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Ridge-to-reef conservation avoids future deforestation and sediment exposure of coral reefs

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ABSTRACT

Land and sea are ecologically connected, and effective conservation of coastal ecosystems requires integrated planning that addresses threats spanning both realms. Deforestation in tropical catchments delivers sediment, nutrients, and other pollutants to downstream coral reefs, where these can impair coral physiology and alter reef community structure and resilience. Failing to address these cross-realm threats impacts ecosystem services vital to forest and coastal communities. A growing body of work has developed ridge-to-reef modelling approaches to link land-use change to downstream marine impacts. Yet, integrating these dynamics into spatial conservation planning remains challenging, particularly at large spatial scales and while accounting for socio-economic costs. Here, we compare alternative ridge-to-reef spatial planning strategies that integrate conservation actions on land and sea, showing that explicit representations of land–sea connectivity can substantially reduce future sediment exposure on reefs. Across the hyper-diverse Wallacea bioregion in Indonesia, we estimated sediment yields from terrestrial catchments for present and future deforestation scenarios. We then quantified and mapped how runoff affected downstream turbidity on reefs. Projected future sediment runoff to reefs varied widely, with the greatest impacts concentrated near large river catchments and deltas, especially in central-southeast Sulawesi. Joint land–sea conservation scenarios reduced reef sedimentation by 25% more than strategies that treated land and sea separately, with approaches that account for where sediment reaches reefs outperforming simpler proxies based on adjacency or distance. In the face of widespread deforestation and reef decline across the tropics, applying data-driven ridge-to-reef conservation approaches could provide major benefits for people and biodiversity.

1. Introduction

Effective conservation in coastal regions requires explicit treatment of the links between actions on land and outcomes in the sea. Deforestation in tropical catchments delivers sediment to downstream reefs, where suspended particles reduce light availability, smother coral

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surfaces, and shift reef communities toward sediment-tolerant taxa (Fabricius, 2005; Richmond et al., 2007; Sahavacharin et al., 2022). Coupled with overfishing and climate change, these land-based pressures degrade reef ecosystems and the services they provide to coastal communities (Burke et al., 2012; Carlson et al., 2019). Yet, conservation planning has historically treated terrestrial and marine systems separately, with priorities in each realm decided independently using realm-specific criteria, and cross-realm threats such as sediment runoff rarely entering either calculation explicitly (Álvarez-Romero et al., 2011).

Addressing sediment-driven reef decline requires coordinated conservation action across so-called ridge-to-reef systems (Álvarez-Romero et al., 2011; Beger et al., 2010a; Hermoso et al., 2021; Klein et al., 2012; Struebig et al., 2022; Tulloch et al., 2021). Explicitly identifying highly impacted reef areas and the upstream catchments responsible for sediment delivery enables strategic and cost-effective targeting of conservation interventions. This need for coordinated action coincides with growing global commitments to area-based conservation. Through the Kunming-Montreal Global Biodiversity Framework, countries have agreed to conserve 30% of terrestrial, inland water, coastal and marine areas by 2030 (Convention on Biological Diversity, 2022). Integration between terrestrial and marine conservation area systems is widely advocated as part of expanding and strengthening these networks, but remains challenging to implement consistently in practice (Balbar and Metaxas, 2019).

Despite limited uptake in practice, a range of approaches have been developed to incorporate ridge-to-reef dynamics into conservation planning. These include distance-based plume models that link watershed pollution to coral reef condition (Klein et al., 2012), combined land-use change and catchment models (Álvarez-Romero et al., 2015; Delevaux et al., 2018; Tulloch et al., 2016), frameworks linking riverine, estuarine, and marine areas of interest (Hermoso et al., 2021), and process-based methods that link land-use change to water clarity on reefs (Brown et al., 2017). However, three gaps limit their application to large, complex regions. First, most applications cover relatively small spatial extents and have not been scaled to whole bioregions. Second, applications often rely on simple spatial proxies for land–sea connectivity (such as adjacency or distance) rather than data-driven estimates of where sediment actually reaches reefs, and the consequences of this choice for prioritisation outcomes are rarely evaluated explicitly. Third, socio-economic considerations such as opportunity costs to local communities are not always integrated alongside ecological data, limiting practical relevance.

The Wallacea region – famed for its foundational role in evolutionary theory – encompasses approximately 1680 islands of eastern Indonesia with 40,900 km of coastline and is a hotspot of marine and terrestrial biodiversity and endemism (Struebig et al., 2022). Wallacea sits within the Coral Triangle, the global epicentre of marine biodiversity, and contains an exceptionally large area of coral reef that supports both regional fisheries and globally significant reef biodiversity (Burke et al., 2012). Terrestrially, Wallacea supports 62 endemic vertebrate genera with forests covering roughly 141,000 km^2 as of 2018 (Struebig et al., 2022). The region is changing rapidly, as governing bodies support development alongside ambitious aims to conserve biodiversity (Struebig et al., 2022). Expanding agriculture, mining, and associated infrastructural development further reduce intact forest areas (Supriatna et al., 2020; Voigt et al., 2021), and contribute to Indonesia having the second highest area of coral reefs impacted by sediment runoff globally (Suárez-Castro et al., 2021). Further, a high dependence on natural resources and widespread poverty require careful planning to support people's livelihoods while achieving conservation goals. Although ridge-to-reef planning has not yet been implemented for Wallacea, and governance fragmentation across terrestrial and marine sectors may constrain coordinated action, it presents a promising opportunity to explore how integrated approaches could improve conservation outcomes (Struebig et al., 2022).

Ridge-to-reef conservation should benefit both forests and reefs by reducing deforestation and reef damage via curbed sediment flows (Fig. 1). Yet, no quantitative estimates exist for this region of how reducing deforestation would translate into reduced sediment delivery and downstream benefits for reefs. Here, we tackle this challenge across the complex assemblage of islands and coral reefs in Wallacea. Aiming to quantify the potential benefit of implementing ridge-to-reef conservation, we first estimate current sediment loads and predict potential runoff from future deforestation. Next, we link sediment contributions to coastal ocean water quality using a Bayesian hierarchical model, letting us assess sediment contributions under future deforestation projections and identify catchments likely to have high impacts. Finally, using spatial prioritisation analyses, we assess the benefit of coordinated conservation to mitigate deforestation and protect coral reefs. We evaluate how alternative representations of ridge-to-reef linkages—ranging from simple spatial proxies to data-driven estimates of sediment impact—affect conservation outcomes, while minimising marine and terrestrial economic impacts on people's livelihoods.

