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Best-practice forestry management delivers diminishing returns for coral reefs with increased land-clearing

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Abstract

1. Protection of coastal ecosystems from deforestation may be the best way to protect coral reefs from sediment runoff. However, given the importance of generating economic activities for coastal livelihoods, the prohibition of development is often not feasible. In light of this, logging codes-of-practice have been developed to mitigate the impacts of logging on downstream ecosystems. However, no studies have assessed whether managed land-clearing can occur in tandem with coral reef conservation goals.

2. This study quantifies the impacts of current land use and the risk of potential logging activities on downstream coral reef condition and fisheries using a novel suite of linked land-sea models, using Kolombangara Island in the Solomon Islands as a case study. Further, we examine the ability of erosion reduction strategies stipulated in logging codes-of-practice to reduce these impacts as clearing extent increases.

3. We found that with present-day land use, reductions in live and branching coral cover and increases in turf algae were associated with exposure to sediment runoff from catchments and log ponds. Critically, reductions in fish grazer abundance and biomass were associated with increasing sediment runoff, a functional group that accounts for ~25% of subsistence fishing. At low clearing extents, although best management practices minimises the exposure of coral reefs to increased runoff, it would still result in 32% of the reef experiencing an increase in sediment exposure. If clearing extent increased, best management practices would have no impact, with a staggering 89% of coral reef area at risk compared to logging with no management.

4. *Synthesis and applications.* Assessing trade-offs between coastal development and protection of marine resources is a challenge for decision makers globally. Although development activities requiring clearing can be important for livelihoods, our results demonstrate that new logging in intact forest risks downstream resources important for both food and livelihood security. Importantly, our approach allows for spatially-explicit recommendations for where terrestrial management might best complement marine management. Finally, given the critical degradation feedback loops that increased sediment runoff can reinforce on coral reefs, minimising sediment runoff could play an important role in helping coral reefs recover from climate-related disturbances.

Keywords: coastal development, coral reef, land use change, logging, marine conservation, ridge to reef, sediment runoff, sustainable development

1. Introduction

Globally, millions of people directly depend on coral reef fisheries for essential protein and micro-nutrients and as a primary livelihood, with many more indirectly reliant on them (Teh et al., 2013, Sadovy, 2005, Kawarazuka and Béné, 2010). Unsurprisingly, this dependence on reefs, coupled with technology advances and greater accessibility to markets, has led to many coral reef fisheries being overexploited (Cinner et al., 2016). In parallel, coral reef fisheries are also under pressure from a range of anthropogenic activities degrading the habitats that support several key fisheries (Hughes et al., 2017a, Hamilton et al., 2017). While many of the drivers of coral reef degradation act on scales beyond the control of local and regional coral reef guardians (Hughes et al., 2017a), it is possible to mitigate many threats known to be negatively impacting coral reefs through local and regional management (Delevaux et al., 2019).

The most common management strategies put in place to protect coral reefs are no-take marine reserves or other area-based management with some fishing restrictions in place (Cinner et al., 2012, Macneil et al., 2015). However, although fishing is one of the most significant stressors on coral reefs, it is by no means the only anthropogenic activity that drives changes on them. There are well-documented impacts to coral reef ecosystems from increasing sediment runoff, including loss of live coral (Wenger et al., 2016) and changes to communities of important fisheries species (Brown et al., 2017, Hamilton et al., 2017). It has been estimated that poor water quality from land-use change threatens over 25% of coral reefs globally (Burke et al., 2011). Crucially, in places where coral reefs are exposed to poor water quality, the benefits of marine protected areas are also undermined (Wenger et al., 2016, Suchley and Alvarez-Filip, 2018). Thus, in places where reduced water quality is a key factor in coral reef degradation, management strategies need to also focus on mitigating the drivers of sediment runoff on land through a ridge-reef approach.

The protection of coastal ecosystems from deforestation for timber, agriculture, and urban development may be the best way to protect coral reefs from sediment runoff, given the strong relationship between land clearing and sediment runoff (Delevaux et al., 2018, Kroon et al., 2012). However, given the importance of these development activities for coastal livelihoods (Lau et al., 2019), the prohibition of development is often not feasible. In light of this, several countries have developed logging codes of practice to mitigate the impacts of clearing and timber extraction on downstream ecosystems while also enabling development (Wenger et al., 2018). However, while there have been numerous studies on coral reefs that have documented biodiversity and ecosystem service benefits that managed access to fisheries resources can deliver to coral reef ecosystems (Cinner et al., 2012, Macneil et al., 2015), there are no studies that assess whether managed land-clearing for coastal development can occur in tandem with coral reef conservation goals. This knowledge gap is particularly problematic for communities reliant on both terrestrial and marine ecosystems for food and livelihood security because it can undermine decision-making around how much clearing can occur before downstream ecosystems are unduly impacted.

The main challenges in providing spatially-explicit recommendations for where and how much land-clearing can occur for development without degrading coral reef resources are well outlined in a review by Brown et al. (2019). In summary, linking current and future land-use change to coral reef resources requires an ability to: (1) quantify soil erosion and sediment runoff from land-use; (2) understand how key hydrodynamic processes (i.e., wave energy, current speed, and current direction) disperse sediment runoff in the marine environment; (3) quantify how much sediment runoff is driving patterns of coral reef communities; and (4) link impacts of sediment to coral reef resources on which local communities depend. The types of data needed to provide recommendations do not exist for many regions and is costly to acquire (Brown et al., 2019, Rude et al., 2015, Albert et al., 2015). Previous studies examining the relationship between land-use change and coral reefs in data-limited environments have therefore used simplified sediment dispersal models that ignore physical processes involved in sediment transport (Halpern et al., 2008, Klein et al., 2012). Although attempts have been made to improve upon these models, they have missed one or more of the key components outlined above (Tulloch et al., 2016, Delevaux et al., 2018, Rude et al., 2015). Decision-making without appropriate data could translate into unintended consequences for coral reefs and communities dependent on them, including misidentifying areas at greatest risk to sediment runoff. However, with improvements in freely available global datasets (e.g., Copernicus Marine environment monitoring service (http://marine.copernicus.eu); National Oceanic and Atmospheric Administration (NOAA) Wave Watch 3; Simulating WAves Nearshore (SWAN) 41.20 (Booij et al., 1999); WorldClim (http://worldclim.org)) and increased ability to quickly process large quantities of data, more complex modelling can occur in data-limited environments to improve decision-making.

