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Impacts of coastal land use change in the wet tropics on nearshore coral reefs: Case studies from Papua New Guinea

Emre Turak[a,*], Lyndon DeVantier[a], Robert Szava-Kovats[b], Jon Brodie[c]

[a] Coral Reef Research, PO Box 129, Millaa Millaa, QLD, Australia
[b] Estonian Marine Institute, University of Tartu, Tartu, Estonia
[c] Formerly ARC Centre of Excellence for Coral Reef Studies, College of Science and Engineering, James Cook University, Townsville, QLD, Australia

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ABSTRACT

Logging and plantation agriculture are vital to economies and livelihoods in tropical nations, including Papua New Guinea. To meet global demand, hundreds of thousands of ha of diverse natural habitat have been logged, cleared and replaced with monoculture crops. Resulting hydrological changes have increased sediment, nutrient and pesticide runoff, impacting down-stream habitats. Here, case studies from Kimbe Bay (New Britain) and Mullins Harbour (Milne Bay), examine effects on nearshore coral reefs. In both places, logging and oil palm development had destabilized soils and removed or degraded riparian vegetation. Downstream, nearshore reefs had high silt levels, which, coincident with minor coral bleaching and predation by crown-of-thorns starfish, were correlated with high levels of coral mortality and low coral species richness. Sediment and related impacts can be reduced by effective catchment management, such as avoiding steep slopes, expanding stream and coastal buffer zones, minimizing fertilizer and pesticide use, monitoring and reactive management.

1. Introduction

Papua New Guinea (PNG), one of Earth's 'mega-diverse' nations, is estimated to host some 5% of world biodiversity in less than 1% of its area, including some of the most species-rich rainforests and coral reefs in the world (Sekhran and Miller, 1995; Veron et al., 2015). PNG is comprised of 22 provinces for governance and administration, most of which have coastal areas and support the majority of the population. With a coastline exceeding 10,000 km, PNG supports an estimated 4,800 km^2 of mangrove forest (Bhattarai and Giri, 2011) and 13,840 km^2 of coral reefs (Spalding et al., 2001), although many reefs remain unmapped and actual reef area may be significantly greater. Situated in the 'Coral Triangle', the centre of tropical marine diversity (Hoeksema, 2007; Veron et al., 2009, 2015), these reefs are globally important in terms of their biodiversity.

Extraction and production of natural resources, from minerals to timber to plantation agriculture, have been major strategies in the economic development of most tropical developing nations, delivering significant economic benefits, but often with major ecological and social impacts. Changes in delivery of land-sourced pollutants can have profound negative impacts on coastal and adjacent marine habitats (Edinger et al., 1998; Brodie et al., 2010, 2012; Fabricius, 2005; Fabricius et al., 2013, 2014; Nelson et al., 2018; Sheaves et al., 2018; Wenger et al., 2020 among many others). Drivers of such changes include modifications to land use, such as occurs during urbanization, forestry and/or agriculture. Of the last, development of mono-cultural plantations of oil palm *Elaeis guineensis*, if not carefully managed, can be a major source of land-based pollutants. Rapid expansion of this industry since the 1960s is considered one of the greatest local impacts to tropical biodiversity (Douglas, 1999; Fitzherbert et al., 2008; Koh and Wilcove, 2008; Turner et al., 2011), causing continuing losses of primary rainforest and other natural habitats (Foster et al., 2011; Gibbs et al., 2010; Nelson et al., 2010), and increasingly threatening dependent species (Edwards et al., 2010). From 1990 to 2005, 55%–59% of oil palm expansion in Malaysia, and at least 56% in Indonesia, occurred at the expense of forests (Koh and Wilcove, 2008). Globally, from 1980 to 2000, more than 55% of new agricultural land resulted from clearing of intact forests, and another 28% was from disturbed forests (Gibbs et al., 2010).

Additionally, expansion of oil palm plantations and other cash crops has changed other biophysical variables, warming the land surface and enhancing the increase in air temperature from climate change (Sabajo et al., 2017). Hence, the significant economic benefits are often accompanied by ecological damage, an ethical dilemma (Obidzinski

* Corresponding author.
E-mail address: emreturak@wanadoo.fr (E. Turak).

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et al., 2012; Meijaard and Sheil, 2019) compounded, in some cases, by harm to workers via inequitable employment arrangements and abuse (Jong, 2020; Transnational Palm Oil Labour Solidarity Network, 2020). In PNG, large-scale logging has been occurring for decades, and has often preceded development of oil palm plantations. In 2015, PNG had approximately 130,000 ha under palm oil production, mainly in West New Britain, Oro, Milne Bay, New Ireland and Madang/Morobe provinces. Some 60% of the plantation area was controlled by companies, with the remainder in smallholder blocks, grown by between 160,000 and 200,000 people, a large proportion of whom rely on oil palm as primary income (Koczberski et al., 2012). Hence, oil palms provide local employment and foreign currency to PNG and continue to be a priority for local development.

Logging and conversion of natural and semi-natural habitats to oil palms has resulted in loss of species richness and decreases in abundance of a wide range of taxa, including species of high conservation value (Persey et al., 2011), with severe impacts on biodiversity (Fitzherbert et al., 2008). Impacts of oil palm production in PNG, as elsewhere, include habitat simplification – the replacement of complex natural habitats with an almost mono-specific landscape – causing significant loss of biodiversity (Novotny et al., 2006; Turner et al., 2011), and with flow-on effects on adjacent freshwater aquatic ecosystems (Nelson et al., 2010, 2018; Sheaves et al., 2018).

