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# Prioritizing forest management actions to benefit marine habitats in data-poor regions

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## Abstract

Land-use change is considered one of the greatest human threats to marine ecosystems globally. Given limited resources for conservation, we adapted and scaled up a spatially explicit, linked land–sea decision support tool using open access global geospatial data sets and software to inform the prioritization of future forest management interventions that can have the greatest benefit on marine conservation in Vanuatu. We leveraged and compared outputs from two global marine habitat maps to prioritize land areas for forest conservation and restoration that can maximize sediment retention, water quality, and healthy coastal/marine ecosystems. By combining the outputs obtained from both marine habitat maps, we incorporated elements unique to each and provided higher confidence in our prioritization results. Regardless of marine habitat data source, prioritized areas were mostly located in watersheds on the windward side of the large high islands, exposed to higher tropical rainfall, upstream from large sections of coral reef and seagrass habitats, and thus vulnerable to human-driven land use change. Forest protection and restoration in these areas will serve to maintain clean water and healthy, productive habitats through sediment retention, supporting the wellbeing of neighboring communities. The nationwide application of this linked land–sea tool can help managers prioritize watershed-based management actions based on quantitative synergies and trade-offs across terrestrial and marine ecosystems in data-poor regions. The framework developed here will guide the implementation of ridge-to-reef management across the Pacific region and beyond.

**KEYWORDS**
coral reefs, decision-making, global data sets, habitat, ridge-to-reef, seagrass, sediment, water quality

Priorización de la Conservación y Restauración de los Bosques para Beneficio de los Ecosistemas Marinos en Regiones con Deficiencia de Datos

**Resumen:** Dados los recursos limitados para la conservación, adaptamos y ampliamos una herramienta de apoyo para la toma de decisiones que es espacialmente explícita y que conecta las decisiones de manejo de los ecosistemas terrestres y marinos. Usamos conjuntos de datos geoespaciales globales de acceso abierto y software para orientar la priorización de las futuras intervenciones de manejo de bosques que pueden tener el mayor beneficio para la conservación marina en Vanuatu (Oceanía). Comparamos la información de dos mapas mundiales de hábitats marinos para maximizar la retención de sedimentos, la calidad del agua y los ecosistemas marinos y costeros funcionales. Mediante la combinación de la información obtenida de ambos mapas, incorporamos elementos únicos para cada uno y proporcionamos una mayor confianza a los resultados de priorización; los sitios prioritarios para la restauración fueron más sensibles a la fuente de datos para el mapeo de los hábitats. Sin importar la fuente de los datos sobre los hábitats marinos, las áreas priorizadas estuvieron ubicadas principalmente en las vertientes del lado de barlovento de las islas mayores y elevadas, las cuales están expuestas a una precipitación tropical más alta, río arriba de grandes secciones de hábitats de arrecife de coral y de pastos marinos. Por lo tanto, estas áreas son vulnerables a los efectos antropogénicos (p. ej.: cambio en el uso de suelo). La protección y restauración de los bosques en estas áreas puede mantener limpia el agua y a los ecosistemas funcionales y productivos por medio de la retención de sedimentos, la cual ayuda al bienestar de las comunidades aledañas. La aplicación en todo el país de esta herramienta vinculante tierra-mar puede ayudar a los gestores a priorizar las acciones de manejo de vertientes basadas en las sinergias cuantitativas y las compensaciones en los ecosistemas terrestres y marinos en las regiones con deficiencia de datos. Nuestro esquema puede usarse para guiar la implementación del manejo de tierra a mar en toda la región del Pacífico y en otras más.

**PALABRAS CLAVE**

arrecifes de coral, calidad del agua, conjuntos de datos globales, de la cumbre al arrecife, hábitat, pastos marinos, sedimento, toma de decisiones

**摘要**

近交衰退对重引入种群来说是一个重要的长期威胁。然而, 由于野生种群难以获得完整的谱系数据和良好的生存和繁殖数据, 因此其近交衰退的强度难以估计。对种群未来响应的预测也格外困难, 因为这还需要预测未来的近交水平及其对长期种群动态的影响, 它们受制于许多不确定因素。本研究基于 1992 年重引入到提里提里马塔基岛的新西兰鸲鹟 (*Petroica longipes*) 26 年的数据集, 阐明了如何用贝叶斯状态-空间建模方法得到以上预测。我们利用谱系数据, 基于潜在繁殖对的亲缘关系模拟了平均近交水平 ($\bar{F}$) 随着时间的增加, 并对$N_e/N$ (有效种群大小/调查种群大小) 进行了经验估计。我们使用多重插补法模拟了近交系数的未知成分, 从而在对密度依赖性和环境随机性进行建模的同时估计了数据集所有 1458 种鸟类近交对存活的影响。模型表明, 近交会降低幼鸟存活率 (1.83 个致死当量 [SE 0.81]), 还可能降低随后的成鸟存活率 (0.44 个致死当量 [0.81]), 但对繁育雏鸟的数量没有显著影响。在$N_e/N$ 比为 0.56 (SE 为 0.1) 的情况下, 随着 25 年间种群大小从 33 只 (SE 为 0.3) 增长到160只 (SE为6), 平均近交水平增加到了0.10 (SE 为 0.001) 。基于同时纳入栖息地再生的模型, 我们预计种群数量在 2130 年将达到最大值, 为 331-1144 只 (中位数 726 只), 然后开始缓慢下降。如果没有近交, 种群数量预计将稳定在 887-1465 只 (中位数 1131 只) 。因此, 通过以上分析可以在考虑多种不确定性来源的情况下, 从经验上获得对近交管理理性决策所需的信息。**【翻译: 胡怡思; 审校: 聂永刚】**

**关键词:** 分层贝叶斯模型, 近交衰退, 新西兰, 新西兰鸲鹟, 种群建模, 重引入, 小种群

## INTRODUCTION

Across much of the tropics, local scale anthropogenic activities, like urbanization, logging and commercial agriculture expansion, threaten coral reefs, mangroves, and seagrass habitats, through increased sediment and nutrient runoff (Mather et al., 1998; Burke et al., 2011). Consequently, integrating land and sea linkages into conservation planning has become urgently and widely advocated to effectively manage land-based threats and maintain the marine ecosystem goods and services upon which human wellbeing depends (Álvarez-Romero et al., 2015; Carlson et al., 2019). A key step to optimize ridge-to-reef management is to track and map the interconnected impact of land use change on marine ecosystems and identify where land-based management interventions can maximize co-benefits across land and sea.