The overarching goal of our study was to examine how land-use change is influencing fish communities that are important for food and livelihoods. Specifically, we developed a new sediment dispersal model that enabled us to: (1) quantify how current land-use is influencing coral reef attributes and key fish communities; (2) determine reef areas that could be vulnerable to future land-clearing; and (3) examine the ability of soil erosion reduction strategies outlined in national logging codes of practice to protect coral reef resources from sediment runoff. We use the island of Kolombangara in Solomon Islands as a case study. Solomon Islands has experienced globally significant rates of land use conversion from forest to logging and agriculture (Hviding and Bayliss-Smith 2000), and information is urgently needed to inform decisions about competing land uses and impacts to coral reefs. Beyond informing future revisions of Solomon Island's logging code of practice and providing guidance on forest clearance, this study has broad applications to tropical high islands around the world. The connection between terrestrial and marine ecosystems on islands is generally more pronounced than on continents due to the smaller sizes of their catchments, which mean that land-based activities occur in close proximity to the coast (Ruddle et al., 1992). Further, given the small size of many islands, island communities may have limited opportunities to seek out alternative natural resources upon which they depend for ecosystem service provisioning if island ecosystems are degraded (Van Der Velde et al., 2007, Connell et al., 2020).

2. Materials and Methods

2.1 Study site

Kolombangara Island (est. pop. 6,301 at time of 2009 census) is located in Western Province, Solomon Islands (7.988946° S, 157.072° E, Fig. 1). It is a steep, montane tropical island (70,105 ha) reaching 1750 m above sea level, with over 75 river catchments.

The coral reefs around Kolombangara Island are a fringing reef system that extends roughly 350 m offshore at which point there is a steep drop off into deep water. The reefs cover an area of 9.03 km^2. More details can be found in the supplementary materials.

The forest area above 400 m (~one-third of the island, 20,300 ha) is under informal protection through a lease held by the Kolombangara Forest Product Limited (KFPL), a Forest Stewardship Council (FSC) Certified Company and a Community Conservation Agreement between the Kolombangara Island Biodiversity Conservation Association (KIBCA) and the Customary land owners. Although logging of forests above 400 m is legally prohibited in Solomon Islands under the Forest and Timber (Amendment) Act 1984, due to corruption and resource limitations for forest monitoring, logging in these areas still occurs (E. Katovai pers. Com.; (Katovai et al., 2015)). Efforts are underway to formally designate the forest above 400 m as a national protected area, under which logging and mining are prohibited under the Solomon Islands Protected Areas Act 2010.

2.2 Overview of methods

Different logging scenarios in the forest above 400 m were developed, in order to communicate the potential impacts that could occur if the forest was not protected. They do not represent scenarios currently being considered by either the lease-holding company or the local communities on Kolombangara Island. In order to assess how increased land-clearing would affect coral reefs, we calculated sediment runoff due to soil loss on hillslopes from present day land-use and two logging scenarios using the Natural Capital Project's Integrated Valuation of Ecosystem Services Sediment Delivery Ratio Model, which has been used extensively to model sediment delivery in a range of study systems (InVEST SDR version 3.2) (Hamel et al., 2015, Delevaux et al., 2018, Hamel et al., 2017). Our scenarios were based on both the Solomon Islands' logging code of practice and other codes of practices in place in tropical environments (Wenger et al., 2018). We used two selective logging scenarios with four different clearing extents (10%, 20%, 30%, and 40%): 1) best practice forestry management based on logging codes of practice (a 100 m riparian buffer and no logging above a slope greater than 25°) and 2) no forestry management, and we modelled four clearing rates (10%, 20%, 30%, and 40%). Full details on how the logging scenarios were generated and the parameterization of the sediment runoff models can be found in Wenger et al. (2018). We calculated bathymetry using a purpose-built tool in Google Earth Engine. We developed a sediment dispersal model that incorporates key physical processes (wave action, current speed, and current direction) to link modelled sediment runoff to our coral reef survey sites. We modelled the impact of present-day sediment runoff on multiple coral reef attributes, including fisheries species important for food and livelihood, using linear modelling and hierarchical partitioning. We evaluated these relationships based on known direct and indirect impacts to benthic communities and coral reef fishes from sediment, described in detail in Fabricius (2005), Tebbett and Bellwood (2019), and (Wenger et al., 2017). We then identified coral reef areas that would become vulnerable to sediment runoff if logging in the forest above 400 m were to occur (Fig. 2). Full details of the methodology can be found in the Supplementary Material.

3. Results

3.1 Relationship between environmental conditions and benthic communities

Proportional increase in model-derived sediment exposure accounted for 11.9, 12.3, and 11.9% of the variation in average microcomplexity, live coral cover, and branching coral cover, respectively (Table 1), with a significant reduction of all three attributes associated with more sediment exposure (Table S2). In addition, distance to logging ponds accounted for 3.9, 28, and 9.4% of the variation in average microcomplexity, live coral cover, and branching coral cover, respectively, with all variables increasing as distance from logging ponds increased. Bathymetry also explained a significant amount of the variation in these three variables (Table S2). In contrast, only 4.5% of the variation of live coral cover was associated with total sediment exposure, as opposed to proportional change in sediment exposure, with more sediment exposure actually related to higher coral cover. Total sediment exposure had no effect on average microcomplexity or branching coral cover.

Proportional increase in sediment exposure explained 40.2% of the of the turf algae cover variation, with significantly higher turf algae cover associated with greater increases in sediment exposure (Tables 1 & S2).

