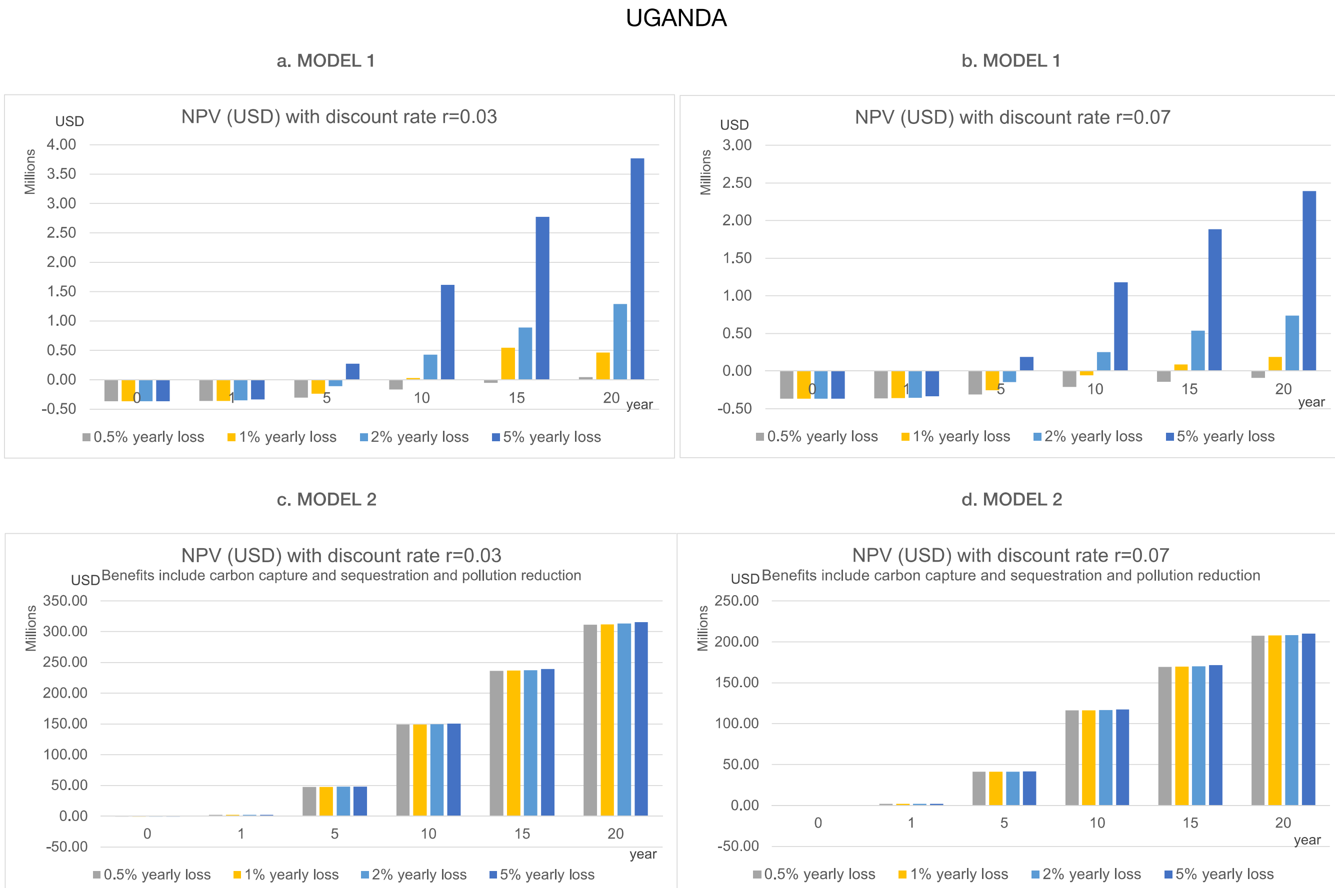

Fig. 7. Results of the cost benefit analysis (CBA) of Eco-DRR interventions in Uganda. Each graph presents the Net Present Value (NPV) (i.e., present value of net benefits) up to 20 years post implementation of the Eco-DRR interventions. Estimates are calculated for four different percentages of annual losses (0.5 %, 1 %, 2 % and 5 %) for two discount rates (3 % and 7 %). **a. b.** The images at the top correspond to Model 1, considers as benefits only the protective services of the Eco-DRR interventions and does not include additional benefits from reforestation-induced carbon capture and sequestration and pollution reduction. **c. d.** Results from Model 2 are below, this scenario takes into account possible benefits from carbon capture and sequestration and pollution reduction.

risk of landslides was mentioned as a positive externality of reforestation leading to improved agricultural production. In Indonesia, peatland rewetting activities, conducted through construction and maintenance of canal blockings/dams and water reservoirs, reduced fire risk and consequent agricultural losses. In India, Eco-DRR contributed to provisioning services by resulting in increased fish populations in restored village ponds, generating increased income for local fishermen.