However, conservation planning tools that can provide spatially explicit land-based management recommendations while promoting co-benefits from ridge-to-reef are often challenging to materialize due to the multiple processes at play. Those challenges consist of linking land-use change to marine ecosystems through quantifying and visualizing change in (1) land-based pollution loads, (2) marine water quality, (3) impact on biodiverse and/or vulnerable coastal and marine ecosystems, and (4) tracing those impacts back to the source watersheds; while accounting for human activities, terrestrial and marine geography, and distribution of marine habitats (Brown et al., 2019; Delevaux et al., 2018a; Wenger et al., 2020). This is particularly challenging on small oceanic islands, where small and steep watersheds coupled with porous volcanic geology often result in tighter land–sea connections through social and ecological processes (Jupiter et al., 2017; Delevaux et al., 2018a).

Implementation of tools that can help make objective, data-driven decisions on where to prioritize terrestrial management actions as a function of marine impacts also requires data that can help translate management options into implementable solutions without unintended consequences for the ecosystems and communities dependent on them (Wenger et al., 2020). Many studies aimed at understanding the impacts of terrestrial runoff on marine resources to prioritize conservation investments range from local-scale, data-intensive models to regional/global-scale, coarse data set models (Paris & Chérubin, 2008; Halpern et al., 2009; Klein et al., 2010, 2012; Rude et al., 2016; Tulloch et al., 2016; Brown et al., 2017a; Wenger et al., 2020; Tulloch et al., 2021). This study builds on this body of work by applying an approach that considers both forest restoration and conservation actions based on key land–sea processes in data-poor regions, using open access data sets and software to help inform where nations should prioritize investments to meet ridge-to-reef management objectives.

In the Pacific region, the Global Environment Facility (GEF) funded the Pacific Community (SPC) Ridge to Reef program tasked with enhancing Pacific Island countries' ecosystem goods and services through integrated ridge-to-reef management to promote resilience to climate change. Therefore, the primary goal of this research was applying a spatial prioritization procedure that supports objective ridge-to-reef management investments in the Pacific region. To do so, we adapted and scaled up a spatially explicit decision support framework using freely available data sets (Delevaux et al., 2018a, 2019). Then, we applied this tool across Vanuatu to identify where forest restoration and conservation interventions can most benefit marine ecosystems of socioecological significance that are susceptible to change in water quality. Currently, the only source of tropical marine habitat information across Vanuatu, and other Pacific Island nations, are two existing global marine habitat maps. Of interest to managers, and a secondary objective of this study, is how prioritizing forest management may differ based on application of either or both global marine habitat mapping products.

Vanuatu comprises 74 populated islands with 81% of the population living in rural areas dependent on subsistence farming and fishing and 19% living in the two main urban centers, Port Vila (Efate) and Luganville (Santo). Rapid land-use change, where forest is cleared for forestry, pasture, and crops, coupled with urban growth, has resulted in increased soil erosion, pollution of coastal areas, and degradation of seagrass and reef habitats along with associated marine resources. To represent and address these cascading environmental issues, we modeled the potential impacts of projected land-use change on nearshore ecosystems through sediment runoff and linked those back to the watersheds driving these impacts, which enabled us to: (1) quantify how sediment export changes under different management scenarios; (2) identify where coral reef and/or seagrass are potentially vulnerable to change in total suspended sediment (TSS) using different marine habitat maps; and (3) determine which watersheds should be prioritized for management by assessing the overlapping downstream impacts of multiple watersheds and leveraging both habitat maps to reduce uncertainty in the modeling process and underlying data sets.

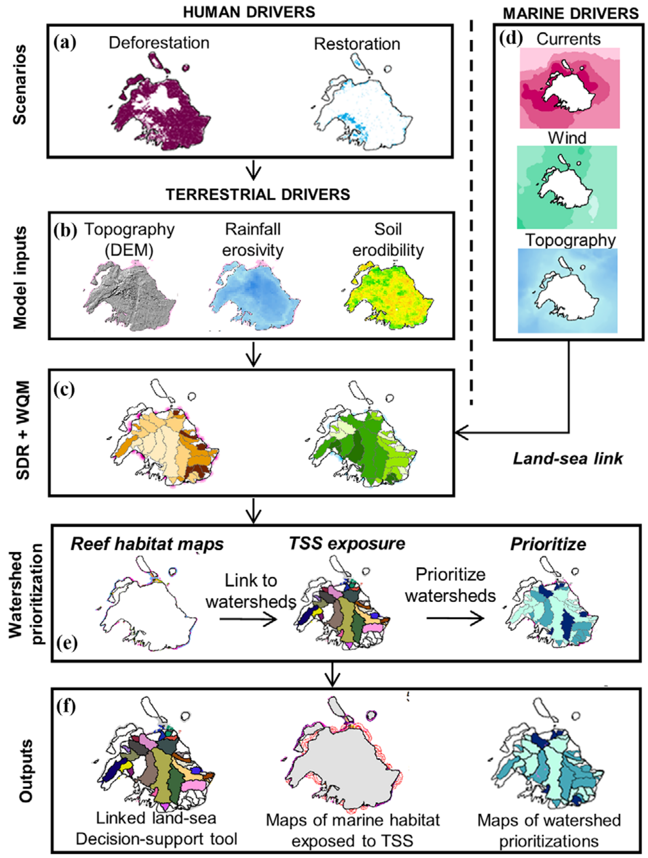


FIGURE 1 Linked land–sea modeling framework. (a) Land-use change scenarios were coupled with (b) topography, rainfall erosivity, and soil erodibility data into (c) InVEST Sediment Delivery Ratio (SDR) model to quantify sediment export (t/year) per watershed and linked to a marine water quality model (WQM), which incorporates the diffusive effect of (d) currents, wind, and depth. (e) The watershed prioritization coupled reef habitat maps and change in TSS exposure to identify land–sea linkages and prioritize watersheds based on marine habitat exposure. (f) The outputs were: (1) a linked land–sea decision-support tool, (2) maps of marine habitat areas exposed to change in TSS, and (3) maps of watersheds and land areas prioritization for forest-based management

# METHODS

## Ridge-to-reef prioritization procedure overview

The procedure for prioritizing ridge-to-reef investments consists of four key components: (1) land use change scenarios (Figure 1a), (2) the open source InVEST Sediment Delivery Ratio (SDR) (version 3.9) (Hamel et al., 2015) to quantify the change in sediment export to the coast based on topography, soil erodibility, and rainfall erosivity (Figure 1b, c) (Appendix S1), (3) a marine water quality model incorporating depth, wind exposure, and currents to estimate TSS (Delevaux et al., 2018a) (Figure 1c, d) (Appendix S1), and (4) a land-based management prioritization approach combining marine habitat exposure to TSS change (Rude et al., 2016) and linking those marine areas to the key watersheds driving those changes (Delevaux et al., 2018a) (Figure 1e). We leveraged existing global and local data sets from the region to apply this decision support procedure

