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Risk-based benefit-cost analysis of ecosystem-based disaster risk reduction with considerations of co-benefits, equity, and sustainability

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ABSTRACT

Ecosystem-based disaster risk reduction (Eco-DRR) measures are gaining attention as creative solutions to reduce community vulnerability against risks while providing multiple co-benefits. We evaluate an Eco-DRR, an afforestation effort, *Boca de Sapo* (hereafter, BdS), in a marginalized community in peri-urban Lima where we perform household surveys and key informant interviews. To estimate the economic viability, we design a benefit-cost analysis (BCA) and include probabilistically estimated DRR benefits and place-based economic and non-market co-benefits representing stakeholder values. Accounting for income differences, we incorporate equity weights to estimate social welfare benefits. We then evaluate BdS impacts based on BCA results and stakeholder responses along broader sustainability dimensions, and benchmark the project's contribution to urban sustainability using two international frameworks. Household surveys revealed high concern for rockfall risk, and a double-bounded contingent valuation indicated an average household willingness to pay (WTP) of $\$3.44 \pm 0.49$/month for BdS maintenance. The equity-weighted risk-based BCA using Monte Carlo simulations indicated BdS was unviable considering DRR benefits with a Benefit-Cost Ratio (BCR) of 0.06 ± 0.08. BCR estimates increased to 1.18 ± 0.42 with incremental integration of tangible property rights co-benefits, and to 1.70 ± 0.59 with addition of WTP representing non-market co-benefits. Our findings demonstrate that inclusion of the multiple Eco-DRR place-based, socio-cultural, and ecological co-benefits with primary DRR benefits is critical as they generate substantial wellbeing impacts for communities. Adapting a sustainability lens revealed holistic Eco-DRR outcomes including access to public green spaces, social inclusion, stronger resource governance, and health and wellbeing benefits, highlighting areas for improvement and pathways for adaptive governance.

1. Introduction

Spatially and socioeconomically marginalized populations in urban areas across the world (also called informal settlements in developing countries) tend to be located in hotspots of natural and anthropogenic hazards (Wisner and Uitto, 2008; UN-Habitat, 2016; Abunyewah et al., 2018). Human drivers such as escalating urban migration, poor planning and governance, environmental degradation, policy uncertainty, and lack of disaster preparedness converge to increase disaster risk and vulnerability in these communities (Renaud et al., 2013; Anderson et al., 2014). Risk exposure along with socio-economic vulnerability exacerbates the inequities faced by the urban poor, already living without access to basic services and safe housing in informal urban spaces (UN-Habitat, 2016). Despite the increasing investment in disaster risk management, funding allocation for pre-event disaster risk reduction (DRR) by cities and development organizations remains insignificant, leading to risk accumulation (Anderson et al., 2014; Gilbert and Ayyub, 2016).

Strategies for DRR traditionally rely on structural measures such as seawalls and retaining walls that are faster to implement and demonstrate effective hazard risk mitigation via quantitative risk assessments (Jones et al., 2012; Moos et al., 2018). Techno-centric measures, however, represent the typical hazard-by-hazard risk management approach, ignoring the deeply interlinked and systemic nature of disaster and climate change related risks (Kelman, 2017; UNDRR, 2019). Highly resource- and capital-intensive, structural measures are often disruptive to ecological processes and further increase vulnerability of

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people and ecosystems (Jones et al., 2012; Renaud et al., 2013, 2016; Depietri and McPhearson, 2017; Markolf et al., 2018; Moos et al., 2018).

In response to the need for more sustainable, low-cost, and multi-beneficial solutions supporting resilience, some at-risk cities are adopting ecosystem-based disaster risk reduction (Eco-DRR) measures that address the primary DRR challenge along with enhancing social and ecological wellbeing (Cohen-Shacham et al., 2019). Part of the wider group of Nature-based Solutions (NbS), Eco-DRR measures conserve, restore, manage, or even create novel ecosystems such as mountain forests, hillside vegetation, wetlands, floodplains, mangroves, and coral reefs, decreasing vulnerability against multiple risks by reducing exposure to hazards and increasing adaptive capacity (Estrella and Saalismaa, 2013; Chausson et al., 2020; Seddon et al., 2020). Most notably, Eco-DRR delivers multiple co-benefits including improved biodiversity, air and water quality, carbon sequestration, recreation, heat mitigation, livelihoods, social cohesion, and physical and mental health (Jones et al., 2012; Keeler et al., 2019). In marginalized urban communities where disaster risk exposure and climate change add to and interact with pre-existing socio-economic vulnerabilities to further exacerbate inequities, Eco-DRR offers opportunities to cost-effectively increase urban resilience and sustainability.

However, to justify investments in Eco-DRR, at-risk cities and development organizations need actionable information about expected benefits and evidence regarding economic viability—proof that Eco-DRR project benefits outweigh costs (Kousky and Walls, 2014; Moos et al., 2018). Worldwide, DRR investments rely on benefit-cost analysis (BCA) as a robust decision-making tool in policy analysis. BCAs adjudge projects economically viable when the Net Present Value (NPV), i.e., project net benefits discounted to present values, is positive, and the Benefit-Cost Ratio (BCR) is greater than 1. These simplified metrics of monetized benefits are relatable communication tools to which decision-makers and public are widely receptive. However, with few exceptions (IFRC, 2011; Vandermeulen et al., 2011; Tuan and Tinh, 2013; Kousky and Walls, 2014; Golub and Golub, 2016), BCAs perpetuate the notion of structural DRR as the more economically viable option than Eco-DRR by failing to account for multiple ecosystem service benefits (ESBs) and equity implications (Lo, 2016). We address key limitations of BCAs that promote shortsighted and siloed approaches to risk management as outlined below.

First, disaster risk is a function of the probability of the physical hazard (magnitude and frequency), the exposure of people and property, and the vulnerability to damage resulting from socio-natural events (Anderson et al., 2014). When analyzing risk, BCAs must capture the variability of the low-probability, high-impact events through probabilistic risk assessments to avoid overestimation of benefits (Mechler, 2016). Additionally, Eco-DRR mitigation varies as dynamic ecosystems respond non-conformingly and non-linearly in space and time to physical forces, climatic changes, and local conditions (Whelchel et al., 2018). Consequently, there is a dearth of studies establishing biophysical evidence of Eco-DRR mitigation (such as Narayan et al., 2016), especially from countries of the Global South (Sudmeier-Rieux et al., 2021). By neglecting risk variability and uncertainty in ecosystems' mitigation effect, conventional BCAs weaken the reliability of Eco-DRR assessments.

Second, despite their objective to improve social welfare or the collective wellbeing of individuals, BCAs reaffirm society's misguided focus on wealth by estimating DRR benefits through avoided losses alone, raising concerns of equity (Kind et al., 2017). Conventionally, potential economic losses of disaster impacts are measured by aggregating values of damages to buildings, infrastructure, production, and equipment (Mechler, 2005). Valuing aggregate assets and production losses as the only disaster losses ignores the disproportionate impacts disasters have on the wellbeing—consumption, health, education, livelihoods, and standard of living—of low-income marginalized communities. The same value of monetary loss has a higher negative impact on the poor, who suffer far greater wellbeing losses post-disaster than the non-poor (Hallegatte et al., 2017). Consequently, BCA-led decisions prioritize structural DRR projects that protect property and high-value assets in wealthier neighborhoods, while low-income and marginalized communities remain disproportionately unprotected against rising disaster risks (Tate et al., 2016; Hallegatte et al., 2017; Siders, 2019).

Third, the narrow-visioned focus of BCAs on wealth and property values excludes the wide spectrum of socio-economic, ecological, and cultural benefits derived from Eco-DRR. ESBs such as improved biodiversity, human health, aesthetics, and recreational benefits have no explicit market price associated with them and hence are difficult to quantify. Over the past decades, economists have developed several innovative ecosystem valuation techniques, each with their own strengths and weaknesses (Freeman et al., 2014; Lo, 2016). However, few BCA studies include valuation of NbS co-benefits (Haase et al., 2014; Rogers et al., 2019). Undercounting the multiple ESBs risks exclusion of these values from decision-making and ultimately leads to policies that reduce social welfare (Munang et al., 2013; Keeler et al., 2019; Rogers et al., 2019).

In this study, we demonstrate that actionable information on Eco-DRR can be produced through a nuanced risk-based BCA that includes DRR and a spectrum of place-based and non-market co-benefits, followed by a comprehensive sustainability assessment. Our case study is a marginalized vulnerable neighborhood of 231 households, El Volante, in Independencia Municipality (hereafter, Municipality) in peri-urban Lima, Peru (Fig. 1). To curb uphill sprawl and reduce disaster risk, an NGO, PREDES (the Centro de Estudios y Prevención d Desastres), the Municipality, and community members cultivated a ~14-ha urban forest, *Boca de Sapo* (hereafter, BdS), on the mountainside above the burgeoning El Volante (Fig .2a,b). The United States Agency for International Development's Office of Foreign Disaster Assistance (USAID/OFDA), now the USAID/Bureau of Humanitarian Aid or USAID/BHA, funded the project as part of their Neighborhood Approach Program. The 3500-plant urban forest with seven native species was established 2015–2018 (Food and Agricultural Organization, 2018). The Municipality plans to replicate the BdS, now a “Sustainable Ecotourism Park” by a 2016 mayoral decree, to form a larger urban green belt on the mountains bordering several communities. A holistic BdS-Eco-DRR assessment of its viability and sustainability would assist stakeholders in informed decision-making for continued conservation and expansion of the BdS.

Thus, the key research questions we address are whether the BdS-Eco-DRR project (1) is economically viable strictly based on the primary DRR benefits, and (2) contributes to larger urban sustainability goals based on a broader range of social, environmental, and economic co-benefits. First, we hypothesize that though its DRR benefits may be small in magnitude, BdS's multiple co-benefits that compellingly align with Eco-DRR's social-ecological wellbeing goals will make it an economically viable project. To understand the range of place- and context-based BdS co-benefits, we perform household surveys and key informant interviews in Lima. Survey results indicate El Volante stakeholders' three most preferred BdS benefits could be grouped into: risk reduction, property rights gains, and remaining co-benefits. Our BCA, representing stakeholder values, thus combines estimates of these three BdS benefits.