Increased labor productivity emerged as an indirect benefit of DRR in all countries. In Haiti more reliable roads due to decreased flood risk are expected to increase accessibility of employment centers and markets for 10,000 people. Reduced flood risk, more reliable transportation and improved mobility are reported in Uganda too. In Indonesia, health improvements (from better air quality and reduced exposure to fire) and more reliable access to employment centers and markets (due to reduced fire events) are also expected to lead to increased labor productivity.

Human capital accumulation from reduced hazard risk and from the enhancement of sustainable practices were reported in every case study site (e.g., health benefits and/or increased access to education). For instance, in Haiti the conservation and protection of the 56 ha of reforested land led to a reduction in over 69,000 t of charcoal production, and CO_2 emissions reduction of approximately 197 tons. This will contribute to a progressive increase in air quality and consequent reduction in mortality and morbidity.

More benefits are reported from reforestation-induced soil stabilization, largely due to a reduction in interruptions to essential services caused by natural hazards (e.g., floods and landslides). For example, more reliable roads are increasing access to health centers for approximately 22,333 people in Haiti and 5000 people in Uganda, leading to a reduction in morbidity and mortality during and after hazards.

More reliable roads due to decreased flood risk are also improving the accessibility of schools for >7000 local children in Haiti and an estimated 3000 in Uganda. This is particularly significant for girls, for whom reliable access to school can lead to increased gender equity via economic empowerment.

In India, the Eco-DRR intervention is contributing to improved stormwater management, and consequently to reduced morbidity and mortality from disasters (primarily landslides and floods) but also from water-borne illnesses, including diarrhea, malaria, and skin infections. Prior to the intervention, the case numbers of water-borne illness swelled in both the Tampara and Kanwar regions. Since wetland cleaning began, malaria case numbers in the area have decreased by 70–77 % and diarrhea case numbers have decreased by 83–86 % (data provided by the India country team). Furthermore, rejuvenated ponds in Tampara have improved accessibility to potable water, leading to fewer deaths related to dehydration.

In Indonesia, as discussed above, reduced fire hazards and improved air quality contribute to reduction in fire-related morbidity and mortality associated with cardiovascular and respiratory diseases. Damage to infrastructure caused by fires can trigger interruptions to essential services (e.g., healthcare and education, markets, and employment centers). Therefore, reduced fire risk contributes to human capital accumulation and local economic growth by expanding access to healthcare, education, labor centers, and markets.

