Check for updates

Received: 24 July 2022 | Accepted: 30 April 2023

DOI: 10.1002/pan3.10481

RESEARCH ARTICLE

PEOPLE AND NATURE
BRITISH ECOLOGICAL SOCIETY

Optimal allocation of nature-based solutions to achieve climate mitigation and adaptation goals

Jaramar Villarreal-Rosas[1,2] | Jonathan R. Rhodes[1,2] | Laura J. Sonter[1,2] | Hugh P. Possingham[2,3] | Adrian L. Vogl[4]

[1]School of Earth and Environmental Sciences, The University of Queensland, Saint Lucia, Queensland, Australia

[2]Centre for Biodiversity and Conservation Science, The University of Queensland, Saint Lucia, Queensland, Australia

[3]School of Biological Sciences, The University of Queensland, Saint Lucia, Queensland, Australia

[4]Natural Capital Project, Stanford University, Stanford, California, USA

Correspondence
Jaramar Villarreal-Rosas
Email: jaramarv@gmail.com

Present address
Jaramar Villarreal-Rosas, Australian Rivers Institute, Griffith University, Nathan, Queensland, USA

Funding information
Australian Research Council, Grant/Award Number: DE170100684, FL130100090 and FT200100096; Consejo Nacional de Ciencia y Tecnología; University of Queensland

Handling Editor: Román Carrasco

Abstract

1. Nature-based solutions (NbS) can prevent further climate change and increase local communities' capacity to adapt to the current impacts of climate change. However, the benefits obtained from implementing NbS are not distributed equally across people. Thus, it is key to further understand how people are impacted when implementing NbS.
2. We developed a multi-objective prioritization approach to identify changes in (i) the biophysical provision of ecosystem services, (ii) optimal allocation of NbS and (iii) monetary benefits when targeting climate mitigation versus climate adaptation goals. We used the increase in metric tons of carbon storage as representative of climate mitigation and the decrease in on-site and downstream tons of sediment per year as representative of climate adaptation.
3. Planning strategies that target climate mitigation or climate adaptation goals separately represent a loss of between 30% and 60% of the maximum possible carbon sequestration or sediment retention benefits. Conversely, targeting climate mitigation and climate adaptation goals at the same time captured more than 90% of the maximum possible benefits for all objectives.
4. Priority NbS in the mitigation planning strategy included soil and water conservation and forest rehabilitation, while priority NbS in the adaptation planning strategy included grassland rehabilitation and hill terrace improvement.
5. Targeting mitigation and adaptation goals at the same time captures 35M USD (89% of the maximum attainable) in value of carbon restored and retained, and 2M USD (100% of the maximum attainable) of avoided maintenance costs to the KGA hydropower plant. Conversely, failing to incorporate adaptation goals when developing climate plans only captures 1M of avoided maintenance costs to the KGA hydropower plant.
6. Our approach can be replicated in other locations to promote cost-effective investments in NbS able to secure both global and local benefits to people. This can improve the outcomes of international climate change financial schemes like the Green Climate Fund and the UN-REDD+ program.

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.
© 2023 The Authors. *People and Nature* published by John Wiley & Sons Ltd on behalf of British Ecological Society.

KEYWORDS
carbon sequestration, disaggregation of beneficiaries, ecosystem services, Nepal, sediment retention, spatial prioritization

1 | INTRODUCTION

Global action is urgently needed to prevent further climate change and counteract the negative impacts that climate change is causing on people's wellbeing and the natural environment. Climate change is increasing the prevalence of extreme temperatures and weather events, having a significant toll on people's lives (Bellprat et al., 2019; Herring et al., 2014; Perkins-Kirkpatrick et al., 2022). For instance, 37% of heat-related deaths can be attributed to anthropogenic climate change (Vicedo-Cabrera et al., 2021). Nature-based solutions (NbS) refer to actions to protect, manage and restore ecosystems in ways that also provide benefits to people, and are considered an alternative to support climate mitigation and adaptation goals (Seddon, 2022). Yet we lack full understanding of the diversity of impacts on people's wellbeing when implementing NbS.

Application of NbS to mitigate climate change centres on protecting carbon stocks and enhancing carbon sequestration to prevent further alteration of current climate patterns, mostly through forest protection or restoration (GCF, 2020a; Seddon, 2022). Use of NbS for climate change adaptation aims to decrease local people's vulnerability to the present impacts of climate change by enhancing ecosystems' health and their capacity to sustain people's wellbeing (i.e. ecosystem services; GCF, 2020b; Seddon, 2022). For example, in Sri Lanka, a climate change adaptation project using NbS focused on improving sustainable farm- and land management practices to decrease upstream erosion and downstream flood risk (GCF, 2020b).

The importance of both mitigation and adaptation actions in fighting climate change has been widely recognized in international policy, yet practical efforts to date have largely focused only on enhancing carbon stocks through forest protection (i.e. a mitigation goal; GCF, 2021; UN, 2022; UNFCCC, 2022). Strong evidence suggests that carbon projects that only promote forest conservation may not enhance the provision of local ecosystem services, and can even adversely affect local communities' wellbeing (Aggarwal & Brockington, 2020; Chhatre & Agrawal, 2009; Duker et al., 2019; Kim et al., 2018; Rana et al., 2017). Therefore, there is a pressing need to better understand how NbS can help achieve climate adaptation and mitigation objectives and how to cost-effectively allocate the finite resources available to achieve both objectives.

Here, we use a spatial planning approach to explore the consequences to different population sectors of investing in NbS when pursuing either climate mitigation or adaptation goals, or both. We evaluated the consequences to people through the biophysical modelling and monetary evaluation of three regulating ecosystem services. We considered carbon storage as representative of climate mitigation goals, an ecosystem service that delivers the global benefit of climate stability. We considered local and downstream sediment retention as representative of climate adaptation goals. Previous work looking at the application of NbS for climate mitigation and adaptation has focused mostly on forest conservation or restoration (Hu et al., 2021; Khorchani et al., 2022; Nolan et al., 2021; Seddon, 2022). Here, we consider the implementation of a wider variety of NbS and we also assess changes in the distribution of benefits to different sectors of the population.

We applied our approach in the Kali Gandaki watershed in Nepal, a country with national-level commitments to climate change financing (Government of Nepal, 2016; MoFE, 2018). Topographical conditions make Nepal highly prone to erosion, which is expected to intensify as a consequence of climate change (GCF, 2020c; Manandhar et al., 2012; Panthi et al., 2016). We specifically ask (1) How do the distribution of ecosystem services differs when targeting climate mitigation versus climate adaptation goals?; (2) How do priority locations and NbS differ when targeting mitigation versus adaptation goals?; (3) To what extent can different mitigation or adaptation planning strategies balance trade-offs in the distribution of ecosystem services, and at what monetary cost?

2 | METHODS

2.1 | Study area

The Kali Gandaki River originates from the Mustang Plateau on the Chinese-Nepali border. We considered as the study region the Kali Gandaki watershed, covering 7600 km^2 (Figure 1). The basin has variable geology, with altitude ranging from 525 to 8144 m (World Bank, 2019). Therefore, the Kali Gandaki watershed holds great climate diversity, from arid tundra at the highest altitudes, alpine, cold temperate, warm temperate and subtropical climates with decreasing altitudes, and monsoon climate in the lowest areas (Manandhar et al., 2012). According to the 2011 national census, there are approximately 590,000 people living in the Kali Gandaki watershed (Government of Nepal, 2013). Agriculture, grazing and collection of fuel wood are the main livelihoods in the region, with 20% forest cover, 20% grassland and 14% cultivation (Figure 1). Agriculture occurs mostly at the lower altitudes, however, there is also agriculture occurring at very steep slopes (with a mean gradient of 41%). The steep slopes and high precipitation require that most croplands are converted to an elaborate system of terraces to control erosion and manage water on the hillslopes (World Bank, 2019). Terrace abandonment and expansion of the road network without stabilization methods exacerbate the high levels of erosion in the watershed (World Bank, 2019). Almost 22 million cubic metres of sediment are transported to the Kali Gandaki Dam each year, resulting in high maintenance costs to the Kali Gandaki A Hydropower Plant (KGA hydropower plant; World Bank, 2019).

