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Global forest restoration opportunities to foster coral reef conservation

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Abstract

Sediment runoff from disturbed coastal catchments is a major threat to marine ecosystems. Understanding where sediments are produced and where they are delivered enables managers to design more effective strategies for improving water quality. A management strategy is targeted restoration of degraded terrestrial areas, as it provides opportunities to reduce land-based runoff from coastal areas and consequently foster coral reef conservation. To do this strategically, a systematic approach is needed to identify watersheds where restoration actions will provide the highest conservation benefits for coral reefs. Here, we develop a systematic approach for identifying global forest restoration opportunities that would also result in large decreases in the flux of sediments to coral reefs. We estimate how land-use change affects sediment runoff globally using high-resolution spatial data and determine the subsequent risk of sediment exposure on coral reefs using a diffusion-based ocean transport model. Our results reveal that sediment export is a major issue affecting 41% of coral reefs globally. The main coastal watersheds with the highest sediment export are predominantly located in Southeast Asian countries, with Indonesia and the Philippines accounting for 52% of the sediment export in coastal areas near coral reefs. We show how restoring forest across multiple watersheds could help to reduce sediment export to 63,000 km^2 of coral reefs. Although reforestation opportunities in areas that discharge onto coral reefs are relatively small across watersheds, it is possible to achieve large sediment reduction benefits by strategically targeting watersheds located in regions with a high density of corals near to the coast. Thus, reforestation benefits on coral reefs do not necessarily come from the watersheds that produce the highest sediment export. These analyses are key for generating informed action to support both international conservation policy and national restoration activities.

KEYWORDS
biodiversity conservation, cross-realm planning, restoration, ridge to reef, spatial planning, water quality

1 | INTRODUCTION

Sediment and nutrient runoff represent a major challenge for sustainable coastal zone management and conservation. Clearing native vegetation and destructive land-use practices (e.g., agrichemical pollution) along coastlines can increase sediment transport to coastal waters, with detrimental impacts on aquatic ecosystems (Fourney & Figueiredo, 2017; Nugues & Roberts, 2003). Globally, poor coastal water quality is widely regarded to be the most serious problem after climate change for tropical coastal ecosystems such as coral reefs and seagrass meadows (Burke et al., 2011; Quiros et al., 2017). Reducing pollution, sedimentation and eutrophication of coastal waters through improved land management is, thus, urgently needed to build resilience and protect marine ecosystems in the face of climate change (Brown et al., 2017; Hoegh-Guldberg et al., 2018). There is, hence, a need to identify terrestrial areas where managing land-use change can provide the highest reduction in sediments reaching coastal and marine environments. This land–sea approach to conservation prioritisation can promote cost-effective conservation actions and maximize conservation outcomes across terrestrial and aquatic systems (Adams et al., 2014; Tulloch et al., 2021; Wedding et al., 2018).

Coral reef ecosystems are at dire risk of extinction: Recent estimates show that around 50% of reefs have been lost over the past 30 years (e.g. D'eath et al., 2012), with expected losses of 70%–90% by the mid-century (Hoegh-Guldberg et al., 2018; van der Zande et al., 2020). Although mitigation of climate change is vital, building ecological resilience through reducing threats such as sediment and pollution is key to improving coral reef resilience and potential for recovery (Beyer et al., 2018; Hoegh-Guldberg et al., 2018). Coral reef ecosystems experience multiple impacts from sediments flowing off terrestrial areas (Burke et al., 2011; De'ath et al., 2012; Tebbett et al., 2018). Impacts include smothering of interstitial spaces (Fabricius & Wolanski, 2000), increased sensitivity to heat stress (Carilli et al., 2009), as well as a decrease in light levels and hence photosynthesis by their symbiotic algae that live inside the tissues of corals (Bessell-Browne et al., 2017). Excess sediment influx also negatively affects the productivity of algal turf-based food chains, with potential impacts on reef-based fisheries (Anthony et al., 2007; Tebbett et al., 2018). A wide variety of corals experiencing high sedimentation rates from land-use change also show a decrease in light available for photosynthesis, low rates of recruitment, reduced growth and high rates of stress and mortality (Babcock et al., 1991; Ricardo et al., 2017). Besides interfering with the ability of corals to survive, feed, grow and reproduce, high sediment levels exacerbate threats such as ocean warming and acidification (Maina et al., 2013; McCulloch et al., 2003). Even for coral reef species that exhibit high resistance to high sedimentation and low-light conditions, increases in sediment runoff could intersect with other threats, such as sea level rise, that may negatively impact the habitat extent and coral reef composition (Morgan et al., 2020; Ogston & Field, 2010). Therefore, controlling runoff from terrestrial areas presents a promising management strategy to enhance the abundance of corals, increase coral resilience to climate driven stresses and reduce the overall loss of coastal ecosystems (Carlson et al., 2019; Harvey et al., 2018; Liu et al., 2018).

A key step to reducing sediment runoff that impacts coral reefs consists of identifying the spatial distribution of sediment impacts, risks and management opportunities across multiple watersheds (Oelsner et al., 2019; Strokal et al., 2017). Land-based conservation actions aim to foster coral reef conservation often focusing on protecting native vegetation to avoid increased sediment fluxes from land-use change in the future (Álvarez-Romero et al., 2015; Klein et al., 2012, 2014). Protecting and restoring native vegetation can reduce sediment export to watersheds not only by limiting soil erosion but also by mitigating runoff through added root retention, soil stabilization and modification of water movement (Dosskey et al., 2010). Therefore, a management action with huge potential for land–sea conservation is the restoration of native vegetation in terrestrial watersheds (Delevaux et al., 2018; Klein et al., 2012; Saunders et al., 2017). By identifying key watersheds where high-restoration benefit might be achieved, managers can not only improve water quality essential for healthy coral reefs but also potentially increase the resilience of nearshore coral reefs to climate change. Priority areas for forest restoration to benefit coral reefs can be identified through spatially explicit estimates of how sediment runoff is expected to change following terrestrial restoration in coastal areas and how these changes sediment fluxes reaching coral reefs. As benefits of forest restoration are highly variable across space (Klein et al., 2012), a standard approach is needed for identifying watersheds where conservation and restoration actions might provide the highest conservation benefits.

Here, we use global, high-resolution spatial data to estimate the expected reduction in sediment export reaching coral reefs after forest restoration. To do this, we map global sediment export for watersheds defined at two extents, river basins and regional watersheds, and use a diffusion-based ocean transport model to quantify the associated risk of sediment exposure on coral reefs. Finally, we estimate the expected reduction in sediment runoff resulting from forest restoration. Ultimately, we present a robust approach to identify watersheds where conservation and restoration actions provide the greatest reduction in sediment export to coral reefs using a consistent and global-scale methodology. In doing this, our analyses have the potential to generate informed action to support both international conservation policy and national restoration activities.

2 | METHODS

The total sediment export from each watershed is calculated using the soil erosion per pixel, as well the amount of sediment eroded from each pixel that actually reaches a stream or similar water course (Hamel et al., 2015). To model soil erosion, we used a high-resolution global potential soil erosion model developed by Borrelli et al. (2017) based on the revised universal soil loss equation (RUSLE; Renard et al., 1997), estimating soil erosion in each watershed. Total sediment exported at watershed scales was quantified using the InVEST sediment delivery model (Hamel et al., 2015), which implements a soil loss algorithm linked to the sediment connectivity algorithm proposed by Borselli et al. (2008). This approach is suitable for our study as we aim to capture the major differences between sub-watersheds that can help to identify hotspots of higher sediment export where priority actions should focus. In this sense, we aim to generate estimates that allow us to optimally capture relative differences and opportunities among watersheds, rather than describing fine-scale within watersheds processes. We estimated the contribution of each watershed to sediment runoff across all reefs globally using a diffusion-based ocean transport model following Halpern et al. (Burke et al., 2011; Halpern et al., 2008). The rate of change in sediment runoff after forest restoration was then estimated in each watershed using the same modelling approach. The workflow for the modelling framework is shown in Figure 1.