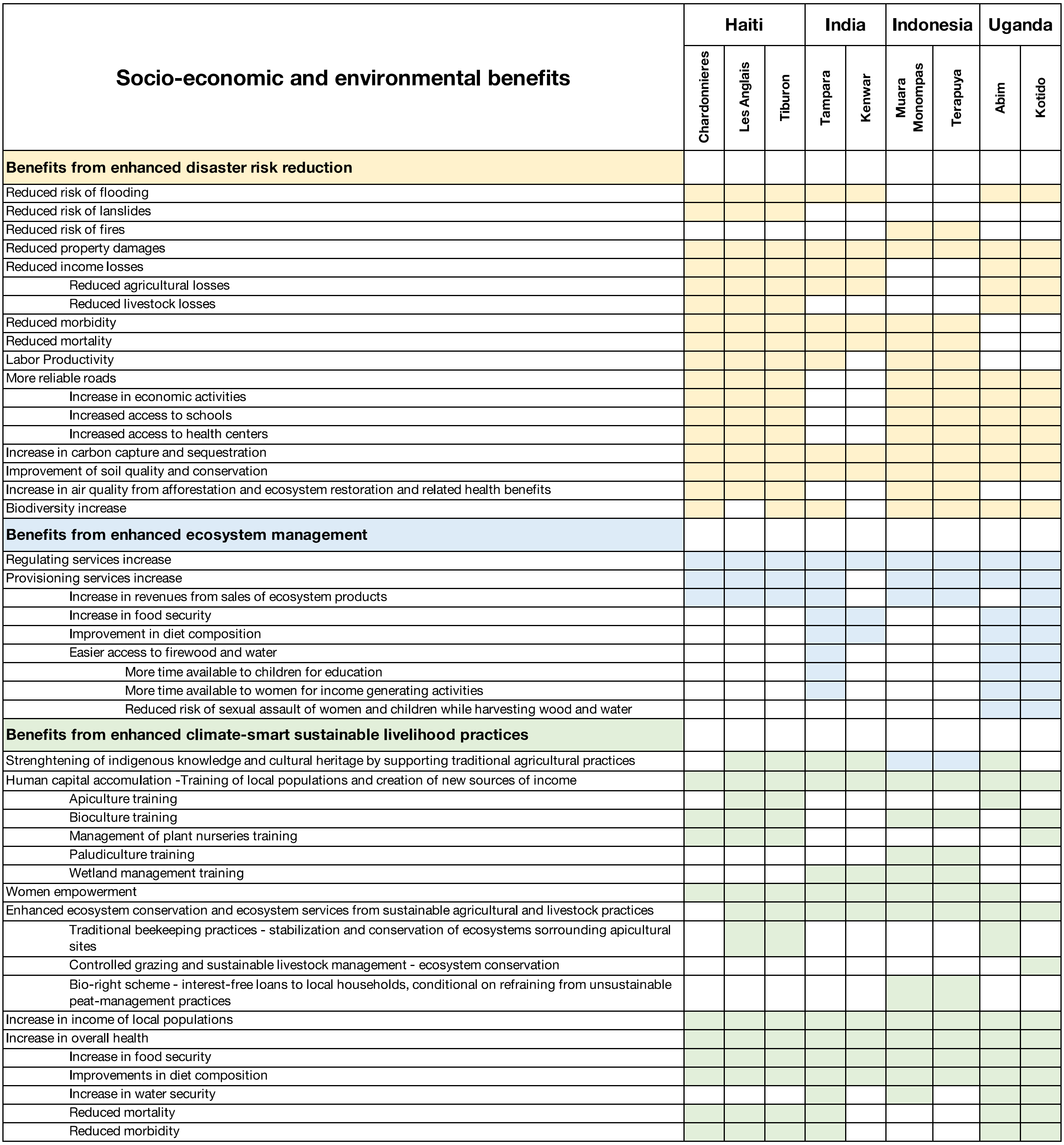

Fig. 8. Socio-economic and environmental benefits identified by country teams and local stakeholders for each of the locations studied.

Enhanced carbon capture and sequestration are important direct environmental co-benefits of the interventions. Our estimates indicate that ecosystem restoration and conservation in the case study areas contribute to carbon sequestration up to >130,000 tons annually, which corresponds to >12 M USD in value (iTree estimates). In addition, we estimated an overall carbon storage of >1.8 million tons once the ecosystems are fully matured, which is equivalent to >150 M USD. Annual pollution reduction is an additional benefit provided by the restored/preserved ecosystems, with an estimated value of >13 M USD.

Biodiversity benefits were reported in every case study as a direct consequence of the Eco-DRR intervention. Biodiversity increase is associated with increased ecosystem protection and enhancement of regulating and supporting ecosystem services (e.g., habitat for species and maintenance of genetic diversity). Biodiversity is also preserved and enhanced by reduced damage from hazards.

4.2.2. Benefits derived from enhanced ecosystem management

Enhanced soil quality and conservation associated with enhanced ecosystem conservation and sustainable ecosystem management are reported by local stakeholders. Wetland restoration and afforestation in India, and peatland rewetting in Indonesia are leading to a progressive improvement in soil characteristics with positive externalities on other ecosystem regulating services. In Uganda and Haiti, reforestation activities over >29,000 ha were reported to contribute to soil stabilization and conservation by preventing erosion. Country teams reported improvements in soil physical structure, water retention, drainage, moisture, and fertility. These improvements in turn aid crop production.

Enhancement of ecosystem regulating services emerged in every case study. In India, local teams reported overall enhancement of ecosystems regulatory services: the trees planted as part of afforestation activities are helping regulate local temperatures and precipitation, purify water bodies through pollutant reduction, and reduce sedimentation. Rewetting of peatland soil in Indonesia was reported to improve the ecosystems' ability to regulate local temperatures, leading to the cooling of local climates, reduction of fire risk and consequent reduction in air pollution. Improvements to air quality were reported also in Haiti and Uganda, in relation to a decrease in wood consumption for energy production. This in turn will result in health improvements associated with reduced mortality and morbidity from air purification.