25758314, 2023, 3, Downloaded from https://besjournals.onlinelibrary.wiley.com/doi/10.1002/pan3.10481 by University of Adelaide Alumni, Wiley Online Library on [27/06/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

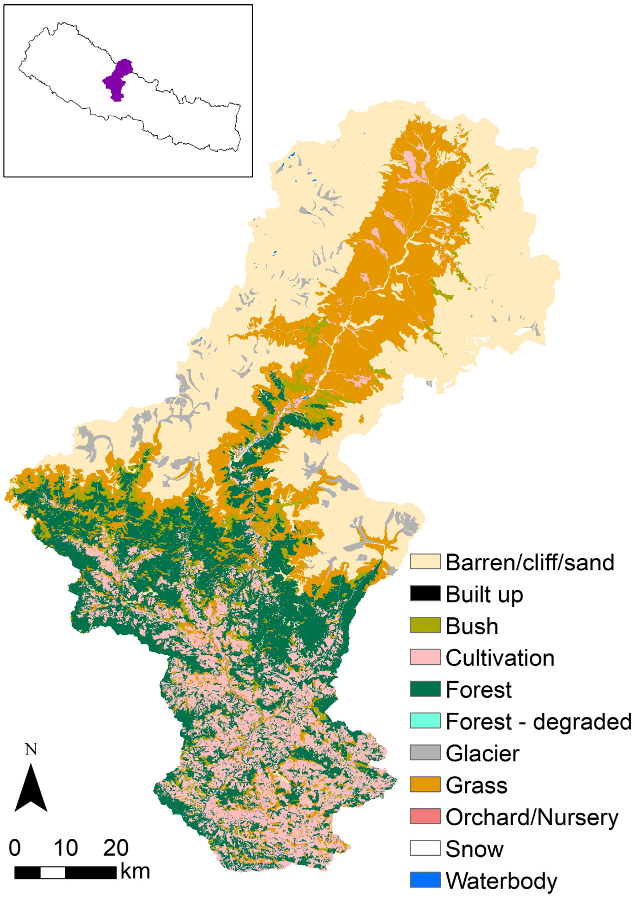

FIGURE 1 Land use–land cover in the Kali Gandaki watershed. Inset indicates the location of the Kali Gandaki watershed in Nepal (modified from World Bank, 2019).

KGA is the largest hydropower power plant in Nepal with an installed capacity of 144MW, and is the largest single generator in the country (NEA, 2019).

2.2 | Climate mitigation and adaptation beneficiaries

We formulated a decision problem to identify priority NbS and locations in the Kali Gandaki watershed to enhance carbon sequestration (climate mitigation goal), and sediment retention (climate adaptation goal; Table 1), considering the following objectives and beneficiaries: (1) increase in metric tons of carbon storage for its global climate regulation benefit, (2) decrease in on-site tons of sediment/year benefitting agricultural landholders and (3) decrease in downstream tons of sediment/year benefitting the KGA hydropower plant.

2.3 | Nature-based solutions

We obtained modelled data from the World Bank (2019), reflecting the impact of different NbS on sediment retention and carbon storage in the Kali Gandaki watershed (Table 2). NbS include hill terrace improvement, soil and water conservation practices, and rehabilitation of forests and grasslands. Modelled data reflect the difference in sediment retention and carbon storage between a baseline landscape reflecting the current management practices in place in the Kali Gandaki watershed and a hypothetical landscape reflecting the implementation of each of the different NbS separately, and as bundles of actions. Bundles of actions included: (1) soil & water conservation practices + terrace improvement, (2) soil and water conservation practices + terrace improvement + forest rehabilitation, (3) soil and water conservation practices + terrace improvement + grassland rehabilitation, (4) soil and water conservation practices + terrace improvement + forest rehabilitation + grassland rehabilitation. Each NbS represents a suite of management practices, for example the NbS of hill terrace improvement accounts for practices like slope correction, planting of nitrogen-fixing species along the terrace margins and agroforestry (Table 2). Hypothetical action implementation models do not account for all of the practices listed under each NbS, instead, models reflect the average impact of the types of practices listed and this is incorporated into the models by changing model parameters. For full details on model equations and parameters used to reflect the baseline and hypothetical (after implementation) landscapes please see Supporting Information Text S1.

NbS and costs were obtained from the World Bank (2019). The methodology used to obtain this information included literature review (Atreya et al., 2008; Dahal & Bajracharya, 2013; ICIMOD, 2007; Paudel et al., 2017; Shrestha, 2016), official reports from the Department of Forests and Soil Conservation, Government of Nepal, and stakeholder consultation during two workshops held in October 2017 and January 2019 in Kathmandu (World Bank, 2019). Costs of each NbS reflect gross costs of the initial establishment and the maintenance costs borne by the landholders adopting the practice. Labour costs were calculated considering a common daily wage rate of US $3 per day, and all costs were adjusted to a common year (2018; World Bank, 2019).

2.4 | Optimization

We used a multi-objective optimization approach to find what NbS and where to apply them in the Kali Gandaki watershed to best achieve climate mitigation and adaptation goals. For this, the study area was divided into 821 sub-watersheds with an average size of approximately 900 ha each, roughly the size of the individual micro-watersheds that the Department of Forests and Soil Conservation typically addresses through their watershed management programs (World Bank, 2019). Each of these sub-watersheds represented a 'decision unit', the spatial regions on which green actions could be implemented. The area within each decision unit available for implementation was calculated based on a suitability layer (information obtained through literature review, official reports and workshops, World Bank, 2019).

25758314, 2023, 3, Downloaded from https://besjournals.onlinelibrary.wiley.com/doi/10.1002/pan3.10481 by University of Adelaide Alumni, Wiley Online Library on [27/06/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

25758314, 2023, 3, Downloaded from https://besjournals.onlinelibrary.wiley.com/doi/10.1002/pan3.10481 by University of Adelaide Alumni, Wiley Online Library on [27/06/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

TABLE 1 Ecosystem services representing mitigation and adaptation goals, the different population sectors that benefit from these ecosystem services, and indicators used to measure benefits to people.

Climate change goal	Ecosystem service	Beneficiary	Indicator and modelling approach used to quantify biophysical benefit World Bank (2019)	Indicator and approach used to quantify monetary benefit (USD) World Bank (2019)
Mitigation	Carbon storage	Climate regulation benefiting people globally	Increase in carbon storage (Mt) from total baseline carbon stock in soils and above- and below-ground biomass using the InVEST carbon model Sharp et al. (2018)	Value of carbon stored and retained based on social cost of carbon using a mid-range estimate of US $60
Adaptation	Sediment retention	Agricultural landholders	On-site decrease in tons of sediment/year lost to erosion, assessed using the Revised Universal Soil Loss Equation from InVEST Sharp et al. (2018)	Not assessed
		KGA hydropower plant	Decrease in downstream tons of sediment/year reaching the KGA hydropower plant, assessed using the InVEST Sediment Delivery Ratio Model Sharp et al. (2018) and the CASCADE model, which quantifies the sediment transport capacity in the river network Schmitt et al. (2018)	Avoided maintenance costs to the KGA hydropower plant and reduction in damage to equipment was calculated as a relationship between the marginal cost of sand removal and marginal damage from not removing a cubic meter of sand

TABLE 2 Description of the specific land management practices and average costs per nature-based solution.

Nature-based solution	Specific practices included in each nature-based solution	Average cost (USD/ha)
Hill terrace improvement	Slope correction on existing terracing, planting nitrogen-fixing hedgerow species along the terrace margins in single or multiple rows, agroforestry	2230
Soil and water conservation practices	Hedgerows, hedgerow intercropping, crop residues, mulches, cover crops, no tillage, reduced tillage, minimum tillage, windbreaks/shelterbelts, buffer strips/greenbelts, conservation trenching, agroforestry	1100
Reclamation/rehabilitation of degraded land (forest)	Planting fuel and fodder tree species, conservation trenching, eyebrow pits, revegetation, hedgerow planting across the slope to regenerate degraded areas	1690
Reclamation/rehabilitation of degraded land (grasslands)	Greenbelts, buffer strips, rotational grazing, fodder planting, silvopasture improvement	880

We used the Restoration Opportunities Optimization Tool (ROOT) to solve our restoration problem (Beatty et al., 2018). ROOT formulates the optimization problem using linear programming where the objectives and constraints are made up of linear functions and the objectives are combined as a weighted sum. The objective function for the optimization problem was defined as:

$$\max_{xj} \sum_{i=1}^{n} w_i \sum_{j=1}^{m} p_{ij}(x_j)$$

subject to

$$\sum_{j=1}^{m} c_j(x_j) = T \quad (1)$$

where w_i is the weight assigned to each objective i, p_{ij} is the value of objective i in decision unit j, as a function of a vector of nature-based solutions x_j. x_j is a binary variable indicating which nature-based solutions are allocated to decision unit j, C_j is the cost of implementing action x_j in decision unit j and T is a 40 million USD budget considering this is the average budget used in recent Green Climate Fund projects for Nepal (GCF, 2019, 2020c).