2.1 | Calculation of sediment export globally

The first step to determine the contribution of each watershed is to estimate the potential soil loss at each pixel. InVEST relies on the RUSLE model, which estimates average annual soil loss and sediment yield resulting from interrill and rill erosion:

$$A = R \cdot K \cdot L \cdot S \cdot C,$$

where A is average soil loss per unit of area during a unit period of time, usually 1 year (tons ha^{-1}year^{-1}), R is the rainfall-runoff erosivity factor, K is an empirical parameter expressing the susceptibility of the soil to be eroded, L is the slope length factor, S is the slope gradient factor and C is the crop and management factor.

Elevation data used to calculate L and S were derived from the gap-filled SRTM 3 arcseconds (c. 90 m) Digital Elevation Model Version 4 (Reuter et al., 2007). The C-factor measures the combined effect of all interrelated cover and management variables on the soil erosion process. R, K and C were obtained based on the analyses developed by Borrelli et al. (2017), who calculated erosion risk using RUSLE (Renard et al., 1997) at an unprecedentedly high resolution of 250 m × 250 m globally. These authors also described surface vegetation patterns globally by processing the MODIS Land Cover Type product MCD12Q1 at 250 m, a product derived from the International Geosphere Biosphere Programme (IGBP) system that reports 17 land-cover classes. We excluded non-vegetated and/or aquatic land-cover types from our analysis (permanent wetlands, barren, snow/ice, water). We used mean values of C factors for 16 land-cover classes reported by Borrelli et al. (2017) (Table S1). For further details on the parameter estimation and modelling of R, K and C factors refer to Borrelli et al. (2017).

To estimate the amount of sediment export that actually reaches streams and is exported from each watershed, soil loss is multiplied by a sediment delivery ratio (SDR) factor, computed for each pixel according to the sediment connectivity algorithm (Borselli et al.,

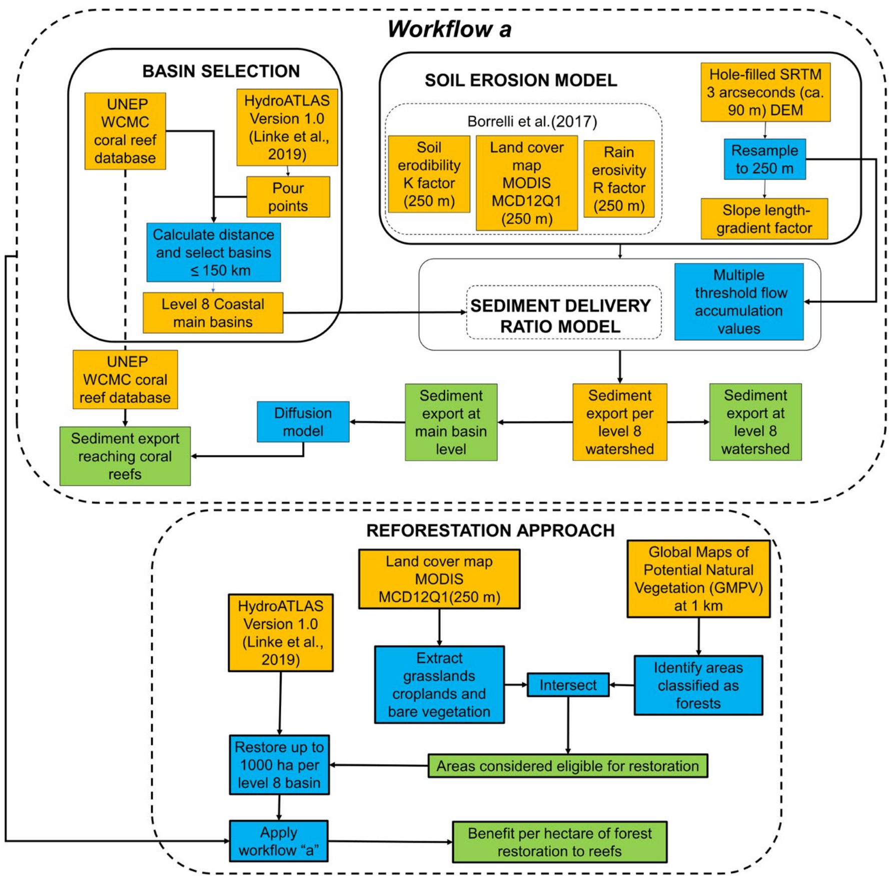

FIGURE 1 General methodology and workflow used in the present study to quantify the expected relative contribution among watersheds according to sediment export and transport to coral reefs. Orange boxes represent inputs, blue boxes represent processes and green boxes represent outputs

2008). The sediment connectivity algorithm represents the transfer of sediment in a system from a source to a sink through processes of sediment detachment and transport per defined unit time (Bracken et al., 2015). Key drivers are the influence of topography on sediment connectivity as well as the drainage area (upslope component) and the flow path length that a particle has to travel to arrive at the nearest sink or the target of the analysis (downslope component; Hamel et al., 2015). The SDR is directly derived from the conductivity index (IC) using a sigmoid function:

$$\mathrm{SDR} = \frac{\mathrm{SDR}_{\max}}{1 + \exp\left(\frac{\mathrm{IC}_0 - \mathrm{IC}}{k_b}\right)},$$

where SDR_{max} is the maximum theoretical SDR, defined as the maximum proportion of fine sediment (<1000 μm) that can travel to the stream; in the absence of detailed soil information, it has a default value of 0.8 (Vigiak et al., 2012). IC_0 and k_b are calibration parameters that define the shape of the sigmoid function SDR–IC relationship (Hamel et al., 2015).

SDR values depend on land-cover types and the balance between the distance of upslope and downslope areas to streams. The longer the distance to the watercourse and the higher the retention sediment capacity of the land cover (e.g., forests), the higher probability that sediments will be trapped before reaching the watercourse. Conversely, the sediment transport capacity of a cell increases if the contribution of the upslope area is large relative to the downslope area. In this case, the amount of sediment delivered from a given cell approaches the total proportion of sediment on that cell. The sediment yield from a given pixel *i*, $\mathrm{sed\_export}_i$ (ton ha^{-1} year^{-1}) is a direct function of the soil loss (*A*) derived from the RUSLE model and the SDR factor:

$$\mathrm{sed\_export}_i = A_i \times \mathrm{SDR}_i.$$

The total sediment export at each pour point was calculated at the main basin level, which represents the entire river basin that a watershed belongs to.