Increased provisioning services were reported in all countries. Ecosystem conservation, sustainable ecosystem management, and growing biodiversity led to an increase in ecosystem provisioning services associated with food, wood, and water. As a consequence, all country teams also reported an increase in revenues from the sales of ecosystem products. For instance, a growing fish population is observed in the Indian wetlands after the eco-DRR implementation. And in Uganda, local stakeholders reported an increase in the number of fruit trees after the enhancement of forest protection practices. Positive reported outcomes in India and Uganda also include higher food security and a richer diet composition, which ultimately led to health improvements for local populations.

Socio-economic benefits from enhanced ecosystem services, particularly provisioning services, appear to have transformative impacts on the most vulnerable populations beyond improved food security. In India and Uganda, reforestation, and the resulting increase in provisioning services (e.g., closer, more reliable, and sustainable access to wood and food) are reported to also facilitate human capital accumulation, as less time spent collecting water and firewood leaves more time for other income generating activities and for education. In Uganda, reduction in violence against women and children has emerged as a positive externality of improved provisioning services: women and children tend to be vulnerable to sexual assault while walking long distances to retrieve food, wood, or water. Closer access to these resources has reduced their vulnerability to sexual violence.

4.2.3. Benefits from sustainable livelihood practices

Indigenous knowledge and cultural heritage have been purposefully integrated in sustainable livelihood practices in each location; for instance, traditional apicultural practices in Uganda, biocultural activities in India and Indonesia, and *jaden lakou* (i.e., traditional vegetable gardens) in Haiti. This led to the strengthening of traditional practices and revalorization of local cultural heritage and indigenous knowledge among local populations.

Human capital accumulation and gender equity are co-benefits of training in sustainable agricultural techniques and in ecosystem-restoration. In all sites, after receiving training and engaging in new sustainable livelihoods, more women felt empowered and started to take on leadership roles, thus gaining respect and stature in their households and community. In Uganda, reported shifts in gender power dynamics led to a reduction in gender-based violence too. In Indonesia, the acquisition of new skills not only allowed women to engage in sustainable livelihood activities, but they were also able to successfully access interest-free credit through the Bio-rights scheme. This further expanded the magnitude of socio-economic benefits to women and their households.

Enhanced ecosystem conservation resulted as a co-benefit of climate-smart sustainable agricultural practices, further reinforcing the Eco-DRR ecosystem conservation efforts. In Haiti and Uganda, training in commercial beekeeping using existing indigenous knowledge and practices has led to the protection of the surrounding ecosystems to guarantee the highest quality of bee forage and honey produced. In turn, the protection of ecosystems surrounding apicultural sites is allowing strengthening and expansion of ecosystem services and DRR. In Indonesia, the Bio-rights scheme associated with the Eco-DRR intervention provided interest free loans to local households, conditional on refraining from unsustainable peat-management practices and actively participating in peatland restoration, environmental conservation, and sustainable agriculture.

Enhanced ecosystem services were reported as benefits from climate-smart sustainable agricultural practices from every local team. In Haiti and Uganda bio-culture training, composting, and the planting of ten community-managed nursery sites are leading to progressive improvement in soil health and soil stabilization, further enhancing soil-related ecosystem regulatory and provisioning services. In Indonesia, participation of local communities in the Bio-rights scheme and paludiculture training led to the adoption and expansion of sustainable agricultural practices. Paludiculture practices decrease greenhouse gas emissions from peat soil, contribute to improved regulatory and supporting ecosystem services, and facilitate the restoration of habitat for threatened species, generating biodiversity benefits.

Increase in local income and related socio-economic benefits from sustainable livelihood practices have been reported in all countries, contributing to sustainable development goals.

In Haiti and Uganda, the introduction and expansion of local sustainable agricultural techniques (e.g., *jaden lakou*, or vegetable gardens, in Haiti), apicultural activities, seedling nurseries management, forest management, and forest products have created new sources of local income and revenues and increased food security. In Uganda, the adoption and enforcement of controlled grazing in four riverine areas is expected to improve land and pasture conditions, enhance livestock production, and ultimately increase local revenues.

In India, as a result of wetland restoration and protection, including the designation of the Karbatal Wetland in Kanwar as a Wetland of International Importance under the Ramsar Convention, local communities have seen an increase in eco-tourism, which has led to an increase in revenues for local businesses depending on hospitality and tourism. Community training and support of sustainable livelihood activities have created new sources of local income and revenues.