For estimating the DRR benefits, we compare El Volante's economic losses in a ‘baseline scenario’ *without* any intervention with a ‘BdS-Eco-DRR scenario’ wherein the forest reduces hazard exposure. The difference in the economic losses between the two scenarios forms the avoided losses or DRR benefit. We estimate these losses using 65 simulations of expected economic losses over 50 years, derived from Cardona (2018)'s probabilistic risk assessment of El Volante.

Key informant interviews and literature review reveal that BdS-Eco-DRR, among other risk reduction endeavors, is a significant factor in acquisition of land tenure security or property rights for El Volante houses and for the Municipality to gain jurisdiction over state-owned public lands on which the forest is now established. For the currently

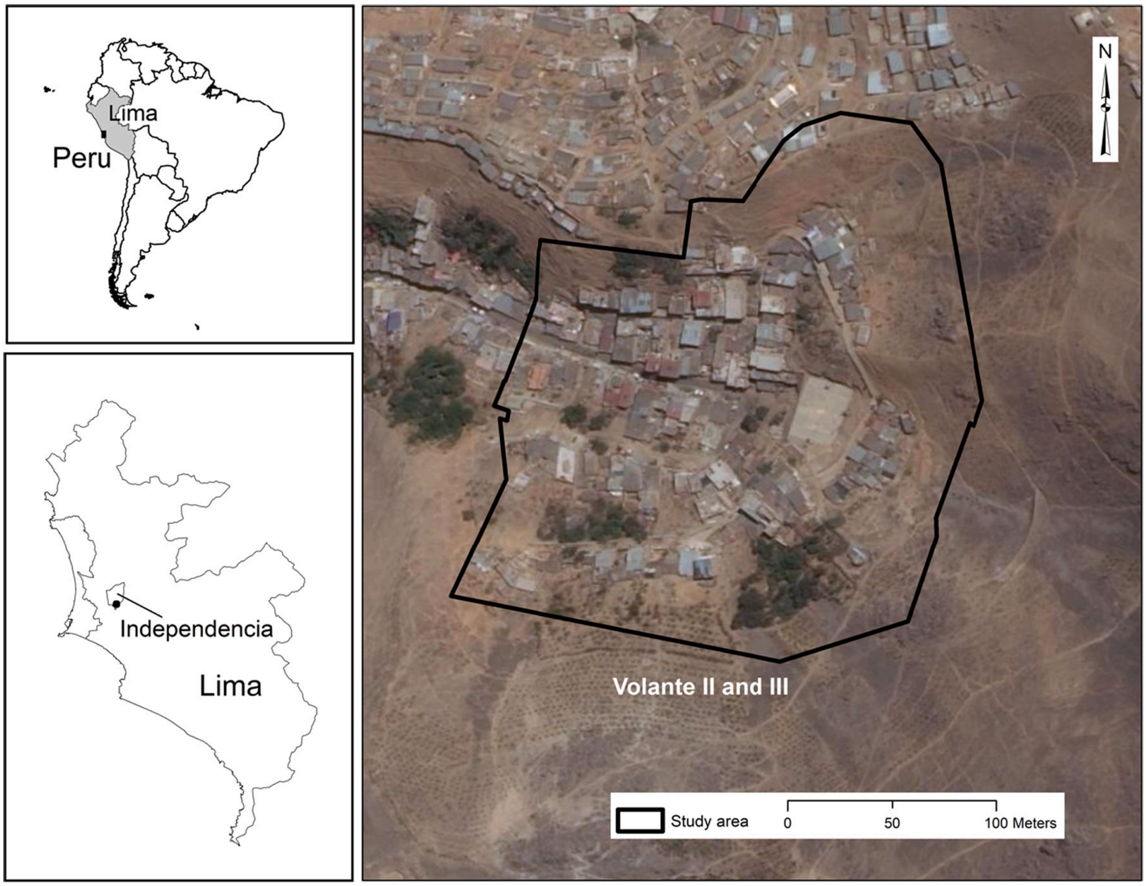

Fig. 1. El Volante neighborhood in Independencia District, Lima, Peru.

Fig. 2. a-c. 2a: El Volante in 2015 before afforestation (Picture: PREDES); 2b: Boca de Sapo urban forest on the mountainside above El Volante housing; 2c: Urban sprawl has been controlled by BdS in El Volante while neighboring San Albino housing continues to sprawl up to the mountaintop (see arrows).

untitled El Volante houses, property rights in the form of land titles are a significant place-based, tangible economic co-benefit. Using Hawley et al. (2018)'s remarkably relevant findings, we apply the benefit transfer approach to quantify BdS-Eco-DRR's apportioned impact on property rights gains in the form of increased rent value of El Volante houses.

To estimate the value of the remaining range of co-benefits, we use our survey results on household willingness to pay (WTP) for BdS maintenance. However, WTP represents the stakeholders' perception of BdS's total economic value (TEV) including risk reduction, property rights gains, and multiple other benefits. Using results of households' preference ranking of BdS-ESBs from our survey, we developed criteria weights to calculate the proportion of WTP representing the remaining non-market co-benefits. Our BCA thus combines three BdS benefits estimates: DRR benefits or avoided losses, the place-based co-benefit of property rights gains represented by increase in rental values of El Volante houses, and the weighted WTP for the remaining non-market co-benefits. The application of the BdS-ESB criteria weight on WTP values avoids double counting in our BCA model.

Next, we counteract the insensitivity of traditional BCAs to distributional consequences by applying equity weights, derived using a utilitarian social welfare function, to BdS benefits accruing to El Volante households. Inclusion of equity weights accounts for the marginal value of income for the low-income marginalized stakeholders and aligns with welfare economics' ethical approach for social welfare (Kind et al., 2017). Then, aggregated and discounted benefits and costs are compared. As a last step in the BCA, we design a stochastic model to capture the multiple sources of risk and uncertainty and use the Monte

Carlo approach for sensitivity analysis to calculate more robust probabilistic distributions of NPVs and BCRs.

To answer the second research question, we hypothesize that the BdS-Eco-DRR, by reducing risk and improving social-ecological wellbeing, ultimately contributes to urban resilience and sustainability. Urban sustainability, a normative concept, is the equitable use and management of resources to guarantee the wellbeing of current and future generations (Elmqvist et al., 2019). To understand the degree to which the BdS-Eco-DRR project addresses the environmental, social, and economic dimensions of urban sustainability, we first evaluate the project's performance in each dimension. Then, we benchmark BdS-Eco-DRR impacts against two international evaluation frameworks: IUCN's Global Standard for NbS and United Nation's Sustainability Development Goal 11 (SDG 11). The former is a facilitative guide for design, implementation, and evaluation of NbS projects with (three) criteria that define project sustainability (IUCN, 2020). SDG 11, "Make cities and human settlements inclusive, safe, resilient and sustainable" (United Nations General Assembly, 2015), includes indicators to evaluate progress toward urban sustainability and resilience. The critical analysis offers an insight into BdS's potential contribution to urban resilience and sustainability.

With growing need for resilience measures in at-risk communities, our study provides guidance in evaluating the economic viability and sustainability of Eco-DRR that local governments and funding agencies can use to justify investments. Our comprehensive Eco-DRR assessment emphasizes two important findings. First, though robust, risk-based BCAs may be inadequate in Eco-DRR evaluation, especially in marginalized vulnerable communities. Inclusion of the multiple Eco-DRR social, cultural, economic, and ecological co-benefits for their substantial social-ecological wellbeing impacts, and of social welfare benefits of vulnerable communities is critical to improving economic viability outcomes in risk-based BCAs for Eco-DRR projects. Second, an urban sustainability lens reveals the holistic social, economic, environmental, and equity outcomes of Eco-DRR, highlighting areas for improvement and pathways for adaptive governance.

Following this introduction, we present the study area and our research methods in Section 2. Subsequently, in Section 3, we present and discuss results, and conclude in Section 4.

2. Methods

2.1. Study area background: marginalized communities and disaster risk accumulation

In Peru, as in the rest of Latin America, a complex phenomenon of contested property rights and unclear jurisdictions rooted in its colonial history perpetuates socioeconomic inequities. Overwhelmed with rapid urbanization, Lima Metropolitan City, with more than 10 million residents, has failed to keep pace with the demand for safe, low-cost housing, a fundamental element of resilient communities. In desperate search for affordable housing, about a million migrants have been forced to settle on the steep Andean mountainsides toward Lima's northern periphery (Fig. 1). These public hillside lands, owned by the central government, but with weak oversight, are outside the purview of local governments. Migrants settle on these contested lands that are cheaper to obtain but exposed to frequent rockfall, landslides, and earthquakes (Sarmiento et al., 2018; Hawley et al., 2018; Almaaroufi et al., 2019).

El Volante in Lima offers a microcosmic view of the multilayered risks faced by low-income marginalized vulnerable urban human settlements. The El Volante neighborhood (295 people/ha) in Lima's Independencia Municipality is located over steep Andean slopes (10°–20°) (Fig. 2a). A lone access road begins at the foot of the mountain from the oldest established neighborhood, Volante I (130 households), crosses Volante II (70 households), and ends just before Volante III (31 households), the most recent settlement. Episodic settlements have gradually increased exposure of people and property to socio-natural risks (Sarmiento et al., 2018).

El Volante falls under high risk for earthquakes (252 cm/s^2) for a 1500-year return period, and Volante II and III lie in 'high' and 'very high' susceptibility of landslide occurrence (Cardona, 2018). A local hazards field study (Ruiz Cubillo in Sarmiento et al., 2018) identified El Volante's exposure to complex rockfall events and rare events like rainfall-triggered *huaycos* (mudslides). Typical zoning prohibits housing on landslide-prone slopes exceeding 14° (Schuster and Highland, 2007). However, El Volante's dense substandard housing built without code at 250–330 m above sea level on unstable slopes >20°, makes the community highly vulnerable to landslides and rockfall (Ruiz Cubillo in Sarmiento et al., 2018).

The spatial exclusion of migrant populations to informal spaces compounds socio-economic vulnerabilities. Besides lack of basic services and public green spaces, households lack land tenure security or property rights, i.e., legal ownership of their house and land. Insecure tenure often leads to forced evictions, loss of housing, land, and livelihoods (Fernández-Maldonado, 2008; Sarmiento et al., 2020). Unsafe housing conditions add to disaster vulnerability (Reale and Handmer, 2011). Disaster aid and recovery programs are conditional to households with tenure, increasing post-disaster vulnerability for informal dwellers (Boano, 2009; Caron et al., 2014; Jahn et al., 2016). The spatial-social-economic exclusion from urban resources keeps marginalized communities, such as El Volante, entrenched in intransigent cycles of poverty, with pressing concerns of social and environmental justice (Almaaroufi et al., 2019; UN-Habitat, 2020).