3.2 Relationship between environmental conditions, benthic communities and fish communities

Both grazer abundance and biomass were significantly associated with branching coral cover, proportional increase in sediment exposure, distance from log pond, and bathymetry (Table S2). There was a positive relationship between branching coral cover and grazer abundance and biomass, explaining 8.0 and 4.7% of the variation in abundance and biomass, respectively. In contrast, proportional increase in sediment exposure negatively affected grazer abundance and biomass, directly and indirectly (via its effect on branching coral cover), explaining 7.3% and 8.6% of their variation (Table 1). Distance from log pond had an even stronger, positive association with grazer abundance and biomass, directly and indirectly explained 12.9% and 11.2% of their variation. Browser biomass and the biomass of highly mobile species increased as microcomplexity increased, with microcomplexity explaining 15.4% and 16.9% of the variation observed, respectively.

3.3 Fisheries surveys

According to fisheries surveys conducted, fish from the grazer functional group were the most abundant fish species caught, accounting for 26.6% of all species caught (Table 2). By weight, invertivores as a group made up the largest proportion of the catch (24.8%), while grazers accounted for 20.4% of the total catch (Table 2). Despite, or perhaps because of their importance in terms of number and weight of individuals in fisheries landings, grazers only accounted for 5.8% of the overall biomass on the reef and 11.6% of the total abundance of individuals on the reef (Table 2).

In line with previous surveys indicating a low number of respondents dependent on fishing as a main source of income (Wildlife Conservation Society, 2018), only 9.5% of all fish caught were sold, with the bulk of the catch intended for consumption. Grazers accounted for 42.8% of the individuals and 24.9% of the biomass being sold at market (Table 3). In contrast, even though pelagic-caught piscivores accounted for only 4.3% of all individuals caught and 8.6% of the biomass caught, they made up 22.5% of the individuals and 13.4% of the biomass sold at market. Grazers accounted for 24.9% of the individuals and 19.7% of the biomass of the catch intended for consumption (~91% of the total catch) (Table 2).

3.4 Predicting the impacts of new logging on coral reef communities

According to the sediment delivery ratio model, at low clearing extents (10%) and no land use management in place, average annual sediment runoff from the whole island increases from 118.9 ± 25.9 tons (0.1 ± 0.01 tons ha $^{-1}$ year $^{-1}$) (mean ± SE) to 3009.6 ± 861.5 tons (1.4 ± 0.3 tons ha $^{-1}$ year $^{-1}$), equating to a proportional increase in sediment runoff of 1549.3 ± 325.3% (Fig. 3). In contrast, with best management practices in place and 10% clearing extent, average island sediment runoff was 991.9 ± 214.6 tons (0.7 ± 0.1 tons ha $^{-1}$ year $^{-1}$), equating to a proportional increase of 618.3 ± 116.4%. In comparison, the proportional increase in sediment runoff between pre-logging conditions and present-day was 82.4 ± 31.9% (Fig. 3).

The potential influence on the marine environment from sediment runoff at 10% logging with no management and best-practice management is apparent in the patterns of plume exposure, which show differences in both the intensity (i.e., greater proportional increase in certain areas with no management vs. with management) and extent of sediment plumes (Fig. 4a,b). For instance, the majority of western side of the island experiences a proportional increase in sediment exposure with no management in place. Whereas with best-practice management, several areas do not experience any increase in sediment runoff, as denoted by the blue colouration in Fig. 4a, b. Although there is an increase in sediment runoff from the river on the southern side of the island when no management is in place, because of the currents and wave exposure, the plume travels west, resulting in protection of the reef area near the southeast corner of the island (Fig. 4a, b). With no management in place, 10% clearing extent exposes 67.8% of reef area to a proportional increase in sediment runoff. However, with best-management practices in place, 10% clearing extent only exposes 32% of reef area to a proportional increase in sediment runoff (Fig. 5), equating to six km^2 of reef that remains protected from sediment runoff.

The ability of best practice management to protect coral reefs diminishes substantially by 20% clearing extent, with 64.7% of reef area exposed to increasing sediment runoff, compared to 75.1% with no management in place (Fig. 5). Once clearing extent reaches 40%, best management practices have limited influence over the area of reef that is exposed to sediment runoff, with 88.9% of the reef area experiencing a proportional increase in sediment exposure, compared to 90.4% with no management in place (Fig. 5); leaving only one km^2 of coral reef protected from sediment runoff, primarily in the southeast and northwest of the island. However, although best management practices do not reduce the extent of the sediment plume, the intensity of the plume is reduced compared to when no management in place (Fig. 4 c,d).

Discussion

Development activities in tropical regions are critical for coastal livelihoods (Lau et al., 2019), but can compromise marine ecosystems when conducted unsustainably (Suchley and Alvarez-Filip, 2018). This study found that sediment runoff from current logging activities threatens the functional integrity and ecosystem services provided by coral reefs. Many communities residing on Kolombangara Island are reliant on both terrestrial and marine resources, and are now faced with decisions around trade-offs between development and protection of coral reef resources. Through the development of a novel sediment dispersal tool, this study has generated spatially-explicit information about which coral reef areas are at risk to increased runoff should further land-clearing occur in the forest above 400 m. Any increase in logging activities, even with best management practices in place, will expose even more reef area to increased sediment runoff, likely driving further changes to the coral reefs in Kolombangara.

Several key benthic attributes were negatively affected by both proportional increases in sediment and proximity to log ponds. Interestingly, it was the proportional change of sediment exposure rather than total sediment exposure that was most associated with current reef state. Nearshore coral reefs have evolved in variable water quality conditions and have adapted to turbid environments (Anthony and Fabricius, 2000, Albert et al., 2015). However, as our results indicate, changes to local water quality conditions, even if a reef is naturally more turbid, can lead to shifts in coral communities (Fabricius et al., 2005). Live coral and highly structured reefs are fundamental for supporting coral reef fish communities and for coastal protection- key ecosystem services provided by coral reefs that need to be maintained (Wilson et al., 2008, Harris et al., 2018). Microcomplexity has also been shown to be an important predictor in how well a coral reef can recover from disturbance events, particularly coral bleaching (Graham et al., 2015). If there are factors present on coral reefs that make them more likely to recover from disturbance events, targeted local management to protect these traits could be key.