In Indonesia, Bio-rights financed sustainable livelihood practices have started generating economic benefits in the form of new wages and revenues. The primary Bio-rights financed sustainable agricultural activity is paludiculture, which accounts for 54 % of new jobs in the local communities and an increase in revenues for 46 % of existing local agricultural businesses. Bio-rights financed sustainable livestock farming is generating new revenues for 57 % of members from the local communities. The Bio-rights scheme also contributed to the financing of an array of new local Small and Medium Enterprises (SMEs), thus contributing to local economic growth. The new SMEs extend to a variety of economic sectors including trade, transport (i.e., motorcycle taxi and repair services) and production of new goods.

In addition to increase in revenues, sustainable livelihood practices supporting ecosystem restoration led to the creation of new permanent jobs. In Indonesia new jobs support the implementation of canal blocking as well as the maintenance of dams, water towers and water reservoirs. The introduction of early warning systems and community emergency preparedness activities have led to the creation of additional professional opportunities, including teams monitoring hydrological levels in the peatland, two community fire-brigade groups, and emergency fire management system operators. In Haiti and Uganda, local stakeholders who received training in nursery management and reforestation practices secured new permanent job positions to support ecosystem-restoration and management.

Improved health, food security and water security related to sustainable livelihood practices are reported in all case study areas. In Haiti and Uganda, sustainable agricultural practices led to a more diverse diet and increased food security, with consequent health improvements. In India, the planting of fruit trees along wetland embankments and increased fish population also led to increased food-security and health improvements. Higher food security was reported in Indonesia by local stakeholders as a consequence of the increase in income and agricultural production associated with bio-rights financed livestock farming. A more reliable and abundant food supply and an improved diet composition has been found to lead to enhanced cognitive and physical development abilities in children [68], which in turn has significant long-term benefits in human capital development of local communities.

4.3. Equity assessment

We examined the distributional implications of the Eco-DRR interventions in relation to four dimensions: inclusivity, economic equality, participation, and capacity building. This analysis builds on the detailed catalog of benefits created through interviews with local stakeholders. Interviewees indicated benefits observed since 2018, the beginning of the project implementation. In each country interventions appear to have increased socio-economic equity by fostering inclusivity, economic equality, participation and capacity building. The positive economic benefits of eco-DRR appear to also contribute to local welfare and economic development.

4.3.1. Participation

The participation of affected local communities is central to the interventions in each case study. The restoration components of the Eco-DRR projects were specifically intended to be led, implemented, and sustained by the local communities. This included local communities identifying restoration sites, implementing soil conservation techniques, participating in restoration practices, and setting up natural protected zones to preserve them from future exploitation. Participation of community organizations was key to the success of disaster preparedness training and the establishment of response systems. In Haiti, for instance, 40 community-based organizations (CBOs) were reached by hazard response training and bioculture training programs to support reforestation. In Indonesia and India, the number of CBOs engaged in Eco-DRR implementation training were 17 and 47, respectively. In Uganda >2500 farmers were trained in nursery management and reforestation. In all locations, staff from civil society and local government organizations were also included as key participants due to their long standing technical and cultural expertise with the target area. Additionally, community members were empowered by climate-smart sustainable livelihood training which allowed them to participate in new economic activities, such as apiculture in Haiti and Uganda, and paludiculture in Indonesia.

4.3.2. Inclusivity

The interventions have been developed and implemented in an inclusive manner that aligned with the project's goal of capacity building. Local communities and community-based organizations (CBOs) were central to the planning and implementation process, with stakeholders including women, youth, and farmers playing a key role. Indigenous knowledge was incorporated into the interventions where possible (e.g., apiculture in Haiti and Uganda, fishing practices in India). Additionally, local agriculture and sustainable natural resource management supported by training programs have been promoting inclusivity by facilitating community involvement in land stewardship, at the individual and at household level, with a particular emphasis on women. Examples include *jaden lakou* in Haiti, sustainable farming in Uganda, and paludiculture in Indonesia. In India, in addition to pond pisciculture training for local community members, a training program on natural resource management, targeting 600 women, led to a significant increase in wages for the trainees.