To address the socioeconomic impacts of the lack of tenure in human settlements, Peru's urban property rights reform began to be implemented by the Organization for Formalization of Informal Property (COFPRI) in 1996 (Hawley et al., 2018). This legal titling process normally takes five years and may be incremental. Additionally, local municipalities can propose urban infrastructure improvement plans to gain jurisdiction over the by-default nationally-owned public lands, and request increased property rights for households in informal settlements.

A hedonic analysis by Hawley et al. (2018) using a Peruvian national survey dataset (2007–2012) determined that gaining property titles increased property values by an average 7% nationally and monthly rent values of informal houses by 8.4% in Lima. Thus, with property rights gains, households experience immediate monetary gains on the market value of their land within the informal real estate market that operates in these settlements. Additionally, increase in property rights can lead to increased revenue for local governments (Hawley et al., 2018). A sizeable scholarship relates improvement in, or acquisition of, property rights with improved socio-economic outcomes such as improvement in employment and income for adults and decrease in child labor (Field, 2007), gender empowerment (Field, 2003), improved child health and education, and lower teen pregnancy rates, smaller households, and increased investments (Galiani and Schargrodsky, 2004, 2010, 2011; Field, 2005).

Collaborative efforts of the Municipality with organizations such as PREDES and USAID/BHA in recent years in El Volante led to building infrastructure like pathways and retaining walls, regulations, and finally, the establishment of the BdS. Perceived as a positive risk management measure, the BdS has halted the sprawl of unsafe housing in the risk-prone area. Based on these improvements, the Municipality was able to obtain jurisdiction from the national government over the hitherto contested public lands on which BdS is cultivated. The Municipality's request also led INDECI, Peru's National Institute of Civil Defense, to endorse the initiation of land titling process for 101 Volante II and III houses as part COFOPRI's property rights reform.

2.2. Study approach

We adapted a mixed method approach that entailed using: (i) probabilistic simulations of expected economic losses from rockfall and landslides for El Volante from Cardona (2018), (ii) household survey data of community's perception of risk and ESBs, and household WTP to maintain BdS, (iii) key actors' perceptions of BdS impacts, and (iv) secondary data from Sarmiento et al., 2018 and Hawley et al., 2018. Using the above data, we designed a BCA model and a sustainability analysis which together formed our comprehensive evaluation of the BdS-Eco-DRR project. Fig. 3 shows this study's assessment framework for the BdS-Eco-DRR project. We designed the equity-weighted risk-based BCA as a stochastic model that incrementally accounted for the primary DRR benefit, place-based economic co-benefit, and remaining use and non-use co-benefits. In the sustainability analysis, we evaluated BdS-Eco-DRR project performance along key dimensions of sustainability and then benchmarked the project's potential contribution to urban sustainability against relevant indicators in IUCN Global Standard for NbS and SDG 11. Results from the BCA model also informed the sustainability analysis. The research was approved by the Office of Research Compliance at Florida International University under protocol IRB-17-0384-AE01.

2.2.1. *Risk analysis without BdS mitigation*

We used sixty-five random simulations of expected economic losses for El Volante II and III over a 50-year period each, developed using the Loss Exceedance Curves (LEC) from the underlying probabilistic risk assessment model created exclusively for this USAID-funded study by the engineering firm INGENIAR, represented by Cardona (2018). The LEC represented El Volante II and III's property loss risk through a probabilistic distribution of expected losses. Each loss simulation was created by sampling random values on the loss and inter-event time distribution of the LEC and designed such that even though losses do not occur every year, a loss of at least \$10,000 or more occurred once in a 50-year timeframe (in 2019 USD). The overall distribution of the loss is the first derivative of the loss exceedance curve, divided by the exceedance rate of zero and multiplied by −1. The loss amount was sampled using the inverse sampling method, widely used for individual random variables. The inter-event times were sampled from the exponential distributions obtained directly from the LEC, the exceedance rate being the parameter of the said exponential distributions (email communication, INGENIAR, 2020).

The monetary losses were computed under two baseline scenarios without BdS mitigation (Table 1): (a) *Baseline Scenario-1* represented the risk of potential monetary losses for Volante II and III in the absence of an intervention and a stable housing stock. Under this scenario, El Volante housing stock was held constant at 231 households (as in 2019), with community risk from earthquakes and landslides that triggered rockfall. (b) *Baseline Scenario-2* represented the additional risk of sprawl in the absence of BdS. We assumed that El Volante III would continue to grow uphill, mirroring the observed rate of sprawl from 2010 to 2015 (31 houses in 5 years). By 2030, we assumed 90 more houses would occupy the hillslope, resulting in a total 39% increase in housing stock. The increased exposure led to additional losses in our BCA model. Under each of the above scenarios, Cardona (2018) provided possible economic losses for high frequency–low impact to low frequency–high impact events, considering the exposure, vulnerability, and economic value of El Volante housing.

2.2.2. *Household surveys and contingent valuation*

We conducted household surveys ($n = 100$) in El Volante I, II, and III neighborhoods in Independencia, Lima, in July 2019. We viewed this sample sufficient as it constituted more than 40% of the total population of households. The survey, in Spanish, was tested with Spanish speakers and implemented through six local enumerators.

The survey explored households' perception of disaster risk from rockfall and landslides with responses to four statements on a five-point Likert scale (1 = 'Strongly Disagree' and 5 = 'Strongly Agree') (Table 2a). These questions asked if households thought rockfalls and landslides could occur in their community in the future, and if so, whether such events would affect their household's and community's daily life. Respondents were asked to rate the importance of ESBs they expected to derive from BdS, on a five-point Likert scale (1 = Not important and 5 = Very important) (Table 2b).

Respondents were also asked to rank the top three ESBs from a given list of 10. We grouped stakeholder-preferred ESBs into three sets, (a) risk reduction (b) property rights gains; and (c) remaining non-market

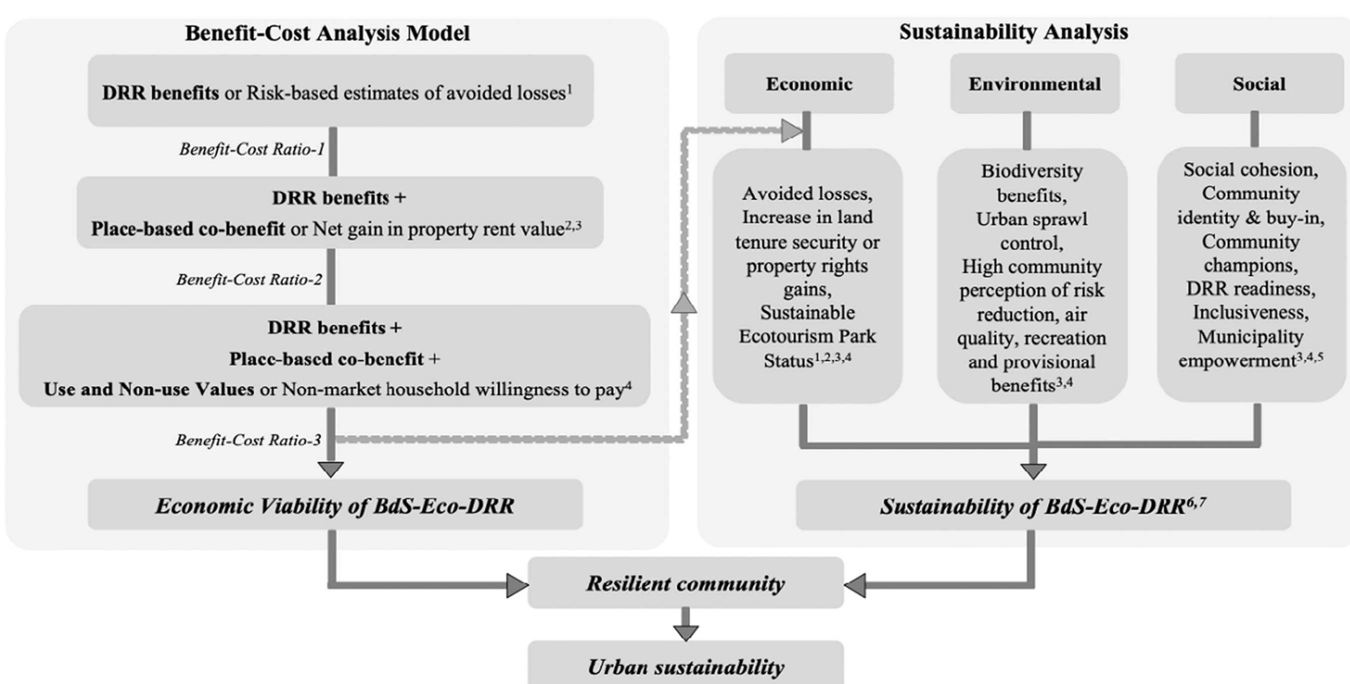

Fig. 3. Assessment framework for *Boca de Sapo* Ecosystem-based Disaster Risk Reduction (BdS-Eco-DRR) project.
Notes: Superscripts indicate the data source of the assessment. [1]Cardona, 2018; [2]Hawley et al., 2018; [3]Key Informant Interviews; [4]Primary household surveys; [5]Sarmiento et al., 2018; [6]IUCN, 2020; [7]United Nations General Assembly, 2015.

Table 1
Benefit-Cost Model for BdS-Eco-DRR: project scenarios, cost and benefit variables, model parameters, and decision measures.