During and following heavy rainfall, flood plumes from rivers can export suspended terrigenous material well offshore, with rates of deposition location-dependent, in respect of volumes, current patterns and wave energy (Devlin et al., 2001; Brown et al., 2017a). Chronic or episodic resuspension of sediment can be as large an issue as delivery of new river-exported sediment, particularly on reefs where local oceanographic conditions enhance resuspension. Small streams do not have the capacity to carry material far offshore. Material transported further offshore may be dissolved (e.g. nitrate or colloidal), while biological activity in river plumes can also convert land-supplied nutrients to phytoplankton and bacteria (Devlin et al., 2001). The impacts on corals, including differential effects on settlement, growth, reproduction and survival, along with various coral acclimation strategies, including interspecific capacities for sediment shedding, are also well documented (see e.g. Stafford-Smith, 1993; Gilmour, 1999; Anthony, 1999, 2000; Anthony and Fabricius, 2000; Anthony and Connolly, 2004; Browne et al., 2014; Bessell-Browne et al., 2017a). Synergistic effects of sedimentation with other parameters and stressors, including light and nutrients, have also been demonstrated (Browne et al., 2014, 2015; Bessell-Browne et al., 2017b; Brown et al., 2017a, 2017b; Humanes et al., 2017). However, impacts from oil palm development on adjacent coral reefs have been less studied. Here we examine the condition of reefs in respect of major coastal land-use changes in two PNG provinces, the western (W) side of Kimbe Bay (Stettin Bay), New Britain Province and Mullins Harbour, Milne Bay Province (Fig. 1) in the years 2003 and 2007 respectively.

2. Materials and methods

2.1. Site descriptions

2.1.1. Environmental setting

The two areas have climatological similarities and geomorphological

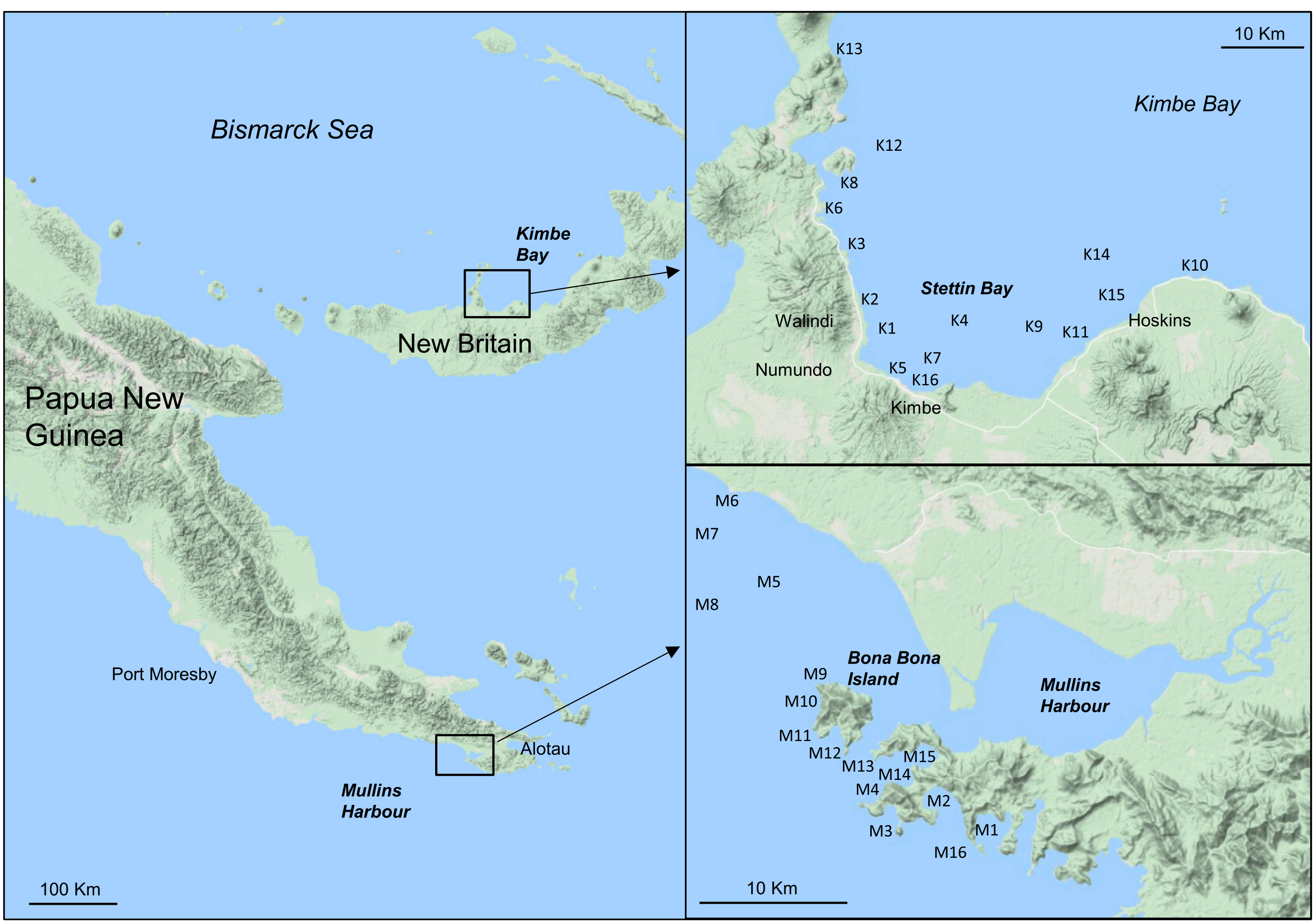

Fig. 1. Map of PNG with insets for Kimbe Bay and Mullins Harbour. Precise GPS locations are listed in Table S1.