2. Methods

2.1. Sedimentation model

We calculated total sediment runoff from land catchments by modelling evapotranspiration and rainfall runoff. The approach has previously been used to trace sedimentation influence on coral reefs and is suitable for data-limited regions (Brown et al., 2017; Zhang et al., 2001). The model uses a catchment-scale water balance framework where precipitation is partitioned into evapotranspiration and runoff. This is grounded in Budyko-type relationships, where evapotranspiration is controlled by the balance between precipitation and potential evapotranspiration (Budyko, 1974; Zhang et al., 2001). We began by generating 1243 spatial polygons of catchments containing entire river networks from source to mouth. We used HydroATLAS levels 8–12, a hierarchical sub-basin classification where higher levels denote finer subdivisions, with level 12 representing the smallest sub-basins (Linke et al., 2019). For each catchment, we quantified the proportion of forest cover in 2018 (Voigt et al., 2021), the latest year available, and average annual rainfall during the wet season from November to April for each year in 2016 to 2019 (Fick and Hijmans, 2017). These values were used to calculate evapotranspiration and the proportion of rainfall runoff from forested and non-forested areas (Brown et al., 2017; Zhang et al., 2001), which were combined to estimate sediment yield per catchment in 2018.

This approach relies on two key assumptions. First, the water balance assumes negligible long-term changes in soil water storage, an assumption that holds at the multi-year timescales we model but may not hold during short-term anomalies such as drought or extreme wet periods. Second, vegetation effects on evapotranspiration are represented through a binary forest/non-forest classification. This classification was derived from Voigt et al. (2021) which uses the Margono et al. (2014) definition of forest (>70% canopy cover at 30 m resolution, consistent with Indonesian Ministry of Forestry classifications). These binary pixel classifications were aggregated to continuous proportional forest cover values for each catchment, so the sediment yield model itself operates on a continuous 0–1 forest cover input rather than a binary one. Vegetation influences evapotranspiration primarily through differences in plant water use, particularly rooting depth and plant-available water capacity. Forested systems typically exhibit higher evapotranspiration than non-forested systems due to deeper rooting and greater access to soil moisture.

This approach simplifies complex hydrological processes by representing vegetation effects through broad land cover classes and does not explicitly account for factors such as soil properties, slope, or land management practices (Zhang et al., 2001). While slope is an important control on erosion rates at finer spatial scales, the Zhang et al. (2001) model does not explicitly account for topography, and this limitation is