Scenarios		Costs	Benefits	Probabilistic and fixed parameters used in Monte Carlo simulations			Economic Efficiency Measures
Without BdS	**Baseline-1:** Potential losses			65 50-year random loss simulations[1]		Real Discount Rate[2], *r,* uniform distribution (2%–6%)	
	Baseline-2: Potential losses + Uphill sprawl			Rate of uphill sprawl: fixed (39% in 11 years)			
BdS-Eco-DRR Scenario	**BCA-1**	Direct and indirect voluntary costs, 2% annual maintenance costs	**Benefit-1** = DRR benefit / Avoided losses	Risk Mitigation Factor, ρ, uniform distribution (10%–30%) Biomass Growth Index, δ	Income equity weight, ω, (3.77)		BCR-1 NPV-1
	BCA-2		**Benefit 2** = DRR benefit + Net gain property rent value	Net gain property rental value, normal distribution (Mean $8582, SE 1.7%) BdS-Eco-DRR contributing factor, μ (20%–40%)			BCR-2 NPV-2
	BCA-3		**Benefit-3** = DRR benefits + Net gain property rent value + non-market WTP	WTP: normal distribution (mean $3.44, SE 0.49) Stakeholder preference-based Ecosystem Benefit Criteria γ, fixed (0.29)			BCR-3 NPV-3

Notes: All costs and benefits in 2019 USD; Timeframe for analysis was 50 years [1]Loss simulations were derived from El Volante II & III's Probabilistic Risk Assessment, Cardona, 2018. More explanation in Section 1.2 and 2.5.1; [2]The discount rate range was centered around the real gross rate of return for Peru, 4.2% (Freudenberg and Toscani, 2019).

Table 2a
Perception of disaster risk among El Volante residents.

Risk Perception Question: Please respond to the following statements using a scale of 1 to 5, with 1 being "Strongly Disagree" and 5 being "Strongly Agree".			
Risk perception	n	Mean	Std. Dev.
It is likely that rockfalls or landslides occur in my community periodically in the future	100	4.27	1.1
A rockfall or landslide event in my community is likely to affect me and cause damage on my property		4.2	1.21
If a rockfall or landslide event affects my property, it will also affect my daily life for several days or weeks		4.25	1.14
A rock failure or landslide, in addition to affecting family, will also affect the daily life of the entire neighborhood		4.32	1.02

Table 2b
Perception of BdS Ecosystem Service Benefits (ESBs) among El Volante residents.

Ecosystem Service Benefits (ESB) perception	n	Mean	Std. Dev.
Prevent rockfall and landslides	99	4.51	1.08
Prevent soil erosion	94	4.03	1.1
Provide slope stability	95	4.25	1.07
Provide sense of security against natural hazards	98	4.24	1.24
Prevent new land occupations	98	4.57	0.97
Increase the value of my home/property	98	4.14	1.19
Reduce Air Pollution	97	4.56	0.76
Provide fruits, seeds, wood	95	3.77	1.44
Provide a place of rest and recreation	95	4.19	1.14
Give me a sense of community and identity	92	3.87	1.37

values. We used rank reciprocal ranking, a subjective weighting method, calculated as normalized reciprocals of the criteria rank (Odu, 2019) to create ESB criteria weights, reflecting stakeholder preference for each group of benefits. The resulting stakeholder-preferred ESB criteria weights indicated that of the TEV that households assign to BdS-ESBs, the proportional value of DRR benefits, α, was 0.41, property value gains, ϵ, 0.30, and non-market values, γ, 0.29. The sum of the three weights added up to 1.

The contingent valuation (CV) is a widely accepted, direct, non-market valuation method to elicit people's preferences from their stated responses to hypothetical questions, making it possible to capture the use and non-use values of the concerned ecosystem (Islam et al., 2019). The survey questionnaire included a double-bounded dichotomous choice (DBDC) CV question (Tiller et al., 1997), with two bid questions that asked for a yes/no response to whether the sample households would be willing to pay for BdS's maintenance. The second bid or follow-up question created a lower and upper bound/limit on the respondent's unobserved true WTP, reducing the variance of the estimate. The probability that a respondent is likely to say yes is assumed to be dependent on a variety of independent variables (Hanemann, 1984) and follows the logistic regression model:

$$P\ (Yes) = \frac{1}{1 + e^{-(b_0 + \beta A + X\phi + \varepsilon)}} \tag{1}$$

where e is the base of natural logarithms, b_0 is the intercept, β is the coefficient of bid variable A, X is the vector of all other independent variables, ϕ is the vector of respective slope parameters, and ε is the error term. The median WTP is calculated by using the estimated parameters from (1):

$$WTP = \frac{b_0 + \overline{X}\phi}{\beta} \tag{2}$$

where $\overline{X}$ represents the vector of average values of the independent variables.

In the initial bid, the amount of money (in soles) was randomly chosen by the enumerator from a given array of 2–20 soles ($0.58–$5.8). The value of the follow-up bid was doubled if the response to the first bid was 'yes' and halved if the response was 'no'. The mean household WTP was calculated using 77 survey respondents' data with valid initial and second bid responses using Lopez-Feldman (2013)'s DOUBLEB command in STATA. (For the theoretical model see Lopez-Feldman, 2013.)

2.2.3. Key informant interviews

We conducted 11 semi-structured face-to-face key informant interviews in Lima, with key actors in three entities involved with the BdS project: Municipality of Independencia, $n = 2$ included the former environmental manager (2014–2018) who initiated and oversaw the project, and an official from the current environment management team; PREDES, $n = 4$ included the project manager (one email and one face-to-face interview), project coordinator, and the consultant agroforestry specialist who designed the afforestation; and the beneficiary community, El Volante, $n = 5$ included the Volante III community leader and women leaders of the local *Vaso de Leche* and *Madre* Clubs.

The interviews documented the key actors' perspectives on the project's intended goals and impacts. Interview data were translated to English and summarized through content analysis in Excel and NVivo 12, a qualitative data analysis software. Iterative readings and analysis of the interviews helped identify key project impacts.

2.3. Economic viability of the BdS-Eco-DRR intervention

Following Mechler (2016) risk-based approach, we designed a 50-year timeframe BCA model, comparing two scenarios: risk *without* mitigation and risk *with* BdS-Eco-DRR (Table 1). The risk analysis *without* mitigation was a do-nothing scenario and included (a) *Baseline-1 or no-mitigation,* and (b) *Baseline-2 or no-mitigation but increased sprawl* (Section 2.2.1).

In the BdS-Eco-DRR scenario we performed three incremental BCAs: BCA-1, BCA-2, and BCA-3. In each progressive BCA, we added a benefit incrementally. In BCA-1 we analyzed DRR benefits or avoided losses due to BdS's protective effect, or 'Benefit-1'. In BCA-2, we added the property rent value gain to Benefit-1, labelling the sum, 'Benefit-2'. In BCA-3, we added household WTP for non-market values to Benefit-2 to form the cumulative 'Benefit-3'. In each BCA step, the benefits were compared to project costs, all in 2019 USD.

Table 1 summarizes the BCA model's scenarios and their components, and model parameters with the range of possible values and their sources.

2.3.1. BCA-1: DRR benefits

The BdS was designed as a pilot project for an urban green belt on the Independencia hillsides to reduce the risk of rockfalls and shallow landslides, discourage unsafe sprawl, and form a conservation buffer zone. The BdS forestation plan design and implementation were led by an agroforestry specialist in Lima (Boca de Sapo Forest Management Plan, Gutiérrez, 2018). The forest management plan detailed the activities and practices necessary for the care, treatment, operation, and maintenance of the plants and the irrigation system. Seven native species planted included the popular *Tara spinosa* (tara) and *Opuntia ficus-indica* (tuna) for their fruits and seeds, and evergreen trees such as *Schinus molle* (Molle serrano), *Mimosa nothacacia* (Mimosa), *Prosopis pallida* (Huarango), *Parkinsonia aculeata* (Palo verde), and *Tecoma stans* (Huaranhuay) for stabilizing the slope and rockfall control.

The forest's physical presence is expected to reduce community vulnerability by reducing hazard exposure. Several studies indicate forest and vegetation cover stabilize hillslopes and reduce shallow landslides risk by increasing soil strength, preserving soil structure, decreasing water yield, and maintaining good biological structure (Douglas et al., 2011; Chirico et al., 2013; Preti, 2013; Stokes et al., 2013, 2014; Temgoua et al., 2016; Rickli et al., 2019; Arce-Mojica et al., 2019). Using Kuriakose et al. (2006), Peduzzi (2010), and Moos et al. (2018), we assumed that BdS would mitigate rockfall and shallow landslides by reducing community exposure *and* by stabilizing the slope in the long-term, by a conservative risk mitigation factor, ρ, ranging from 10%–30% to calculate avoided losses. We estimated DRR benefits as avoided losses by calculating the difference between the expected losses *with* BdS mitigation (i.e., rockfall loss mitigation and no further sprawl) and *without* BdS, using Baseline-2 (i.e., rockfall loss without mitigation and with increasing sprawl).

We assumed BdS's DRR benefits, generated through its regulating ecosystem services (soil stability, erosion prevention) would not be realized immediately but increase with forest biomass growth. We modeled a biomass growth index (BGI), or rate of forest biomass growth, to moderate DRR benefits such that BdS's protective ability increases with forest growth each year in the 50-year BCA model. Using biomass at carrying capacity, K, for a dry Andean region as 44.5 Mg/ha (Álvarez-Dávila et al., 2017), and maximum sustainable yield, MSY, as 10% of the stock at $K/2$, we derived the intrinsic growth rate $a_1 = 0.2$, and the rate of decrease in growth $a_2 = 0.004$, to derive the logistic growth rate, $G = a_1 * b – a_2 * (b)^2$, where b is the annual biomass stock (Nebel et al., 2001). The BGI (δ)was calculated as the ratio of annual biomass stock to biomass at K. The BGI-moderated avoided losses formed '**DRR benefits' or 'Benefit-1'** in BCA-1.

2.3.2. BCA-2: DRR and increased property rent value benefits

Key informant interviews revealed BdS afforestation, among other DRR works, led INDECI to acknowledge the containment of risk for the community and endorse the initiation of land titling process for 101 Volante II and III households as part of COFOPRI's property rights reform.

Based on Hawley et al. (2018)'s empirical study on the impact of property rights gains on informal housing in Lima, we assumed that the 101 Volante households will experience an increase in their property rent values upon gaining land titles in approximately five years. We used the benefit transfer approach to estimate the tangible economic benefit, deriving values from the highly relevant Hawley et al. (2018) study. The net increase in annual property rent values of 101 El Volante houses (average monthly rent: 266 soles with 8.4% increase), was $8582. We applied the Standard Error (SE) of $1737, from Hawley et al. (2018)'s hedonic model, in our stochastic BCA to account for uncertainty in the rental market.

As the property rights gains were a result of two other factors (infrastructure works and regulations) along with BdS, we assumed BdS-Eco-DRR's contribution to the net increase in rental values was approximately 30%. We used a factor (μ) ranging 20%–40% in the BCA model to apportion BdS-Eco-DRR's contribution to property rights gains. We added the benefit in the 10th project year for a more conservative estimate. The sum of the property rent value gain and DRR benefits formed '**Benefit-2'** in BCA-2.