4.3.3. Economic equality

All four interventions help to fulfill basic human rights and promote economic equity by improving socio-economic outcomes for women, children, and for the communities as a whole. As a result of the reduced disaster impacts achieved through Eco-DRR, communities will be more resilient to natural hazards and less likely to suffer economic losses from property damage and business interruptions. The overall outcome is therefore an enhanced protection of beneficiaries' rights to a home and livelihood. Reduction in vulnerability to hazards, combined with the numerous sustainable livelihood initiatives introduced in these communities, will also decrease the risk of poverty traps. The poorest and most marginalized individuals are likely to benefit the most from vulnerability reduction initiatives.

As a result of more accessible roads, due to lower meteorological risks (i.e., floods and droughts) in Haiti, India, and Uganda, and lower risk of fire in Indonesia, children's education is less likely to be interrupted by inaccessible roads preventing them from getting to school. This is particularly significant for girls whose ability to complete their education will lead to future economic empowerment and will have positive effects for generations to come. Additionally, local communities' members will be more reliably able to access key markets and employment centers, creating economic opportunity and promoting economic equality.

An additional example of economic empowerment is associated with women's engagement in new sustainable livelihood activities. In India 26 women self-help groups were trained in sustainable practices relying on the ecosystem provisioning services generated by the Eco-DRR intervention (e.g., plantation, marketing and trade of sustainably harvested plants). In Haiti, 8 women community groups were trained in traditional vegetable gardening for livelihood strengthening. As a result of the interventions, women can gain new skills and access new economic opportunities, therefore increasing their stature in their community and impact on economic markets.

The Eco-DRR interventions also promote basic human rights to clean air and food security. Ecosystem restoration initiatives in all case study areas contribute to cleaner air by mitigating pollution and CO2 emissions. In Haiti benefits are further enhanced by the consequent decline in charcoal production. Moreover, thanks to sustainable agricultural practices and increased income levels communities are already benefiting from greater food security and increased access to nutritious foods. All this will lead to healthier communities and promote human capital accumulation.

4.3.4. Capacity building

The interventions were focused on building the capacity of local organizations, municipal authorities, and communities to independently manage disaster risks in the target areas. This was achieved in all target areas by leveraging existing capacities and expertise, including indigenous knowledge, while providing additional training and resources to increase the skills and knowledge of local stakeholders. Overall, in the four locations, thousands of community members have participated in DRR training. The centrality of training and community participation to the interventions ensures that stakeholders have the necessary knowledge, skills, processes, and resources to continue these sustainable practices in the future, as well as to adapt to future challenges that may arise. Moreover, capacity building efforts are further reinforced by the successful economic outcomes described above, including sustainable economic growth, women empowerment, enhanced health and safety, and disaster risk reduction.

5. Discussion and conclusions

This study contributes to the literature assessing the economic efficiency and the equity implications of NbS for Disaster Risk Reduction. Through a participatory scientific approach involving local stakeholders, we examined four distinct Eco-DRR interventions implemented in four countries in the Global South: Haiti, Uganda, India, and Indonesia.

We performed an economic efficiency assessment including a quantitative CBA and a qualitative analysis that takes into account also non-monetary benefits. Our quantitative economic estimates show that the benefits of the Eco-DRR interventions outweigh the initial costs. Our qualitative economic analysis corroborates these findings presenting a rich catalog of long-lasting benefits associated with Eco-DRR strategies, ecosystem management, and sustainable livelihood practices.

We complemented our economic efficiency assessment with a qualitative equity assessment providing a comprehensive overview of the distributional impacts of the intervention on different socio-economic groups in the target populations. Our equity assessment indicates that the project promotes equity by enhancing participation, inclusivity, economic equality, and capacity building. The resilience interventions implemented result in significant education, health, safety and economic improvements for women, children, and economically vulnerable members of the local communities.

5.1. Limitations

The methodology adopted for the present study had to conform to the timeline of the project implementation, which imposed some time and resources constraints. With more time and resources, local socio-economic outcomes could be studied by implementing a multi-year, and ideally multi-decadal, panel survey of all households participating in and affected by the implementation of the Eco-DRR interventions. Snowball sampling techniques were employed to collect qualitative data, and local stakeholders assisted the research team to the best of their abilities. Country teams collected new data from local populations, thus also laying the groundwork for future monitoring efforts, data collection, and analysis.

Leveraging on long-term monitoring efforts, future research and CBA estimations would be enhanced by including the observed correlation between intensity of extremes and corresponding damages to properties and income losses. Such data would allow us to better ground the value of the yearly economic damages due to climatic extremes into a robust statistical framework.