differences. The broader region experiences two distinct seasons associated with the Southeast Asian/Australian monsoon system. The southeast monsoon typically extends from May to October and the northwest monsoon from November to March. Onset and break of the monsoons is affected by the Equatorial Madden Julian Oscillation or Intra-seasonal Oscillation (ISO) (Madden and Julian, 1971; Godfrey et al., 1998; Steinberg et al., 2006). Both places receive significant annual rainfall and were heavily forested, including extensive coastal mangrove forests, some of which has been cleared for various forms of land use. Significant logging over the past five decades preceded and coincided with development of oil palm plantations at both locations, with estimates of modification to catchment areas of more than 75% (Bun et al., 2004; Brodie and Turak, 2004). Seagrass beds and algal meadows are located in shallow water (typically less than 10 m depth) adjacent to the coasts. A variety of reef types are also developed, from immediately adjacent to the coast to well offshore.

2.1.2. *Kimbe Bay*

Situated on the north coast of New Britain Island in the volcanically-active West New Britain Province, Kimbe Bay is a broad, open expanse approximately 140 km across and more than 2000 m deep in places, facing into the Bismarck Sea. It is comprised of several smaller bays, notably Stettin Bay in the west and Commodore Bay in the east (Fig. 1). On the eastern side, the shelf drops steeply into deep water close to shore. The western side is shallower, but still reaches depths > 600 m. Water circulation is driven by episodically reversing eddies in the eastern Bismarck Sea. Eastward flow past Willaumez Peninsula can result in eddying in the lee and upwelling in West Kimbe Bay (Steinberg et al., 2006).

Geology and soils in the catchment are dominated by the presence of several active or recently active volcanoes. The landscape is in places unstable, with visible landslips on the steeper slopes and mobile river channels. Rainfall typically ranges between 3000 and 4000 mm annually, and is distinctly seasonal. The catchment was until recent times primarily forested with lowland and montane rainforest, coastal freshwater swamps of several types and coastal mangroves. Much of the catchment has been logged, particularly in the period 1965 to 1990 (Brodie and Turak, 2004), although logging has continued into the new millennium. Also since the 1960s the coastal plain, in places abutting the littoral zone, and lower slopes of the range which forms the boundary of the catchment, have been gradually planted in oil palm (Fig. 2a–g). The total area of oil palm exceeds 60,000 ha (Brodie and Turak, 2004). The Kimbe Bay Catchment Area of approximately 3000 km^2 is drained by two small rivers (Kapiura, Dagi) and a large number of smaller streams, all emptying into the Bay. Plumes from these various sources (see e.g. Fig. 2h) are likely to disperse evenly in the Bay in low wind conditions, or to the west and north-west with South-east winds.

The focus of this research, Stettin Bay in western Kimbe Bay (herein as Kimbe Bay W), has a narrow shelf adjacent to the land with depths of less than 200 m, seaward of which depths increase rapidly to approximately 400–600 m. Reefs are extensive and include those fringing the adjacent coast, generally within 500 m of the shore and in water depths of less than 50 m, or as narrow bands around offshore islands; 'barrier reefs' generally just inshore of the 200 m isobath and within about 10 km of the coast; and patch reefs towards the centre of the Bay, developed on antecedent topography rising out of deep (generally >400 m) water.

Prior reef research, most in unpublished reports, has documented loss of coral cover and more general degradation over past decades (Maragos, 1994; Jones et al., 1999, 2000; Munday, 2000, 2003; Turak and Aitsi, 2002). This has been variously attributed to a combination of the following: sedimentation caused by runoff and drought-initiated erosion, predation by crown-of-thorns starfish, coral diseases and coral bleaching (Jones et al., 2001; Munday, 2003).

2.1.3. *Mullins Harbour*

Situated on the south-eastern end of mainland PNG (Fig. 1) in Milne Bay Province, Mullins Harbour is roughly oblong in shape, approximately 24 km long and 11 km wide, and comprises some 97 km^2 of open water. With an annual rainfall of more than 3000 mm, the Harbour comprises the largest estuarine and coastal wetland system in the eastern part of the PNG mainland (Fig. 1). Approximately 81 km^2 of mangrove forests fringed much of Mullins Harbour, surrounded by coastal wetlands (Osborne, 1987). A large mangrove forest complex at the extreme inner end of the system is developed on the delta of the Sagarai River, the major river draining the south-eastern mainland. Of the other rivers and streams entering Mullins Harbour, the largest is the Wegulani River, flowing from the north into the central estuary. Streams drain directly into the ocean to the west of Mullins Harbour and others to the east into Milne Bay.

Mostly land-locked, Mullins Harbour has a narrow entrance approximately 1.5 km across, opening towards the south-west onto the Coral Sea. This limits water exchange with the coastal zone, other than during episodic flooding when plumes can extend well offshore. A long smooth coast extends to the west of the harbour entrance. Eastward, the coast is more strongly dissected, and includes the nearshore Bona Bona Island. Offshore surface currents tend to flow longshore, towards the east during the NE monsoon, and to the west in the SE monsoon. Closer to shore, there is a dearth of oceanographic information, although the dissected coastline to the east of the harbour is expected to produce more turbulent, eddying flow. The area hosts a range of coral reefs, from coastal fringing reefs, nearshore patch reefs to the barrier reef further offshore. Condition of the reefs prior to this study was unknown, as no earlier studies had been undertaken.