2.2 | Delimitation of watersheds and coastal pour points

Watershed hydrological information was extracted from HydroATLAS Version 1.0 (Linke et al., 2019), a database that provides hydro-environmental information for all watersheds and rivers of the world at high spatial resolution. HydroATLAS presents 12 nested levels of sub-watersheds at the global scale, each depicting sub-watershed polygons at scales ranging from millions (level 1) to tens of square kilometres (level 12). The HydroATLAS watershed and sub-watershed delineations are based on the HydroSHEDS drainage direction map at 15 arc-second resolution (Lehner & Grill, 2013) following the topological concept of the Pfafstetter coding system (Verdin & Verdin, 1999). We calculated total watershed sediment export from rill soil erosion for each watershed as the sum of the sediment export from all pixels inside a watershed. Calculations were summarized at two extents: River basins and level 8 sub-watershed (mean = 733.7 km^2 SD = 751.3 km^2). Basins correspond to a group of watersheds that discharge to a common outlet and are defined by the MAIN_BAS attribute in the HydroATLAS data set. We assumed that level 8 sub-watershed represents a reasonable approximation of regional patterns of water and sediment discharge. To calculate sediment export to coastal waters, we first selected watersheds that discharge into the ocean. Watersheds discharging to the ocean were identified by selecting rivers where the distance of the most downstream pixel to the final downstream location along the river network equals zero and then excluding all endorheic watersheds (i.e. inland sinks that do not drain to the ocean). We then selected all the watersheds that shared the same main basin with the coastal watersheds. The sediment export at each pour point location (where the watershed drains into the ocean) corresponded to the sum of all the sediment export from all the sub-watersheds upstream of a coastal watershed. In some cases, multiple rivers from the most downstream level 8 sub-watersheds discharged to the ocean. In these cases, we distributed the sediment export across all points weighted by the mean annual discharge (m^3 year^{-1}) of each river as reported in the HydroATLAS database.

2.3 | Linking sediment export to sediment exposure on coral reefs

We used a diffusion model to quantify the potential relative impact of sediment export from watersheds on reefs. For this analysis, we only focused on watersheds with pour points that were less than 150 km away from any coral reef mapped in the UNEP WCMC coral reef database (UNEP-WCMC, 2018). We chose 150 km to select all the watersheds with any potential impacts on coral reefs, although we acknowledge that the distance travelled by sediments to coral reefs tends to be much lower (Burke et al., 2011). The discharge point of the watershed is used as the source location for sediment, the dispersion of which is then modelled as a 2D diffusion process. The dispersal of potential sediment at each river mouth was modelled using a cost-path surface, where a decay function evenly distributes 0.5% of the initial potential sediment value to all adjacent cells, until either a threshold of 0.05% of the global maximum value (Burke et al., 2011; Halpern et al., 2008), or a distance of 80 km from the river mouth was reached. The sediment plumes from each river mouth were then summed to provide a cumulative sediment exposure value, measured as tonnes of sediment/year. Coral reef exposure to sediments was determined by intersecting the locations from the UNEP WCMC coral reef database (UNEP-WCMC, 2018) and the sediment plumes from each discharge point. Specifically, we quantified the reef area–weighted sum of relative sediment exposure for each discharge point. Hence, this value will be higher for (i) larger values of total sediment export at a discharge location; (ii) discharge points that are in close proximity to coral reefs and (iii) sediment diffusion that impacts a larger total area of coral reefs. As such, this is a useful estimate for quantifying the relative potential impact of watersheds on coral reefs globally.

2.4 | Model performance evaluation

RUSLE models require regular calibration with measured data and may have higher levels of uncertainty associated with load estimates compared with time-integration of monitored discharge and concentration data (Hamel et al., 2017). Even though a validation sensu strictu of USLE-based modelling at regional or larger scales is not feasible due to the lack of long-term field-scale measurements, the multiple cross-comparison approaches used to evaluate GloSEM modelling results (Borrelli et al., 2017, 2020) provided positive insights on the validity of the soil loss predictions (Borrelli et al., 2017). Here, we evaluate if the outcomes of our modelling approach coincide with regional estimates of sediment export. For this, we examined absolute model predictions, and compared them with observed data from a subset of areas having reported empirical sediment loads in coastal watersheds (Table S2). Although these values have large uncertainties themselves, they provide an independent metric for the performance of the model, enabling us to a measure of how accurately the model predicts which watersheds have the highest sediment exports. Further insights in support of the validity of the global model estimates were gained by comparing spatial patterns of sediment export with the ones reported by previous global studies on soil erosion (Borrelli et al., 2017). More details about the model performance evaluation and the calibration process can be found in Supporting Information S1.

2.5 | Contributions of forest restoration to reduction of sediment exports

To quantify the benefit of forest restoration on coastal water quality, we constructed a metric that reflects two parameters. The first was based on the extent to which sediment discharge from a watershed is reduced by forest restoration, and the second was based on the degree to which a reduction in sediment translates as reduced impacts on coral reefs. The first component of this metric was quantified by simulating forest restoration within each watershed and calculating the change in sediment discharge per unit area of forest restoration. The second component of the metric was calculated using the ocean transport model described above.

Global forest restoration was simulated as follows. For each watershed, we identified the potential natural (native) areas that are classified as forests using the Global Maps of Potential Natural Vegetation (GMPV) at 1-km resolution developed by Hengl et al. (2018). This map shows the vegetation cover in equilibrium with climate that would exist at a given location if it was not impacted by human activities. We then intersected areas classified as forests in the GMPV layer with areas classified as grasslands, croplands and bare vegetation from the MODIS land-cover layer processed by Borrelli et al. (2017). We assume that areas classified as grasslands within areas that were once estimated to be forests do not represent natural grasslands, which would not be a suitable target for forest restoration. Within the areas considered eligible for restoration in each watershed (grasslands, croplands and bare vegetation that was previously native forest), we used the InVest model to estimate the change in total sediment export following the randomly distributed restoration of 1000 ha of forest (or the area available if less than 1000 ha) was reforested. We chose 1000 ha as an arbitrary area intended to compare a relative rate of sediment reduction per unit area across watersheds, as our objective is not to estimate absolute values of sediment export in each watershed. To test how sensitive the change in sediment export was to the random selection of cells for restoring, we repeated this process 10 times for a random sample of 1000 8-level watersheds (see Supporting Information S1, Figure S1). Specifically, the rate of benefit per area of forest restoration to reefs (B) is calculated as:

$$B_{\mathrm{I}} = \frac{D_i \sum_{j}^{N_r} (s_j c_j)}{a_i},$$

where D_i is the sediment export change following forest restoration in watershed i (units Mg year^{-1}), N_r is the set of coral reefs exposed to non-zero sediment concentrations from watershed i, s_j is the mean sediment density at coral reef j (units Mg year^{-1} km^{-2}), c_j is the area of coral reef j (km^2) and a_i is the area restored in each watershed i. Thus, this metric is an estimate of the rate of improvement in water quality on coral reefs arising from terrestrial sediment runoff reduction following forest restoration.

3 | RESULTS

3.1 | General patterns of sediment export globally

We analysed 5551 main basins with pour points located less than 150 km away from coral reefs. The estimated total sediment export within these basins is approximately 6 Gt year^{-1}. Based on the quantile classification method, coastal watersheds classified as having low sediment export rates (<=2 Mg ha^{-1} year^{-1}), represent about 73.6% the total coastal watershed surface evaluated (~26 million km^2). Moderate (>2 and <10 Mg ha^{-1} year^{-1}) and high (>10 and <40 Mg ha^{-1} year^{-1}) sediment export values are predicted for about 12.4% and 7.7% of the study area, respectively. The remaining land surface evaluated (about 2.6 million km^2 in total, 6.3%) shows a sediment export higher than 40 Mg ha^{-1} year^{-1}. Sediment export is disproportionately distributed across continents (Figure 2; Table 1), with most of it (2.1 Gt year^{-1}) being exported from watersheds in Asia, whereas South America (0.8 Gt year^{-1}), North America (0.6 Gt year^{-1}) and Oceania (0.3 Gt year^{-1}) show considerably lower predicted values.