2.3.3. BCA-3: DRR, increased property rent value, and non-market WTP benefits

BdS benefits are incomplete without including the preferences and perceptions of El Volante households whose daily life and future are directly affected by the Eco-DRR measure. El Volante household WTP represents the TEV of benefits residents perceive to derive from BdS for their wellbeing and comprises a wide range of use and non-use values including provisional, regulating, and cultural benefits, and market and non-market values (Krutilla, 1967; Bateman et al., 2002; Chan et al., 2011; Haque et al., 2011). Non-use and non-market values are a significant and indispensable part of TEV (Freeman et al., 2014; Sousa et al., 2019) and often instrumental in motivating stakeholders to adopt holistic actions for risk mitigation and adaptation to improve living conditions (Bain et al., 2016).

Similarly, El Volante households' WTP represents the wide spectrum of BdS benefits that can be grouped into DRR, property rent gains, and remaining non-market values. The former two benefits are accounted for in BCA-1 and BCA-2. To include the non-market value of the remaining BdS use and non-use co-benefits in BCA-3, we applied the stakeholder preference-based ESB criteria weight for non-market values (γ=0.29) (section 2.2.2) to the household WTP. The weighting segregated the value of BdS's non-market values from the total WTP and avoided double counting and overlapping of benefits in the BCA model.

The non-market WTP benefits were also moderated with the biomass growth index as we expect household WTP to increase with forest growth. The annual weighted non-market WTP values of all 231 El Volante 1, II, and III households were added to Benefit-2 to form '**Benefit-3'** in BCA-3 (Table 1**).**

2.3.4. Considerations of equity

Upon aggregating benefits in the BCA model, equity weights derived from a social utilitarian function were applied to the benefits accruing to El Volante low-income stakeholders to account for income differences.

The ethical approach in welfare economics advances income distribution, individual wellbeing, and social welfare over allocative efficiency (Sen, 1987). The use of equity weights in BCA, as recommended by the IPCC (Kolstad et al., 2014) and Kind et al. (2017), reflects the social welfare approach and the different value that money holds for different income groups in society. Based on the diminishing marginal utility of income wherein an incremental income increase has a larger wellbeing impact on those with lower income (Easterlin, 2005), higher weights are applied to low-income groups and lower weights for high income groups (Kind et al., 2017). Moreover, application of equity weights to the income-based WTP estimates of lower-income developing countries compensates for the unfair income distribution (Fankhauser et al., 1997).

Our survey data showed El Volante's average annual income per person was $1096, confirming a very low-income group in comparison to Peru's equivalent annual per capita and official minimum income at $6740, and $3308, respectively. We applied equity weights to the benefits accrued to the stakeholders, all of whom are low-income, to adjust for income differences. The project costs, borne by the international aid agency, USAID/BHA, representing a high-income source, were left unadjusted.

Layard et al. (2008) estimated the elasticity (change) in the marginal utility of income from subjective wellbeing datasets of ~50 countries from 1972 to 2005 as 1.19–1.34, with a combined estimate of 1.26. Using the average estimate of the elasticity of marginal utility of income $\gamma = 1.26$, (Layard et al., 2008) and following the utilitarian social welfare function in Kind et al. (2017), we derived the equity weight for an individual with income Y_i in El Volante for a marginal increase in income: $\omega = (Y_i/Y_{avg})^{-\gamma}$, where the marginal change in income is the first derivative of the utility function, $U'(Y) = Y^{-\gamma}$ (See OECD, 2006; European Commission (EU), 2008; Kind et al., 2017). We applied the resulting equity weight (ω=3.77) to the DRR, property rent, and non-market WTP benefits accruing to the El Volante households using the ratio of average income per person in El Volante ($1096/yr.) and the official minimum wage income ($3308/yr.).

2.3.5. BdS afforestation costs

Forest establishment costs included costs of planning, digging holes in the rocky mountain, purchase and planting of native plants, and the irrigation system. The total costs in 2019 USD included (a) direct costs to USAID and PREDES, $83,844 (2015–2018), (b) opportunity costs of community members' 3-year voluntary work, $11,940, and (c) 50-year annual maintenance (2% of initial costs).

2.3.6. Monte Carlo simulations and stochastic BCA

We designed a stochastic BCA, integrating multiple sources of risk and project uncertainty through input variables and used the Monte Carlo approach, a form of sensitivity analysis, to address the uncertainty related to the flow of BdS benefits. The distributions of the stochastic input parameters were defined using data from our survey and evidence-based studies (Table 1). We ran 10,000 Monte Carlo simulations with randomly sampled values of each of the stochastic variables to generate distributions of the economic efficiency measures, BCR and NPV. The NPV was calculated as:

$$NPV = \sum_{t=1}^{T} N_t (1+r)^{-t}$$

where N_t is the net cash flow during period t, r the discount rate, and T the total observation period. Net cash flow during the period t is calculated as:

$$N_{t,BCA-1} = \omega.\delta.DRR_t — C_t$$

$$N_{t,BCA-2} = \omega.\delta.DRR_t + \omega.\mu.PR_t — C_t$$

$$N_{t,BCA-3} = \omega.\delta.DRR_t + \omega.\mu.PR_t + \omega.\delta.\gamma.WTP_t — C_t$$

for BCA-1, BCA-2 and BCA-3, respectively, where $DRR_t$is the simulated risk reduction benefit in year t, PR_t is the net increase in property rent for 101 Volante households in year t, WTP_t is the Willingness To Pay benefit in year t, C_t is the total annual project cost, ω is the income equity weight, δ is the biomass growth index, μ is the BdS-Eco-DRR contributing factor to property rights gains, and γ is the stakeholder preference-based ESB criteria weight for non-market values. Note that WTP_t in the above calculation of $N_{t,\ BCA-3}$is adjusted by the factor γ to ensure DRR_t and PR_t benefit portions embedded in the household's WTP valuation are not double counted. The discount rate ***r*** was a range of values 2%–6%, centered around the real gross rate of return for Peru, 4.2%, used by Freudenberg and Toscani (2019), who based their assumptions thus: (a) real rates of return generally mirror the long-term real GDP growth, estimated at 3.75%–4% for Peru by the International Monetary Fund (IMF); (b) rate of return estimates by previous authors for Peru such as Alonso et al. (2015)'s 5% and the OECD/IDB/The World Bank (2014)'s 3.5%.

Three sets of BCRs (BCR-1, BCR-2, BCR-3) and NPVs (NPV-1, NPV-2, NPV-3) were generated for the three incremental benefits, Benefit-1, Benefit-2, Benefit-3, respectively. BCR-3 and NPV-3 represented BdS project's comprehensive economic efficiency measures.

2.4. Assessment of BdS-Eco-DRR's project performance and contribution to urban sustainability

To assess BdS-Eco-DRR's project performance, we collated the project impacts estimated and documented in this study as impact indicators under the three dimensions of sustainability: environmental, ecological, and social. Each BdS impact indicator was given an equal weight of 1. However, some impact indicators represented different aspects of the same benefit. For example, 'perceived risk reduction' from BdS's physical presence, social impact of 'DRR readiness', and economic 'avoided losses' are all components of DRR benefits. Therefore, we adjusted the weights of these component indicators such that they added up to 1 to avoid double counting. Similarly, 'sprawl control' that reduced environmental risk, led to economic 'property rent value' gains, and will likely result in social 'inclusiveness' or protection from forced evictions, all represent various facets of land tenure security benefit.

We then scored each indicator out of 100 and rated them as insufficient (<25), partial (≥25& < 50), adequate (≥50& < 75), or strong (≥75), using a scale adapted from IUCN (2020). Our scoring relied on this study's BCA, key informant interviews, ESB perceptions from primary household surveys, field observations, and data from three related studies (Cardona, 2018; Hawley et al., 2018; Sarmiento et al., 2018). The weighted score for each indicator was a product of raw scores and weights. The indicator scores within each dimension were normalized to have equal weightage in the overall BdS-Eco-DRR performance score.

Next, to assess BdS-Eco-DRR's contribution to urban sustainability, we aligned BdS impacts with relevant sustainability indicators in Criteria 3, 4, and 5 in IUCN's Global Standard for NbS and with relevant target indicators 1.4.2, 11.b.2, 11.5.2, 11.6.2, 11.7.1 in SDG 11 that represent evaluation standards for progress toward urban resilience and sustainability.

3. Results and discussion

Survey respondents were on average 42 years old, mostly women (69%), and of mixed race (61%). 64 of the 100 households surveyed had actively participated in afforestation activities and likely belonged to Volante III and II, located closest and next closest to BdS, respectively.

3.1. Disaster risk and ecosystem service benefits (ESB) perception

El Volante households perceived a high risk from rockfall and landslides (Table 2a). Sample respondents overwhelmingly believed that rockfall and landslide events would occur in their community (mean score = 4.27), and those events would negatively impact their property (mean score = 4.2), their daily life (mean score = 4.25) and their entire community (mean score = 4.32). Respondents also scored very high on perceived BdS ESBs, such as "prevent new land occupations," (mean = 4.57), "reduce air pollution" (mean = 4.56), "prevent rockfall and landslides" (mean = 4.51) (Table 2b). Most other ESBs also scored a mean score higher than 4.0 except "give a sense of community" (mean = 3.87).

3.2. El Volante's willingness to pay

Table 3 presents the WTP results of the DBDC model. The independent variables, namely, respondents' participation in afforestation, their sex, education, and high perception of BdS's DRR and provisional benefits had positive and statistically significant relationship with respondents' WTP for BdS maintenance. Counterintuitively, respondents' high level of risk perception (Table 2a) did not influence their WTP. The variable 'recreation', too, did not significantly affect WTP, possibly because the young BdS forest has not been developed for use yet, and hence respondents do not currently derive recreational values from it. However, other key ecosystem service variables representing provisional benefits, afforestation participation, and risk perception (an indicator for potential future risk reduction benefits) did have significant impacts on respondents' likelihood of willing to make a monthly contribution. Furthermore, the chi-square value suggested an overall goodness of fit. The model estimated the average monthly household WTP as $3.44 (SE. 0.49) (11.85 soles, SE. 1.69), or 1.2% of median household income.