2.2. *Field methods*

Rapid Ecological Assessment (REA) surveys were conducted using SCUBA at selected reef locations in Kimbe Bay W and Mullins Harbour (Fig. 1). At Kimbe Bay W, reefs were surveyed at 16 locations in late November – early December 2003. This included seven coastal fringing reefs, three mid-shelf reefs, five shelf-edge (outer-shelf) reefs and one offshore patch ('semi-atoll') reef. At Mullins Harbour, reefs at varying distance from the harbour entrance were surveyed at 16 locations in October 2007 (Fig. 1). These included coastal and island fringing reefs and offshore patches. Survey locations, each of approx. 1 ha in area, were selected to provide a range of different reef types, developed in different environmental conditions (e.g. exposure to waves, slope angle, depth), and particularly increasing distance away from streams and rivers in Kimbe Bay and the entrance to Mullins Harbour. Locations were selected initially from satellite imagery (NASA Worldwind, Google Earth).

As comprehensive a list of corals and other sessile benthos as practicable was recorded during each roving diver survey swim. The swims, on SCUBA, typically progressed from the base of the reef slope to the reef flat. At most locations, two vertically-adjacent, non-overlapping depth ranges were sampled, on the deeper (typically >8–10 m depth) and shallower reef slopes respectively. At three locations at Kimbe Bay W, the entire reef slope was assessed (Table S1). Reef-building corals were identified to species level wherever possible (Veron et al., 2015, 2016), otherwise to genus and growth form. Other benthos was recorded at higher taxonomic levels. At the end of each survey swim, each taxon was categorized in terms of its relative abundance in the community. The categories approximate a log 4 scale, and are analogous to those long employed in vegetation analysis (van der Maarel, 1979; Jongman et al., 1995, and see DeVantier et al., 1998, 2020 for details).

Each survey location was characterized in respect of the benthic cover of 13 ecological and environmental variables, estimated visually to the nearest 5%, other than for very low cover (estimated to nearest 1%). Cover estimates of environmental and ecological variables were independent, based on assessment integrated over the survey swims. The ecological variables were living hard coral (HC), dead standing hard coral (DC, with skeletons intact, not rubble), soft coral (SC), macro-algae