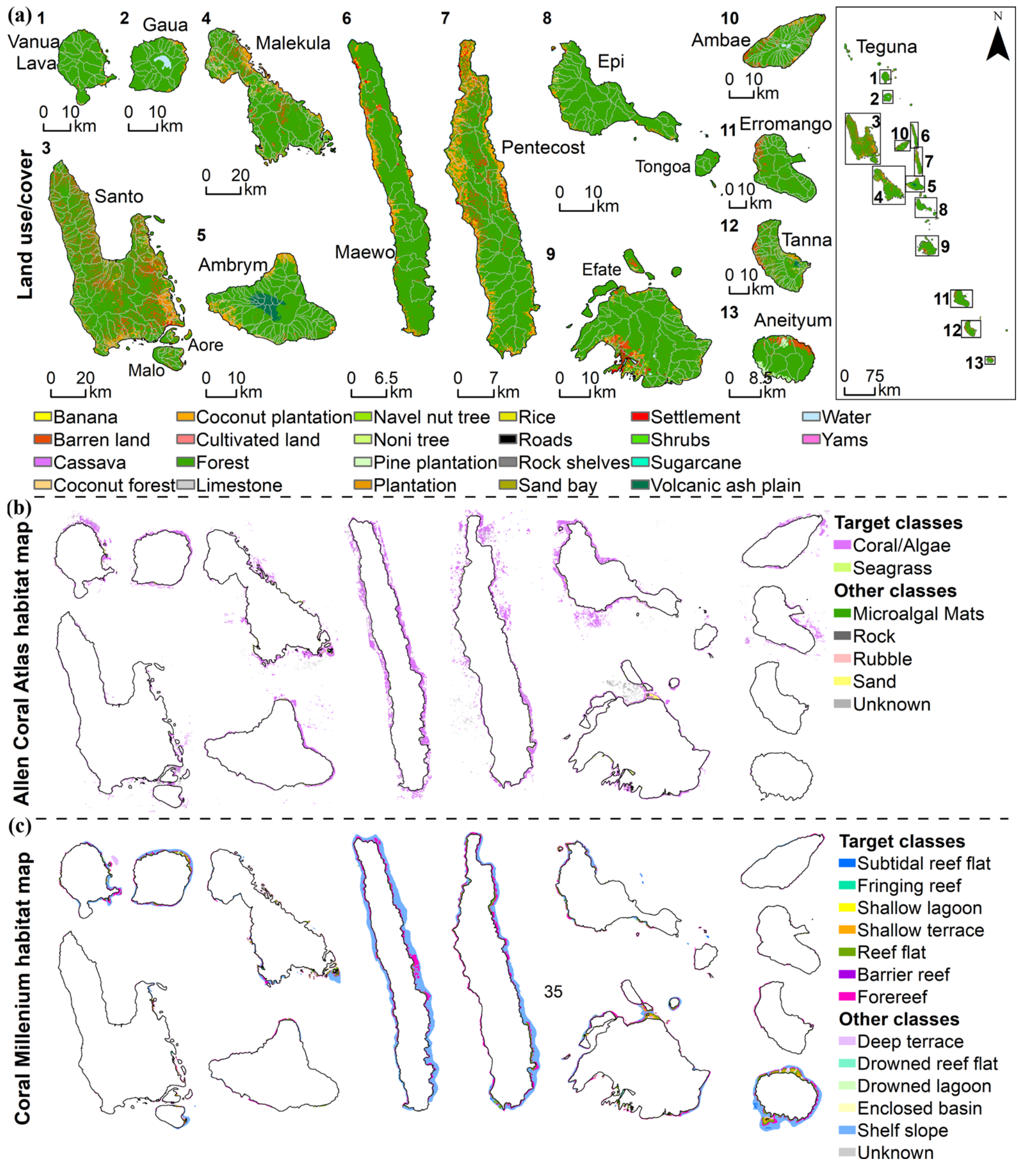


**FIGURE 2** Study site. (a) The largest 17 islands of Vanuatu were modeled. Teguna is the smallest modeled island with one watershed and is not provided as an inset. (b) The Coral Allen Atlas and (c) Coral Millennium marine habitat maps, with the habitat classes considered for the terrestrial impact assessment and the other classes

(Appendix S2). We conducted this workflow on each marine habitat map independently and then combined the outputs to reconcile and identify areas where management interventions can simultaneously promote sediment retention, marine water quality, and healthy coastal/marine habitats (Figure 1f).

## Site description and data inputs

We modeled sediment exports across the 17 main islands of Vanuatu covering 11,663 km$^2$ and 412 watersheds (4.6–461.9 km$^2$) (Figure 2). The most current land use/cover map (2010) was a shapefile, provided by SPC, with a composition of forest (82.3%), grassland (10.4%), plantation (6.2%) (e.g., bananas, coconut, cassava, and yam), human settlement (0.3%), volcanic ash plain (0.6%), and pine plantation (0.1%) (Figure 2a & Appendix S2) (SPC, 2017). Downstream, the extent of coral reef habitat varies between 792.3 and 13,489.1 km$^2$ according to the Coral Allen Atlas (Atlas hereafter) (Figure 2b) and the Coral Millennium (Millennium hereafter) habitat maps (Figure 2c), respectively. For the purpose of this analysis, we ignored the habitat classes that were unlikely to support live cover or other cover types sensitive to sediment deposition (Saunders et al., 2017; Carlson et al., 2019) and thus retained only two habitat classes from the Atlas benthic zone classification: (1) coral/algae (227.8 km$^2$) and (2) seagrass (14.8 km$^2$) (Figure 2b). For the Millennium habitat map, we only retained habitat classes that represent coral reef habitat (702.4 km$^2$) (e.g, subtidal reef flat, fringing reef, shallow lagoons, reef flat, barrier reef, and forereef), but were not able to consider seagrass habitats using this product (Figure 2c) (see Appendix S1 Marine habitat preprocessing) (Andréfouët et al., 2006).