2.5 | Identifying trade-offs between climate mitigation and adaptation goals

To identify how the distribution of ecosystem services differs when targeting climate mitigation versus climate adaptation goals (research question 1) we constructed Pareto efficiency frontiers between pairs of objectives representing a set of spatially explicit optimal solutions where returns to one objective cannot be increased without diminishing returns to another objective (Gourevitch et al., 2016). Efficiency frontiers between pairs of mitigation and adaptation objectives also allowed us to identify how optimal allocation of NbS differed across decision units (research question 2). Pairs of objectives were combined as a weighted sum with proportional increases and decreases in weight on each objective across 1000 iterations, that is, from 100% to 0% weight on one objective to 0% to 100% on the other objective. Solutions giving 100% weight to carbon sequestration represent climate mitigation goals. Solutions giving 100% weight to local ecosystem services (i.e. on-site and downstream sediment retention) represent climate adaptation goals.

We also integrated all objectives into a multi-objective optimization, with predefined weight allocations across objectives to represent climate planning strategies giving different relative importance to mitigation and adaptation goals (Table 3). Our three climate strategies included: (i) Mitigation strategy: gives all weight to increasing carbon sequestration, (ii) Adaptation strategy: distributes weight equally between decreasing on-site and downstream sediment and (iii) Mitigation + Adaptation strategy: distributes weight equally between increasing carbon sequestration, decreasing on-site and downstream sediment. This allowed us to assess the extent to which different mitigation and adaptation planning strategies help balance trade-offs in the distribution of ecosystem services (research question 3). We compared benefit for each objective across climate strategies as the proportion captured relative to the maximum obtained when each objective is given 100% of the weight. We then compared how monetary benefit associated with each objective changed between climate planning strategies.

3 | RESULTS

3.1 | Change in the distribution of benefits to people

A planning strategy 100% focused on increasing carbon storage (i.e. representing a mitigation goal) captures ~70% of the maximum possible value of on-site and downstream sediment respectively (i.e. representing adaptation goals; Figure 2a). Conversely, a planning strategy 100% focused on decreasing sediment loads locally and downstream (i.e. representing adaptation goals), only captures 56% of carbon storage (Figure 2b). A planning strategy that gives the same weight to mitigation and adaptation goals significantly decreases the trade-offs between all objectives, capturing 93% of carbon storage, 96% of decrease in downstream sediment and 97% decrease in on-site sediment loads (Figure 2c). The trade-offs between adaptation and mitigation strategies are not impacted by the specific adaptation goal pursued (i.e. either on-site or downstream sediment) as targeting the decrease in on-site or downstream sediment loads captures 95% of either objective (Figure S1). This is because the amount of sediment reaching streams was estimated based on the on-site sediment load values (Supporting Information Text S1).

TABLE 3 Matrix of weight allocations among mitigation and adaptation goals representing different climate planning strategies.

		Ecosystem service goal		
		Increase in metric tons of carbon storage	Decrease in on-site tons of sediment/year	Decrease in downstream tons of sediment/year
Climate planning strategy	Mitigation	1	0	0
	Adaptation	0	0.5	0.5
	Mitigation and adaptation	0.333	0.333	0.333

3.2 | Change in the allocation of nature-based solutions

In the mitigation planning strategy, soil and water conservation is the main NbS selected in priority decision units (45% of the total number of decision units selected) followed by forest rehabilitation (35%), and hill terrace improvements (20%) (Figure 3a). In the adaptation planning strategy, grassland rehabilitation is the main NbS selected in priority decision units (57% of the total number of decision units selected), followed by hill terrace improvements (41%) and forest rehabilitation (2%). In the mitigation + adaptation planning strategy, the main NbS selected in priority decision units shifted to forest rehabilitation (76% of the total number of decision units selected), followed by hill terrace improvements (17%) and grassland rehabilitation (7%). Decision units selected are located mostly in the South of the Kali Gandaki watershed for the three planning strategies, although soil and water conservation actions are also allocated North for the mitigation strategy. Despite the changes in the configuration of selected NbS across decision units, hill terrace improvements are the action with the highest area selected for implementation across planning strategies (15,700–17,000 ha), followed by grassland

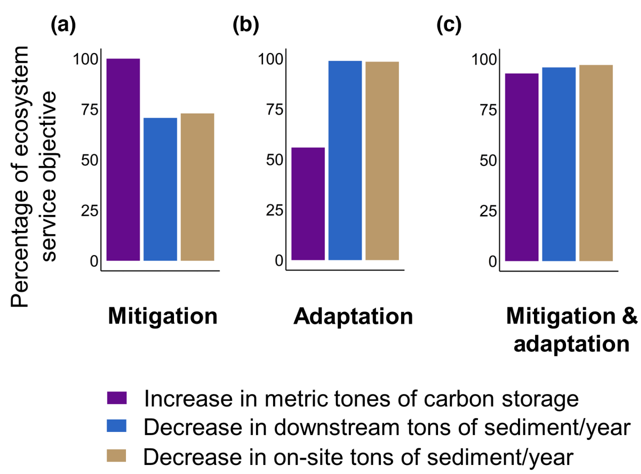

FIGURE 2 Proportion of ecosystem service objectives captured under different climate planning strategies at a $40M budget. *Y*-axis units are in percentages relative to the maximum benefit obtained if each objective is given 100% of the weight. (a) Mitigation: planning strategy where 100% of the weight is given to carbon storage; (b) adaptation: planning strategy where weight is equally distributed between decrease in on-site and downstream sediment; (c) mitigation and adaptation: planning strategy where weight is equally distributed between all mitigation and adaptation objectives.

25758314, 2023, 3, Downloaded from https://besjournals.onlinelibrary.wiley.com/doi/10.1002/pan3.10481 by University of Adelaide Alumni, Wiley Online Library on [27/06/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