Importantly, we found that grazers, an important functional group for both subsistence and livelihoods were both directly and indirectly impacted by sediment exposure, from proportional increase in sediment runoff and proximity to log ponds. Grazers accounted for almost a quarter of the fish catch used as food and over 40% of the fish sold at market, indicating the crucial role of grazer fisheries in food security. Even though our results did not find a strong relationship between abiotic and biotic variables and most of the other fish functional groups or home-range groups, the relationship between coral communities and reef fish is well established, particularly for small-bodied individuals and early life history stages (Wilson et al., 2008, Jones et al., 2004, Hamilton et al., 2017). While there is evidence from the Philippines to suggest that some fish species, especially goatfish from the invertivore functional group, will benefit as reefs degrade (Russ et al., 2015), we did not find a relationship between invertivores and any of the abiotic or biotic variables. However, since invertivores made up a large proportion of the catch, it may be that some of the negative impacts of sediment runoff on grazers could be offset by an increase in invertivores on the reef. Nationally, 90% of the total animal protein consumed in the Solomon Islands is from fresh fish (Bell et al., 2009); therefore, a reduction in the abundance or biomass of a key functional group like grazers from increasing logging activities has the potential to threaten food and livelihood security.

Beyond being important for food and livelihood security, grazers also play a key functional role on coral reefs via the removal of turf algae and overfishing of them can lead to algal overgrowth (Ceccarelli et al., 2011, Marshell and Mumby, 2015). Turf algae can rapidly colonize dead coral and its presence can suppress coral recruitment, further degrading the system (Birrell et al., 2005, Arnold et al., 2010). Increasingly, the accumulation of sediment in turf algae is seen to be a major factor in reinforcing turf-dominated states (Goatley et al., 2016). We found that proportional increases in sediment runoff were associated with 40% of the variation of turf algae cover at our study sites. However, we did not find a relationship between turf algae cover and grazers, which indicates a de-coupling between turf algae and grazing pressure. Sediment-laden turf algae suppress grazing, regardless of the population of herbivores present, which can lead to the overgrowth of long, unpalatable algal turfs (Goatley et al., 2016, Bellwood and Fulton, 2008). Moreover, this sediment-laden turf can reduce coral recruitment and enhance the competitive abilities of turf algae compared to corals via multiple pathways, further destabilizing the system (Tebbett and Bellwood, 2019). Climate and other disturbance events are likely to drive coral reefs to an alternative, degraded stable state via positive feedback loops (Mumby and Steneck, 2008). Since sediment runoff has the ability to both degrade coral reefs and prevent reef recovery following climate or other acute disturbances then local and regional management of sediment runoff must be an integral part of coral reef management.

Given how current sediment runoff is shaping reefs, we identified those coral reef areas that would become vulnerable to more sediment runoff if logging activities were to occur in the intact forest above 400 m. At low levels of logging, best management practices minimized the exposure of coral reefs to increased runoff, as compared to logging with no management in place, although management still resulted in a third of the reef experiencing a proportional increase in sediment exposure. However, as logging increased, best management practices did not work, putting essentially the same amount of coral reef area at risk compared to logging with no management. Importantly, there were large areas of reef that had been previously protected from sediment that were newly exposed once runoff rates really increased (Fig. 4). Given that the increase in sediment runoff from present day conditions to 10% clearing with best management in place is eight times greater than the increase in sediment runoff from an intact system to present day, it is highly likely that sediment runoff would drive much more variation in coral reef communities than it does currently. Additionally, although we did not model how more logging activities could lead to more logging ponds, new logging ponds associated with increased logging activities would also likely negatively impact nearby reefs, according to our models. Our modelled estimates of sediment runoff fall within the range of sediment runoff rates measured in a variety of tropical catchments (Kroon et al., 2012, Falinski, 2016; N. Hutley unpublished data), indicating that our clearing scenarios represent realistic possibilities. Although the high sediment runoff rates would not be sustained long-term; both due to soil being a finite resource and the re-growth of vegetation in cleared areas that would stabilize soils, a large pulse of sediment runoff from land-clearing can cause significant degradation to nearshore coral reefs (Wenger et al., 2016).

Decision-making around trade-offs between development on land and protection of key marine resources is vital for decision makers across the world and especially in Small Island Developing States, where limited economic opportunities can often lead to an over extraction of terrestrial and marine resources (Van Der Velde et al., 2007, Connell et al., 2020). Furthermore, we calculated that 41 million hectares of both primary and secondary tropical forest exist within reef catchments (Burke et al., 2011, Hansen et al., 2013). Given the 1) high rate of deforestation in tropical forests (Hansen et al., 2013); 2) the fact that poor water quality from land-use change threatens over 25% of coral reefs globally (Burke et al., 2011); and 3) the dependence on many communities living in these environments on both development activities and coral reef resources (Teh et al., 2013, Lau et al., 2019), assessments of the kind done in this study are critical to ensure adequate protection of coral reefs. With the advancement in processing power and globally available data, it is now possible to incorporate known physical processes into models that can be used in data poor systems, as we have done here. The tools we developed here used freely available data available at a global scale, and so could be deployed in other systems facing similar challenges. Further research is necessary to test how well they work in different environments to ensure they are providing reliable information.