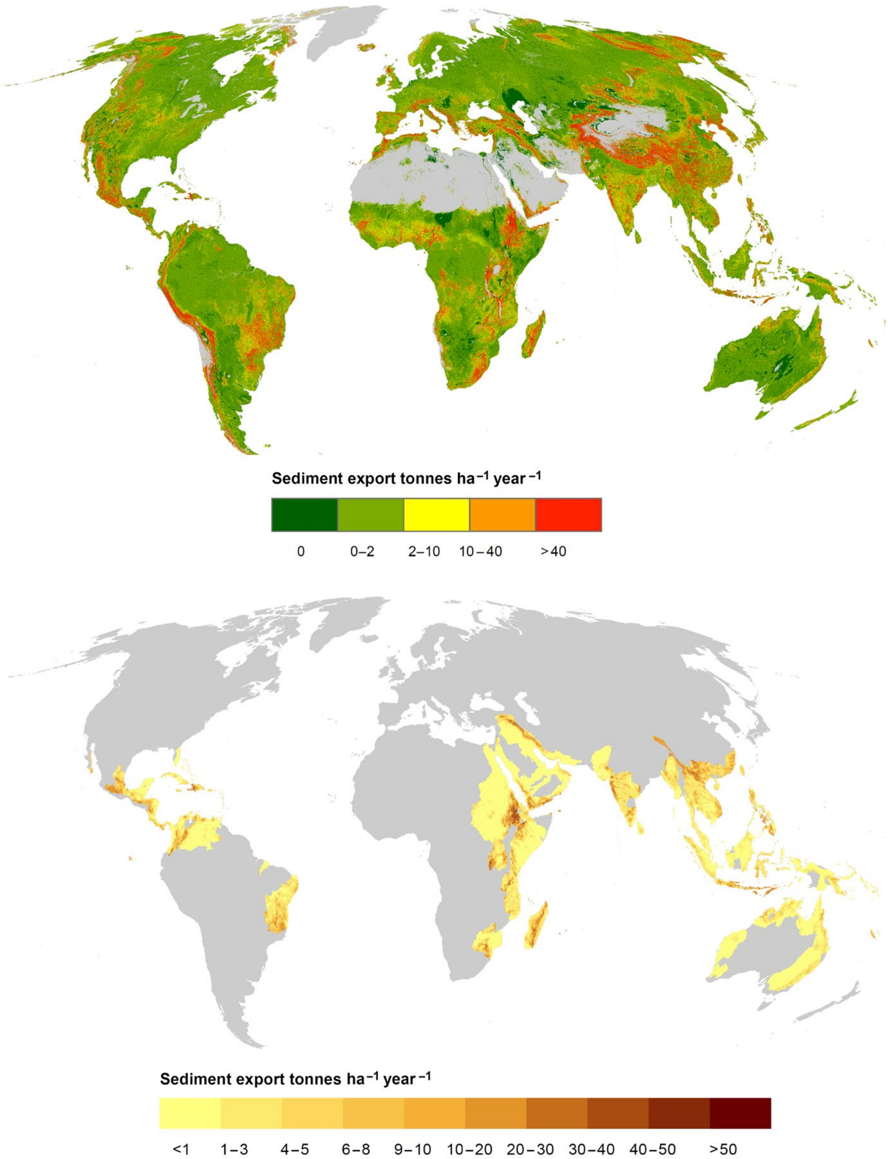

FIGURE 2 Global high-resolution estimates of sediment export predicted using InVEST models through a RUSLE-based modelling framework. The top panel illustrates sediment export estimates on a ~250 × 250 m cell basis for the land surface of 202 countries (c. 125 million km^2). The colour gradation from green (low) to red (high) indicates the intensity of the predicted erosion rates. Classes from low to high were defined using the quantile classification method. Grey indicates areas excluded due to lack of data. The bottom panel illustrates sediment export rates per hectare aggregated for level eight watersheds considered in this analysis

TABLE 1 Total sediment export (in Mt per year) from basins that are less than 150 km away from coral reefs across different regions of the world

Region	Total sediment export	Sediment export reaching corals	Percentage of sediment reaching corals reefs
Africa	840	9	1.6
Asia	2100	3	0.2
Coral Triangle	610	221	39.1
North America	530	4	0.6
Oceania	270	3	0.8
South America	720	0.2	0.02

The main coastal watersheds with the highest sediment export to reefs are disproportionately shared among few countries. Of the 82 countries with coral reefs in their coastal watersheds, the vast majority of watersheds with the highest sediment exports are located in Southeast Asia (Figure 2), with Indonesia and the Philippines accounting for 52% of the global sediment export in coastal areas near coral reefs. Watersheds in Eastern Indonesia from Central and East Java and eastern coasts of Timor Leste account for 39% of the sediment export in coastal waters discharging to the Coral Triangle, which includes the most biodiverse coral reefs worldwide. Another hotspot of discharge to the Coral Triangle is the Sulu Sea bioregion in the Philippines (21%, Figure 2). The top 10 countries with the highest sediment discharge globally are completed by Tanzania, Madagascar, Kenya and Mozambique in East Africa, Australia in Oceania and India and Vietnam in Asia (Table S3). Hotspots of high sediment discharge are found particularly along the coastline of Vietnam discharging to the South China Sea, the south-central region along the coastline from Danang to Binh Thuan Province, the coasts of the Red Sea in Yemen and Sudan as well as the Caribbean Islands in the Western Coast of Haiti and South Eastern Cuba (Figure 2).

3.2 | Performance of sediment export model

Most of the main basins (58 out of 65) analysed to evaluate the performance of our model showed good agreement with observed values of empirical sediment export and export normalized by catchment area (0.66 and 0.84, respectively, measured by Spearman rank coefficient, Figure S2a,b). However, our model showed differences of one order of magnitude compared with the observed values of seven of the main basins we analysed. For example, the Purari and Fly basins in Papua New Guinea have reported values of 24 and 10 Mg $year^{-1}$ ha^{-1}, respectively (Milliman & Farnsworth, 2011). Despite this, our model only predicted sediment exports of 3 and 0.3 Mg $year^{-1}$ ha^{-1} for these basins. Varying the k_b and threshold flow accumulation parameters did not improve the predictions of the model for these basins significantly (Figure S3). When these basins were included, the correlation coefficients decreased to 0.72 for the log of observed versus predicted values and to 0.51 for values standardized by basin area. There was also variation when correlation values were compared across regions and ranged from 0.69 in Oceania and some regions of the Coral Triangle to 0.46 in Papua New Guinea and Java. Although substantial variations in model performance exist across regions, there is a high correlation between observations and predictions for 89% of the analysed basins. In addition, our model showed good agreement with the spatial patterns of the soil erosion model presented by Borrelli et al. (2017; Spearman correlation coefficient of 0.91, Figure S2c) for all the studied regions. Even though the number of basins available for model validation was low, the good fit with Borrelli's erosion model provides confidence that our model was able to correctly identify high and low sediment export areas at global scales.

3.3 | Sediments reaching coral reefs

We found that 4610 out of 5551 coastal watersheds export some sediment to coral reefs (hereafter coral coastal watersheds). Based on the sediment plume model, we estimate that the total amount of sediment reaching coral reefs is approximately 234 Mt $year^{-1}$ (4% of the total sediment export from pour points in coastal watersheds). Within these watersheds, our model shows that sediment export is highly variable among level 8 sub-watersheds (mean = 0.239 Mt $year^{-1}$ SD = 0.468 Mt $year^{-1}$). According to the sediment dispersion model, 116,000 km^2 of the world's reefs are exposed to some level of sediment-related pollution. This area corresponds to 41% of the coral reefs globally based on the global estimated reef area of 284,803 km^2 (UNEP et al., 2018). The coral reefs in Southeast Asia have the highest proportion of sediment exposure in the world, with 67% overlapping with sediment plumes from coastal watersheds. Areas particularly affected by sediment export in this region occur in the Northern and Central Philippine islands, Mindanao island in the Southern Philippine islands, Indonesia, East and Central Java and Timor-Leste. Indonesia, second only to Australia in the total area of coral reefs that lie within its jurisdiction, has the largest area of reefs exposed to sedimentation, followed by the Philippines, where more than 60% of coral reefs within 50 km from the coast are affected by sediment runoff. In the Atlantic region, more than 75% of reefs overlap with sediment plumes, with more than 30% having high levels of sediment export (according to the quantile categories displayed in Figure 3).