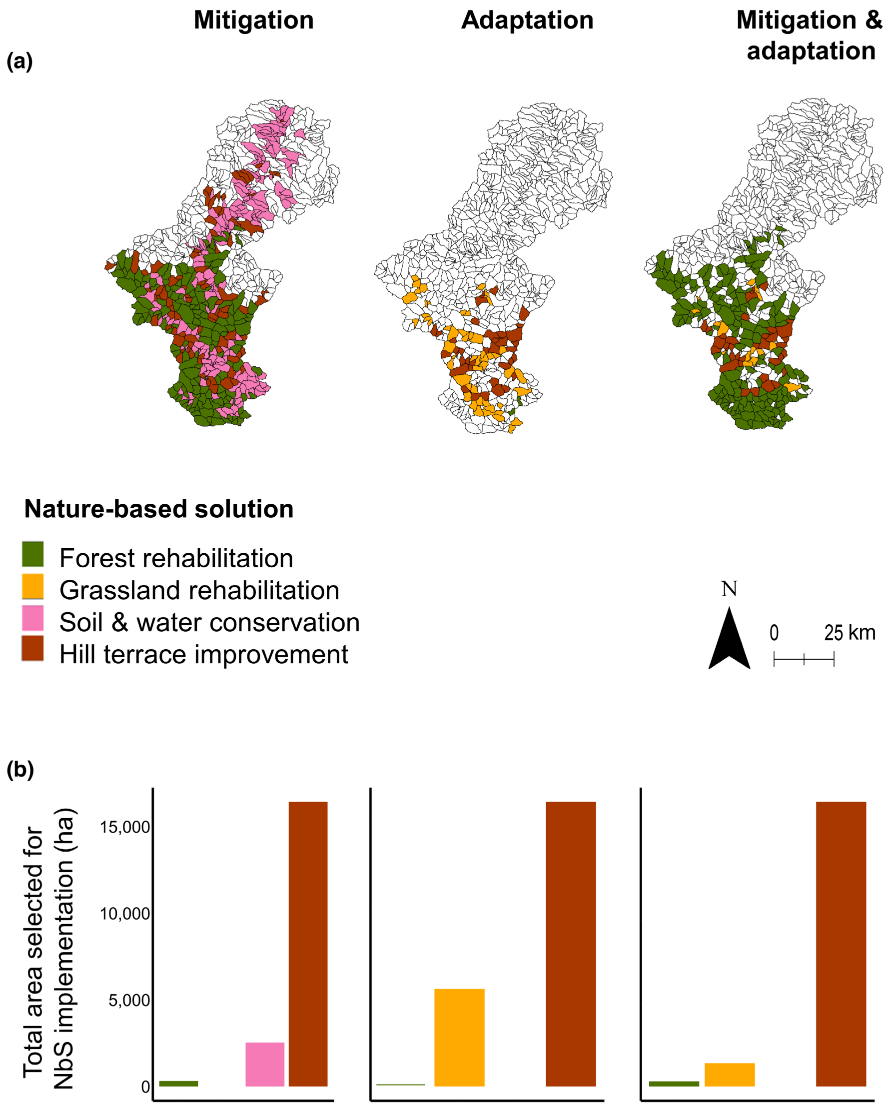

FIGURE 3 Change in the allocation of nature-based solutions at a $40M budget. (a) Optimal allocation of nature-based solutions across priority decision units. (b) Area available for implementing nature-based solutions within priority decision units. Mitigation: planning strategy where 100% of the weight is given to carbon storage; adaptation: planning strategy where weight is equally distributed between decrease in on-site and downstream sediment; mitigation and adaptation: planning strategy where weight is equally distributed between all mitigation and adaptation objectives.

rehabilitation (0–5500 ha), soil and water conservation (0–2542) and forest rehabilitation (307–321 ha; Figure 3b).

3.3 | Change in the distribution of monetary benefits

A planning strategy 100% focused on increasing carbon storage (i.e. a mitigation goal) captures 39M in monetary benefits, from that figure, 38M represents the value of carbon restored and retained by implementing NbS, and 1M represents the value of avoided maintenance costs to the KGA hydropower plant (Figure 4). A planning strategy focused on decreasing on-site and downstream sediment at the same time (i.e. adaptation goals) captures 23M in monetary benefits. In this strategy, the value of carbon restored and retained decreases to 21M, which represents 54% of the maximum possible value attainable. Conversely, the value of avoided maintenance costs to the KGA hydropower plant increases to almost 2M, which represents 100% of the maximum possible attainable. The mitigation + adaptation planning strategy captures 37M in monetary benefits. In this strategy, the value of carbon restored and retained only decreases to 35M, which represents 89% of the maximum possible value attainable. While the value of avoided maintenance costs to the KGA hydropower plant remains at near 2M.

4 | DISCUSSION

4.1 | Use of nature-based solutions to achieve climate mitigation and adaptation

The need to better integrate adaptation and mitigation into climate change agendas has been highlighted (IPCC, 2018, 2022a, 2022b; OECD, 2021). Yet this integration is not prominent in current policy or practice (Hurlimann et al., 2021; Seddon, 2022; UN, 2022). For instance, the Green Climate Fund, the biggest international mechanism supporting the use of NbS to fight climate change in developing countries (https://www.greenclimate.fund/), evaluates mitigation and adaptation goals separately (GCF, 2020a, 2020d, 2021). Using spatial prioritization, we show how pursuing climate mitigation and

25758314, 2023, 3, Downloaded from https://besjournals.onlinelibrary.wiley.com/doi/10.1002/pan3.10481 by University of Adelaide Alumni, Wiley Online Library on [27/06/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

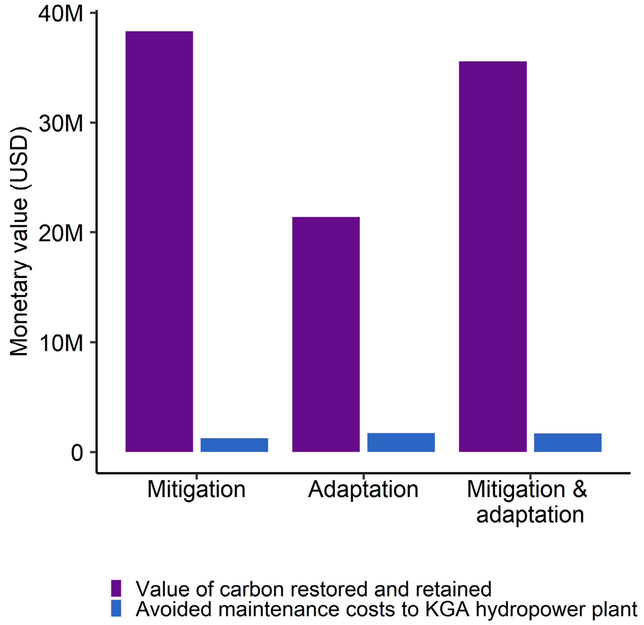

FIGURE 4 Change in monetary value for two benefit streams captured from different climate planning strategies at a $40M budget. Mitigation: planning strategy where 100% of the weight is given to carbon storage; adaptation: planning strategy where weight is equally distributed between decrease in on-site and downstream sediment; mitigation and adaptation: planning strategy where weight is equally distributed between all mitigation and adaptation objectives.

adaptation goals separately can miss more than 30% of local benefits to people and more than 40% of carbon storage benefiting people globally. Conversely, integrating climate mitigation and adaptation goals at the same time captures 90% of the maximum possible global and local benefits (Figure 2). Our results highlight the need to better understand how implementation of NbS impacts different groups of people in a landscape, and we show how this information can be used to cost-effectively achieve both mitigation and adaptation goals.

Previous research identified that protecting healthy ecosystems, improving land management and restoring ecosystems are the three most cost-effective NbS for climate mitigation (Cook-Patton et al., 2021). In this study we show that a combination of NbS (including improved management practices and ecosystem rehabilitation) is necessary to evenly achieve both climate mitigation and adaptation goals. Particularly, we find that the most feasible and effective NbS to achieve climate mitigation and adaptation is hill terrace improvements (Figure 3). Our results align with recent research indicating that improved terracing practices increased soil sequestration by more than 30% across different mountainous landscapes in China (Chen et al., 2020). Terracing systems have been used for agriculture in mountainous landscapes for thousands of years, and have been shown to reduce sediment loads by 52% if adequately maintained (Deng et al., 2021). We also find that forest rehabilitation is selected as the optimal NbS in most decision units, however, with significantly lower area available for implementation relative to hill terrace improvement actions. This is due to the relatively low extension of remaining forest cover in the Kali Gandaki Watershed, covering 20% (155,300 ha) of the total land use land cover (Figure 1). From the total extension of forest cover, only 330 ha are considered degraded and therefore available to implement rehabilitation actions (World Bank, 2019).

Our results also emphasize the need to consider relevant NbS according to the local context in order to achieve both climate mitigation and adaptation. Particularly, we highlight the importance of supporting traditional land management practices like hill terracing systems. Agroforestry practices have been shown to achieve mitigation and adaptation goals while also providing biodiversity cobenefits and supporting local communities' livelihoods (Seddon, 2022). In cases of high-intensity climate hazards (e.g. storm water management in cities), approaches that use a combination of NbS and technological or engineering solutions may be preferred (Chen et al., 2021). Achieving climate adaptation also requires careful consideration of cultural and social norms (Friedman et al., 2022; Mashi et al., 2020). For instance, in Papua New Guinea, women and men obtain climate information through different social networks (Friedman et al., 2022). Understanding these social complexities is key when delivering prevention and education campaigns to improve people's responses to climate emergencies like flood events (Mashi et al., 2020).