There are several key considerations for management on Kolombangara Island based on our results. The most significant is that low levels of clearing in compliance with logging codes of practice still allows a very large area of coral reef to be exposed to sediment runoff, while at high levels of clearing the mitigating measures have no effect. A previous study in the same location using the same catchment models also found that logging led to unsustainable soil erosion rates and contamination of drinking water that exceeded international standards for water quality for safe drinking, despite best management practices (Wenger et al., 2018). We therefore recommend that total allowable clearing extent in intact catchments, even with best practice management, should not exceed 10%. Although development activities that require vegetation clearing can be important for livelihoods, it is clear that new logging of the forest above 400 m risks downstream resources utilized by several of the communities on Kolombangara. Our results also indicate that patterns of benthic communities and some fish functional groups have already been influenced by present-day sediment runoff rates and logging ponds. Kolombangara has a lot of forestry plantations that will eventually be harvested, albeit not at the same time. For these areas, adherence to best management practices and a harvesting schedule that restricts the area that can be cleared at any given time could help to minimize further impacts to the reef. Additionally, placement of any new logging ponds should take into consideration nearby reefs or important fishing grounds. Finally, given the importance of grazers as a food source, some fishing restrictions or protected areas could be put in place to mitigate the impacts to these species. Grazers are generally low to moderately vulnerable to fishing and will likely respond well to well-designed and implemented periodically harvested closures, a commonly practiced fisheries management strategy in the Solomon Islands (Abesamis et al., 2014, Carvalho et al., 2019). Furthermore, their functional role can be maintained even at intermediate biomass levels (Macneil et al., 2015, Brown and Mumby, 2014), suggesting that they will not require several years of strict protection to recover, which is unlikely to be a feasible management strategy given their importance in the local fishery. The power of our sediment dispersal model is that we can identify where sediment from each catchment is dispersed, meaning that we can provide spatially-explicit recommendations for where marine management might best complement terrestrial management.

In an era of global change caused by humanity's influence on the planet, long-standing paradigms about how to best protect coral reefs from climate change impacts are being challenged. Increasingly, the idea that local management actions will make coral reefs more resistant to climatic events is being shown to be not true in most circumstances (Bates et al., 2019, Hughes et al., 2017b). However, our research clearly demonstrates that management of local stressors is key for food and livelihood security and the protection of coastal communities. Furthermore, given critical feedback loops on coral reefs that increased sediment runoff can reinforce, management of water quality will play an important role in helping coral reefs recover from climate-related disturbances.

Authors' contributions

AW, DH, SW, SJ, FV, CK, JW, and PM conceived of the study; AW, DH, SW, SJ designed the study; FV provided important background and insights into the history and management of the Island; YN, WN, AH, SJ collected and processed the data; AW, DH, SW, JD conducted data analyses; AW, DH, SW, and SJ wrote the manuscript; all authors gave final approval for publication

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Data availability statement

Data available via the Dryad Digital Repository https://doi.org/10.5061/dryad.vdncjsxrr (Wenger et al., 2020).

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Table 1: The overall variation of each response variable explained by each predictor variable.

Response variable	**Predictor variables**	**Hierarchical partitioning results**	**Adjusted R-squared**	**Percent variance of response variable explained by each predictor variable**
microcomplexity	Proportional difference in sediment exposure	35.7	0.33	11.9
	Bathymetry	52.7		17.6
	Distance from log pond	11.6		3.9
Live coral cover	Total sediment exposure	9	0.50	4.5
	Proportional difference in sediment exposure	24.8		12.3

	Bathymetry	9.8		4.9
	Distance from log pond	56.4		28.0
branching coral	Proportional difference in sediment exposure	24.9	0.48	11.9
	Bathymetry	18.9		9.1
	Distance from log pond	19.6		9.4
generalist corals	Distance from log pond	100	0.30	29.5
Weedy corals	Proportional difference in sediment exposure	13.3	0.19	2.5
	Bathymetry	63.2		11.9
	Distance from log pond	23.5		4.4
Competitive corals	Proportional difference in sediment exposure	26.7	0.43	11.3
	Distance from shore	50.2		21.3
	Distance from log pond	23.1		9.8
Turf algae	Total sediment exposure	6.5	0.44	2.8
	Proportional difference in sediment exposure	93.5		40.2
Browser biomass	Microcomplexity	77.8	0.20	15.4
	Bathymetry	22.2		4.4
	Proportional difference in sediment exposure*			1.8
	Bathymetry*			2.7
	Distance from log pond*			0.6
Grazer abundance	Branching coral cover	21.5	0.37	8.0
	Proportional difference in sediment exposure	16.9		6.3
	Bathymetry	32.7		12.2
	Distance from log pond	28.9		10.7

	Proportional difference in sediment exposure*			1.0
	Bathymetry*			0.4
	Distance from log pond*			2.2
Grazer biomass	Branching coral cover	16.9	0.28	4.7
	Bathymetry	18.4		5.1
	Proportional difference in sediment exposure	28.9		8.0
	Distance from log pond	35.7		9.9
	Proportional difference in sediment exposure*			0.6
	Bathymetry*			0.2
	Distance from log pond*			1.3

*variables indirectly affecting response variables via their significant association with benthic predictor variables in each model.

Table 2: The results of the fisheries surveys

Functional group	Average biomass (kg/ha)	Average abundance (number of individuals)	Fish caught (number of individuals)	Biomass caught (kg)	Proportion of total catch (percent of total fish caught)	Proportion of total catch by weight (percent kg)
Browser	63.2 ±13.1	3.9 ± 0.7	40	12.9	1.7	3.2
Detritivore	29.6 ± 6.4	7.1 ± 2	173	31.2	7.3	7.8
Excavator/scraper	450.3 ± 75.9	28.5 ± 2.4	80	31.8	3.4	7.9
Grazer	99.4 ± 14.2	24.5 ± 2	630	82.1	26.6	20.4
Invertivore	240.6 ± 47.3	38.1 ± 1.7	600	99.7	25.3	24.8
Mixed	32.2 ± 13.9	4.7 ± 1.3	31	4.5	1.3	1.1
Pisci Invertivore	222.8 ± 39.9	25.4 ± 4	167	28.8	7.0	7.2
Piscivore (reef)	379.3 ± 85.1	3.2 ± 0.4	267	46.8	11.3	11.7
Piscivore (pelagic)	ND	ND	102	34.5	4.3	8.6

Planktivore (reef)	208.6 ± 33.8	76.9 ± 11	281	29.2	11.9	7.3
Planktivore (pelagic)	ND	ND	3	2.0	0.1	0.5
Total	**2607.9 ± 396.4**	**215.4 ± 13.5**	**2371**	**403.5**		