Table 3
Double-Bounded Dichotomous Choice Model (DBDC) for contingent valuation: El Volante's Willingness to Pay to maintain Boca de Sapo.1, 2, 3, 4

Variable	Coefficient	Standard Error
Participation-Afforestation	7.1894**	3.6456
Risk Perception	0.9697	2.0097
Age	5.3385***	2.7736
Female	8.6302**	4.2814
Marital Status	−4.1097	3.5702
Race	−4.6181	4.0270
Education	4.3513**	2.0862
Risk Reduction	1.0484***	0.5571
Provisional	3.1627**	1.3388
Recreation	0.6847	1.4523
Community-Identity	0.4831	1.2161
Trust-in-Govt[1]	1.6244	1.2934
Resp-Govt[2]	−0.0172	1.1836
Sprawl[3]	−0.64160	1.1229
_cons	−57.1312	18.9830
Number of observations	77	
Wald chi-square (14)	23.87	
Prob > χ^2	0.0475	
Log likelihood	−98.5231	
W		

	Mean	Standard Error
WTP[4] ($/month)	3.44**	0.49

A triple asterisk (***) denotes statistical significance at the 10% level and a double asterisk (**) denotes statistical significance at the 5% level.
The STATA DOUBLEB command directly estimates the WTP value; the WTP is simply z' B.
[1] In your opinion, how likely is it that the Municipality will continue to manage BdS after 2022? (1 = Very unlikely, 5 = very Likely").
[2] If the Municipality abandons the care and management of Boca de Sapo, how likely is it that the land will be occupied by new inhabitants? (1 = Very unlikely, 5 = very Likely").
[3] The Municipality of Independencia should be maintaining, preserving, and guarding the forest Boca de Sapo completely on its own. (1 = Strongly disagree, 5 = Strongly agree).
[4] Household WTP is approximately 1.2% of El Volante median household income.

3.3. Key informant interviews

Based on key informants' observations and perceptions, Table 4 presents BdS's envisioned goals in response to community challenges, and the state of project impacts.

3.3.1. BdS goals

While the evident goal of afforestation was to reduce community exposure to rockfall and shallow landslides, the forest's role as a firm obstacle to steadily increasing unsafe housing was viewed as an integral part of DRR goals in curbing further exposure of people and property to risk. In addition to improving environmental conditions and access to public green space, BdS was envisioned as a profitable revenue-building ecotourism park. The Municipality's Office of Environment Management noted CCA as an integral project goal, suggesting the linkage between afforestation and climate change impacts was clearly envisioned.

3.3.2. Project impacts

The increased sense of protection against rockfall risk among community members, a view consistent with our household surveys, was noted by most key informants. Most significantly, BdS had successfully stabilized El Volante housing in comparison to the steady increase in settlements observed in pre-afforestation years. Meanwhile, San Albino, the community adjacent to El Volante, has continued to sprawl up the mountainside with some houses even reaching the mountain peak (Fig. 2c). Curbing El Volante sprawl was thus inextricably tied to DRR goals as BdS has the potential to reduce exposure of vulnerable housing to hazards.

The 14-ha native species-rich green public space has increased access to public green space, improved landscape aesthetics, and created potential for recreation and wellbeing. The status of a 'Sustainable Ecotourism Park' by a 2016 mayoral decree for BdS is likely to assure institutional support and project longevity.

Besides DRR, sprawl control, and environmental impacts, key informants spoke at length on BdS's positive impact on local governance processes and community interactions. With the acquisition of jurisdiction over the hillsides, the Municipality is now committed to (a) conserve, maintain, and develop the BdS as an ecotourism park for public recreation (b) enforce sprawl control in El Volante and (c) replicate the BdS model to seven other sites, creating a larger urban green belt to control invasion, reduce risk, and possibly form a biodiversity-rich buffer zone for conservation of the unique Peruvian lomas ecosystem. However, in practice, high turnover and frequent change in governments brings uncertainty to forest maintenance, according to interviewees. Informants reported lack of communication, transparency, and inclusiveness in BdS-related governance processes post-project handover by PREDES.

For the community households, the most significant impact is the imminent increase in land tenure security because of afforestation. After decades of being spatially, socially, and economically excluded from basic urban resources such as right to land, the provision of property rights could potentially lead to several socio-economic wellbeing outcomes. Lastly, the process of afforestation (2015–2018) saw the emergence of exceptional leadership and collaboration by the community toward a common goal (Table 4; Sarmiento et al., 2018). The dedicated network of actors that came together to create and implement the Eco-DRR measure continues to actively engage in BdS maintenance.

Table 4
Key informant interviews: project goals and state of impacts.

Challenges cited by informants	Goals envisioned	Impacts made by BdS, as articulated by informants
1. Risk Fear of rockfalls, shallow landslides were the primary concern identified by all informants	**Risk Reduction** *Short-term*: instill feeling of safety by reducing exposure *Long-term*: BdS will prevent soil erosion and stabilize slopes	**Sense of security:** Forest presence restricts access to upper slopes, discourages trigger factors for rockfall, e.g., movement of people and animals, and housing construction. Increasing sense of security has persuaded return of 10 families who had abandoned their homes because of disaster risk. *However*, only periodic risk assessments can determine BdS mitigation.
2. Increasing sprawl Desperate search for housing leads to **land invasions**. More unsafe housing implies more people exposed to disaster risk.	**Curb uphill sprawl** *Short-term*: curb uphill sprawl *Long-term*: BdS replication to create larger urban green belt to control Municipality-wide sprawl.	**Sprawl Control** in El Volante: With the planting of trees, Volante III housing has remained stabilized at 31 houses since 2015. In contrast, San Albino, the community adjacent to El Volante, with no barrier forest, has continued to sprawl up the mountainside with some houses reaching the mountain peak. Sprawl control, *however*, can lead to spillover effects in neighboring locations.
3. Environmental degradation	**Environmental improvement**	
(a) **Lack of publicly available green space** in informal settlements.	**Increase public green space** *Short-term*: recreational space for improved physical and mental wellbeing for residents. *Long-term*: Build a profitable revenue-generating ecotourism park with pathways, shelters.	With BdS, Volante residents now have **public green space** available in their neighborhood. A 2016 mayoral decree assigned BdS the status of a **Sustainable Ecotourism Park.** This commits the Municipality to create walkways, shelters, picnic spots, and vantage viewpoints to make BdS a useable green space for the community. *However,* recreational benefits to residents are contingent upon making the BdS a useable and accessible space with pathways and shelters.
(b) Not only is the mountainside plant-less, but the nearby iconic Lomas de Amancaes on the upper heights of the Andes is an endangered ecosystem.	**Increased biodiversity** *Short-term*: Forest sustainability *Long-term*: Replication to foster a conservation buffer zone for the lomas	**Increased biodiversity**: 3500 plants of eight native species on 14 ha of land were grown in 4 years. The native trees were planted for BdS longevity and sustainability in the harsh dry conditions. *However,* a conservation buffer zone is not likely to positively impact the endangered lomas without a large-scale effort.
(c) Air pollution from the city affects day-to-day living	**Reduce pollution**	Informants now perceive improved air quality.
(d) Bare, dry rocky mountain landscape	**Improve landscape**	**Bare rocks to lush green winter forest:** The bare mountainside is now full of trees. Every winter, when the air is filled with moisture (*garua*), the forest floor gets carpeted with moss-like and herbaceous plants. **Cleanliness**: The improved aesthetics fosters residents' civic sense and keeps neighborhood clear of garbage.
4. Municipality officials expressed **climate change impacts** as a challenge for the urban community	**Climate Change Adaptation**	The BdS nature-based measure will support the larger urban CCA strategy.
5. El Volante II and III households lack land tenure security or property rights	*Land tenure security was not an explicit objective*	**Increased property rights:** With BdS establishment, INDECI[1] has deemed that the presence of BdS has lowered disaster risk for the neighborhoods. As part of the property rights reforms by COFOPRI,[2] a multi-step 5-year process to grant legal land titles to the Volante III and II households has been initiated.
6. Lack of Municipality jurisdiction over hillsides led to increasing unauthorized settlements	*No explicit project objective*	**Local government empowerment:** Following BdS proposal, the Municipality of Independencia acquired jurisdiction over the hitherto state-owned hillsides.
7. Lack of community cohesion	*Unplanned, fortuitous consequence of project implementation*	**Network of champion-actors**: A remarkable story to emerge was of the exceptional leadership that fueled the project from inception to successful completion. The BdS was conceived and initiated by the Municipality's former environmental manager, whose dogged advocacy, initially received as a fanciful idea, eventually brought in an army of support from the Municipality, PREDES, USAID, the community, and private actors (e.g., DHL). The exemplary direction, leadership, and collaboration orchestrated by the PREDES project manager and support from the coordinator and agroforestry specialist ensured a smooth project implementation. El Volante III community leader brought community members together and is currently the forest caretaker. With the community's voluntary labor, over 3500 holes were dug into the dry rocky mountain, as many native trees planted, and an irrigation system was installed.

Notes: [1]National Institute of Civil Defense, Peru; [2]Organization of Formalization of Informal Property, Peru.

3.4. Benefit-cost analysis: considerations of risk, co-benefits, and equity

Table 5 presents the average incremental BCRs and NPVs from the 10,000 Monte Carlo simulations. Fig. 4 depicts the incremental NPV distributions across discount rates.

BCA-1 results indicated BdS project is unviable considering DRR benefits alone. DRR benefits were low mainly because of the probabilistic framework of the assessment, where losses are avoided only in the event of disaster occurrence. Gravitational hazards like earthquakes and rockfalls are rare as compared to floods, making actual DRR benefits smaller (Mechler, 2016). Consequently, the lower economic viability fails to justify DRR projects. Second, in the absence of evidence-based studies to quantify hazard mitigation by forests and vegetation, our use of a conservative range for mitigation factor (10%–30%) and the application of the biomass growth index avoided overestimation of DRR benefits.

Including the place- and context-based benefit in BCA-2 significantly increased the economic viability of the BdS project. With property rent benefits from increased property rights, the BdS project demonstrated economic viability in ~63% Monte Carlo scenarios (Fig. 4). The increased property rent value may only nominally represent the significant increase in socio-economic benefits that results from property rights gains. The provision of legal titles to households without tenure has been shown to produce a broad set of positive social outcomes (Field, 2007; Galiani and Schargrodsky, 2011; Hawley et al., 2018).