These global habitat maps differ in terms of classification methods and scheme. The Allen Coral Atlas is a current initiative which has released hierarchical geomorphic and benthic maps of a number of regions with the goal of completing maps of the entire globe by the end of 2021 (Allen Coral Atlas, 2020). The Atlas uses a semi-automated machine learning classification followed by object based contextual editing that utilizes new and existing field habitat data, water depth, and 3.7-m satellite imagery data from Planet's Dove satellite mosaic, to classify large coastal marine areas into hierarchical biological and geomorphic classes (Allen Coral Atlas, 2020). In contrast, the Millennium map is based on supervised classification (trained experts) and employs a hierarchical geomorphic structure classification applied to 30-m resolution satellite imagery from which biological benthic cover is inferred (Andréfouët et al., 2006). The Millennium Coral Reef Mapping Project has created geomorphic maps of coral reefs worldwide since 2004 and has been widely applied and vetted by numerous studies (Andréfouët & Bionaz, 2021). Effectively, the different classification methods result in high resolution though patchier (pixelated) maps in the case of the Atlas and lower resolution and more continuous maps for the Millennium map. Atlas map habitats also had a greater range of distance from shore compared to the Millennium map where most habitats are relatively close to shore. The Millenium classes cover more area than the Atlas classes used in this study since they are solely geomorphic structure classifications. For example a reef flat class could include a lot of bare rock area or a fringing reef could include rubble areas with no biological cover. Although still in development, the Allen Coral Atlas employs newer technology in terms of satellite imagery and classification methods, which show much promise.

## Scenario design

We considered two extreme deforestation and forest restoration scenarios to assess how future land use change and management could impact marine ecosystems through sediment runoff (Figure 1a). The deforestation scenario represents the potential future expansion of commercial timber logging, following the collapse of overexploited sandalwood, combined with the establishment of large commercial pastures and coconut plantations due to land alienation (Regenvanu et al., 1997). We used historical spatial deforestation trends (1990–2000) (Eckardt et al., 2008) to project future deforestation relative to present land use/cover, coupled with local logging practice codes (i.e., no deforestation on slopes > 30°; or within 20 m of streams <20 m wide, 30 m of streams > 20 m wide, or 100 m from lakes, lagoons and the coast) (McIntosh, 2013). Hence, the future deforestation scenario assumed that existing forest, on slopes <20°, altitude <300 m, and within 3 km of existing roads, agriculture, or urban areas would convert to the nearest land use type, except for existing forest located within the riparian buffers of streams, lakes, and coastal zone (Figure 3a) (SPC, 2017; OSM, 2019). For the restoration scenario, we assumed that barren land and existing agriculture (i.e., bananas, cassava, coconut, navel nut and noni plantations, rice fields, sugarcane, and yams) were converted back to forests (Figure 4a). Although these scenarios were developed based on historical deforestation trends and common forest restoration practices (Eckardt et al., 2008), they do not predict future land use and are instead used to reveal where potential forest protection or restoration interventions can generate the greatest sediment retention while maximizing marine water and habitat quality.

## Management prioritization

For each scenario, we separately calculated a watershed prioritization score using the Atlas (Allen Coral Atlas, 2020) and Millennium habitat maps (Andréfouët et al., 2006). First, we identified and quantified the area of coral reef and seagrass habitat (ha) exposed to a change in TSS, by overlaying the footprint of the change in modeled TSS plumes relative to present (Rude et al., 2016). We did not model coral reef and seagrass response to change in water quality following Delevaux et al. (2018a) or Saunders et al. (2017), respectively, due to lack of empirical surveys across the archipelago. Second, we linked the marine habitat areas exposed to change in TSS to the watersheds contributing the largest change in sediment load to those areas under each scenario, relative to present. To do so, we identified the three watersheds that together contributed over 85% of the total change in sediment export to each habitat grid cell and calculated the fraction of sediment contributed by each (Delevaux et al., 2018a). Third, for each watershed, we independently calculated the total marine habitat areas (ha) ($H_{w_i}$) exposed to change in TSS for which that watershed was the first, second, and third largest contributor (if applicable). Last, we took the weighted average of these values for each watershed $w$, to obtain a watershed prioritization score ($P_w$), using Equation (1):

$$P_w = \left( \sum_{i=1}^{3} H_{w_i} \times F_{w_i} \right) / n_w, \qquad (1)$$

where $P_w$ is the prioritization score for each watershed $w$ (unitless), $H_{w_i}$ is the total marine habitat area (ha) exposed to change in TSS for each watershed $w$, $F_{w_i}$ is the average fraction of TSS change for each habitat grid cell contributed by each watershed $w$ (unitless), and $n_w$ is the number of times the watershed $w$ was identified as a major contributor of sediment.

We conducted this analysis on both the Atlas and Millennium habitat maps and rescaled $P_w$ between 0 and 100 to derive a comparable prioritization score for each watershed. To visually compare the prioritization scores for each habitat map and across both scenarios, we mapped them separately, classifying values into low (0–10), medium (10–30), and high (30–100) categories, which are based on natural break intervals rounded to the nearest 10. We also plotted them against each other for each future scenario and estimated the $R^2$ and $p$-values. To reconcile the differences between both the Atlas and Millennium habitat maps and provide more confidence in the results, we averaged the watershed prioritization scores from each map and categorized them into the same low (0–10), medium (10–30), and high (30–100) priority categories. Lastly, we used the sediment export maps (30 m × 30 m) from the SDR models to identify the land areas within each watershed contributing a significant change in sediment runoff, compared to present (Delevaux et al., 2018a). In other words, we identified where the greatest increases and decreases in sediment export occurred under the deforestation and the restoration scenarios, respectively. For each scenario, we calculated the significant differences ($\alpha = 0.10$) in sediment export in the linked watersheds per grid cell, compared to present conditions using the SigDiff function (Januchowski et al., 2010). Finally, we created a 100-m buffer around those priority land areas based on conservation and logging best management practices (McIntosh, 2013).

# RESULTS

## Deforestation scenario

Under the deforestation scenario, over 59.1% (5178 $km^2$) of forest cover was lost to expansion of human activities (Figure 3a), resulting in an increase of 62.6% of sediment export per year. This increase in sediment export led to an increase in TSS around most islands and particularly around Efate, Epi, and Malekula (Figure 3b). Correspondingly, using the Atlas map, 22.4% (5093.2 ha) of marine habitats were exposed to change in water quality, including 20.5% of coral/algae and 1.8% of seagrass habitats (Figure 3c, pink area). For the Millennium map, 30.1% (20,737.9 ha) of marine habitats were exposed to change in water quality, or roughly four times the total habitat area exposed using the Atlas map (Figure 3d, pink area), with the breakdown by habitat type shown in Appendix S3. When combining both habitat maps exposed to an increase in sediment export, the overlap of marine habitat was 11.6% (2680 ha), whereas the total habitat area was 23,151 ha, with 10.4% (2413 ha) from the Atlas map and 78% (18,058 ha) from the Millennium map. The watershed prioritization analysis with the Atlas map resulted in 303, 85, and 24 watersheds receiving a low, medium, and high score, respectively; compared to the Millennium map analysis, which resulted in 268, 110, and 34 watersheds receiving a low, medium, and high score, respectively (Figure 3c, d).