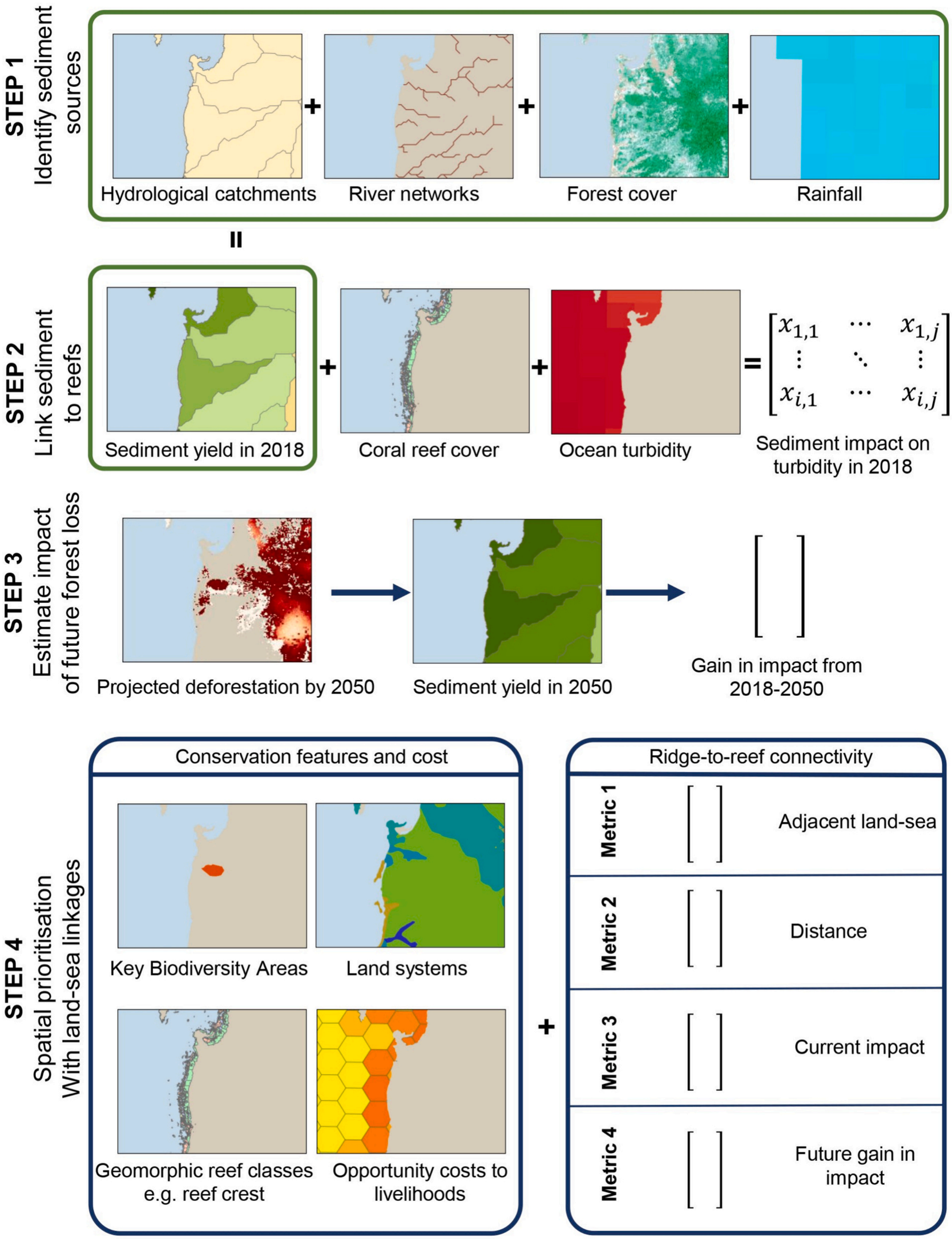

Fig. 1. Conceptual steps of ridge-to-reef conservation analyses for Wallacea, combining changing sediment loads given future deforestation, sediment dissipation across coral reefs, multi-scale cost to represent livelihood activities, and an evaluation of different ridge-to-reef integration methods. In Step 1, we use an evapo-transpiration and rainfall runoff model to estimate sediment yield from terrestrial catchments in 2018. In Step 2, we link sediment yield to ocean turbidity to estimate the relative impact of catchments on downstream marine areas. In Step 3, we estimate future sediment loads for projected forest cover changes in 2050 (Voigt et al., 2021) to calculate future impact of terrestrial catchments on coral reefs. In Step 4, we compare the reduction in sediment load for conservation prioritisations where ridge-to-reef processes are represented by one of four strategies, 1) length of boundary between adjacent terrestrial and marine areas, 2) distance between terrestrial and marine areas, 3) current sediment impact, and 4) future gain in sediment impact. Maps are zoomed in to Southeast Sulawesi.

inherited in our application. As such, the model captures first-order differences in runoff generation associated with deforestation but does not resolve fine-scale variation in sediment production. The resulting estimates should therefore be interpreted as relative indicators of sediment generation rather than precise predictions.

To assess the impact of future deforestation on sediment runoff, we applied a deforestation model for Wallacea (Voigt et al., 2021). The model predicts the probability of forest loss from past deforestation, slope, fire activity, accessibility from settlements, human population pressure, distance to villages with different main commodities, distance to transmigrant settlements, mining concessions, and land-use designation. To calculate the threshold of probability to define a binary 2050 forest cover dataset, we extrapolated average annual forest loss from 2000 to 2018 historical data (Hansen et al., 2013), assuming constant forest loss into the future. We then recalculated sediment yield from each catchment under this deforested 2050 scenario.

We linked the sediment runoff to satellite observations of ocean turbidity to assess the impact of individual land catchments on water quality using a Bayesian hierarchical model (Brown et al., 2017). The model represents observed turbidity at each marine location as the combined influence of multiple sediment sources (river catchments), where contributions decline with distance from each source and are constrained to scale with independently estimated sediment yields. The relative influence of each source is estimated within the model as a latent parameter. This approach is particularly suited to data-limited systems where multiple sources contribute to observed environmental signals and the problem is inherently underdetermined, meaning that no unique solution exists for attributing source contributions. The Bayesian framework allows the integration of multiple data sources (e.g. land-use, rainfall, and remotely sensed water quality) while explicitly representing uncertainty in parameter estimates. The model was implemented using Markov Chain Monte Carlo (MCMC) sampling, with convergence assessed using standard diagnostics (e.g. Gelman–Rubin statistic <1.05), following established Bayesian workflows (Brown et al., 2017).

Turbidity was measured by the diffuse attenuation coefficient at 490 nm at 2.32 km resolution (Wang et al., 2009). Turbidity is a reliable proxy for increased siltation and is associated with decline in coverage of sediment sensitive coral genera (Brown et al., 2017), and reduced coral growth rates, fecundity, and species richness (Fabricius, 2005). We defined the marine study area as a 20 km buffer extending seaward from the coastline and from all coral reefs in the region (Allen Coral Atlas, 2022). This buffer was divided into a regular grid of 5 km hexagonal cells, which served as the spatial units for the prioritisation analysis ('planning units') as well as for the turbidity analysis. For each hexagonal cell, we extracted satellite-observed turbidity values during the wet season (November to April) for each year from 2012 to 2018 (Wang et al., 2009), and took the geometric mean across years to obtain a single turbidity value per cell. We then calculated the distance between each cell and every river delta in the region. The 20 km buffer was chosen to capture the effective extent over which reef-associated ecological and human-use processes operate. Local fishing vessels typically travel up to this distance from shore to reach reef fishing grounds (Pet-Soede et al., 2001), making 20 km a reasonable approximation of the seascape within which terrestrial inputs and human use of reef resources interact.

Sedimentation analyses are typically undertaken at small spatial scales owing to computational challenges. Due to the extensive size of the study area and coastlines, computation of the Bayesian model was not possible for all 33,011 marine hexagons and 1243 land catchments. Therefore, we used a subsample of the marine hexagons to calculate model parameter estimates. We ran 5%, 10% and 20% subsamples and chose the 10% sample as it offered a good balance between model accuracy and computing time (see S3 in supplemental material for additional details). Subsampling and Bayesian model fitting were implemented in R v4.3.0 (R Core Team, 2023) using the rjags package v4.14 (Plummer, 2023). We used the mean model parameter estimates to interpolate the results to the entire region and ran the model for the two scenarios – current sediment runoff in 2018 versus future runoff in 2050. The gain in impact between the two timeframes was calculated as the difference in impact between the two scenarios.

2.2. Ridge-to-reef prioritisation approach

We ran a series of spatial prioritisation analyses to determine where limited conservation resources should be spatially allocated to achieve the greatest impact. Our analysis aimed to represent important species distributions and habitat areas, minimise socioeconomic opportunity costs, and mitigate impacts of terrestrial runoff on downstream reefs.

We divided the Wallacea region into a grid of planning units and determined which terrestrial and marine planning units were conservation priorities. We assumed that a terrestrial planning unit selected for conservation would be managed to avoid the projected deforestation and associated gain in sediment runoff. As planning units, we used 2391 hydrological basins on land at the smallest available sub-basin division (Linke et al., 2019) and our grid of 33,011 hexagons on sea. Planning units were either selected or not selected for conservation according to meeting biodiversity targets, cost, and linkage criteria to form part of final solutions.