Levels of sediment export do not necessarily correlate with the amount of sediments reaching coral reefs, and it is highly variable across regions (Figure 3; Table 1) and countries (Figure 4; Table S3). Both the Philippines and Indonesia are ranked highest in terms of the total amount of sediments reaching coral reefs and the area of coral reefs affected (Figure 4a,b), even though these countries are not top ranked when total amount of sediment export is considered. Countries such as China and Vietnam have the highest levels of sediment export, but according to our model, less than 2% of sediments coming from these countries actually reaches coral reefs. In contrast, Fiji and the Solomon Islands are ranked 28 and 51, respectively, in terms of sediment export globally, however, more than 98% of coral reefs in these countries are influenced by coastal sediment discharge. We also found that the area of coral reefs affected per region does not correlate to the total amount of sediment discharging to the coast. For example, even though less than 3% of sediment coming from countries including Australia, Tanzania and Madagascar is estimated to reach coral reefs (Figure 4c), these countries rank within the top 10 of coral area affected in the world (Figure 4b).

3.4 | Watersheds with the highest reforestation benefits

Focusing on around of 1000 ha of forest per watershed resulted in around 4,100,000 ha of area restored across river basins affecting coral reefs. This could reduce the sediment export to coral reefs by an average of 8.5% among 63,000 km^2 of coral reefs. Regarding the total area available for forest restoration, opportunities to reduce sediment exports through reforestation are highly variable across level 8 watersheds and depend on the region studied. Most of the areas identified as suitable for restoration appear in the Coral Triangle (~1,900,000 ha) followed by Africa and the Middle East (~800,000 ha) and Asia (~750,000 ha). In contrast, Oceania presents the lowest proportion of area available for restoration that would benefit coral reefs (140,000 ha). In addition, opportunities for restoration are heterogeneously distributed across main basins and differ drastically among regions. Whereas almost all watersheds

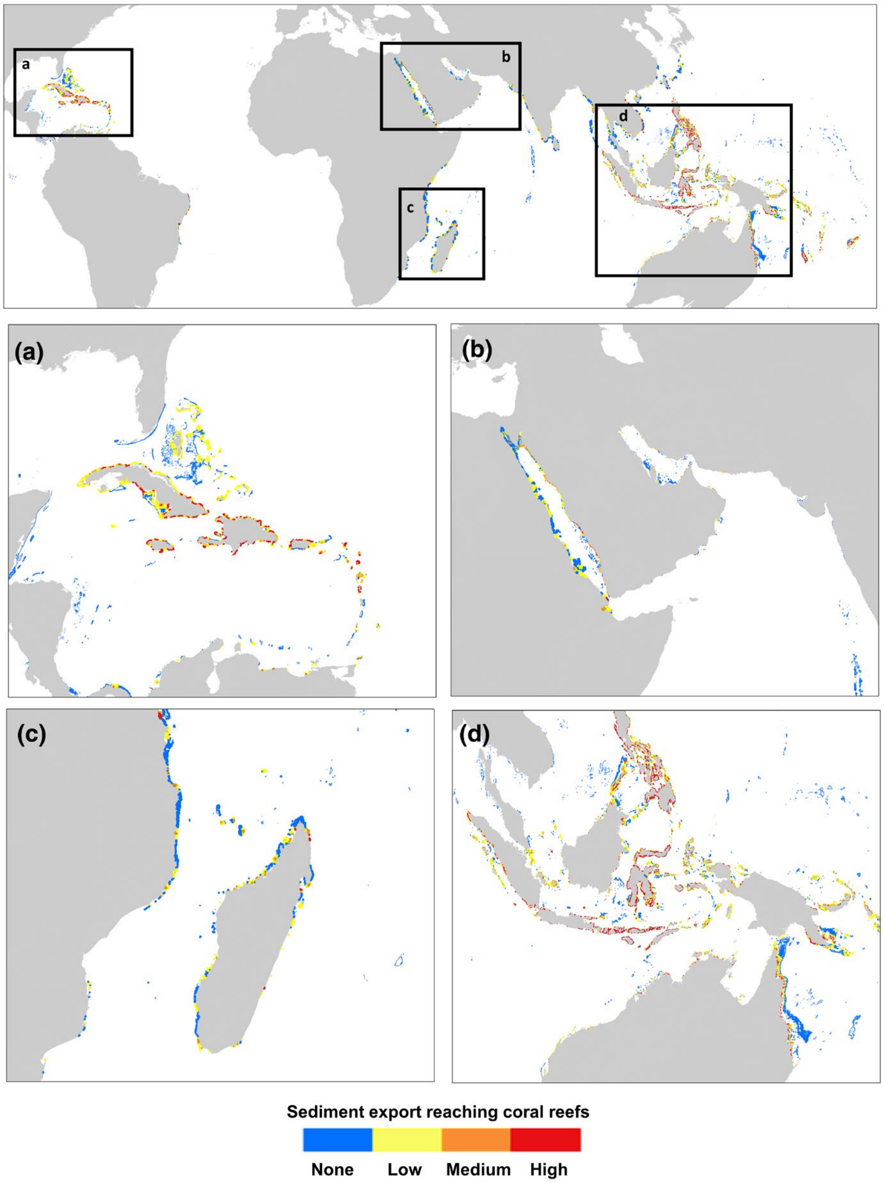

FIGURE 3 Levels of coral exposure to sediment runoff (Mt ha^{-1} year^{-1}) globally. Sediment export values were categorized based on the quantile method to assign colours. (a) Caribbean Islands; (b) Red Sea and Persian Gulf; (c) East Africa; (d) The Coral Triangle and the Great Barrier Reef

in the Coral Triangle (98%) and North America (99%) have area available for restoration, this percentage decreases in Asia (56%), Oceania (43%), and it is highly reduced in Africa (10%).

We identified several hotspots where reforestation could foster coral benefits through sediment reduction (Figure 5). These areas include the Coral Triangle, particularly Eastern Java, the South-western and North-eastern region of the Sulawesi Island (Indonesia) and the Mindanao Island in the Southern Philippine islands, where almost 50% of coastal sub-watersheds have the potential to reduce sediment exports reaching coral reefs. Although the proportion of level 8 watersheds available for restoration is lowest in Africa, areas along the coast of Mozambique reached the maximum values for our reforestation benefit index. Furthermore, the relationship between total sediment export and reforestation benefits is highly variable across the studied regions (Figure S4). In some regions such as Africa, Mid-Asia, South America and North America, the highest restoration benefits appeared in watersheds with intermediate to high levels of sediment export. Conversely, the highest reforestation benefits in the most diverse coral reef areas such as the Coral Triangle appeared in a high proportion of watersheds with relatively low sediment exports.