Functional group	**Proportion of individuals used for food (percent)**	**Proportion of individuals sold at market (percent)**	**Proportion of biomass used for food (percent kg)**	**Proportion of biomass sold at market (percent kg)**
Browser	1.6	2.7	3.3	2.4
Detritivore	8.1	0.0	8.8	0.0
Excavator/scraper	2.9	8.1	7.0	14.4
Grazer	24.9	42.8	19.7	24.9
Invertivore	27.2	6.8	26.2	13.8
Mixed	1.4	0.0	1.3	0.0
Pisci Invertivore	7.4	4.1	5.9	16.7
Piscivore (reef)	12.2	1.8	12.5	4.7
Piscivore (pelagic)	2.4	22.5	7.9	13.4
Planktivore (reef)	11.9	11.3	7.5	5.5
Planktivore (pelagic)	0.0	1.4	0.0	4.3

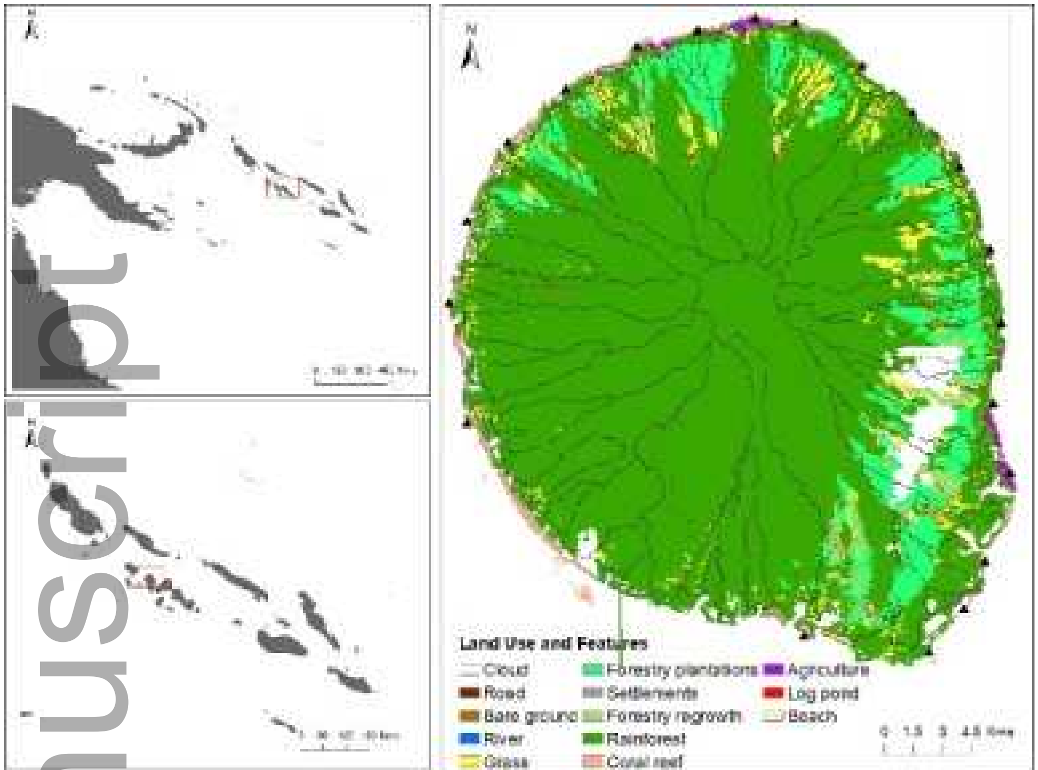
Figure 1: Location and current land use on Kolombangara Island, Solomon Islands. The black lines on the Island denote the catchment boundaries and the black triangles show the survey locations.

Figure 2: Data flow diagram of the methods.

Figure 3: The Island average (± Standard Error) proportional increase in sediment runoff under present day conditions (0% clearing extent) and each clearing extent examined.

Figure 4: The proportional increase in sediment exposure with a) no management and 10% clearing extent, b) best-practice management and 10% clearing extent, c) no management and 40% clearing extent, and d) best-practice management and 40% clearing extent. The region within the black outline at the centre of the island is the forest above 400 m that has never been logged, with a-d displaying the different logging scenarios (brown colouration on land represents the area cleared). Each map displays, in gradients of brown, where and by how much proportional sediment increases in the marine environment. The blue colouration denotes areas where proportional sediment does not increase.

Figure 5: The percent of reef area exposed to a proportional increase in sediment runoff under the two logging scenarios and four clearing extents.



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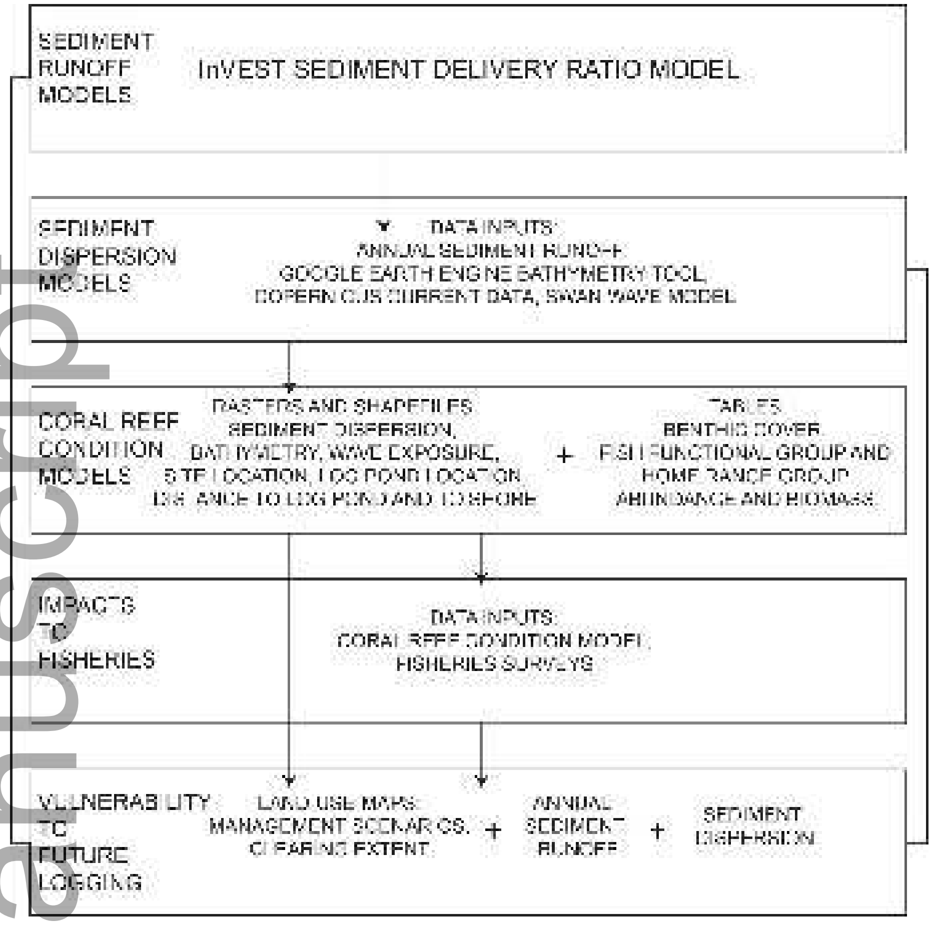