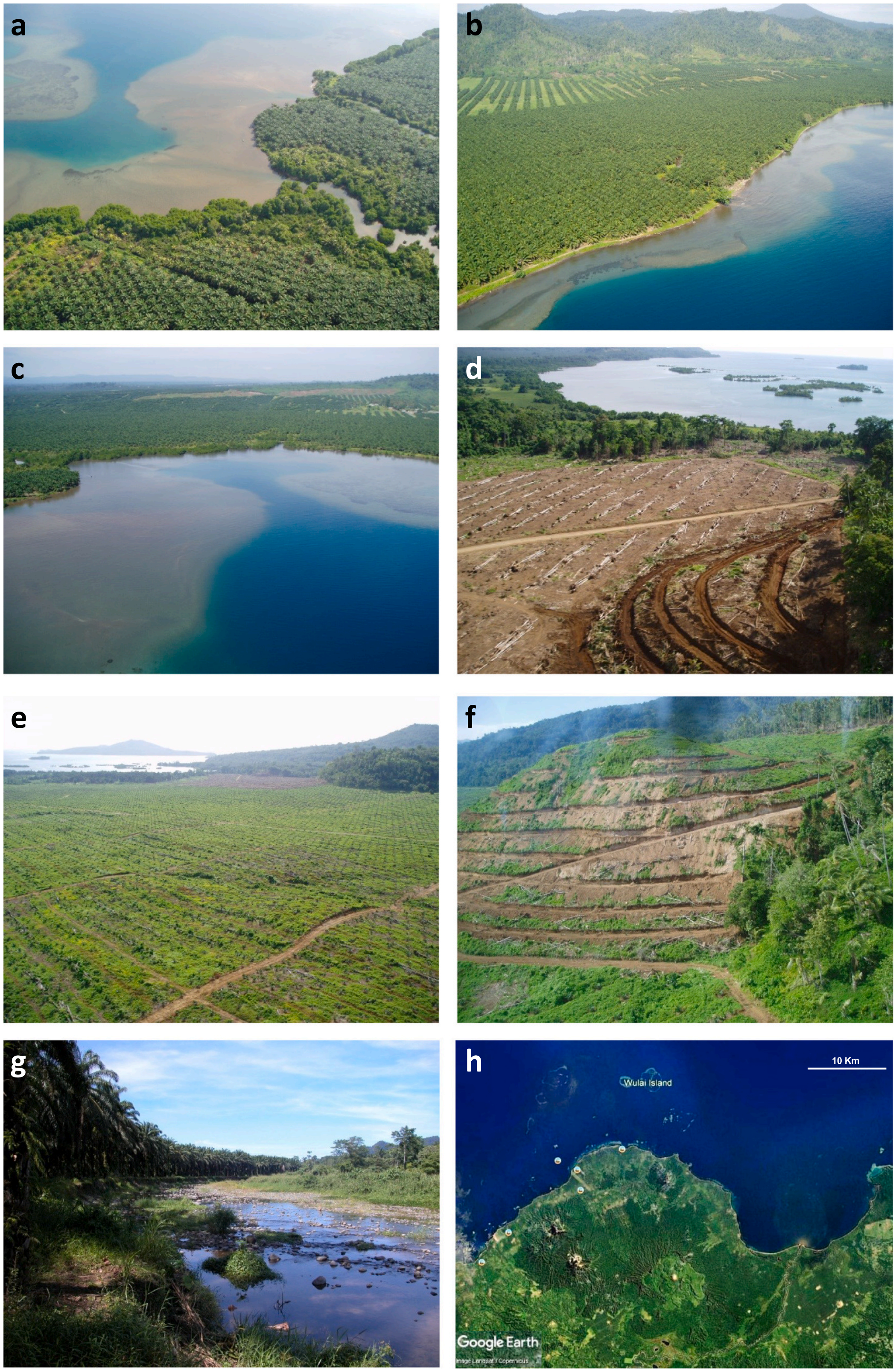

Fig. 2. Photos illustrating aspects of oil palm development on and adjacent to the coastal zone, Kimbe Bay West. a, b) Oil palm plantations abutting the coast and edges of waterways in and around Numundo; c) red-brown sediment deposits on reef flats along the coast immediately adjacent to oil palm plantations at Numundo; d) new clearing of mostly old coconut plantation for oil palm at Numundo; e) new plantation with young oil palms at Numundo; f) very steep slope cleared for oil palm, with high erosion potential; g) oil palms bordering river banks with little or no riparian buffer; h) Kapiura River flood plume in December 2001, bottom right of photo. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(MA), turf algae (TA) and coralline algae (CA). The environmental variables were hard substrate (HS, which included continuous reef pavement, large blocks (>2 m max. diam.) and small blocks (<2 m max. diam.)), coral rubble (RB), sand (SD) and silt (SI). Sand, mainly of calcareous origin, was differentiated from silt by the former's larger size and courser texture. Silt, of terrigenous origin, was characterized by its much finer grain size, darker colouration and ease of resuspension when disturbed. As an environmental variable, silt cover was estimated independently to cover of the ecological variables (e.g. TA) on which it had settled.

Additional environmental variables were also estimated. These were: Exposure to waves (Exp), as one of four categories, from sheltered (protected from wave energy by topography), to semi-sheltered to semi-exposed to fully exposed; maximum depth surveyed (Max, in m), average angle of reef slope to the horizontal (Slope, estimated visually to the nearest 10 degrees); reef development (RD), as one of four categories, from non-accretional coral communities (developed on non-biogenic substrate), incipient reefs (with some calcium carbonate accretion but no reef flat), reefs with moderate flats (<50 m wide), to reefs with extensive flats (>50 m wide) (after Hopley, 1982; DeVantier et al., 1998); and underwater visibility (VIS, estimated visually to the nearest m), as a proxy for water clarity – turbidity. Given these were 'one-off' surveys, an important caveat is that clarity can be affected, episodically, by the interaction of local meteorological and/or oceanographic conditions with terrigenous or carbonate sediments and plankton. Evidence of impacts, such as coral bleaching, predation by crown-of-thorns starfish or *Drupella* or other snails, coral diseases, blast or poison fishing or anchor damage, were also recorded.

Given the earlier REA survey in Kimbe Bay W by Maragos and Holthus in 1993 (Maragos, 1994), our estimates of living coral cover were compared with those made a decade earlier, at 12 reefs that had been surveyed twice. Although the same reefs and, as far as could be determined, general locations were surveyed, precise locations of the 1993 study are not known. A second caveat is that the earlier cover estimates of Maragos (1994) were made as ranks, representing ranges of 1–10%, 11–25%, 26–50%, 51–75% and 76–100% respectively. The rank scores for each reef were converted to their cover midpoints for comparison (Table S2).

2.3. Photography

At both Kimbe Bay W and Mullins Harbour, digital underwater photography was used to document reef condition. At Kimbe Bay W, an aerial survey of the coast and hinterland adjacent to the survey reefs was also undertaken, from a light aircraft, by ET and JB in 2003. Representative photographs that illustrate the condition of the reefs, and the adjacent coastal area, are included herein.

2.4. Analyses

Data from the two depth ranges at reef locations in both Kimbe Bay W and Mullins Harbour were averaged for analysis at 'reef' level. Analysis of the relationships between environmental and ecological characteristics, and coral community structure, was examined by means of Redundancy Analysis (RDA) and Distance-based Redundancy Analysis (db-RDA) (Legendre and Anderson, 1999; Legendre and Legendre, 2012) using the rda and capscape functions, respectively, in the "vegan" R package (Oksanen et al., 2020). In RDA the ecological and environmental characteristics served as the response and explanatory variables, respectively. Two db-RDA models were constructed with species abundance (rank scores) as the response variables and the environmental and ecological characteristics, respectively, as the explanatory variables. Owing to differences in measurement units, explanatory variables were standardized prior to analysis. Db-RDA models were performed using the Bray-Curtis distances between species compositions, after affirming its suitability by examining the rank correlations of a suite of potential distance measurements (rankindex function in "vegan"). Statistical significance of the models, axes and explanatory variables were determined by randomization (1000 permutations) (Legendre and Legendre, 2012). Statistical significance was assigned when $p < 0.05$.