4 | DISCUSSION

Identifying restoration opportunities that can provide joint benefits for terrestrial and coastal ecosystems is a key conservation priority at a global scale. Our framework constitutes a major step forward for establishing guidelines to foster coral reef conservation through land-based runoff reduction beyond protected area establishment. Besides showing high spatial agreement with other previous estimates of sediment export globally (Beusen et al., 2005), our modelling approach has several improvements over previous estimates. First, by using the nested design of the

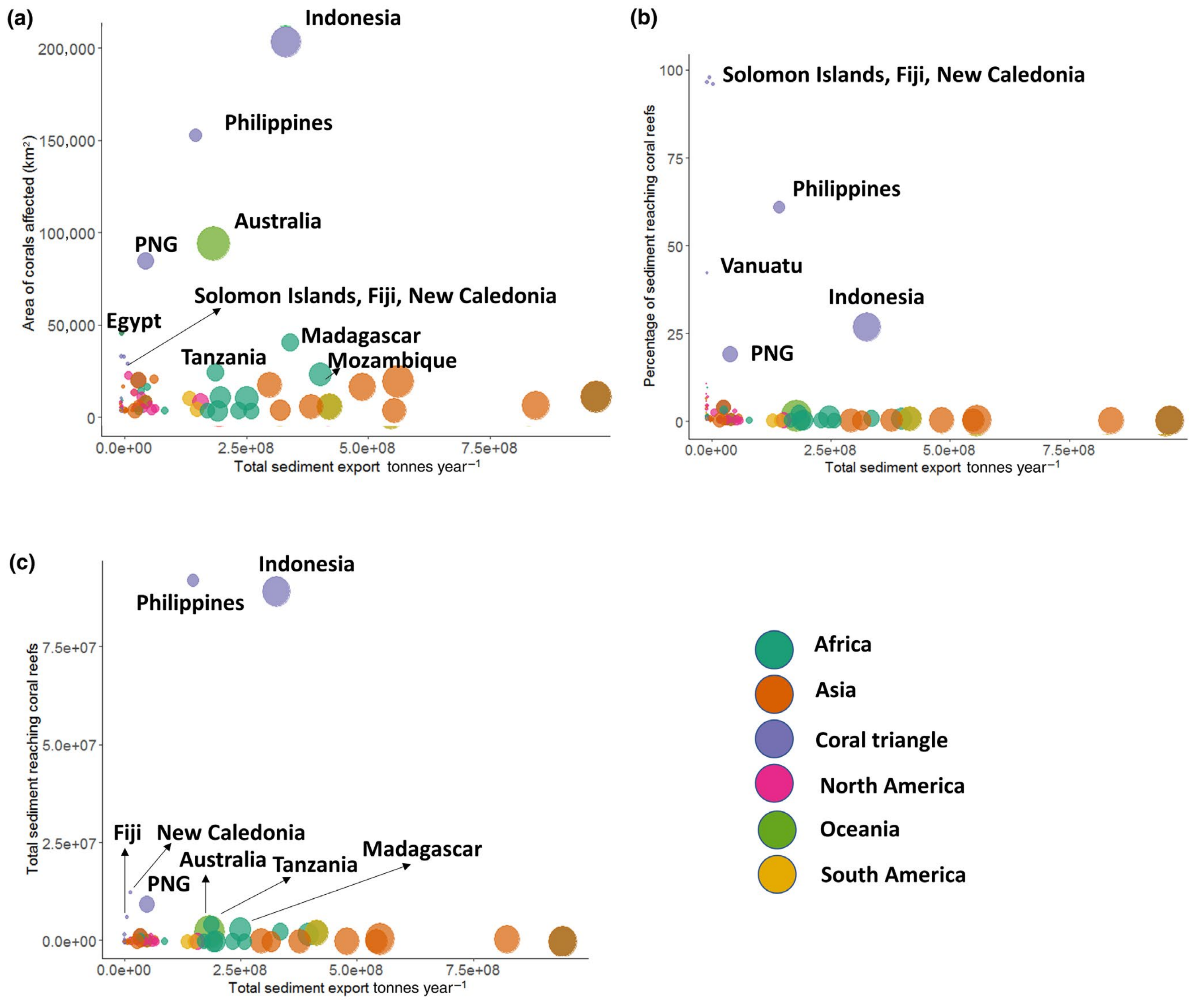

FIGURE 4 Relationship between total sediment export (tonnes per year) and (a) the area of corals affected, (b) the percentage of sediment and (c) the amount of sediment export that is actually reaching corals from different countries. The names of the top ten countries in each category are shown. Bubble sizes represent the total main basin area size in square kilometres and colours represent different regions

HydroAtlas database, we were able to present a framework that identifies not only the main basins that affect coral reefs but also the relative contributions of local watersheds to sediment export. In addition, we present a spatially explicit model that identifies where forest restoration will bring the highest benefits to reducing sediment export reaching coral reefs.

Our results show that sediment export is a widespread issue affecting a high proportion of coral reefs globally. Most places with high coral reef diversity tend to have a high area of coral reefs affected by sediment runoff, even though they are not necessarily associated with watersheds producing the highest amounts of sediment. Some examples include Fiji, the Solomon Islands and New Caledonia, which are ranked in the top 10 countries regarding the total area of coral reef affected by sediment runoff. Other areas where total sediment export is relatively low but where the total area of coral reefs affected is high include Indonesia and Philippines in the Coral Triangle. This is related to a greater proportion of coral reefs being near the coast, where most terrestrially derived sediment is deposited (Fabricius et al., 2013). Watershed-based pollution in coral-rich regions is also widespread in low-density-populated areas, where deforestation and agricultural expansion are increasing soil erosion and sedimentation (Burke et al., 2011; Carlson et al., 2019; Kroon et al., 2014; Oelsner & Stets, 2019). This is the case in areas around Lesser Sunda Islands in Indonesia and Papua New Guinea, where focusing only on targeting watersheds with high sediment export is an ineffective strategy for improving water quality in coral-rich areas. Explicitly integrating the location and potential levels of sediment reaching coral reefs is key to focusing restoration efforts to those areas where they will achieve the largest return-on-investment. Future research should incorporate climate change