## Restore forest scenario

Under the restoration scenario, forest cover increased by 19% (1895.8 $km^2$) due to conversion of agriculture land back to forest (Figure 4a), resulting in a decrease of 97.3% of sediment export year (96.6%/$km^2$/year). Consequently, the increase in sediment export led to a decrease in TSS around most islands and particularly around the large islands: Santo, Efate, Malekula, and Pentecost (Figure 4b). Correspondingly, the Atlas map revealed that 18.3% (4164.9 ha) of marine habitats were exposed to change in water quality, including 16.8% of coral/algae and 1.5% of seagrass habitats (Figure 4c, pink area). Whereas the Millennium map showed that 23.9% (16,433.6 ha) of marine habitats were exposed to change in water quality (Figure 4d, pink area), or roughly four times the total habitat area exposed using the Atlas map, with the breakdown by habitat type shown in Appendix S3. When combining both habitat maps exposed to an increase in sediment export, the overlap of marine habitat was 11.1% (2054 ha), whereas the total habitat area was 18,545 ha, with 11.4% (2111 ha) from the Atlas map and 77.5% (14,380 ha) from the Millennium map. The watershed prioritization analysis with the Atlas map resulted in 333, 64, and 15 watersheds receiving a low, medium, and high score, respectively; compared to the Millennium map analysis, which resulted in 245, 108, and 59 watersheds receiving a low, medium, and high score, respectively (Figure 4c, d).

## Habitat maps comparison

When comparing the prioritized watersheds across both maps under the deforestation scenario, we found that both analyses resulted in similar watershed prioritization scores ($R^2 = 0.7$, Figure 5a). When the results for both maps are combined using the same classification, 316 watersheds receive a low score, 76 score medium, and 20 score as high priority for conservation (Figure 5c). The watersheds that scored high to protect existing forest (i.e., avoid deforestation in the future) are generally located on the windward side of the islands. These are more abundant on the large islands, including Santo, Efate, Malekula, and Ambrym, with a few on the smaller islands, including Vanua Lava and Gaua (Figure 5c). These watersheds correspond to areas where existing human activities may expand based on historical trends and where extensive marine habitat areas are located downstream. Land areas where the change in sediment export was significantly different from present conditions were selected as priorities for conservation to prevent sediment runoff (shown in pink in Figure 5a).

When comparing the prioritized watersheds across both maps under the forest restoration scenario, we found a greater division between watershed prioritization scores compared to the deforestation scenario ($R^2 = 0.2$, Figure 5b). In this case, the Millennium map generally scored watersheds higher compared to the Atlas map. When the results for both maps were combined using the same classification, 266 watersheds received a low score, 113 scored medium, and 33 scored as high priority for restoration (Figure 5c). The watersheds that scored high to restore degraded forest are generally located on the windward and north side of the islands. They are more widespread across the archipelago, spanning islands north to south, including the large islands, such as Santo, Efate, Malekula, Pentecost, and Ambrym, and the smaller islands, such as Vanua Lava, Gaua, Ambae, Malo, Tanna, and Aneityeum (Figure 5d). These watersheds also correspond to areas where human activities are currently the most extensive compared to other less populated islands and where extensive areas of marine habitats are located downstream. Land areas where the change in sediment export