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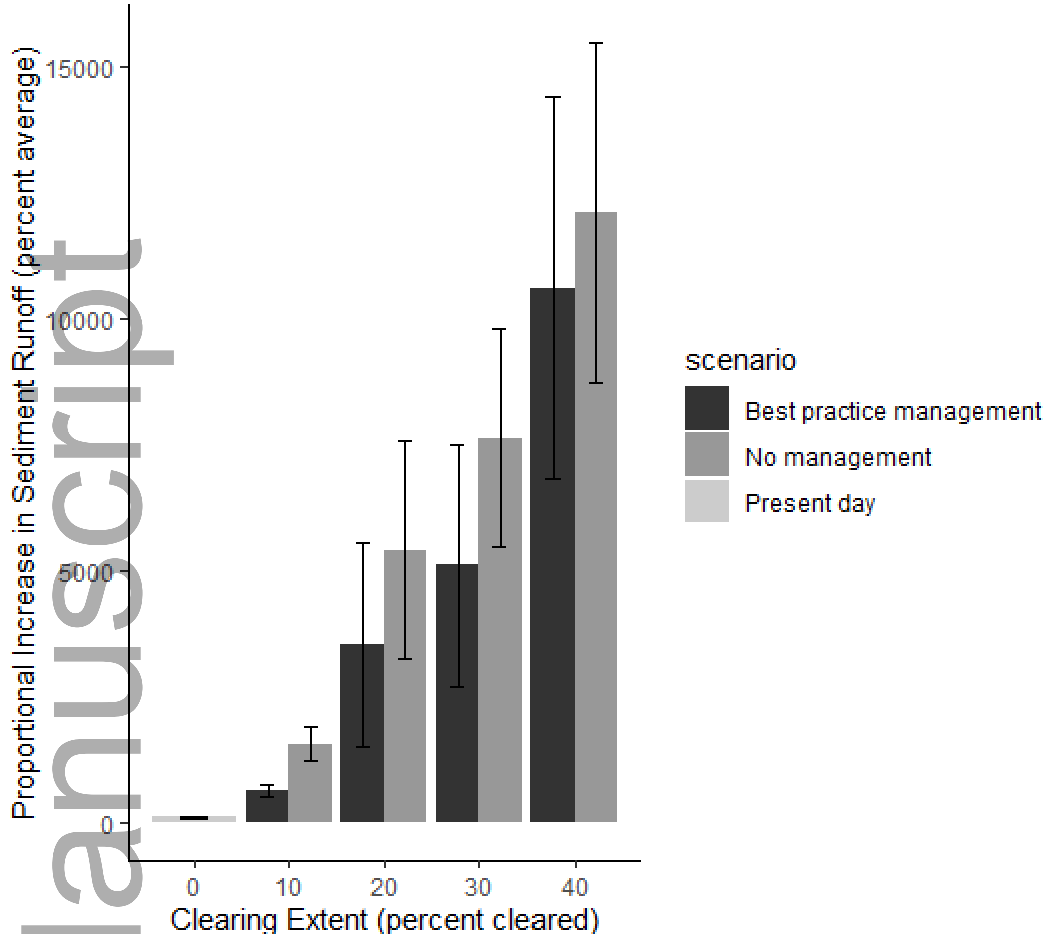