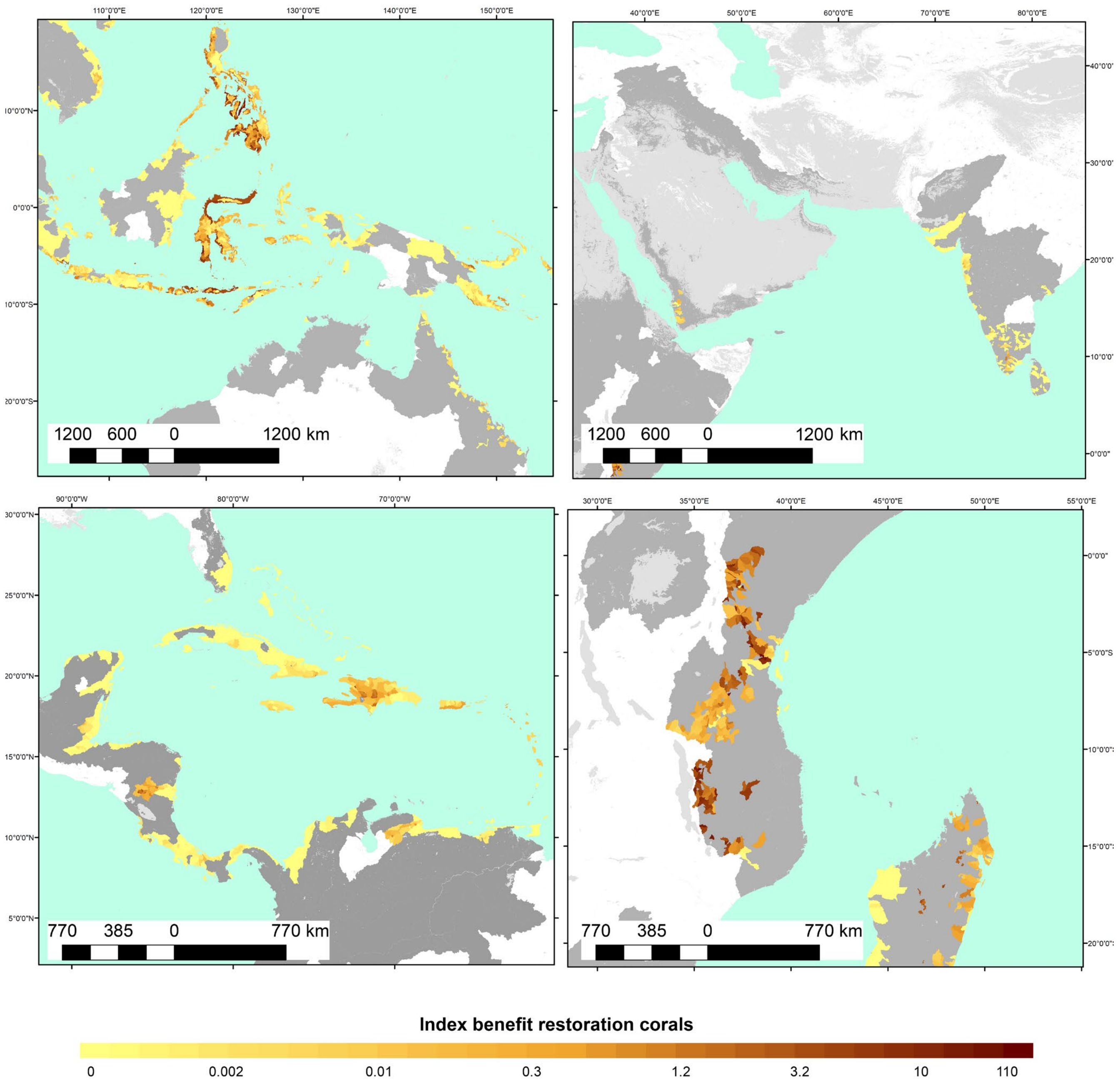

FIGURE 5 Index of benefit of forest restoration within watersheds for improvements in water quality for coral reefs. The index is summarised at the Level 8 watershed scale and is a composite measure of (i) the rate at which sediment discharge from a watershed is reduced by forest restoration, and (ii) a measure of the area of reefs impacted by that sediment discharge and the intensity of that impact (see Section 2). Dark grey are the coastal basins analysed. Light grey colour indicates the areas that were excluded from the modelling due to data unavailability (i.e., ice-covered land, terrestrial water bodies, large area of bare rock, deserts and land with bare soil)

and other terrestrial and marine conservation objectives to pinpoint areas that could achieve multiple benefits across the land and sea.

Forest management and restoration could substantially reduce sediments reaching coral reefs globally. Although the area analysed for restoration opportunities that foster coral reef conservation is relatively small (~ 4,000,000 ha), our results show that there could be a reduction of export to coral reefs by an average of 8.5% among 63,000 km^2 of coral reefs under the evaluated conditions. Importantly, different approaches are needed in different areas. For example, in the Coral Triangle, sediment discharge to coral reefs is a widespread issue that involves multiple watersheds distributed across entire islands. In these regions, there is a need for large scale restoration programs where restoration needs to be distributed among many, relatively small sub-watersheds. On the other hand, regions such as East Africa and South America have more spatially aggregated patterns of sediment discharge. Reforestation programs in these regions will need to focus on areas within single, large watersheds that can promote high sediment reduction benefits.

Our model provides a substantial and developing framework where novel scenarios can be modelled to simulate global restoration commitments. This approach can enable the identification of optimal actions for preserving 'win-wins'' for multiple ecosystems from land and sea (Ran et al., 2018). We show how it is possible to quantify relative contributions of multiple watersheds to sediment export and their potential effects on coral reefs at global scales. A next step consists of adapting this workflow to local planning by accounting for other data sources (Figure 6, also see Brown et al., 2017; Tulloch et al., 2021). The utility of modelling soil loss from watersheds to identify the potential management options has been demonstrated by several small-scale studies (Delevaux et al., 2018; Tulloch et al., 2021; Wenger et al., 2020). Follow-up analysis could address additional sources of sediment, for example, gully erosion or bank erosion to the river. Addressing these additional sources has been demonstrated in a prioritisation framework similar to the current study, albeit only as a pilot in a very small coastal watershed in Australia (Hermoso et al., 2015). We used a relatively simple model for achieving our goal of providing a relative measure of sediment exposure on reefs at the global scale. We have also treated coral reef habitat as a uniform feature, even though the heterogeneity of coral reef habitats can display different sensitivities to disturbance by excess sedimentation. Calibration with localised data would be ideal; however, data is missing in many regions that hinder calibration and validation analyses with more complex models. As global data sets evolve, including refined coral habitat map and bathymetry (Li et al., 2019), higher-resolution global coverage on both erosion sources and coral data are expected to become available within the next decade.

Further analyses can also include the potential benefits from marine-based conservation actions (Adams et al., 2014), as well as the cumulative effect of multiple threats such as climate change,