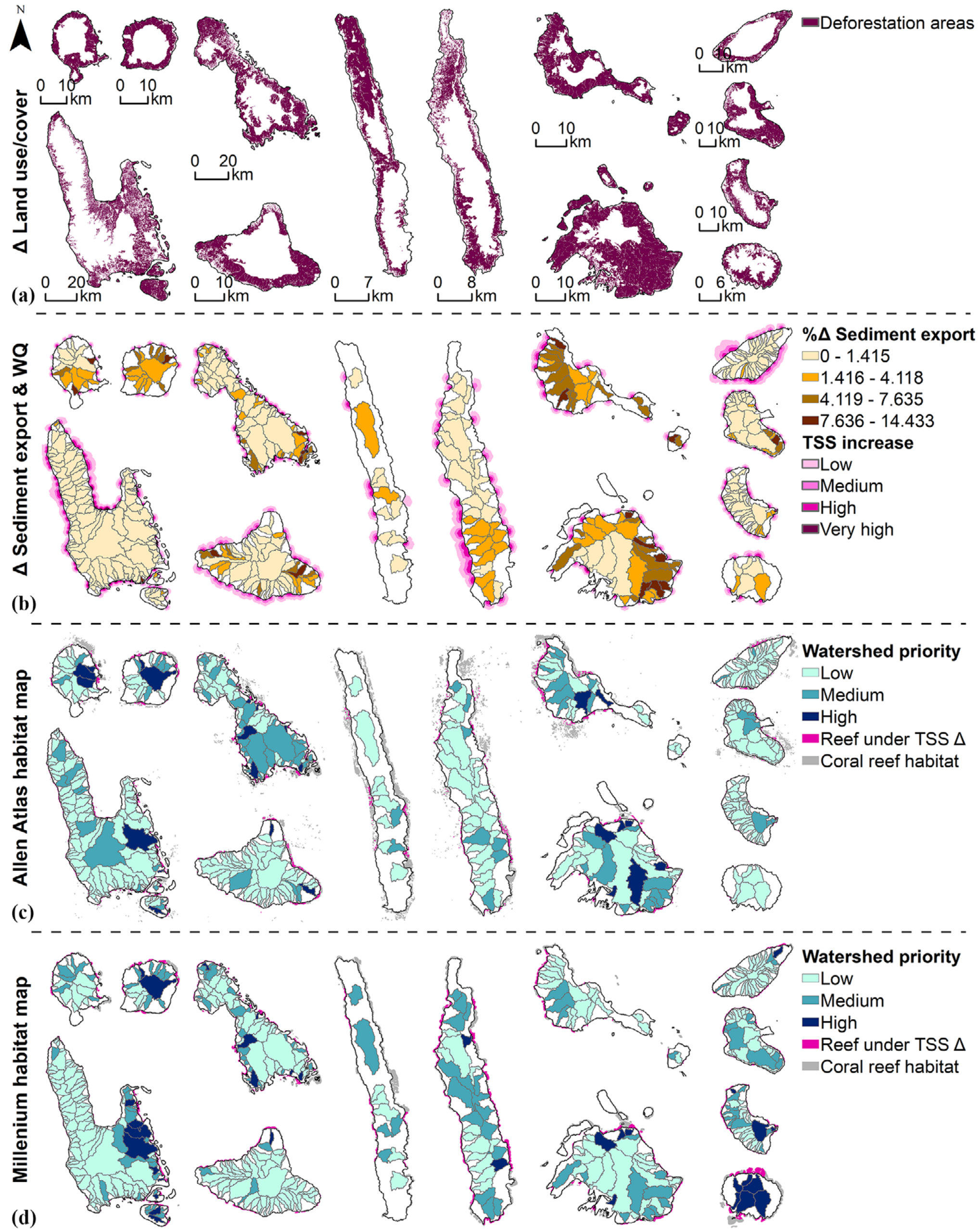


**FIGURE 3** Ridge to reef modeling under the deforestation scenario. (a) Areas where existing forest areas can be lost under the deforestation scenario. (b) Sediment export (relative % change from current conditions) by watershed and associated change in TSS. (c) Watershed prioritization scores based on coral reef and seagrass habitats exposure to change in TSS using the Atlas and (d) the Millennium habitat maps

was significantly different from present conditions were selected as priorities for restoration to foster sediment retention (shown in pink in Figure 5b).

## DISCUSSION

We coupled extreme deforestation and restoration scenarios with a linked land–sea decision support tool to pinpoint land areas where forest conservation or restoration can mutually benefit marine ecosystems potentially vulnerable to land use change, and thereby optimize management investments. This application demonstrates that open access global data sets can support the application of ridge-to-reef decision support tools in data-poor environments to inform ridge-to-reef conservation planning. It provides a rapid assessment procedure and science-based foundation to help managers, such as SPC and their local partners, begin participatory planning processes by identifying a portfolio of potential target sites where to implement future ridge-to-reef investments in Pacific island settings and beyond. In addition, these results can foster coordinated management across different agencies, which remains a key challenge in implementing ridge-to-reef management (Jupiter et al., 2014). For instance, simple, map-based outputs can

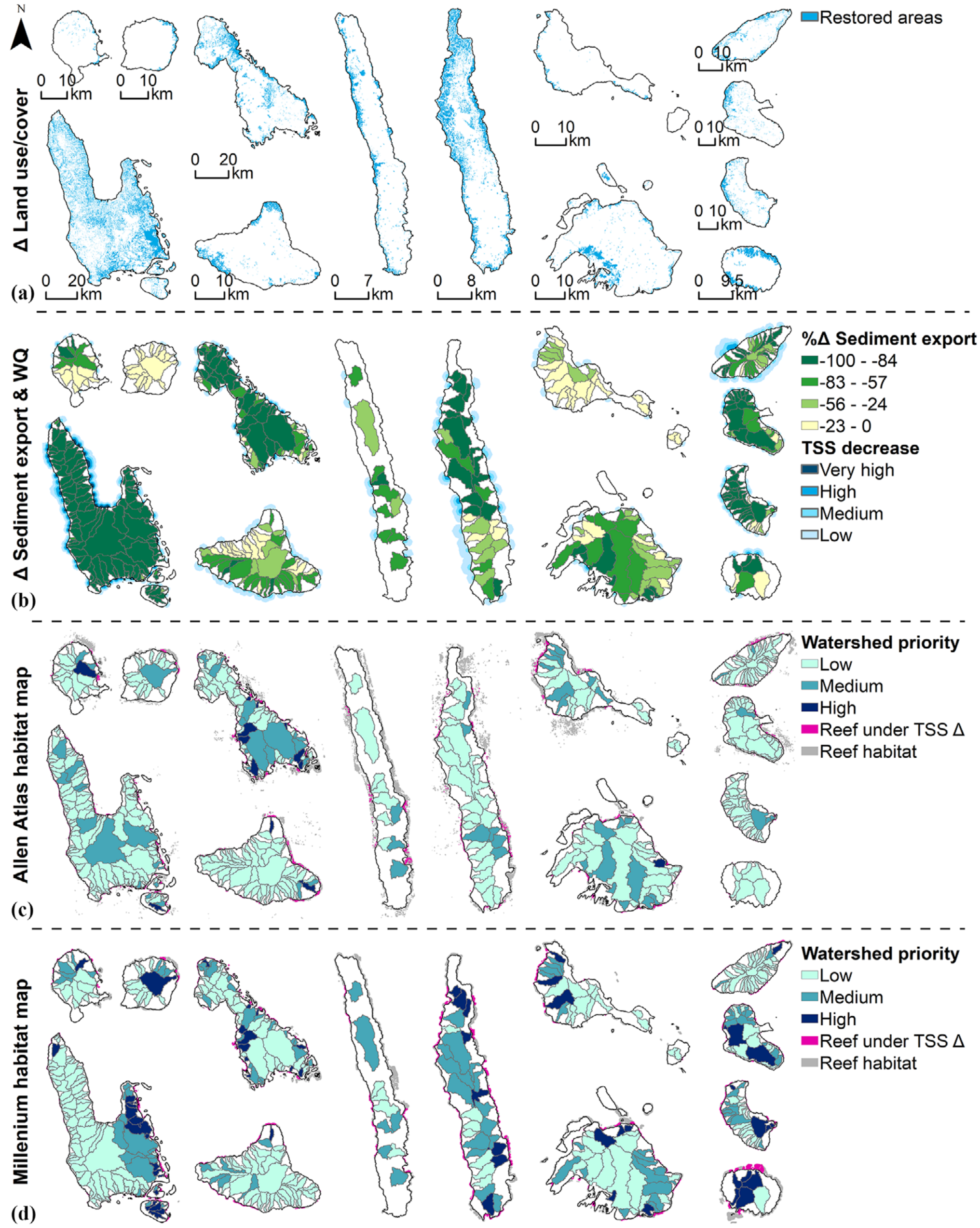


**FIGURE 4** Ridge to reef modeling under the forest restoration scenario. (a) Areas where existing degraded and agricultural landscape can be restored to forest under the forest restoration scenario. (b) Sediment export (relative % change from current conditions) by watershed and associated change in TSS. (c) Watershed prioritization scores based on coral reef and seagrass habitats exposure to change in TSS using the Atlas and (d) the Millennium habitat maps

facilitate discussions across agencies and stakeholders by allowing for more transparency in the decision-making process, which can ultimately foster community buy-in and compliance (Stamoulis & Delevaux, 2015).