4.2 | Valuing mitigation and adaptation benefits

In this study we measured the benefits of implementing NbS in a landscape in terms of biophysical change in ecosystem function, and we translated two of these benefit streams into monetary terms. Understanding change in ecosystem function from intervention is key in evaluations of NbS, as it is the processes and dynamics occurring within ecosystems that fundamentally supports the benefits people obtain from nature (e.g. reductions in soil loss, increase in carbon stocks, improved water quality) (Chan & Satterfield, 2020). However, we also translate biophysical change into monetary benefits as international climate funding mechanisms operate under the monetization of the benefits obtained from nature. Carbon credits have been used since 1997 with the adoption of the Kyoto Protocol on climate change (UN, 1998). The Green Climate Fund and programs like REED+ (Reducing emissions from deforestation and forest degradation in developing countries) also operate through carbon credits. Carbon credits are a unit of exchange (equivalent to one metric ton of greenhouse gases removed from the atmosphere) that businesses and developed countries use to pay developing countries to offset their greenhouse gas emissions (UN, 2015). Even though the monetization of the benefits provided by nature has been widely debated (Chan & Satterfield, 2020; Jacobs et al., 2016; Martin-Ortega et al., 2019), the creation of international climate funds indicates that monetization is a useful method to assist private and government sectors to integrate climate change into policy and action.

Here, we use on-site and downstream reductions in sediment retention benefiting local landholders and reductions in maintenance costs of the Kali Gandaki hydropower plant to represent climate adaptation benefits. We did not measure the monetary benefits

25758314, 2023, 3, Downloaded from https://besjournals.onlinelibrary.wiley.com/doi/10.1002/pan3.10481 by University of Adelaide Alumni, Wiley Online Library on [27/06/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

25758314, 2023, 3, Downloaded from https://besjournals.onlinelibrary.wiley.com/doi/10.1002/pan3.10481 by University of Adelaide Alumni, Wiley Online Library on [27/06/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

that agricultural landholders would obtain from on-site decreases in sediment loads due to lack of appropriate data. However, based on reported cost-share by local landholders from similar implementation programs (World Bank, 2019), we estimate that landholders would obtain an equivalent of 84% benefit from the total project cost. Considering a 40M budget, agricultural landholders would obtain 34M of benefit from reduced on-site erosion in the form of improved soil fertility, water capture and agricultural productivity (World Bank, 2019). Agriculture takes place on hillslope terraces that are highly susceptible to erosion from precipitation events, exacerbated by climate change (Panthi et al., 2016). Thus, investing in hill terrace improvement practices increases soil carbon sequestration and helps improve the adaptive capacity of local farmers to climate change. We also find that reducing downstream sediment loads can avoid 2M USD in maintenance costs from de-sanding turbines and maintaining reservoir capacity in the KGA hydropower plant. Maintaining reservoir capacity is only valuable when the flow in the Kali Gandaki River is insufficient to meet electricity demands (World Bank, 2019). Thus, the benefit of implementing NbS to ensure reservoir capacity is likely to become more valuable with the increased variability of the monsoon season associated with climate change (Panthi et al., 2016).

We acknowledge, however, that monetary valuations do not capture the many benefits people receive from nature. Particularly the nonmaterial connections that people have with nature and that are shaped by people's unique cultural lenses (as is captured by the term 'nature's contributions to people' that encompasses the more common term of ecosystem services; Díaz et al., 2018). For example, the significance that practicing terrace agriculture may have for farmers (Salas & Tillman, 2021) or community perceptions of the indirect impacts of hydropower plants (Sousa et al., 2019). Other methods would be required to capture these nonmaterial connections between people and nature. For example, participatory mapping, focus groups, photograph analysis, among others (Chan et al., 2012; Hirons et al., 2016). Extraction of forest resources for sustenance and other provisioning services were also out of the scope of our study. However, finding planning solutions to ensure climate mitigation goals while securing people's access to forest resources is a key area that requires further consideration. Specifically in light of the range of literature demonstrating the negative impacts that strict forest protection strategies for climate mitigation are causing on local communities' livelihoods (Aggarwal & Brockington, 2020; Chhatre & Agrawal, 2009; Duker et al., 2019; Kim et al., 2018; Rana et al., 2017). These considerations are bolstered by this study's findings that only planning for climate mitigation can result in a lower realization of local benefits than it would if both local and global benefits were considered.

It is also important to note that the reductions in on-site and downstream sediment loads from the interventions we show here are likely to be conservative estimates. In the Himalayas, sediment sources include glaciation, mass-movement (i.e. landslides and rockfalls), sheet and rill erosion from natural hillslopes and agricultural areas, and erosion in river channels (Wasson, 2003). In addition, anthropogenic activities like road construction or mining can also increase sediment loads (Sidle & Ziegler, 2012). However, our estimates of on-site and downstream sediment loads, based on the InVEST Sediment Delivery Ratio model, only account for sheet and rill erosion processes (Sharp et al., 2018). Our estimates of carbon sequestration are also subject to model limitations. The InVEST carbon model assumes linear change in carbon sequestration over time and does not account for biophysical conditions such as photosynthesis rates and the presence of soil organisms that facilitate carbon sequestration. The model also assumes carbon sequestration is not affected by land cover and management practices in neighbouring areas (Sharp et al., 2018).

4.3 | Policy implications

In November 2022, at the United Nations Climate Change Conference COP27, an unprecedented Climate Adaptation Implementation Plan was announced (UNFCCC, 2022). This plan acknowledges that developing countries experience greater loss and damage to livelihoods and infrastructure from climate change disasters than previously recognized, and urges to increase financial support for climate adaptation (UNFCCC, 2022). Underlying this urgent call for climate adaptation is the recognition of the existing gap between the low support available for climate adaptation relative to the high levels of adverse climate change impacts that people are experiencing today (UN, 2022; UNFCCC, 2022; Vicedo-Cabrera et al., 2021). Our study provides pertinent and timely information to improve the development of spatial plans that focus on the use of NbS to contribute to the climate change mitigation and adaptation goals pursued globally. NbS can significantly improve local people's adaptation capacities (Seddon, 2022); however, it is important to note that the contribution of NbS to global climate mitigation goals is relatively small compared to the impact that would be obtained if fossil fuels were drastically cut down (Anderson et al., 2019). On the other hand, countries like Nepal that currently have very low levels of annual per capita emissions—only 0.59 Mt in 2020, compared to >12 Mt from the 20 highest countries (Crippa et al., 2021)—have less potential for drastically reducing emissions but have tremendous potential to achieve mitigation and adaptation targets through the strategic use of NbS.

Our study could also help incentivize local watershed and forest management policies in Nepal and in the Himalayan Region. The Nepalese government has incentivized community forest management for over 50 years, and there is interest from local government institutions in developing watershed management programs that emphasize local benefits (GCF, 2019; Paudyal et al., 2018; Sharma et al., 2017). Our study indicates how local benefits from NbS would be distributed across different sectors and locations in the Kali Gandaki watershed based on assumptions of the relative importance between mitigation and adaptation goals. Our results only reflect the extreme distributions of relative importance across objectives and a set budget of 40M for implementation, other weight allocations and budgets may result in different distributions of benefits across beneficiaries. Setting different weight allocations among objectives usually reflect planning preferences or social values assigned to ecosystem services (Li et al., 2020). To improve equitable outcomes for the Kali Gandaki watershed, open negotiations about the trade-offs incurred at different weight allocations would be required between the practitioners and beneficiaries involved in the planning process (Kovacs et al., 2016).

Ensuring benefits from implementation are realized would require successful engagement and cooperation between the different beneficiaries and stakeholders involved. Enablers for successful implementation of NbS include good governance, secure land tenure, sustainable livelihoods and finance and positive values for nature (Seddon, 2022). For instance, the estimated 2M of avoided damages and maintenance costs benefiting the KGA hydropower plant can only be achieved if hill terracing practices are maintained and implemented by upstream landholders. We have also identified that landholders could benefit from improved agricultural productivity. Yet, lack of access to financial capital, lack of information about the benefits obtained from improved hill terracing or high implementation costs could discourage the adoption of NbS (Kovacs et al., 2016). Considering the social context where NbS are to be implemented is therefore necessary to develop parallel strategies directed at incentivizing local engagement, capacity building and gaining community trust (Pagdee & Kawasaki, 2021; Ruano-Chamorro et al., 2022).