With inclusion of non-market WTP to DRR and property rent gains in BCA-3, ~92% BdS-Eco-DRR project estimates demonstrated economic viability in the Monte Carlo analysis (Fig. 4), with average BCR, 1.70,

Table 5
Economic efficiency measures (BCR and NPV) of *Boca de Sapo* project based on the 10,000 Monte Carlo analysis runs.[1]

Average values of incremental BCRs and NPVs		BCR 1	NPV 1	BCR 2	NPV 2	BCR 3	NPV 3
Average (10, 000 Monte Carlo runs)	Average	0.06	($120,919)	1.18	$28,427	1.70	$97,957
	Std. Dev	0.0792	$16,951	0.428	$60,073	0.592	$89,752

Variation of incremental BCRs and NPVs across Discount rate			BCR 1	NPV 1	BCR 2	NPV 2	BCR 3	NPV 3
Discount rate	2%	Average	0.08	($137,725)	1.58	$86,566	2.35	$203,302
		Std. Dev	0.111	$16,658	0.388	$58,283	0.40	$60,783
	4%	Average	0.05	($118,862)	1.14	$16,995	1.61	$76,628
		Std. Dev	0.062	$7826	0.276	$34,602	0.28	$35,647
	6%	Average	0.03	($106,063)	0.83	($18,621)	1.12	$13,428
		Std. Dev	0.0354	$3880	0.203	$22,290	0.21	$22,665

Notes: [1]Numbers in parentheses are negative.

and NPV, $98,000 (Table 5). The beliefs, actions, and behavior of individuals form the guiding principle of values (Ives and Kendal, 2014), and change in ESB values reflects whose values are included and measured (Meerow and Newell, 2016). The inclusion of implicit monetary values and preferences of the marginalized at-risk community, the direct stakeholders who continue to maintain the forest, distinguishes the equity approach of our analysis from a pure risk-based BCA.

By using the appropriate portion (30%) of property rights gain and applying the biomass growth index to the WTP we avoided overestimation of the two co-benefits. The application of the stakeholder preference-based ESB criteria weight to WTP benefits ensured that the DRR and property rights benefits embedded in the WTP were not double counted in the BCA.

Among the stochastic variables in the BCA model, the discount rate had the most effect on the incremental BCR and NPV values, with lower discount rates leading to higher returns (Table 5). At 6% discount rate, the BdS project was economically viable only when all three benefits were considered in the BCA model (average BCR 1.12, NPV $13,400). At 4% discount rate, the project was viable with the inclusion of property rent gains and DRR benefits (average BCR 1.14, NPV $17,000), leading to higher returns with non-market WTP benefits (BCR 1.61, NPV $76,600). The 2% discount rate maximized returns for BdS-Eco-DRR, with BCR 2.35 and NPV $203,000, inclusive of all benefits. Generally, the real and nominal interest rates in developing countries tend to be higher (Lopez, 2008). A higher discount rate makes the Eco-DRR intervention appear financially untenable, when in fact such projects may warrant considerations based on equity and overall social-economic co-benefits. A lower social discount rate of 2%, as recommended by leading experts (Drupp et al., 2018), places importance to future wellbeing vis-à-vis DRR and CCA benefits.

3.5. Beyond BCA: a sustainability analysis

Besides economic viability, a performance assessment and benchmarking of the project impacts against two international frameworks helped us review the BdS-Eco-DRR project's potential contribution to urban sustainability.

3.5.1. BdS-Eco-DRR performance assessment

Table 6 shows the performance assessment of BdS-Eco-DRR's impacts under environmental, economic, and social dimensions. Environmental impacts would ideally involve a more in-depth evaluation of system-level factors and ecological integrity including species composition, ecosystem structure and functions, water quantity and quality, physical and chemical properties of soil, and ecosystem connectivity would be required for a rigorous assessment (IUCN, 2020). Our environmental impacts assessment included El Volante residents' ESB perceptions for risk reduction, air quality, recreation, and provisional benefits (assessment score: strong). We measured biodiversity benefits by a direct measurable metric of increase in number of species/ha over time (assessment score: adequate). If the model is replicated to 300 ha of public land as planned, BdS could be a potential conservation buffer zone for the lomas (see Table 4) (assessment score: partial).

The social dimension of BdS's benefits included impacts on governance and community processes (section 3.3 and Table 4). The Municipality's empowerment from gaining jurisdiction over Independencia hillsides implies more effective control on sprawl and commitment to BdS conservation (assessment score: strong). The afforestation process led to the emergence of a network of actors who championed the project from design and implementation to completion (assessment score: strong). We assessed BdS impacts on social cohesion and community DRR readiness based on Sarmiento et al. (2018)'s findings. We assessed El Volante's ownership of the BdS as high: all Volante III households and majority of Volante II actively participated in afforestation and thereafter, the care and maintenance of the forest (assessment score: strong). However, near-future assessments of inclusiveness, transparency, and adaptive governance are uncertain and will determine the sustainability of social benefits.

The BdS is an economically feasible venture based on avoided losses and increased land tenure security alone (assessment score: strong). BdS's designation as an ecotourism park assures forest maintenance, but recreational benefits and consequent economic revenues are dependent on its development as a usable and accessible park (assessment score: partial). Overall, our assessment ranked the BdS as adequately addressing community sustainability goals (score: 66%).

3.5.2. BdS-Eco-DRR's contribution to urban sustainability

Several estimated BdS impacts aligned with nine of 13 sustainability criteria indicators included in the IUCN' Global Standard (Table 7). The BdS project identified clear measurable biodiversity outcomes (Criterion-3.2). With possible replication to 300 ha of public lands, and the proxy measure of perceived ESBs, the BdS has potential to enhance ecosystem integrity and connectivity (Criterion-3.4). This study's BCA established economic viability (Criteria-4.1, 4.2, 4.3) and the longer-term plan for ecotourism park development incorporates future market-based resourcing option for the venture (Criterion-4.4). Among the social dimension indicators, resident participation in afforestation and DRR trainings during project implementation, together with protection from forced evictions enhanced stakeholder involvement and social inclusiveness (Criteria-5.2, 5.3).

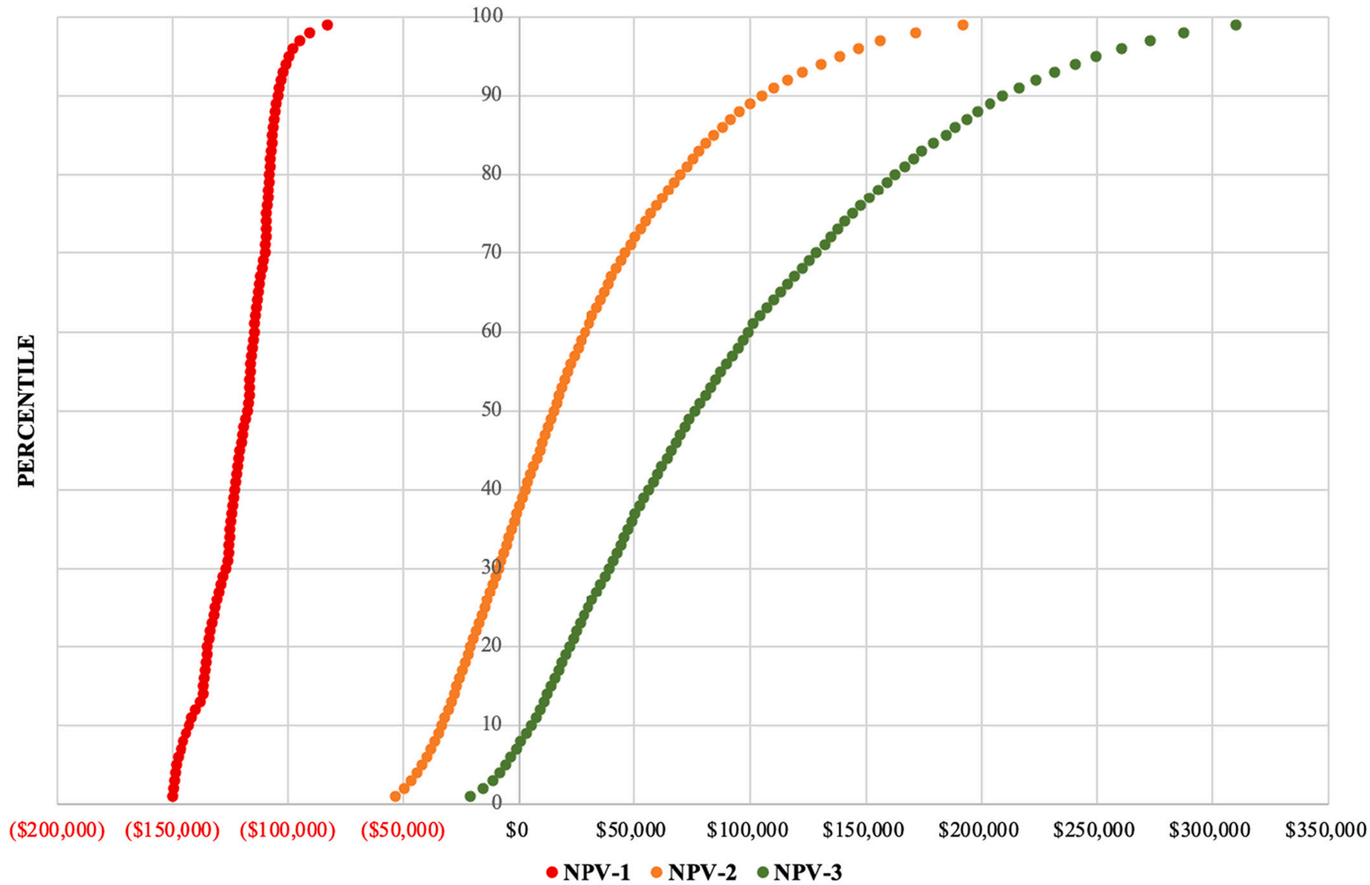

Fig. 4. Incremental Net Present Value (NPV) distributions based on 10,000 Monte Carlo simulations.
Notes: NPV-1 is the difference between Benefit-1(stochastic DRR benefits) and BdS project costs.
NPV-2 is the difference between Benefit-2 (DRR + net gain in property rent value co-benefits) and BdS project costs.
NPV-3 is the difference between Benefit-3 (DRR + net gain in property rent value + WTP non-market co-benefits) and BdS project costs.