3. Results

3.1. Reef status

3.1.1. Kimbe Bay W

Cover of live reef-building corals ranged from 2% nearshore to 80% offshore (mean 21%, s.d. 17%, Fig. 3a, Table S1a). Cover of dead standing corals ranged from 2% to 60% (mean 24%, s.d. 17%), higher than living corals overall. Dead coral cover was highest on coastal and mid-shelf reefs, particularly in the southwest corner of Kimbe Bay (Fig. 3a, and see examples in Fig. 4b, c). No recent coral bleaching was apparent, but low numbers of crown-of-thorns starfish were recorded at six locations, along with evidence of recent predation (Fig. 4h). Cover of silt ranged from 0% on one offshore reef to 90% on the worst-impacted nearshore reef (mean 29%, s.d. 24%, Fig. 3b, see e.g. Fig. 4a–d). Coincident with silt, underwater clarity also ranged in a gradient from just 1 m of underwater visibility on the most turbid nearshore reefs, to more than 30 m on the clear water, shelf-edge reefs (Fig. 3b, Table S1a). Of the 12 locations in Kimbe Bay W for which a general comparison of living coral cover from 1993 (Maragos, 1994) to 2003 (this study) could be made, 10 locations showed declines of greater than 50%, one of >25%, and two had slight increases (Fig. 3c, Table S2). Overall, living coral cover declined by more than half (mean 55%, s.d. 35%) its 1993 mean value. Of the regional pool of 330 reef-building coral species, highest local richness occurred on the clear-water offshore reefs (Fig. 3d, Table S1a). Local richness for reef corals ranged from 46 to 169 species (mean 124 spp., s.d. 36 spp.), with a nearshore – offshore gradient of increasing richness. The relatively depauperate nearshore reefs were comprised of a subset of species typical of turbid environments (see later).

3.1.2. Mullins Harbour

Cover of living and dead reef-building corals was lower than at Kimbe Bay W ranging 2% to 40% for live corals (mean 17%, s.d. 10%) and from 0 to 70% for dead corals (mean 16%, s.d. 17%, Fig. 5a, Table S1b). No recent coral bleaching or crown-of-thorns starfish were found during the survey. Silt cover was lower than at Kimbe Bay W, ranging from 0 to 18% (mean 7%, s.d. 6%, Table S1b and see e.g. Fig. 6a–h). Water clarity ranged from 2 m to 15 m of underwater visibility (mean 6 m, s.d. 3 m, Table S1b), being most turbid closest to the harbour entrance. As the survey occurred in a period of low rainfall, little tidal movement and calm sea conditions, water clarity would be expected to decline further during flood events, and during periods of strong onshore winds and/or waves, as fine terrigenous sediments become resuspended in the water column. The regional species pool of 374 species was higher than at Kimbe Bay W, with local richness ranging from 99 to 182 species (mean 154 spp., s.d. 22 spp.) and richest locations hosting 46% of the regional species pool. Changes in species richness with increasing distance from the harbour entrance were also less distinct at Mullins Harbour (Fig. 5b) than the nearshore – offshore pattern at Kimbe Bay W.

The RDA model resulted in a single statistically significant axis ($p = 0.001$, accounting for 16.8% of total variability, details in Table S3), a weakly significant axis ($p = 0.094$, 11.3%) and statistical significance of water clarity, silt and depth. A biplot of the RDA model reveals a strong association between silt and cover of dead coral and an inverse relationship with silt and species richness (Fig. 7). A positive association exists between the other explanatory variables (especially VIS and Max depth) and cover of hard corals and coralline algae, and a corresponding inverse relationship with cover of soft corals, turf and macro-algae.