Establishing local compensatory mechanisms between upstream and downstream beneficiaries could also incentivize adoption of land practices by compensating landholders (Jack et al., 2008). For example, in the Chure region in Nepal, previous studies have found that downstream beneficiaries would be willing to pay a higher amount for drinking water than they were currently paying if the quality of the water improved (Bhandari et al., 2016). Incentivizing local engagement and compensatory programs would also require incorporation of the views and values of the different beneficiaries involved, and consideration of power dynamics between them (Paudyal et al., 2018; Wunder et al., 2018). For example, in North India, monetary compensation for upstream beneficiaries to protect and sustainably manage forested areas was provided by downstream beneficiaries in return of better water quality and increased protection against flood events (Kovacs et al., 2016). However, imbalances in power relations between the rural upstream and wealthier downstream towns created intra-community conflicts in the upstream town, undermining their capacity to build collective institutions fundamental for the long-term existence of the compensatory schemes (Kovacs et al., 2016). Further research in the Kali Gandaki watershed could also characterize the socioeconomic status of agricultural landholders. With this information, management plans could be developed to specifically direct benefit to the most vulnerable population sectors (Gourevitch et al., 2016; Li et al., 2020).

AUTHOR CONTRIBUTIONS

Jaramar Villarreal-Rosas was involved in conceptualization, methodology, software, validation, formal analysis, investigation, resources, writing—original draft and visualization. Jonathan R. Rhodes was involved in methodology, writing—review and editing and supervision. Laura J. Sonter and Hugh P. Possingham were involved in writing—review and editing and supervision. Adrian L. Vogl was involved in conceptualization, methodology, software, validation, resources and writing—review and editing. All authors contributed critically to the drafts and gave final approval for publication.

ACKNOWLEDGEMENTS

J.V.-R. was supported by a University of Queensland Research Training Scholarship, University of Queensland AOU Top Up scholarship and the Mexican National Council for Science and Technology. L.J.S. was supported by ARC Discovery Early Career Researcher Award (DE170100684). H.P.P. was partially supported by an ARC Laureate Fellowship (FL130100090). J.R.R. was supported by an ARC Future Fellowship (FT200100096).

CONFLICT OF INTEREST STATEMENT

The authors confirm there is no conflict of interest in this study.

DATA AVAILABILITY STATEMENT

The data on which this research is based are achieved at the World Bank repository under the name 'Valuing Green Infrastructure: Case Study of Kali Gandaki Watershed, Nepal (English). Washington, D.C., World Bank Group. http://documents.worldbank.org/curated/en/422301574090916059/Case-Study-of-Kali-Gandaki-Watershed-Nepal'.

ORCID

Jaramar Villarreal-Rosas https://orcid.org/0000-0001-6056-3268
Jonathan R. Rhodes https://orcid.org/0000-0001-6746-7412
Laura J. Sonter https://orcid.org/0000-0002-6590-3986
Hugh P. Possingham https://orcid.org/0000-0001-7755-996X
Adrian L. Vogl https://orcid.org/0000-0001-9369-1071

REFERENCES

Aggarwal, A., & Brockington, D. (2020). Reducing or creating poverty? Analyzing livelihood impacts of forest carbon projects with evidence from India. *Land Use Policy*, *95*, 104608. https://doi.org/10.1016/j.landusepol.2020.104608

Anderson, C. M., DeFries, R. S., Litterman, R., Matson, P. A., Nepstad, D. C., Pacala, S., Schlesinger, W. H., Shaw, M. R., Smith, P., Weber, C., & Field, C. B. (2019). Natural climate solutions are not enough. *Science*, *363*(6430), 933–934. https://doi.org/10.1126/science.aaw2741

Atreya, K., Sharma, S., Bajracharya, R. M., & Rajbhandari, N. P. (2008). Developing a sustainable agro-system for Central Nepal using reduced tillage and straw mulching. *Journal of Environmental Management*, *88*(3), 547–555. https://doi.org/10.1016/j.jenvman.2007.03.017

Beatty, C. R., Raes, L., Vogl, A. L., Hawthorne, P. L., Moraes, M., Saborio, J., & Meza Prado, K. (2018). *Landscapes, at your service: Applications of the restoration opportunities optimization tool (ROOT)*. IUCN, vi + 74pp.

Bellprat, O., Guemas, V., Doblas-Reyes, F., & Donat, M. G. (2019). Towards reliable extreme weather and climate event attribution. *Nature Communications*, *10*(1), 1732. https://doi.org/10.1038/s41467-019-09729-2

25758314, 2023, 3, Downloaded from https://besjournals.onlinelibrary.wiley.com/doi/10.1002/pan3.10481 by University of Adelaide Alumni, Wiley Online Library on [27/06/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Bhandari, P., KC, M., Shrestha, S., Aryal, A., & Shrestha, U. B. (2016). Assessments of ecosystem service indicators and stakeholder's willingness to pay for selected ecosystem services in the Chure region of Nepal. *Applied Geography*, *69*, 25–34. https://doi.org/10.1016/j.apgeog.2016.02.003

Chan, K. M. A., Guerry, A. D., Balvanera, P., Klain, S., Satterfield, T., Basurto, X., Bostrom, A., Chuenpagdee, R., Gould, R., Halpern, B. S., Hannahs, N., Levine, J., Norton, B., Ruckelshaus, M., Russell, R., Tam, J., & Woodside, U. (2012). Where are cultural and social in ecosystem services? A framework for constructive engagement. *BioScience*, *62*(8), 744–756. https://doi.org/10.1525/bio.2012.62.8.7

Chan, K. M. A., & Satterfield, T. (2020). The maturation of ecosystem services: Social and policy research expands, but whither biophysically informed valuation? *People and Nature*, *2*(4), 1021–1060. https://doi.org/10.1002/pan3.10137

Chen, D., Wei, W., Daryanto, S., & Tarolli, P. (2020). Does terracing enhance soil organic carbon sequestration? A national-scale data analysis in China. *Science of the Total Environment*, *721*, 137751. https://doi.org/10.1016/j.scitotenv.2020.137751

Chen, W., Wang, W., Huang, G., Wang, Z., Lai, C., & Yang, Z. (2021). The capacity of grey infrastructure in urban flood management: A comprehensive analysis of grey infrastructure and the green-grey approach. *International Journal of Disaster Risk Reduction*, *54*, 102045. https://doi.org/10.1016/j.ijdrr.2021.102045

Chhatre, A., & Agrawal, A. (2009). Trade-offs and synergies between carbon storage and livelihood benefits from forest commons. *Proceedings of the National Academy of Sciences of the United States of America*, *106*(42), 17667–17670. www.pnas.org/cgi/doi/10.1073/pnas.0905308106

Cook-Patton, S. C., Drever, C. R., Griscom, B. W., Hamrick, K., Hardman, H., Kroeger, T., Pacheco, P., Raghav, S., Stevenson, M., Webb, C., Yeo, S., & Ellis, P. W. (2021). Protect, manage and then restore lands for climate mitigation. *Nature Climate Change*, *11*(12), 1027–1034. https://doi.org/10.1038/s41558-021-01198-0

Crippa, M., Guizzardi, D., Solazzo, E., Muntean, M., Schaaf, E., Monforti-Ferrario, F., Banja, M., Oliver, J., Grassi, G., Rossi, S., & Vignati, E. (2021). *Emissions database for global atmospheric research, version v6.0_FT_2020 (GHG time-series)*. European Commission. http://data.jrc.ec.europa.eu/collection/edgar

Dahal, N., & Bajracharya, R. M. (2013). Effects of sustainable soil management practices on distribution of soil organic carbon in upland agricultural soils of mid-hills of Nepal. *Nepal Journal of Science and Technology*, *13*(1), 133–141. https://doi.org/10.3126/njst.v13i1.7452

Deng, C., Zhang, G., Liu, Y., Nie, X., Li, Z., Liu, J., & Zhu, D. (2021). Advantages and disadvantages of terracing: A comprehensive review. *International Soil and Water Conservation Research*, *9*(3), 344–359. https://doi.org/10.1016/j.iswcr.2021.03.002

Díaz, S., Pascual, U., Stenseke, M., Martín-López, B., Watson, R. T., Molnár, Z., Hill, R., Chan, K. M. A., Baste, I. A., Brauman, K. A., Polasky, S., Church, A., Lonsdale, M., Larigauderie, A., Leadley, P. W., van Oudenhoven, A. P. E., van der Plaat, F., Schröter, M., Lavorel, S., ... Shirayama, Y. (2018). Assessing nature's contributions to people. *Science*, *359*(6373), 270–272. https://doi.org/10.1126/science.aap8826

Duker, A. E. C., Tadesse, T. M., Soentoro, T., de Fraiture, C., & Kemerink-Seyoum, J. S. (2019). The implications of ignoring smallholder agriculture in climate-financed forestry projects: Empirical evidence from two REDD+ pilot projects. *Climate Policy*, *19*(S1), S36–S46. https://doi.org/10.1080/14693062.2018.1532389

Friedman, R. S., Mackenzie, E., Sloan, T., & Sweaney, N. (2022). Networking for gender equitable climate-smart agriculture. *Climate and Development*, 1–11. https://doi.org/10.1080/17565529.2022.2076645

GCF. (2019). *Building a resilient Churia region in Nepal*. Green Climate Fund. https://www.greenclimate.fund/sites/default/files/document/funding-proposal-fp118-fao-nepal.pdf

GCF. (2020a). *Areas of work*. Projects and Programmes. Areas of Work. https://www.greenclimate.fund/themes

GCF. (2020b). *GCF thematic brief, adaptation*. Green Climate Fund. https://www.greenclimate.fund/sites/default/files/document/thematic-brief-adaptation.pdf

GCF. (2020c). *Improving climate resilience of vulnerable communities and ecosystems in the Gandaki River Basin, Nepal*. Green Climate Fund.