To represent important areas for biodiversity in the prioritisation, we used a set of conservation features, the spatial elements that the prioritisation aims to represent in protected sites, such as species distributions and habitat types. We used 224 terrestrial and 40 marine conservation features and determined how much of each feature was contained within each planning unit. Terrestrial features comprised the distributions of 206 Key Biodiversity Area trigger species classified as Vulnerable, Endangered or Critically Endangered on the IUCN Red List (BirdLife International, 2022; IUCN, 2023) and 18 categories of forested land taken from Indonesia's land classification system (RePPProT, 1990). The 40 marine conservation features were taken from the Allen Coral Atlas and comprised the ten geomorphic layers (back reef slope, deep lagoon, inner reef flat, outer reef flat, plateau, reef crest, reef slope, shallow lagoon, sheltered reef slope, and terrestrial reef flat) stratified by benthic layers of coral/algae, rock, rubble, and seagrass (Allen Coral Atlas, 2022). We retained all combinations from the Allen Coral Atlas as non-coral substrates support a diversity of reef organisms and contribute to reef structural complexity and ecosystem functioning (Wolfe et al., 2021). The use of Allen Coral Atlas habitat classifications as surrogates for marine biodiversity reflects a data gap in spatially comprehensive and reliable distribution data for reef fish. Habitat maps are commonly used as the primary spatial dataset for marine reserve design where species data are unavailable (Dalleau et al., 2010).

We set a 30% coverage target for each of these species, forested land types, and marine habitat types. This target aligns with Indonesia's commitment to help achieve Target 3 of the Kunming-Montreal Global Biodiversity Framework to effectively conserve and manage at least 30% of terrestrial, inland water, coastal and marine areas by 2030 (Convention on Biological Diversity, 2022). A full list of conservation features is provided in Table S1.

Conserving a planning unit incurs a cost, which can reflect either financial or non-financial costs of management or opportunity costs from loss of access. Non-financial costs include restrictions on access to resources, increased labour for compliance or monitoring, and potential social or cultural impacts on local communities. Our cost dataset represented opportunity costs of using the natural resources in land or sea for generating income and food. We calculated a terrestrial cost index by combining human population size (Bondarenko et al., 2020) and two metrics from Indonesia's Potensi Desa (village potential) census from 2018 (Bureau of Statistics Indonesia, 2018; Morgans et al., 2024): a socioeconomic deprivation score and community dependency on forest (Morgans et al., 2024). The terrestrial cost, $C_{Terrestrial}$, was derived using the following equation:

$$C_{Terrestrial} = P \times D \times F$$

where P is the population count; D is the deprivation score expressed in whole numbers from 0 to 5 which we converted to corresponding values of 0.001, 0.2, 0.4, 0.6, 0.8 and 1; F is the dependency on forest where we assigned medium or low dependency a value of 0.001 and high dependency a value of 1. The value of 0.001 was chosen as a small positive floor value to prevent planning units from being assigned zero cost, which would cause numerical instability in the prioritisation and make those units freely selectable. This is a pragmatic modelling convention rather than an empirically calibrated parameter. The large ratio between the values means high-dependency communities carry substantial relative weight in the cost function, which reflects our intent to prioritise avoiding costs to communities most dependent on forest resources. The multiplicative formulation ensures that all three dimensions must be elevated simultaneously for a planning unit to register as high-cost, preventing any single dimension from dominating.

For the marine realm, we applied an existing opportunity cost layer that represents the relative economic and livelihood cost of restricting access to marine resources, based on factors influencing fishing activity and dependence (Muenzel et al., 2024). Marine cost (C_{Marine}) is derived using the following equation:

$$C_{Marine} = \frac{F + DistS + G}{3} * A$$

F is a binary value of whether fishing was a main livelihood of neighbouring villages. Distance (DistS) captured fishing from small vessels and was calculated as the overwater distance to the nearest coastal village. Gravity (G) captured seascape level fishing pressure exerted by large population centres and was calculated as the population of the nearest city divided by travel time over sea (Cinner et al., 2018). Area of non-rubble habitat (A) captured the lost fishery yield from habitats that typically support higher fish biomass. These variables were combined into a single cost surface representing relative opportunity cost across the seascape.

To evaluate how different assumptions about land–sea connectivity influence conservation outcomes, we developed four alternative ridge-to-reef linkage strategies spanning a gradient from simple spatial proxies to more data-driven representations of sediment connectivity. These strategies reflect commonly used approaches in the literature, including adjacency- and distance-based connectivity, as well as models incorporating spatially explicit estimates of sediment impact. We hypothesised that approaches incorporating sediment impact would outperform simpler spatial proxies in reducing downstream sediment exposure on reefs.

We first ran a baseline prioritisation without any ridge-to-reef linkages, aiming to protect 30% of conservation features at minimum cost. We then developed four strategies that explicitly link land and sea in the prioritisation, each also protecting 30% of conservation features. Each strategy works by assigning a penalty between pairs of connected terrestrial and marine planning units. The prioritisation aims to minimise this penalty by selecting both members of a strongly connected pair together, so that protecting a terrestrial catchment also captures the downstream marine areas it influences (Beger et al., 2010b; Daigle et al., 2020). The four strategies differ in how the strength of connection between each land–sea pair is calculated:

1. The 'adjacent land-sea' approach seeks to protect neighbouring land and sea zones using shared coastal boundary information (Álvarez-Romero et al., 2011; Beger et al., 2010a). This is a traditional and widely used proxy for land–sea connectivity in the absence of more sophisticated data. Longer shared coastlines incurred a higher penalty, making pairs of adjacent planning units more likely to be designated together.
2. The 'distance-based connectivity' approach uses distance functions reflecting commonly used distance-decay assumptions in ridge-to-reef modelling (Klein et al., 2012; Makino et al., 2013; Weeks, 2017). Planning units closer together (measured as the inverse overwater distance between river deltas and downstream reefs) received a higher penalty.
3. The 'current sediment impact' approach provides a data-driven estimate of spatially variable sediment influence using sedimentation data from 2018. Estimated sediment effects on reef turbidity (Brown et al., 2017) were applied as the boundary penalty between terrestrial and marine planning units.
4. The 'future gain in sediment impact' approach captures dynamic changes in connectivity under projected land-use change. Projected changes in sediment impact (here, 2018–2050, using predictions from the deforestation and sedimentation modelling) were used as the terrestrial–marine boundary information.

We applied a constraint requiring linkage strategies to produce a greater reduction in sediment runoff compared to the baseline. This additional step was necessary as the prioritisation algorithm could feasibly minimise the linkage penalty by altogether avoiding areas with strong land-sea linkages. We tested a range of values for the boundary penalty, which set the relative importance of the linkage penalty over area targets and cost, to explore a range of potential solutions for each strategy. To facilitate comparison across strategies, we focused on solutions with approximately 5% higher opportunity cost than the baseline, as this marks a visible inflection in the cost–sediment relationship for the two impact-based strategies, beyond which the marginal sediment gained per unit additional cost decreases. To evaluate the four methods, we compared the total cost of protection, the amount of sediment runoff avoided through prevention of deforestation, and the spatial overlap between scenarios. Existing protected areas were not explicitly included or locked into the prioritisation analysis, allowing us to identify optimal spatial configurations unconstrained by current designations.