The db-RDA model with environmental characteristics as

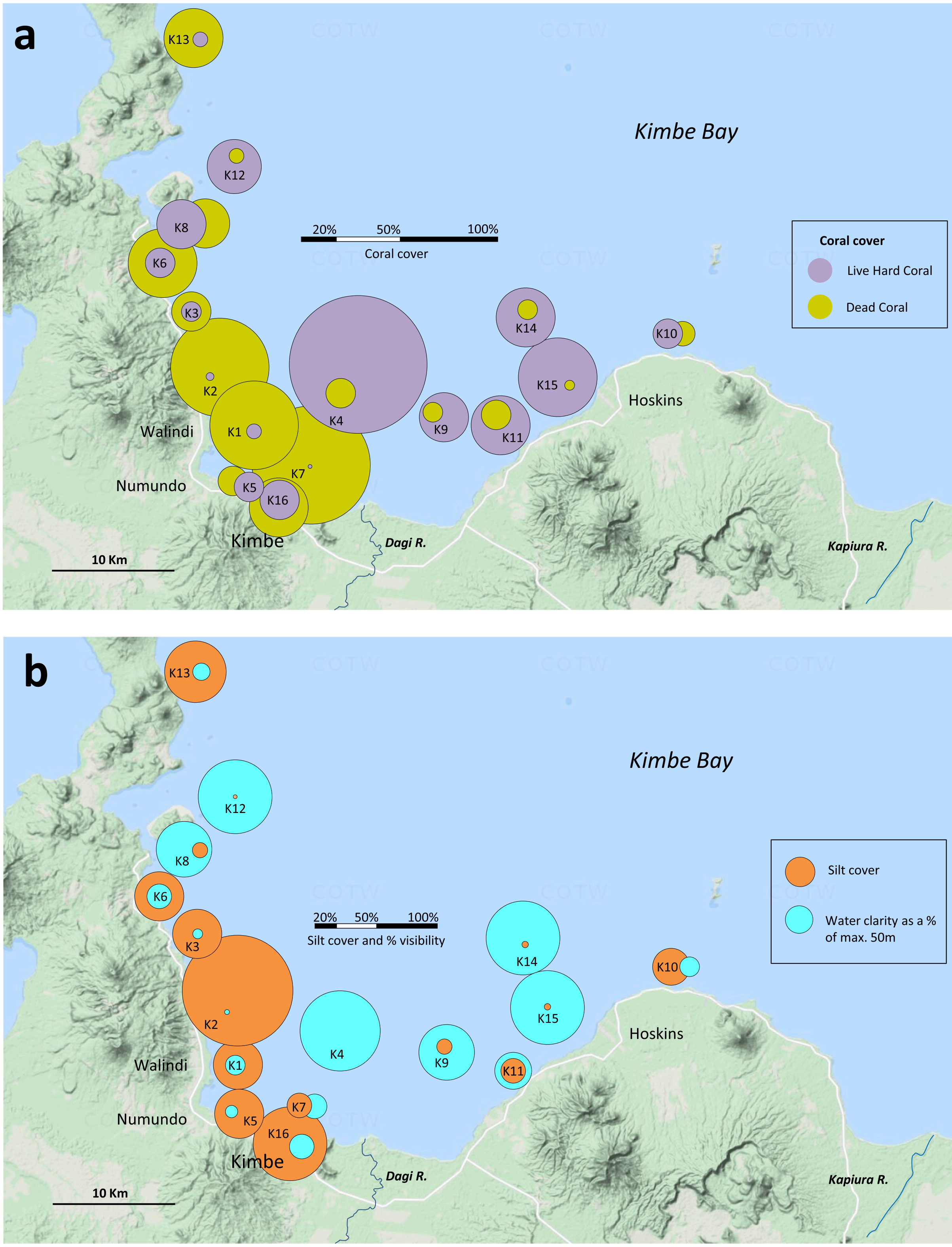

Fig. 3. Kimbe Bay W. Bubble plots of a) percent cover of living and dead hard coral; b) water clarity, as a % of a maximum of 50 m, and percent cover of silt; c) comparison of estimates of cover of living hard coral at 12 locations in Kimbe Bay W, from 1993 (Maragos, 1994) and 2003 (this study); d) species richness of reef-building corals, as percent of the regional pool of 330 species. Shading in d illustrates three coral communities derived from the db-RDAs.

explanatory variables resulted in two statistically significant axes ($p = 0.001$ and $p = 0.004$, accounting for 46.1% and 20.8% of variability, respectively). The model contains four statistically significant explanatory variables: silt, depth, exposure to waves and water clarity (details in Table S4). A biplot of this model reveals an aggregation of communities into four distinct groups, three for the Kimbe Bay W

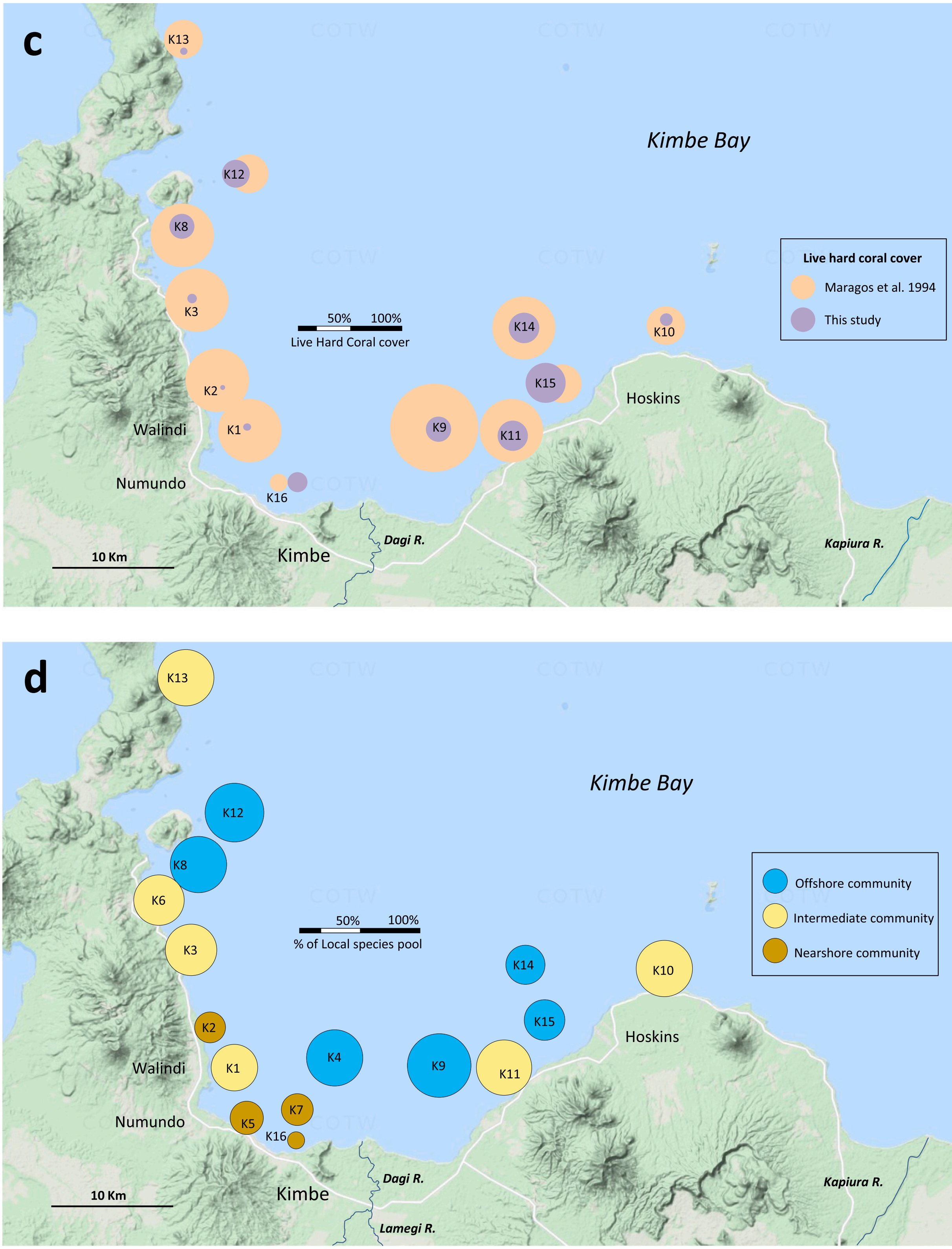

Fig. 3. (*continued*).