Instead of modeling the response of coral reef and seagrass habitats to TSS, we applied an overlay analysis based on mapped habitats of high ecologic value. The adverse direct and indirect impacts of sedimentation and turbidity on coral reef habitats have been well established (Fabricius, 2005), including hindered competition for space by reef calcifiers (Smith et al., 2016), altered benthic community structure and composition (Rogers, 1990), reduced benthic and fish recruitment (DeMartini et al., 2013; Wenger et al., 2014), altered fish foraging patterns (Johansen & Jones, 2013), and habitat association (Brown et al., 2017b). Similarly, the adverse impact of increased sedimentation has been shown to smother and reduce the extent of seagrass habitat (Saunders et al., 2017). Based on these established impacts, we assumed that increases in TSS over coral reef and seagrass habitats negatively affect live coral cover, seagrass beds, reef fish biomass, and nurseries to prioritize land areas for forest conservation or restoration. However, we also acknowledge that coral reefs can flourish in turbid waters and, therefore, are already resilient to sedimentation due to previous exposure (Anthony, 1999). These coral

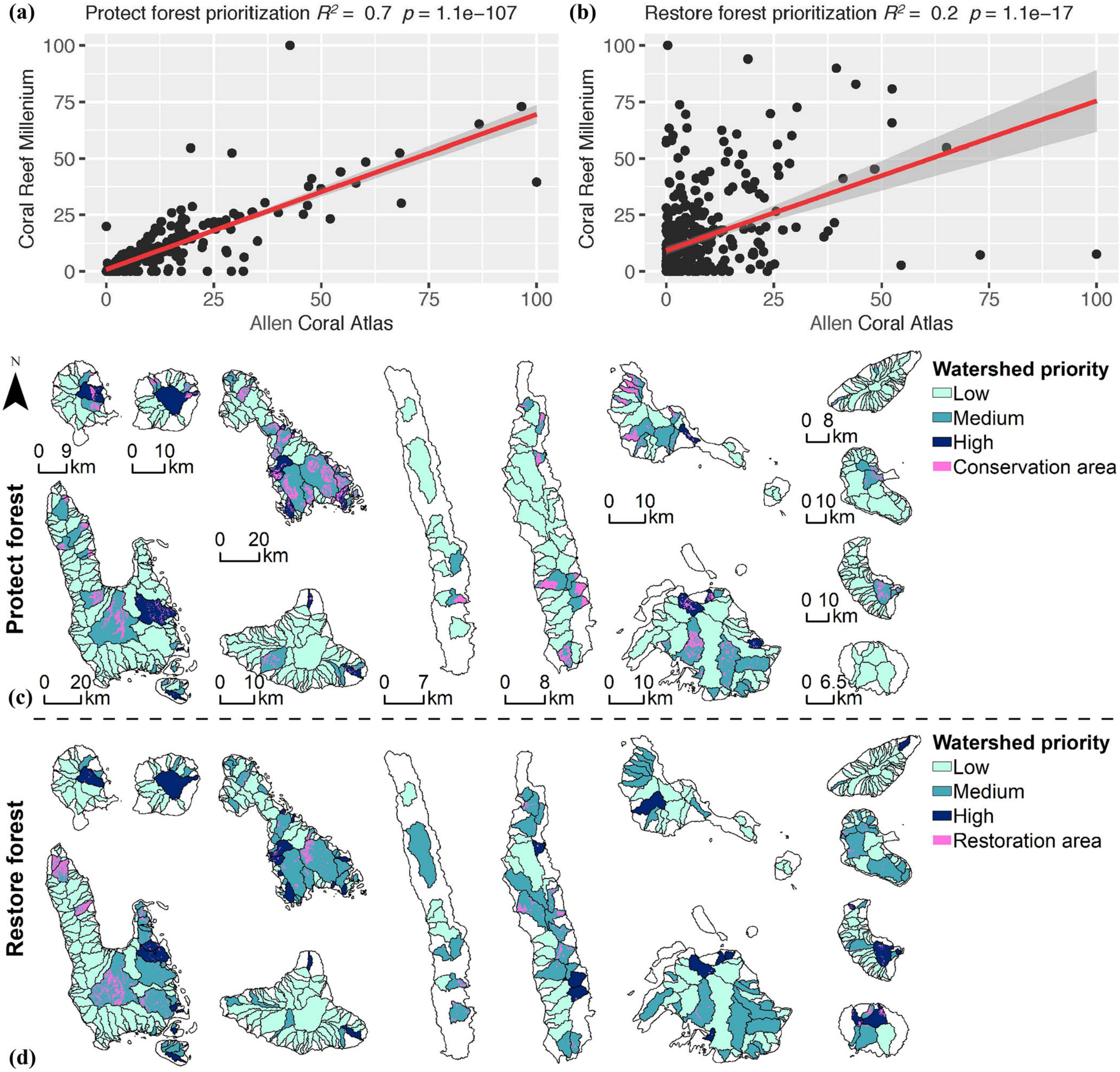


**FIGURE 5** Watersheds prioritized for management actions. Graphical comparison of watershed prioritization scores for (a) forest protection (i.e., avoiding deforestation) and (b) forest restoration based on the Allen and Millennium habitat maps. Spatial comparison of watershed prioritization scores and associated priority land areas under (c) forest protection (i.e., avoiding deforestation) and (d) forest restoration that would most benefit sediment retention, marine water quality, and habitats

communities are generally restricted to shallow waters (4–10 m) (Fabricius et al., 2005), with fewer species, slower growth rates, and poorer recruitment (Rogers, 1990). Although we are limited by the ecological resolution of both marine habitat maps, based on this we may have overestimated the potential effect of change in TSS on those marine habitats regularly exposed to sediments.

We utilized two habitat maps generated using different classification methods and habitat classes to conduct the watershed prioritization analysis. Estimates of coral reef habitat area exposed to change in water quality were generally four times higher using the Millennium map versus the Atlas map for both scenarios, though this translated into comparable differences in percentages of habitat affected. It is likely that assumed coral cover is overestimated using the Millennium map and mapped coral/algae cover may be underestimated using the Atlas map. Also, the Atlas map provides the ability to include seagrass habitats, whereas the Millennium map does not. The prioritization analysis using each map provided similar results for the deforestation scenario with greater differences for the restoration scenario. This may be due in part to the greater extent and magnitude of sediment export for the deforestation scenario compared to the restoration scenario. The larger and more numerous sediment plumes modeled in the deforestation scenario overlaid more marine habitats in more locations, perhaps minimizing differences between habitat maps. In contrast, the restoration scenario resulted in much smaller sediment exports focused close to shore where habitats represented by the Millennium map are more prevalent. This could explain why watersheds generally received a higher prioritization score using the Millennium map under the restoration scenario. By combining the analysis results obtained from using each habitat map for the watershed prioritization, we took advantage of the strengths and mitigated the weaknesses of each.