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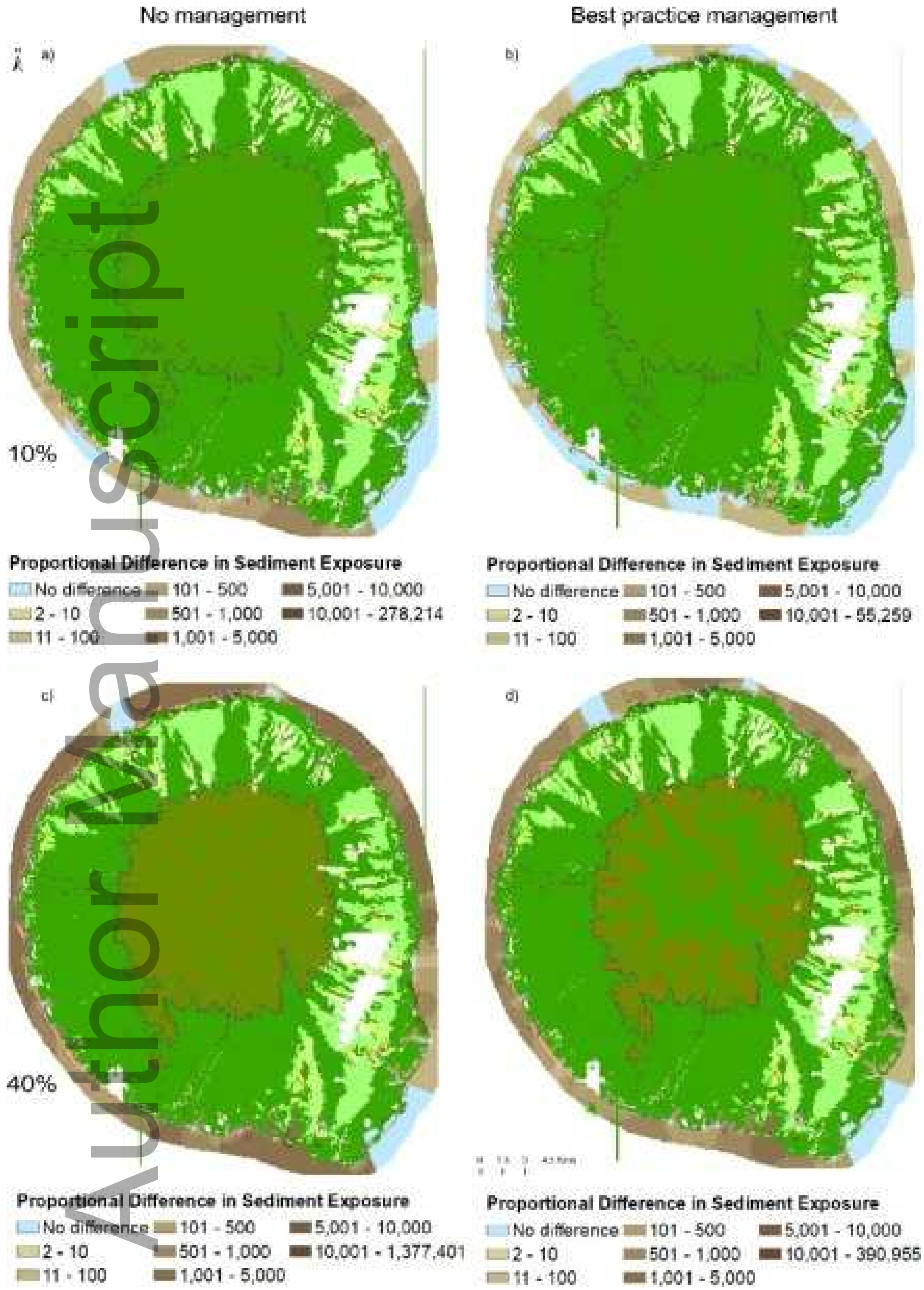

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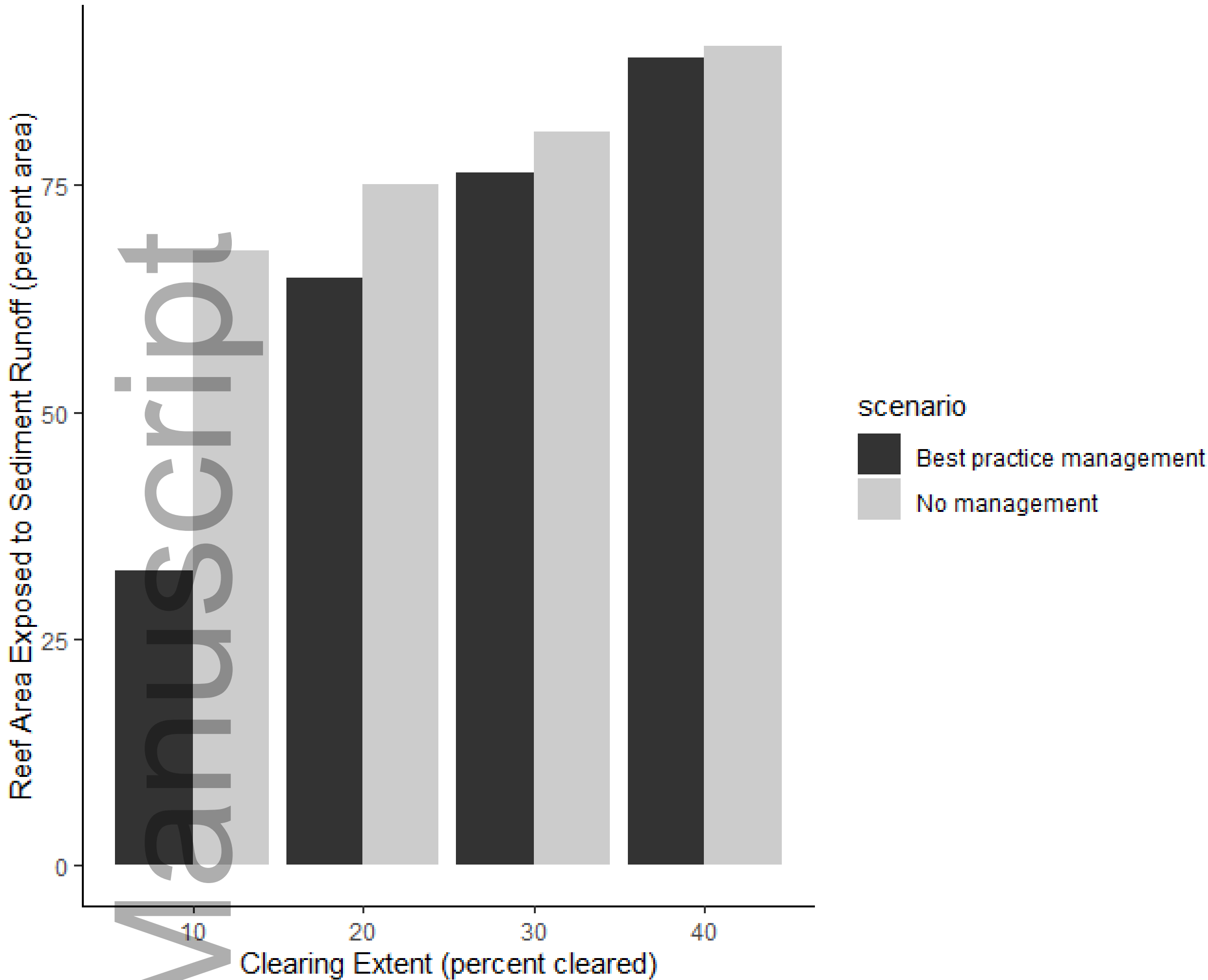

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