Future analyses could potentially be strengthened by considering local climatological trends (i.e., weather conditions averaged over a period of at least 30 years), and the historical frequency (i.e., probability of occurrence) and magnitude of climatic extremes (i.e., El Nino and Climate Change). However, by affecting biological, physical and economic systems, climate change inevitably engenders uncertainty in forecasts and forward-looking economic estimations of net benefits. An additional source of complexity and uncertainty is related to how ecosystems will respond to climatic change with possible impacts on the effectiveness of Eco-DRR interventions; this aspect still represents a research gap [21].

The net benefits estimated in this economic efficiency assessment (i.e. CBA) are likely to be higher than our calculations indicate. There are multiple reasons for this:

- The CBA assessment considered only socio-economic benefits associated with reduced property damage and reduced GDP per capita losses. Because of data availability constraints, we could not include in the calculations other important benefits related to provisioning, regulatory, supporting, and cultural ecosystem services (e.g., increased agricultural productivity, health improvements, increased access to education, enhanced gender equity). These benefits were qualitatively discussed in Section 3.2 *Qualitative Efficiency Assessment*.
- We adopted a conservative approach and assumed that benefits associated with ecosystem protection and pollution regulation reach their maximum value 5 years after the end of the project implementation (the underlying assumption, supported by country teams, is that the ecosystems will reach maturity at that point). However, this is a strong assumption and in some of the case studies this might lead to an underestimation of the actual benefits. For instance, in India a large portion of the almost 4,000 ha wetland covered by this project is already a mature ecosystem. Indeed, besides ecosystem-restoration the project is enhancing the conservation and protection of the existing wetland, which is already generating ecosystem services.
- We estimated an overall carbon storage of >1.8 million tons once the ecosystems are fully matured, which is equivalent to >150 M USD (iTree estimates). The CBA models used in this study did not include the value of carbon permanently stored in the ecosystems, it considers only annual carbon capture and sequestration flows. If this value was included the benefits would be significantly higher than the ones reported.

Because of these reasons, the interventions could be even more beneficial to local communities than estimated in the quantitative efficiency assessment (i.e., CBA). The qualitative efficiency assessment that complements the CBA mitigates these limitations by providing evidence of the additional numerous benefits reported by local stakeholders. Even though these additional benefits could not be measured in monetary terms in the time frame available to the research team, they do have significant positive implications for local communities and could be monitored and measured in the future.

5.2. Contributions and future research

Despite these methodological and resource limitations, this study provides valuable insights into the economic efficiency and distributional outcomes of NbS for reducing disaster risk.

Limited scientific evidence on economic performance of Eco-DRR appears to be a major obstacle to the transformative upscaling of such interventions [21,30]. In their global review of studies performing an economic evaluation of NbS for disaster risk reduction, Vicarelli et al. [21] found that cost-benefit analysis techniques were adopted only in 22 % of studies; moreover, only a subset followed best practices such as using multiple discount rates (37 %) and considering multiple time horizons (16 %) for robustness checks. From a methodological standpoint, by incorporating both an economic efficiency assessment and an economic equity assessment, this study contributes to the development of a comprehensive analytical frameworks to catalog, measure, compare, and communicate the benefits and costs of Eco-DRR to support better-informed projects. The large amount of qualitative data and quantitative data obtained from interviews of local stakeholders contributed to the strength and relevance of our analyses.

Our results corroborate the growing global scientific evidence that ecosystems conservation and restoration contribute to mitigate hazards through ecosystem protective services [3]. In each country, our results also confirm that NbS can generate positive synergies between reduced disaster risk, enhanced climate resilience, and broader ecological and social outcomes [4]. Indeed, we observed enhanced sustainable livelihoods, increased health, equity, participation, social inclusion and capacity building in each one of the sites.

The restoration and preservation of native species was a key component in the NbS analyzed in this study. Biodiversity conservation and restoration has been highlighted in international fora as one of the main co-benefits of NbS [6,10,69,70]. However, in their global review of cost-effectiveness of NbS for disaster risk reduction [21] found that this aspect was not widely investigated by peer-reviewed literature. Only 48 % of articles in their global review stated that the ecosystem conservation or restoration program analyzed increased biodiversity, and very few examined biodiversity benefits from an economic standpoint. Every Eco-DRR implementation site in this study reported an increase in biodiversity and carbon capture and sequestration. These outcomes are further evidence that NbS can simultaneously enhance biodiversity and

BS Impacts and Implications:

Please note here how your paper addresses Environmental, Economic, and Social concerns. Each paper is required to have at least 2 of these 3 topics addressed in a bullet point of no >50 words each. Addressing all 3 topics (in one bullet point each) is preferred and reflects the scope of the journal.