We ran 317 prioritisations in R v4.3.0 (R Core Team, 2023) with the prioritizr package v8.0.0 (Hanson et al., 2025). Prioritizr uses a mixed integer linear programming algorithm to provide optimum solutions to custom-tailor conservation problems, where users can supply a range of objectives, penalties, and constraints. We generated near-optimal solutions within 1% of the best possible solution due to constraints of computational runtime, although prioritizr can be used to generate optimal solutions.

3. Results

3.1. General patterns of sediment export

We estimated that sediment runoff from Wallacea's catchments will increase by 148.1 Mt from 916.8 Mt in 2018 to 1064.9 Mt by 2050 under business-as-usual deforestation (Fig. 2). The amount of sediment runoff in 2018 was moderately spatially correlated with the increase in sediment runoff by 2050 ($r_s = 0.65$, $p < 10^{-6}$, $n = 2391$). Three provinces on the largest island, Sulawesi (Central, Southeast, and South) contributed 77% of the projected increase in sediment. The marine areas downstream of these catchments experienced the highest rise in turbidity, clustered around river deltas (Fig. 2). Catchments in Sulawesi's rugged and mountainous interior contributed more sediment than coastal catchments. In contrast, 5% of catchments (primarily in East and West Nusa Tenggara) are projected to reduce sediment output due to higher rates of afforestation than deforestation by the 2050s.

3.2. Reduced sedimentation with ridge-to-reef conservation

The uncoordinated conservation planning strategy, whereby terrestrial and marine conservation areas are prioritised separately, designated 73,881 km^2 of land and 22,330 km^2 of sea for protection, reducing future sediment runoff by 39.6 Mt through avoided deforestation.

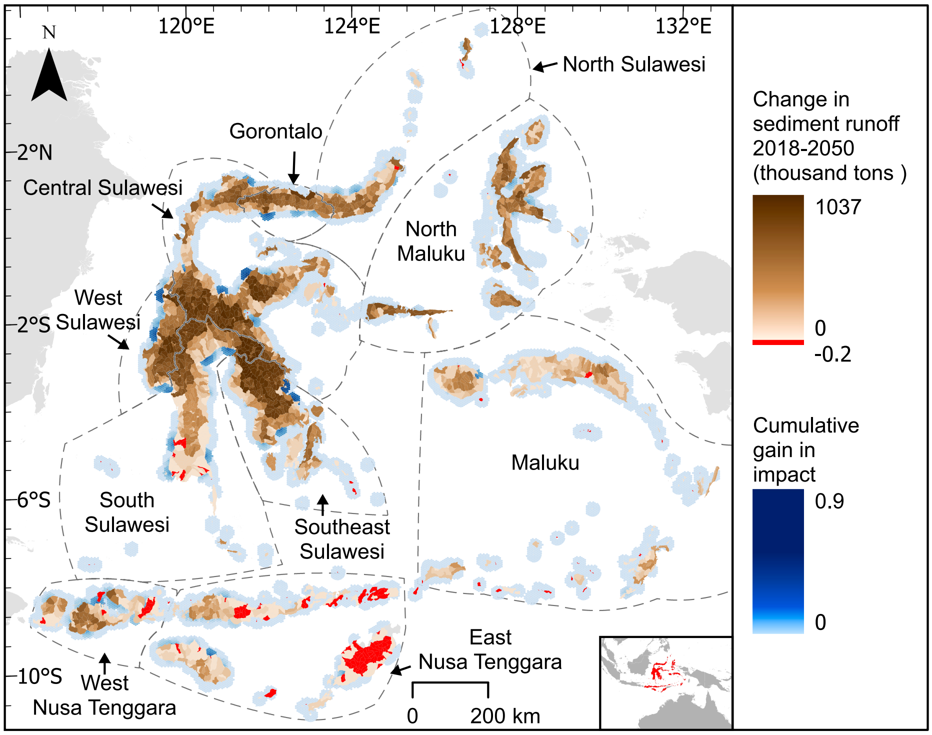

Fig. 2. Change in sediment runoff from terrestrial planning units in the Wallacea region of Indonesia between 2018 and 2050. Terrestrial colours show the projected change in sediment runoff from each catchment under business-as-usual deforestation, with darker shades indicating greater increases. Marine colours show the cumulative gain in sediment impact on water quality at each marine planning unit, summed across all upstream terrestrial sources.

However, it did not consider how remaining sediment might affect reefs downstream. In contrast, the integrated ridge-to-reef strategy reduced sediment runoff by an additional 9.7–9.9 Mt—a 25% improvement—when planned with just 5% higher opportunity costs (Fig. 3). In absolute terms, the uncoordinated strategy's 39.6 Mt reduction represents 27% of the projected 148.1 Mt increase in sediment runoff between 2018 and 2050 under business-as-usual deforestation, and the integrated strategy's additional 9.7–9.9 Mt represents a further 7% of that projected increase. Because comparisons across strategies were made at fixed opportunity cost rather than fixed area, the total area designated for protection varied across strategies: adjacent land-sea (72,922 km^2 land and 26,920 km^2 sea), distance (82,165 km^2, 40,284 km^2), current sediment impact (79,930 km^2, 25,198 km^2), and future gain in impact (76,926 km^2, 26,153 km^2).