Overall, the watersheds prioritized for both conservation and restoration interventions were more exposed to high rainfall and upstream from extensive marine habitats, and restoration prioritized existing agriculture and burnt land, whereas conservation prioritized places where urbanization and agriculture are projected to expand the most. Consequently, our findings highlighted that similar watersheds should be prioritized for both forest protection and restoration. However, the areas identified for forest conservation or restoration within those watersheds differ based on targeted land cover types, suggesting that these management actions could be complementary. Research has shown that wetter tropical watersheds are more susceptible to erosion when forest cover has been removed by human activities (El-Swaify et al., 1982; Pimentel & Kounang, 1998; Borrelli et al., 2017), and therefore would also benefit more from forest restoration than drier watersheds. However, it is important to note that we did not calibrate SDR due to lack of empirical data across the region and, therefore, we only interpreted relative changes (Hamel et al., 2017). Although InVEST SDR was developed for temperate systems, it has been found to reasonably predict change in sediment exports in tropical, oceanic island systems similar to Vanuatu (i.e., Hawaii and Solomon Islands) because it accounts for spatial variability in key environmental drivers of erosion (rainfall, soils, topography, and proportion of land cover types [C and P factors]) (Falinski, 2016; Hamel et al., 2017; Bremer et al., 2018; Hutley et al., 2020). In addition, we only considered the impact of TSS on marine habitats in our prioritization, though nutrients and herbicides are also important stressors of tropical marine habitats (Tulloch et al., 2016; Delevaux et al., 2018b, 2019; Barnes et al., 2019). Lastly, we did not consider the opportunity cost of restoring or protecting forests, or any other social and economic constraints, which may influence feasibility of future ridge-to-reef investments (Klein et al., 2012; Tulloch et al., 2021).

Given that over 80% of the population of Vanuatu lives in rural areas, often economically isolated with reduced transportation opportunities and high reliance on farming and fishing for subsistence (Eriksson et al., 2017), people living on these islands might be particularly vulnerable to the impacts of sedimentation on reef resources. Therefore, it is critical to maintain the quality and productivity of the soils and marine habitats because they are foundations for local food production. In areas where reefs have been degraded by increased land-based pollution due to urbanization, such as Tagabe reef in Port Villa (Efate), local fishing communities have observed increases in health issues and decreased ability to gather food from those systems (IMMT, 2019). In addition, research increasingly shows that marine closures are less effective when exposed to elevated land-based pollution (Halpern et al., 2013; Wenger et al., 2015). Therefore, prioritizing forest conservation or restoration in those watersheds can help maintain multiple co-benefits, including sediment retention, water quality, and healthy seagrass and coral reefs, which provide more productive nursery and fisheries grounds for local communities (Delevaux et al., 2018a; Wenger et al., 2020), while also indirectly mitigating the impacts of climate change on coral reefs (Delevaux et al., 2019). Ridge-to-reef management requires actions that benefit ecosystems beyond protected area and land–sea boundaries.

This decision support tool was implemented in a data-poor region and, therefore, under several key data gaps. First, the resolution of the input foundational layers, including the rainfall, soils, bathymetry, and currents, is coarse resolution for some of the small islands found in Vanuatu. Because soil and rainfall maps are coarser resolution than the Digital Elevation Model (DEM) input, at which SDR operates, it may obscure small-scale processes and spatial nuances which can occur in small watersheds. Similarly, bathymetry and current data are coarser than the water quality model resolution and were interpolated nearshore to fill in the gaps along the shoreline, which may create erroneous values and impact the dispersion of the TSS plumes in some regions. No in-situ water quality data were available for the streams and coastal waters modeled, which prevented us from ground-truthing our models. Although local observations can significantly improve the accuracy of modeled outputs, recent work has shown that complex, data-rich models only performed marginally better compared to InVEST SDR in data-poor regions (Hutley et al., 2020). Lastly, generating more refined bathymetry data using satellite imagery (Roelfsema et al., 2013) can help refine modeled water quality and provide input data for marine species distribution modeling (Delevaux et al., 2018a). More information on caveats and modeling assumptions are included in Appendix S4.

In the meantime, ridge-to-reef management requires the ability to trace where land-based pollutants come from and where they are likely to cause marine impacts. Therefore, decision makers need information to prioritize efforts on the ground and these global data sets are freely available and provide consistent coverage for data-poor regions. This project adapted and scaled up a linked land–sea decision support tool (Delevaux et al., 2018a), to quantify, track, and visualize the impact of land-use change on coral reefs at the subwatershed scale. This approach leveraged existing data, reducing the amount of time and resources needed to identify areas to prioritize for management, making this approach useful for regions with limited resources. In addition, this modeling framework relies on two freely available software packages (i.e., InVEST SDR and R) and the proprietary software ArcGIS (also available with open access QGIS) (ESRI 2011; Team, 2014, 2015; Hamel et al., 2015). We account for uncertainty in the sediment and water quality models by applying a novel method of tracing back modeled sediment impact from marine habitats to up to three watersheds and averaging the resulting estimates of habitat area affected, while incorporating the respective contributions to total sediment loads, into prioritization scores for each watershed. Additionally, by integrating two global habitat maps in our assessment, we buffer for uncertainty in the data sets and provide a higher level of confidence in our results.

Our study advances current approaches to land–sea planning in the Pacific region and around the globe, through developing a method and products at a spatial-scale relevant to management that can engender collaborative stewardship among agencies, communities, and other stakeholders. By simultaneously evaluating the effect of land-use change, sediment runoff, and coral reef habitat, this research highlights potential spatially explicit trade-offs and synergies arising between land and sea under different land-based management interventions. The implementation of this approach in GIS allows managers to visualize and foresee the potential outcomes of management interventions. The next steps would be to build a suite of land-use management scenarios within the priority areas identified in this study and evaluate ecological, social, and economic trade-offs to identify optimal management solutions. These findings can also help inform priorities for future conservation leases or other payment for ecosystem service schemes by: (1) identifying relevant communities, (2) facilitating communication using maps as visuals, and (3) locating where forest conservation or restoration actions can benefit coral reefs and improve fisheries livelihoods. By adopting a ridge-to-reef conservation planning process, management interventions can be designed for multiple benefits, including soil retention, biodiversity, clean water, healthy habitats, and reef fisheries, supporting nature and people together.

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