Environmental concerns

This study performs an economic efficiency and equity analysis of Ecosystem-based Disaster Risk Reduction (Eco-DRR) interventions in Haiti, India, Indonesia and Uganda. The first step of our analysis focuses on the environmental and ecosystemic benefits of the Eco-DRR interventions studied (i.e., enhancements in provisioning, regulatory, supporting, and cultural ecosystem services).

Economic concerns

For each ecosystem-based intervention studied, an economic efficiency assessment was performed through a quantitative Cost-Benefit Analysis comparing implementation costs and economic benefits. Our quantitative analysis is strengthened by the analysis of additional benefits qualitatively reported by local stakeholders and associated with provisioning, regulatory, supporting, and cultural ecosystem services.

Social concerns

An analysis of the distributional effects of the interventions among local populations complements our economic efficiency assessment. We examined how the Eco-DRR interventions enhanced social inclusivity, economic equality, participation, and capacity building among local stakeholders. Dimensions studied include education, health, economic empowerment, and safety.

contribute to climate adaptation and mitigation, when they are grounded in sound biodiversity science [5,6]. Eco-DRR, and more generally NbS, are emerging as important instruments to address the combined climate-biodiversity crisis.

This study contributes also to the limited literature on the equity and social justice dimension of NbS. Indigenous groups and local communities may have an important role in protecting/conserving ecosystems, and NbS policies may have significant socio-economic impacts on these populations. However, the nexus between NbS and indigenous groups and local communities is seldom analyzed in peer-reviewed literature [21]. In our qualitative equity assessment, we carefully examined the role of indigenous knowledge in Eco-DRR and sustainable livelihoods. We also examined community participation, inclusivity, economic equality, and capacity building and found improvements in each of these dimensions thanks to the NbS.

Among the many positive social outcomes, we found evidence of more reliable and abundant food supply and an improved diet composition thanks to both decreased vulnerability to hazards, increased income, and enhanced ecosystem provisioning services. Hazards-related changes in nutrition in utero and early childhood have been found to negatively affect cognitive and physical development abilities in children [68], which in turn has significant long-term effects on the human capital development of local communities. More broadly, negative hazard-related conditions in early-life stages have considerable consequences that remain into adulthood; impacts have been found to importantly reduce school attainment [71,72], affect employment [73], and reduce income and wealth [72,74]. By reducing vulnerability to hazards in local communities the NbS analyzed have the potential to mitigate these negative effects. Moreover, by improving nutrition and income the NbS also generate positive long-term, multi-generational, socio-economic outcomes.

Based on all these findings the Eco-DRR initiatives analyzed appear to have greater potential than engineering based solutions by contributing to numerous sustainable development goals (SDGs): No poverty (SDG 1), Zero hunger (SDG 2), Good health and well-being (SDG 3), Quality education (SDG 4), Gender equality (SDG 5), Clean water and sanitation (SDG 6), Decent work and economic growth (SDG 8), Industry, innovation and infrastructure (SDG 9), Reduced inequalities (SDG 10), Sustainable cities and communities (SDG 11), Responsible consumption and production (SDG 12), and Climate action (SDG 13).

Recommendations for future research, if more resources were available and a longer time frame for data collection and analysis was possible, include monitoring the project areas to measure the observed efficacy of the local Eco-DRR interventions in limiting disaster risks. Since the project is in its early stages, there is growing but not ample quantitative empirical evidence of the protective power of the Eco-DRR interventions implemented in the project area. In five to ten years, the collected data could be used to perform a broad and empirically rigorous project evaluation.

Thanks to knowledge dissemination and engagement with local partners, our quantitative analysis lays the foundation for a possible future broader CBA of the Eco-DRR interventions in the case study areas. Indeed, as part of the project the research team created learning materials and organized a learning workshop for the country teams to allow local stakeholders to update the analysis as the project develops, and to conduct independent analyses of future projects.

CRediT authorship contribution statement

Marta Vicarelli: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing, Funding acquisition. **Anamaria Georgescu:** Conceptualization, Data curation, Investigation, Methodology, Visualization, Writing – review & editing. **Karen Sudmeier-Rieux:** Conceptualization, Resources, Visualization, Writing – review & editing, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.nbsj.2024.100196.

Data availability

Data will be made available on request.

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