GCF. (2020d). *Updated strategic plan for the green climate fund: 2020–2023*. Green Climate Fund. https://www.greenclimate.fund/sites/default/files/document/updated-strategic-plan-green-climate-fund-2020-2023.pdf

GCF. (2021). *GCF annual results report*. Green Climate Fund. https://www.greenclimate.fund/document/annual-results-report-2021

Gourevitch, J. D., Hawthorne, P. L., Keeler, B. L., Beatty, C. R., Greve, M., & Verdone, M. A. (2016). Optimizing investments in national-scale forest landscape restoration in Uganda to maximize multiple benefits. *Environmental Research Letters*, *11*(11), 114027. https://doi.org/10.1088/1748-9326/11/11/114027

Government of Nepal. (2013). *Nepal—National Population and housing census 2011*. Government of Nepal. https://unstats.un.org/unsd/demographic/sources/census/wphc/Nepal/Nepal-Census-2011-Vol1.pdf

Government of Nepal. (2016). *Nationally determined contributions*. Ministry of Population and Environment.

Herring, S. C., Hoerling, M. P., Peterson, T. C., & Stott, P. A. (2014). Explaining extreme events of 2013 from a climate perspective. *Bulletin of the American Meteorological Society*, *95*(9), S1–S104. https://doi.org/10.1175/1520-0477-95.9.S1.1

Hirons, M., Comberti, C., & Dunford, R. (2016). Valuing cultural ecosystem services. *Annual Review of Environment and Resources*, *41*(1), 545–574. https://doi.org/10.1146/annurev-environ-110615-085831

Hu, X., Li, Z., Chen, J., Nie, X., Liu, J., Wang, L., & Ning, K. (2021). Carbon sequestration benefits of the grain for green program in the hilly red soil region of southern China. *International Soil and Water Conservation Research*, *9*(2), 271–278. https://doi.org/10.1016/j.iswcr.2020.11.005

Hurlimann, A., Moosavi, S., & Browne, G. R. (2021). Urban planning policy must do more to integrate climate change adaptation and mitigation actions. *Land Use Policy*, *101*, 105188. https://doi.org/10.1016/j.landusepol.2020.105188

ICIMOD. (2007). *Good practices in watershed management: Lessons learned in the Mid Hills of Nepal*. International Centre for Integrated Mountain Development.

IPCC. (2018). Summary for policymakers. In V. Masson-Delmotte, P. Zhai, O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, & T. Waterfield (Eds.), *Global warming of 1.5°C. an IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* (pp. 3–24). Cambridge University Press.

IPCC. (2022a). In H. Pörtner, D. Roberts, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, & B. Rama (Eds.), *Climate change 2022: Impacts, adaptation, and vulnerability. Contribution of working group II to the sixth assessment report of the intergovernmental panel on climate change*. Cambridge University Press. https://doi.org/10.1017/9781009325844

IPCC. (2022b). In P. Shukla, J. Skea, A. Reisinger, R. Slade, R. Fradera, M. Pathak, A. Khourdajie, M. Belkacemi, R. van Diemen, A. Hasija, G. Lisboa, S. Luz, J. Malley, D. McCollum, S. Some, & P. Vyas (Eds.), *Climate change 2022: Mitigation of climate change. Contribution of working group III to the sixth assessment report of the intergovernmental*

25758314, 2023, 3, Downloaded from https://besjournals.onlinelibrary.wiley.com/doi/10.1002/pan3.10481 by University of Adelaide Alumni, Wiley Online Library on [27/06/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

panel on climate change. Cambridge University Press. https://www.ipcc.ch/report/ar6/wg3/

Jack, B. K., Kousky, C., & Sims, K. R. E. (2008). Designing payments for ecosystem services: Lessons from previous experience with incentive-based mechanisms. *Proceedings of the National Academy of Sciences of the United States of America*, *105*(28), 9465–9470. https://doi.org/10.1073/pnas.0705503104

Jacobs, S., Dendoncker, N., Martín-López, B., Barton, D. N., Gomez-Baggethun, E., Boeraeve, F., McGrath, F. L., Vierikko, K., Geneletti, D., Sevecke, K. J., Pipart, N., Primmer, E., Mederly, P., Schmidt, S., Aragão, A., Baral, H., Bark, R. H., Briceno, T., Brogna, D., … Washbourne, C.-L. (2016). A new valuation school: Integrating diverse values of nature in resource and land use decisions. *Integrated Valuation of Ecosystem Services: Challenges and Solutions*, *22*, 213–220. https://doi.org/10.1016/j.ecoser.2016.11.007

Khorchani, M., Nadal-Romero, E., Lasanta, T., & Tague, C. (2022). Carbon sequestration and water yield tradeoffs following restoration of abandoned agricultural lands in Mediterranean mountains. *Environmental Research*, *207*, 112203. https://doi.org/10.1016/j.envres.2021.112203

Kim, Y.-S., Latifah, S., Afifi, M., Mulligan, M., Burke, S., Fisher, L., Siwicka, E., Remoundou, K., Christie, M., Masek Lopez, S., & Jenness, J. (2018). Managing forests for global and local ecosystem services: A case study of carbon, water and livelihoods from eastern Indonesia. *Ecosystem Services*, *31*, 153–168. https://doi.org/10.1016/j.ecoser.2018.03.018

Kovacs, E. K., Kumar, C., Agarwal, C., Adams, W. M., Hope, R. A., & Vira, B. (2016). The politics of negotiation and implementation: A reciprocal water access agreement in the Himalayan foothills, India. *Ecology and Society*, *21*(2), 1–11. https://doi.org/10.5751/ES-08462-210237

Li, R., Zheng, H., Polasky, S., Hawthorne, P. L., O'Connor, P., Wang, L., Li, R., Xiao, Y., Wu, T., & Ouyang, Z. (2020). Ecosystem restoration on Hainan Island: Can we optimize for enhancing regulating services and poverty alleviation? *Environmental Research Letters*, *15*(8), 1–14. https://doi.org/10.1088/1748-9326/ab8f5e

Manandhar, S., Pandey, V. P., & Kazama, F. (2012). Hydro-climatic trends and people's perceptions: Case of Kali Gandaki River Basin, Nepal. *Climate Research*, *54*(2), 167–179. https://doi.org/10.3354/cr01108

Martin-Ortega, J., Mesa-Jurado, M. A., Pineda-Vazquez, M., & Novo, P. (2019). Nature commodification: 'A necessary evil'? An analysis of the views of environmental professionals on ecosystem services-based approaches. *Ecosystem Services*, *37*, 100926. https://doi.org/10.1016/j.ecoser.2019.100926

Mashi, S. A., Inkani, A. I., Obaro, O., & Asanarimam, A. S. (2020). Community perception, response and adaptation strategies towards flood risk in a traditional African city. *Natural Hazards*, *103*, 1727–1759. https://doi.org/10.1007/s11069-020-04052-2

MoFE. (2018). *Nepal national REDD+ strategy (2018–2022)*. Ministry of Forest and Environment, Government of Nepal. https://lib.icimod.org/record/34500

NEA. (2019). *Nepal electricity authority. A year in review-fiscal year 2018/2019*. Nepal Electricity Authority.