3.3. *Comparing ridge-to-reef planning approaches*

Comparing potential sediment avoided across the four approaches, the 'adjacent land-sea' approach was the least effective strategy. This is the most often advocated and easiest to implement method of

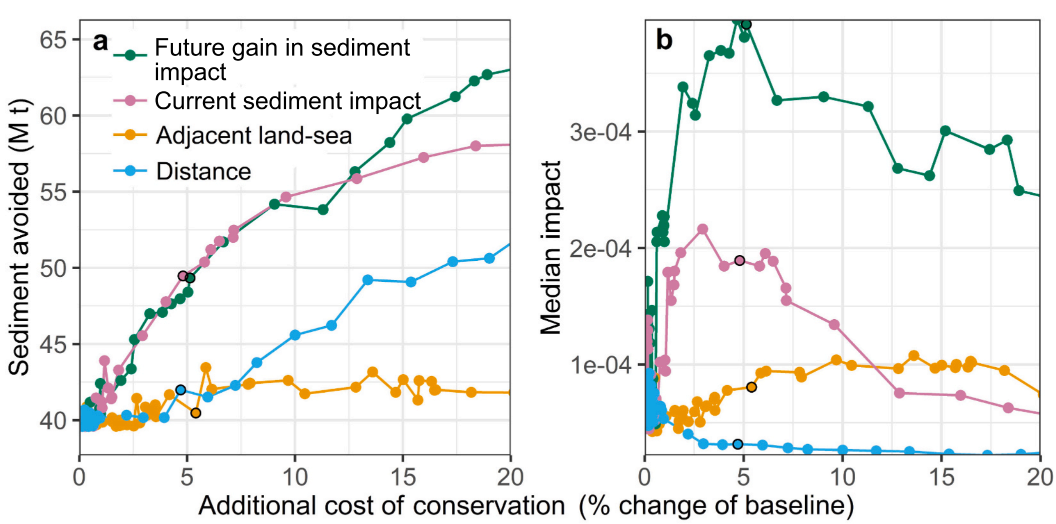

Fig. 3. Comparison of each of the four conservation strategies of ridge-to-reef linkage planning across different total opportunity costs (x-axis) by a) the amount of sedimentation reduction achieved and b) the median gain in impact between pairs of terrestrial and marine areas both designated for protection (y-axes). The origin 0 is scaled to the baseline cost when conservation planning is conducted without any ridge-to-reef linkages. Each point represents a specific prioritisation solution along a range of costs. Solutions representing approximately 5% higher total opportunity cost than the baseline are outlined in black circles.

conserving adjacent coastal land and sea areas, but at 5% higher cost it avoided just 0.9 Mt more sediment than the uncoordinated baseline. The 'distance-based connectivity' approach slightly improved outcomes, avoiding 2.4 Mt more sediment at the same 5% increase in cost. However, the greatest reduction in runoff was achieved when we accounted for the differential sediment impact on turbidity. An additional 9.9 and 9.7 Mt of sediment was avoided at 5% higher cost when information was used from current or projected future timeframes. In other words, strategies using estimates of sedimentation impact on turbidity captured the most strongly connected land and sea areas (Figs. 3b, 4). Notably, these areas were often located inland in Sulawesi, where sediment contributions to reefs were greatest.

3.4. *Cost-effectiveness and trade-offs in conservation*

Implementing ridge-to-reef strategies without explicitly accounting for land-sea linkages represents a cost optimum – that is, conservation actions in additional areas generate additional reductions in sediment runoff, but are more costly to implement. The 5% higher opportunity costs incurred for the alternative ridge-to-reef approaches represent an optimum trade-off between sediment reduction and increase in cost, but it is worthwhile to explore performance at higher costs. We therefore explored outcomes at incremental increases (0–20%) in opportunity costs.

Across a range of higher costs, the ridge-to-reef approaches designed around contemporary or future impact avoided four times more sediment than the distance-based approach and up to twelve times more than the adjacent land-sea method (Fig. 3A). Between the two impact-based approaches, current sediment impact outperformed future gain in impact at lower cost thresholds, but this reversed at ≥12.5% higher cost, beyond which prioritising projected future sediment impacts consistently avoided more sediment (Fig. 3A). This pattern was also evident in the per-site median impact of selected planning units. Both impact-based approaches showed diminishing returns, peaking at low additional cost before declining as progressively lower-impact catchments were added at higher budgets (Fig. 3B). In contrast, the median impact of planning units selected by the distance-based approach remained low across all cost levels tested, well below that of either impact-based approach. The adjacent land–sea approach rose more gradually to a later, lower peak before also declining (Fig. 3B). These patterns were reflected spatially. Additional priority areas identified by the less effective adjacent and distance approaches were mostly coastal (Fig. 4 A, B), whereas the impact-based strategies prioritised inland catchments with high projected sediment increases—primarily in Sulawesi (Fig. 4 C, D). Together, these results indicate that impact-based prioritisation—whether based on current or future sediment impact—avoids more sediment cumulatively than distance- or adjacency-based approaches by explicitly targeting the catchments contributing disproportionately to reef sedimentation.

4. Discussion

4.1. *Effectiveness and scope of ridge-to-reef planning*

Integrated ridge-to-reef management is crucial in coastal areas, where marine conservation alone cannot address land-based threats to