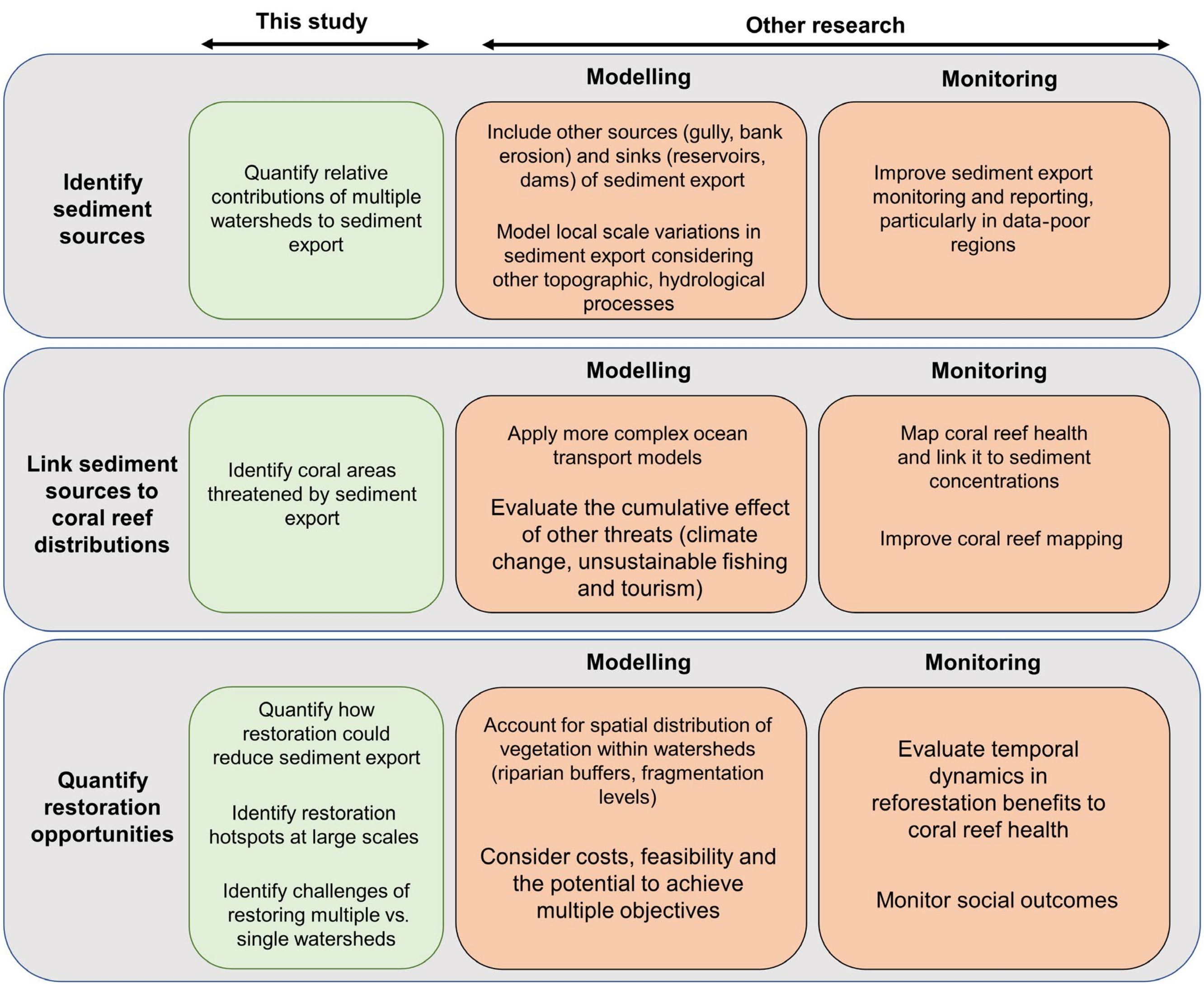

FIGURE 6 Major considerations to link estimates of sediment export to coral reefs at global and local extents. "Other research" consists of aspects that may have been addressed by local scale studies, but that do not count with reliable information across multiple regions

unsustainable fishing and tourism (Delevaux et al., 2019; Wong et al., 2019) to identify the relative impact of restoration benefits on coral reefs. Restoration strategies should be designed accounting for cross-realm connections (Tulloch et al., 2021), but stakeholders are impacted in different ways for management actions and have different associations with natural resources (Álvarez-Romero et al., 2015). As there is a growing spatial mismatch between the escalating scale of threats and current or planned responses (Bellwood et al., 2019), future research also needs to consider how to synchronize land restoration with sea-based conservation priorities. The cross-realm nature of our modelling approach reveals that there is a high heterogeneity in potential conservation benefits that will be interesting to explore in future work.

Accounting for temporal dynamics in reforestation benefits and within watershed spatial variation is also important. Better outcomes in rates of sediment reduction per unit area of restoration may be possible if the location and configuration of restored forest is planned strategically to account for the dynamics of sediment transport. By failing to account for the spatial configuration of restored forest we may be underestimating the potential benefits in sediment reduction that could result from forest restoration; hence, our estimates are conservative. Similarly, assessing riparian buffers, which can remove up to 90% of sediment transport to streams (Daniels & Gilliam, 1996; Mekonnen et al., 2015), would be a logical next step. In addition, our objective was to identify relative contributions of watersheds under current land-use conditions. Further conversion of native habitats to agriculture would invalidate our sediment export estimates. Furthermore, it may take years before the benefits of forest restoration translate to reduced sediment export (Le et al., 2012; Marden, 2012). It is important to account for the time frame of anticipated outcomes of conservation actions to ensure that management in the intervening period is sufficient to ensure the persistence of these systems (Delevaux et al., 2018).

From a marine perspective, coral reef response to change in sediment runoff will also vary over time based on taxon physiology and environmental conditions (Anthony, 2000; Stafford-Smith et al., 1992). Indeed, previous research has revealed that many turbid zone reefs exhibit relatively high live coral cover (Anthony et al., 2007; Browne et al., 2012). We call for further research linking reef condition with water quality at global and local scales to gain further insight into these interactions. Our study assumes a parsimonious view that limiting the amount of sediments would be beneficial for most corals, but we recognize that setting goals for reducing sediment export to coastal watersheds will also depend on the target coral assemblages affected. To understand the benefits of reforestation on coral reefs, an important avenue of research consists on monitoring and linking water quality with coral reef health across multiple regions.

Consideration of costs and feasibility to achieve multiple objectives across scales (e.g. carbon sequestration and biodiversity conservation, Strassburg et al., 2020) is imperative for achieving efficient and effective watershed management (Beher et al., 2016; Klein et al., 2010, 2012). Restoration must be coupled with policy to prevent leakage effects (e.g. the displacement of unsustainable land practices to other regions) as this could diminish the net benefit of restoration (Lewison et al., 2019). In some regions, agricultural intensification and a shift away from low productivity grazing systems could be a way of addressing this (Byerlee et al., 2014). Stakeholder engagement in these processes is key to ensure equitable solutions are achieved for different actors. This could include implementation of opportunity cost analysis and/or ensuring conservation actions do not disproportionately impact one group more than another (e.g. taking land away from farmers to benefit fishers).

We identify three further issues that present challenges to developing forest restoration programs that reduce sediment export to coastal ecosystems. First, sediment exports reaching coral reefs, as well as other ecosystems such as mangroves and seagrasses, come from a set of jurisdictions with a diverse range of socioeconomic and geopolitical contexts that must be accounted for (Chazdon & Brancalion, 2019; Strassburg et al., 2020). A broad range of policy and management initiatives may be required to achieve forest restoration in this context. Multiple local examples have shown the importance of developing integrated coastal management plans that account for differential needs from the land and sea (Adams et al., 2014; Arkema et al., 2014; Jupiter et al., 2017) Second, in many cases, the predominant sources of sediment export are located outside the administrative boundaries containing the coral reefs they impact. Finally, coral reefs with the greatest amount of sediment exposure tend to be influenced by several nearby watersheds. As global analyses have shown, the benefits and costs of achieving restoration targets depend greatly on where this restoration occurs (Strassburg et al., 2020), and, hence, multi-jurisdictional cooperation may therefore be needed to achieve management outcomes that benefit coral reefs. A major challenge is to develop restoration programs that reflect the needs and capacities of local stakeholders while delivering multiple socioeconomic and ecosystem service benefits (Chazdon et al., 2020).

Land-based runoff from degraded and deforested areas drives reductions in coastal water quality, which is one of the leading non-climate-related threats to marine ecosystems globally. Forest restoration has recently garnered significant attention for its potential to help combat climate change, improve human livelihoods, as well as reduce terrestrial species losses. This is evidenced through several global initiatives (e.g. the Bonn Challenge, the UNFCCC Paris Accords and the UN Decade of Ecosystem Restoration) that are bringing forest restoration to the forefront of global conservation discussions, as well as voluntary pledges by many countries to restore hundreds of millions of hectares of forest globally. However, clear regional and global targets on how to improve marine ecosystems through land-based management actions are still lacking. Our results show that targeted forest restoration has the potential to also achieve substantial benefits for marine ecosystems, specifically coral reefs. Encouragingly, many countries with high coral diversity have committed large areas (e.g. >20 Mha in Indonesia) to land restoration (Fagan et al., 2020). However, net forest loss and net agricultural expansion over the past 15 years, as well as political and social barriers, may make it difficult to achieve these ambitious goals. We urge conservation organisations to explicitly acknowledge and account for benefits to marine systems when identifying restoration goals and priorities. Threats to coral reefs can only be addressed through globally coordinated, long-term action. In the interim, managing the suite of other biophysical and socioeconomic factors impacting reefs can help to improve the resilience and recovery of reefs over shorter time frames. Doing so will help to bridge the land–sea interface in international conservation action and more efficiently achieve multiple conservation objectives through forest restoration.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

DATA AVAILABILITY STATEMENT

All data used to produce our findings is publicly available from previous studies. The only exception is the data from Borrelli et al. (2017), which is available from the corresponding author upon reasonable request. The layer used to calculate the sediment export reaching coral reefs can be found in the Dryad repository: https://doi.org/10.5061/dryad.g4f4qrfqq.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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