Nolan, C. J., Field, C. B., & Mach, K. J. (2021). Constraints and enablers for increasing carbon storage in the terrestrial biosphere. *Nature Reviews Earth & Environment*, *2*, 436–446. https://doi.org/10.1038/s43017-021-00166-8

OECD. (2021). *Strengthening adaptation-mitigation linkages for a low-carbon, climate-resilient future*. 23. https://doi.org/10.1787/6d79ff6a-en

Pagdee, A., & Kawasaki, J. (2021). The importance of community perceptions and capacity building in payment for ecosystems services: A case study at Phu Kao, Thailand. *Ecosystem Services*, *47*, 101224. https://doi.org/10.1016/j.ecoser.2020.101224

Panthi, J., Aryal, S., Dahal, P., Bhandari, P., Krakauer, N. Y., & Pandey, V. P. (2016). Livelihood vulnerability approach to assessing climate change impacts on mixed agro-livestock smallholders around the Gandaki River Basin in Nepal. *Regional Environmental Change*, *16*(4), 1121–1132. https://doi.org/10.1007/s10113-015-0833-y

Paudel, D., Tiwari, K. R., Bajracharya, R. M., Raut, N., & Sitaula, B. K. (2017). Agroforestry system: An opportunity for carbon sequestration and climate change adaptation in the mid-hills of Nepal. *Octa Journal of Environmental Research*, *5*(1), 022–031.

Paudyal, K., Baral, H., Bhandari, S. P., & Keenan, R. J. (2018). Design considerations in supporting payments for ecosystem services from community-managed forests in Nepal. *Ecosystem Services*, *30*, 61–72. https://doi.org/10.1016/j.ecoser.2018.01.016

Perkins-Kirkpatrick, S. E., Stone, D. A., Mitchell, D. M., Rosier, S., King, A. D., Lo, Y. T. E., Pastor-Paz, J., Frame, D., & Wehner, M. (2022). On the attribution of the impacts of extreme weather events to anthropogenic climate change. *Environmental Research Letters*, *17*(2), 024009. https://doi.org/10.1088/1748-9326/ac44c8

Rana, E., Thwaites, R., & Luck, G. (2017). Trade-offs and synergies between carbon, forest diversity and forest products in Nepal community forests. *Environmental Conservation*, *44*(1), 5–13. https://doi.org/10.1017/S0376892916000448

Ruano-Chamorro, C., Gurney, G. G., & Cinner, J. E. (2022). Advancing procedural justice in conservation. *Conservation Letters*, *15*(3), e12861. https://doi.org/10.1111/conl.12861

Salas, M. A., & Tillman, T. (2021). The transformative power of knowledge in terraced landscapes. *Vegueta*, *21*(1), 267–301. https://doi.org/10.51349/veg.2021.1.11

Schmitt, R. J. P., Bizzi, S., Castelletti, A. F., & Kondolf, G. M. (2018). Stochastic modeling of sediment connectivity for reconstructing sand fluxes and origins in the unmonitored Se Kong, Se San, and Sre Pok tributaries of the Mekong River. *Journal of Geophysical Research: Earth Surface*, *123*(1), 2–25. https://doi.org/10.1002/2016JF004105

Seddon, N. (2022). Harnessing the potential of nature-based solutions for mitigating and adapting to climate change. *Science*, *376*(6600), 1410–1416. https://doi.org/10.1126/science.abn9668

Sharma, B. P., Shyamsundar, P., Nepal, M., Pattanayak, S. K., & Karky, B. S. (2017). Costs, cobenefits, and community responses to REDD+: A case study from Nepal. *Ecology and Society*, *22*(2), 1–14. https://doi.org/10.5751/ES-09370-220234

Sharp, R., Tallis, H., Ricketts, T. H., Guerry, A., Wood, S. A., Chaplin-Kramer, R., Nelson, E., Ennaanay, D., Wolny, S., Olwero, N., Vigerstol, K., Pennington, D. N., Mendoza, G., Aukema, J., Foster, J., Forrest, J., Cameron, D. R., Arkema, K. K., Londsfort, E., … Douglass, J. (2018). *InVEST 3.5.0. user's guide*. The Natural Capital Project, Stanford University, University of Minnesota, The Nature Conservancy, and World Wildlife Fund.

Shrestha, S. B. (2016). *Soil erosion and payment for sediment retention in Kulekhani watershed*. Agricultural and Forestry University.

Sidle, R. C., & Ziegler, A. D. (2012). The dilemma of mountain roads. *Nature Geoscience*, *5*(7), 437–438. https://doi.org/10.1038/ngeo1512

Sousa, S., Botelho, A., Costa Pinto, L. M., & Valente, M. (2019). How relevant are non-use values and perceptions in economic valuations? The case of hydropower plants. *Energies*, *12*(15), 2986. ProQuest Central; ProQuest One Academic. https://doi.org/10.3390/en12152986

UN. (1998). *Kyoto Protocol to the United Nations framework convention on climate change*. United Nations. https://unfccc.int/resource/docs/convkp/kpeng.pdf

UN. (2015). *Climate neutral now*. United Nations. https://unfccc.int/resource/docs/convkp/kpeng.pdf

UN. (2022). *Adaptation gap report 2022: Too little, too slow—Climate adaptation failure puts world at risk*. United Nations Environment Programme. https://www.unep.org/adaptation-gap-report-2022

UNFCCC. (2022). *Sharm el-sheikh implementation plan*. UNFCCC. https://unfccc.int/documents/624444

Vicedo-Cabrera, A. M., Scovronick, N., Sera, F., Royé, D., Schneider, R., Tobias, A., Astrom, C., Guo, Y., Honda, Y., Hondula, D. M.,

25758314, 2023, 3, Downloaded from https://besjournals.onlinelibrary.wiley.com/doi/10.1002/pan3.10481 by University of Adelaide Alumni, Wiley Online Library on [27/06/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Abrutzky, R., Tong, S., Coelho, M. d. S. Z. S., Saldiva, P. H. N., Lavigne, E., Correa, P. M., Ortega, N. V., Kan, H., Osorio, S., … Gasparrini, A. (2021). The burden of heat-related mortality attributable to recent human-induced climate change. *Nature Climate Change*, *11*(6), 492–500. https://doi.org/10.1038/s41558-021-01058-x

Wasson, R. J. (2003). A sediment budget for the Ganga–Brahmaputra catchment. *Current Science*, *84*(8), 1041–1047. https://www.jstor.org/stable/24107666

World Bank. (2019). *Valuing green infrastructure: Case study of Kali Gandaki watershed, Nepal*. World Bank Group. http://documents.worldbank.org/curated/en/422301574090916059/Case-Study-of-Kali-Gandaki-Watershed-Nepal

Wunder, S., Brouwer, R., Engel, S., Ezzine-de-Blas, D., Muradian, R., Pascual, U., & Pinto, R. (2018). From principles to practice in paying for nature's services. *Nature Sustainability*, *1*(3), 145–150. https://doi.org/10.1038/s41893-018-0036-x

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Table S1. Land cover and land use-based baseline carbon stock values used to estimate carbon sequestration.

Table S2. Baseline USLE C (crop) factors used in hillslope erosion modelling.

Table S3. Baseline USLE P (practice) factors used in hillslope erosion modelling.

Table S4. USLE C (crop) factors for management activities.

Table S5. USLE P (practice) factors for management activities.

Text S1. Overview of models used to value ecosystem services.

Figure S1. Efficiency frontiers between pairs of objectives with optimal intervention allocation maps. Both axes' units are in percentages relative to the maximum benefit obtained at a $40M budget. Associated maps indicate the optimal allocation of actions per decision unit. Associated graphs indicate the area available for intervention within priority decision units (ha). A: Associated map and graph when on-site sediment is given 100% weight. B: Associated map and graph when downstream sediment is given 100% weight.

How to cite this article: Villarreal-Rosas, J., Rhodes, J. R., Sonter, L. J., Possingham, H. P., & Vogl, A. L. (2023). Optimal allocation of nature-based solutions to achieve climate mitigation and adaptation goals. *People and Nature*, *5*, 1034–1045. https://doi.org/10.1002/pan3.10481

25758314, 2023, 3, Downloaded from https://besjournals.onlinelibrary.wiley.com/doi/10.1002/pan3.10481 by University of Adelaide Alumni, Wiley Online Library on [27/06/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License