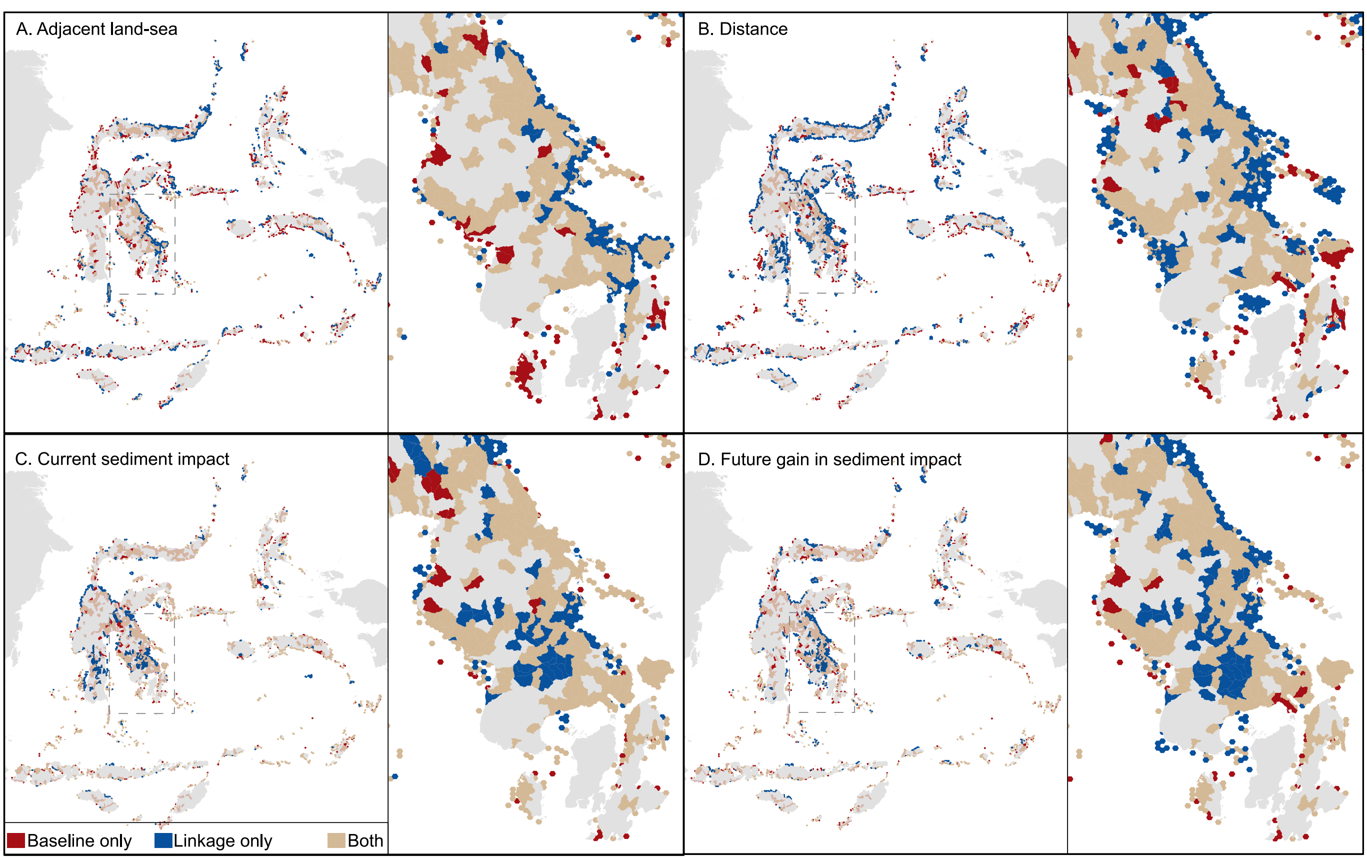

Fig. 4. Conservation priority areas in Wallacea identified using four different methods of accounting for ridge-to-reef linkages (A, B, C, D). Impact-based strategies (C, current sediment impact; D, future gain in impact) systematically prioritise inland catchments where projected sediment runoff increases are concentrated, while spatial-proxy strategies (A, adjacent land-sea; B, distance) prioritise coastal areas and miss the upstream catchments driving downstream impact. Each panel shows the baseline (no-linkage) solution and the linkage solution at 5% higher opportunity cost for the entire Wallacea region, with a zoomed inset of Sulawesi where the greatest sedimentation impacts on coral reefs occur. Planning units selected only under the baseline solution are shown in red, only under the linkage solution in blue, and under both solutions in tan. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

reef ecosystems (Álvarez-Romero et al., 2011; Beger et al., 2010a; Carlson et al., 2019; Struebig et al., 2022). Our spatial analysis across Wallacea demonstrates that such coordinated planning can meaningfully reduce these threats. Linking land and sea planning through sediment load modelling and reef exposure could prevent an additional 9.7–9.9 Mt of sediment from entering marine systems under future deforestation predictions. While modest against the existing baseline load of 916.8 Mt, this represents around 7% of the projected 148.1 Mt increase under business-as-usual deforestation, a meaningful share of the additional impact that conservation planning can realistically influence, since avoided-deforestation interventions can only act on future land-use change. The ecological value of these reductions is determined by where they are realised. Sediment impacts on reefs are spatially heterogeneous and concentrated near river mouths and within plume footprints, so reductions targeted at catchments draining onto high-value reef areas can yield disproportionately large local benefits.

The integrated strategy also delivers co-benefits beyond sediment reduction. These include protection of vulnerable terrestrial species and habitats threatened by deforestation and the identification of priority areas that generate joint outcomes for terrestrial and marine ecosystems. Our work complements other studies that highlight the need for and benefits of ridge-to-reef planning in areas of Mesoamerica (Delevaux et al., 2024), the Gulf of California (Álvarez-Romero et al., 2015), and the Pacific (Tulloch et al., 2016). Like these studies, we find that conservation priorities shift inland once land-sea linkages are explicitly represented, with strategies that ignore connectivity systematically under-prioritising the upstream catchments that contribute most to downstream impact. In our analysis, impact-based strategies avoided up to four times more sediment than distance-based proxies, demonstrating the practical significance of this shift for conservation efficiency. Critically, we build upon previous highly localised approaches that coupled river plume and land-use (Klein et al., 2012; Makino et al., 2013; Tulloch et al., 2016) or land-use change models (Álvarez-Romero et al., 2015; Delevaux et al., 2018) by incorporating realistic and spatially-explicit opportunity costs and applying this approach across an extensive and highly heterogeneous bioregion. Although ridge-to-reef approaches in the broader literature encompass linkages between terrestrial systems and a range of downstream coastal and marine ecosystems, including mangroves, seagrass meadows, and estuaries, our analysis focuses specifically on sediment-mediated impacts on coral reefs which are particularly sensitive to terrestrial runoff. The framework is nonetheless transferable to other downstream marine ecosystems where land-based threats can be modelled and linked to ecological exposure.

4.2. Spatial priorities and implementation

The greatest sedimentation impact on reef turbidity occurs in the central-southeast region of Sulawesi, implying that ongoing land-cover changes have significant downstream impacts on coral reefs that are hitherto underappreciated. This region has experienced substantial agricultural expansion in recent years, with oil palm plantations and smallholdings of corn, coffee and cacao prominent around deforested landscapes (Supriatna et al., 2020; Voigt et al., 2021). Since 2010 Indonesia's nickel mining boom also exacerbated deforestation in this region (Lo et al., 2024), leading to flooding, sedimentation and fish population collapse in some areas (Hudayana et al., 2020). Our analysis identified some overlaps with previous prioritisations of biodiversity, forest cover, and important terrestrial habitats, such as the large Mekongga landscape in the northern end of Southeast Sulawesi province (Pusparini et al., 2023). Such continuous large landscapes may be more appropriately managed as watershed protection forests, instead of strict protected areas, which are also managed to provide ecosystem services by preventing deforestation and erosion. Meanwhile, large expanses of East Nusa Tenggara islands contributed relatively little increase in sedimentation.