We also aligned five BdS impacts with 13 indicators outlined in SDG 11 (Table 7). The increase in land tenure security, real or perceived (1.4.2), and public green space availability (11.7.1) because of BdS imparts 'inclusiveness' to marginalized communities by improving access to basic urban resources. The adoption of DRR strategies by the Municipality local governments (11.b.2), with support from USAID/BHA and PREDES, integrated risk resilience into urban policy, ensuring project longevity through institutional support. Finally, our BCA estimates provided evidence for indicator 11.5.2: reduction in economic losses to disasters.

Juxtaposing estimated BdS impacts with IUCN and SDG indicators placed the potential of small-scale Eco-DRR interventions such as BdS in perspective with broader urban sustainability goals. The community's decision to curb sprawl by avoiding further use of structural interventions, and instead choosing an Eco-DRR intervention to address risk accumulation and socio-environmental challenges defies the urban growth paradigm. The BdS can thus be viewed as a positive risk management action supporting sustainable use and management of land resources that ensures the needs of current and future generations and contributes to longer-term economic resilience. The afforestation's enhancement of ecological integrity and potential lowering of environmental risk factors can improve local environmental resilience to disaster risks. The concomitant positive impacts of social inclusion, social cohesion, DRR readiness, and human health and wellbeing have potential to improve the marginalized community's socio-economic resilience. The BdS-Eco-DRR impacts provide resources that potentially increase the ability of the social-ecological system to adapt, cope with, and recover from disaster events, ultimately leading to urban resilience. Coupled with appropriate institutional and governance support, BdS-Eco-DRR has the potential to become part of a broader urban sustainability initiative.

4. Conclusions

Our paper addressed the need for mainstreaming Eco-DRR interventions, underscoring their multiple benefits with actionable information on economic viability and potential contribution to urban sustainability. We designed a comprehensive assessment with (1) an equity-weighted risk-based social BCA that (a) probabilistically assessed potential DRR benefits, (b) integrated place- and context-based ecosystem co-benefits' values that influence social and ecological well-being, (c) incorporated equity consequences for marginalized stakeholders by accounting for income differences, and (d) addressed uncertainty in analysis through a stochastic BCA model using Monte

Table 6
Boca de Sapo Eco-DRR performance assessment.

Sustainability dimension	BdS Impact Indicator	Performance estimate	Indicator Weight	Raw score /100	Weighted Score	Normal-ized (%)	Overall score (%)
Environmental	Biodiversity	3,500 plants, 8 native species /14 ha/4yrs[4]	1	80	80	74	66
	Buffer zone for lomas	High potential if BdS replicated[4]	1	25	25		
	Perceived risk reduction[1]	Households' high perception[5] (4.26/5)	0.33	85	28.1		
	Perceived recreation benefit	Households' high perception[5] (4.19/5)	1	84	84		
	Perceived air purification	Households' high perception[5] (4.56/5)	1	91	91		
	Perceived provisional	Households' perception value[5] (3.77/5)	1	75	75		
	Urban sprawl control[2]	Volante III settlements have halted[4]	0.33	100	33		
Social	Social cohesion[3]	BdS and physical works' contribution[6] (68%)	0.5	68	34	80	
	Community identity[3]	Households' perception[4,5] (3.87/5)	0.5	77	38.5		
	Community ownership	High participation in forest activities[4,5]	1	100	100		
	Community champions	Vision & effort of local leaders[4]	1	75	75		
	Community DRR readiness[1]	BdS & physical works' contribution[6] (79%)	0.33	79	26.07		
	Inclusiveness[2]	Protection from forced evictions[4]	0.33	60	19.8		
	Municipality empowerment	Jurisdiction transfer improves risk governance[4]	1	80	80		
Economic	Avoided losses[1]	BCR is 0.06, project not viable [4,5,7,8]	0.34	25	8.5	45	
	Property value[2]	Project viability in ~63% scenarios[4,8,9]	0.34	80	27.2		
	Sustainable Ecotourism Park	Park status by mayoral decree[4]	1	40	40		

Notes: [1]*Indicator component of DRR benefit;* [2] *Indicator component of property rights benefit;* [3]*Complementary benefits;* [4]*Key informants' interviews;* [5]*Primary household survey;*[6]*Sarmiento et al., 2018;* [7]*Cardona et al.,2018;* [8]*This study's BCA;*[9]*Hawley et al. 2018.*

≥75	Strong	*Expected BdS impacts adequately address community sustainability goals*
≥50 & < 75	Adequate	
≥25&< 50	Partial	
<25	Partial	

Table 7
Sustainability analysis: *Boca de Sapo* ecosystem-based disaster risk reduction.

Sustainability dimensions	BdS Impact indicator	Alignment of estimated BdS impacts with indicators of sustainability dimensions in IUCN's Global Standard for NbS design and implementation	Alignment of estimated BdS benefits with indicators in Sustainable Development Goal, SDG 11: *Making cities and human settlements inclusive, safe, resilient and sustainable*
Environmental	Biodiversity	C-3.2: Clear, measurable conservation outcome	
	Buffer zone for lomas		
	Perceived risk reduction[1]		
	Perceived recreation benefit		
	Perceived air purification		
	Perceived provisional	C-3.4: Enhanced ecosystem integrity & connectivity	
	Urban sprawl control[2]	C-5.5: Scaling jurisdictions	11.7.1 Safe inclusive, accessible green public space 11.6.2 Reduction of adverse impacts on air quality 1.4.2 Increased real/perceived secure land tenure rights 11. b.2 Cities adopt, implement DRR, CCA strategies
Social	Social cohesion[3]		
	Community identity[3]		
	Community ownership		
	Community champions		
	Community DRR readiness[1]	C-5.3 Stakeholder participation & involvement	
	Inclusiveness[2]	C-5.2: Inclusiveness	
	Municipality empowerment		
Economic	Avoided losses[1]		
	Property value[2]	C-4.1, C-4.2, C-4.3 Benefit-cost analysis	11.5.2 Reduction of economic losses due to disasters 1.4.2 Increased real/perceived secure land tenure rights
	Sustainable Ecotourism Park	C-4.4: Market-based resourcing option	11.7.1 Safe inclusive, accessible green public space

Notes: [1]Indicator component of DRR benefit; [2] Indicator component of property rights benefit; [3]Complementary benefits.

Carlo simulations, and (2) a sustainability analysis to monitor the Eco-DRR measure's contribution to broader urban resilience and sustainability goals that (a) subjectively reviewed project performance, and (b) benchmarked project impacts against IUCN's Global Standard and SDG 11 frameworks.

The perspective of our analysis was, however, limited to the vulnerable community directly affected by the Eco-DRR measure. A larger perspective could have included spillover effects of sprawl on neighboring communities, the exclusionary impacts of 'gating' El Volante's 'affordable' housing on newer migrants whose 'right to the city' (Lefebvre, 1968) may thus be jeopardized, and the political economy implications for the Municipality who will potentially increase tax collection with property rights gains. Additionally, our assumptions in the probabilistic assessment and DRR benefit estimations were limited by the uncertainty arising from insufficient data and studies on ecosystem benefits relevant to specific hazards and locations in developing countries. Finally, though the BdS-Eco-DRR project provides ample evidence of economic viability and sustainability benefits, we recommend careful generalizations of these results because of the limited size and unique characteristics of our study site. Eco-DRR benefits' estimates will vary with the risk profile, social, ecological, and economic factors influencing the study area chosen, and on the relevant place- and context-based co-benefits generated. Nevertheless, this study underscores Eco-DRR's potential to provide multiple benefits and support community sustainability. Our study illustrates a holistic assessment of risk mitigation measures and can guide local governments, cities, and development organizations in producing actionable information to mainstream sustainable Eco-DRR measures into policy and legislation.

First, our results demonstrate the importance of integrating place- and context-based co-benefits and non-market values in a risk-based BCA of Eco-DRR measures. The probabilistic DRR benefits, based on avoided property losses of a marginalized urban settlement, failed to ensure economic efficiency of BdS-Eco-DRR. However, the project demonstrated economically viability in ~63% Monte Carlo scenarios with inclusion of increased land tenure security co-benefits (BCR = 1.18), and in ~92% scenarios with addition of stakeholder WTP for remaining ecological and socio-cultural co-benefits values (BCR = 1.70). Our research reiterates the indispensability of co-benefits that often drive adoption and maintenance of ecosystem-based risk mitigation and adaptation actions by communities. Consequently, the inclusion of co-benefits representing the wellbeing of people and ecosystems, besides the primary DRR benefits, is essential to Eco-DRR assessments.

Second, the inclusion of income-based equity implications in the BCA reflects the ethical social welfare approach that prioritizes collective wellbeing than property values. The BdS was an equity oriented DRR intervention targeting a spatially, socially, and economically marginalized and vulnerable community exposed to disaster risk and environmental degradation. The application of equity weights explicitly acknowledges the higher wellbeing impacts generated by BdS-Eco-DRR for the marginalized stakeholders. Third, our BCA incorporated multiple sources of uncertainty and wider ranges of risk, co-benefits, and cost estimates using Monte Carlo simulations. The analytical estimates of NPVs and BCRs of our study are, therefore, statistically more robust, and capable of providing better confidence about the associated decisions.

Finally, the project performance assessment across key sustainability dimensions underscored the holistic BdS outcomes such as access to public green spaces, social cohesion and inclusion, stakeholder participation, and health and wellbeing benefits. The assessment also highlighted areas of potential improvement such as the need for adaptive governance practices to improve stakeholder participation, accountability, and transparency in BdS's maintenance. The alignment of BdS impacts with relevant sustainability indicators forms a guiding framework for the monitoring and evaluation of the project's contribution to urban resilience and sustainability. The curbing of unfettered housing sprawl through an equitable and positive risk management Eco-DRR measure potentially enhances sustainable resource management and socio-economic risk resilience while responsibly directing the onus of increasing affordable and safe social housing for the urban poor on governments. The full potential of BdS benefits will be determined through monitoring of unintended consequences (such as sprawl spill-over), ongoing institutional processes, and inclusivity and empowerment of marginalized stakeholders in governance processes.

In rapidly urbanizing environments with mounting socio-natural risks, cities around the world require DRR solutions that provide multiple benefits including optimal environmental and equity outcomes and conform with sustainable pathways. This research offers a useful starting point for robust, equitable, and transparent decision-making support that encourages shared responsibilities of adequate capital investments into scalable ecosystem-based solutions.

Declaration of Competing Interest

The authors whose names are listed immediately below certify that they have no affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

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