Translating these modelled priorities into action faces practical constraints that vary across the identified catchments. The inland catchments in central-southeast Sulawesi that contribute most to projected sediment runoff overlap with active oil palm and nickel mining concessions. These represent areas of competing economic interest where outright deforestation prevention is difficult to implement under current regulatory frameworks (Lo et al., 2024; Supriatna et al., 2020). However, several mechanisms already exist in Indonesian law and practice through which protection of upstream catchments could be pursued. Watershed protection forests are an established land-use category that prioritises hydrological function over strict no-use restrictions, and which already cover parts of the Mekongga and other upland landscapes our analysis identified as priorities (Pusparini et al., 2023). Social forestry schemes allow local communities to formally manage forested land under conservation-compatible use agreements, and have been shown to deliver both avoided deforestation and improved community welfare (Meijaard et al., 2021; Santika et al., 2019). Evidence from these evaluations also indicates that outcomes are strongly contingent on zone-specific investment, for example, watershed-protection contexts benefit most from support for basic living conditions and recognition of customary forest knowledge (Meijaard et al., 2021). Realising the modelled benefits will therefore depend on matching the policy instrument to the land-use context and on coordinating across the terrestrial and marine governance bodies whose mandates currently sit in different ministries.

We model interventions of preventing deforestation in terrestrial areas selected by the prioritisation analysis. Such interventions have the additional co-benefit of protecting vulnerable terrestrial species at risk from deforestation (Struebig et al., 2022). However, sediment and nutrient load on coral reefs can also be mitigated through other means, such as restoration of degraded forests or improving management of agricultural and urban land, e.g. improved fertiliser application or better grazing management (Álvarez-Romero et al., 2015). Key regions for forest restoration to reduce land-based runoff to coral reefs differ significantly from areas prioritised for forest protection, with critical zones identified along the coasts of West and East Nusa Tenggara, North Sulawesi, South Sulawesi, and the northern part of Central Sulawesi (Suárez-Castro et al., 2021). This is unsurprising as areas of degraded forests suitable for restoration will differ from areas of intact forests for conservation. Interventions can be complementary, as restoration can help reconnect existing forest landscapes to promote species migration and genetic mixing (Chazdon, 2019). Cost-benefit analyses, which compare different intervention costs and expected returns, could assist decision-making (Chazdon, 2019; Klein et al., 2010).

4.3. Methodological context and limitations

Ridge-to-reef planning is particularly relevant for volcanic islands where land-sea linkages are strong due to erosive soils and steep watersheds (Jupiter et al., 2017; Verbist et al., 2010), so appropriately capturing land-sea linkages is important. Across Wallacea, watersheds with the highest sediment runoff were larger and predominantly situated inland with short or no coastlines (Fig. 2). Consequently, the ‘adjacent land-sea’ strategy favoured the selection of smaller, coastal catchments with low runoff. This strategy may be appropriate if objectives are to protect important coastal habitats (e.g. mangrove nurseries) or to specifically mitigate coastal human impacts (e.g. coastal development). Meanwhile, the ‘distance’ strategy did not account for the large variation in the total runoff from different catchments. Simple spatial distance strategies may be inappropriate for complex topographies, where catchments have highly variable sediment outputs, as in Wallacea. Within the impact-based approaches which explicitly model sediment loads and reef exposure rather than relying on spatial proxies, relatively similar outcomes were achieved regardless of whether sedimentation accounted for only a present 2018 scenario or for a future 2050 land-use change scenario, with only incremental additional gains when accounting for future land-use change scenarios. This is promising for management applications in other regions of the world as maps of forest cover (Hansen et al., 2013), rainfall (Fick and Hijmans, 2017), catchments (Linke et al., 2019), and ocean turbidity (Wang et al., 2009) are available at global scale, whereas future deforestation projections are not. It does not, however, suggest that simpler distance- or adjacency-based heuristics are an adequate substitute for impact-based modelling.

Several limitations should be considered when interpreting our results. First, the sediment model represents hydrological processes using a simplified vegetation-based framework and does not account for factors such as soil properties, slope, or land management practices, which may influence sediment production at finer scales. Second, the Bayesian turbidity model provides a simplified representation of sediment dispersion and does not explicitly incorporate oceanographic processes such as currents or tides, instead approximating these through spatial relationships. Third, opportunity cost layers are based on available proxies and may not fully capture the complexity of local socio-economic systems. Finally, biodiversity feature data are unevenly distributed across the study region. The threatened and endemic species on Sulawesi are better studied and mapped than those on the other islands in Wallacea (Ardiantiono et al., 2024), which may partly explain why more of Sulawesi was selected compared to Nusa Tenggara and Maluku (Fig. 4). Future work should therefore include biodiversity surveys in understudied regions to address this potential sampling bias. Together, these assumptions mean that results should be interpreted as relative patterns and comparative outcomes across scenarios, rather than precise predictions.

Our findings demonstrate that the way land–sea linkages are represented in conservation planning can strongly influence outcomes, with data-driven approaches that account for spatial variation in sediment impacts substantially outperforming simpler proxies. In Wallacea, this leads to a shift in conservation priorities toward inland catchments with high sediment export, highlighting the importance of integrating terrestrial processes into marine conservation strategies. More broadly, our approach provides a scalable framework for evaluating ridge-to-reef conservation options that balance ecological benefits with socio-economic considerations.

CRediT authorship contribution statement

Dominic Muenzel: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Eleanor Stewart:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Noviar Andayani:** Writing – review & editing, Conceptualization. **Alex J. Dumbrell:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization. **Jamaluddin Jompa:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization. **Gino Limmon:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization. **Jatna Supriatna:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization. **Johny S. Tasirin:** Writing – review & editing, Conceptualization. **Nurul L. Winarni:** Writing – review & editing, Conceptualization. **Zuliyanto Zakaria:** Writing – review & editing, Conceptualization. **Zoe G. Davies:** Writing – review & editing, Project administration, Methodology, Funding acquisition, Conceptualization. **Matthew J. Struebig:** Writing – original draft, Visualization, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Maria Beger:** Writing – review & editing, Visualization, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Robert J. Smith:** Writing – review & editing, Visualization, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2026.112058.

Data availability

Data will be made available on request.

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