locations and a single group for Mullins Harbour (Fig. 8a). One Kimbe Bay W group comprising nearshore locations is strongly associated with silt, whereas a second group comprising offshore locations is associated with the other explanatory variables. The third Kimbe Bay W group represents an 'intermediate' group both spatially and with respect to the explanatory variables. The Mullins Harbour group is inversely associated with the variables associated with the offshore Kimbe Bay W group with no strong association with silt.

The db-RDA model with ecological characteristics as explanatory variables likewise resulted in two statistically significant axes ($p = 0.001$

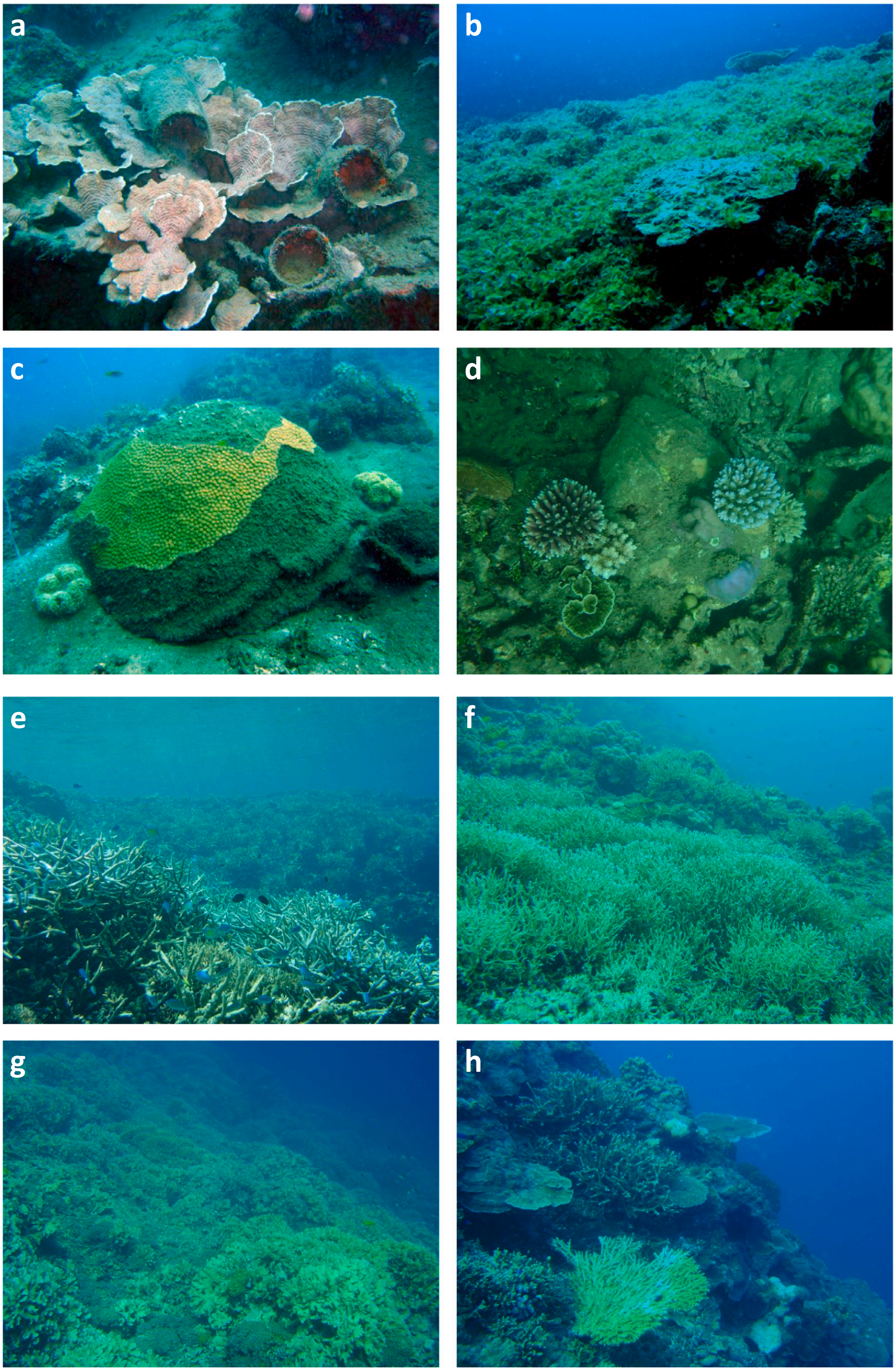

Fig. 4. Photos illustrating some of the range in coral condition at Kimbe Bay W, where a) Litter and silt accumulated on living coral *Pachyseris foliosa*; b) expansive beds of *Padina* overgrowing dead coral; c) large part-dead colony of *Diploastrea heliopora*. Time of most-recent coral mortality is estimated to be between 2000 and 2002; d) surviving *Acropora*, *Montipora*, *Pocillopora* and *Ctenactis* recruits on part-dead *Porites*, surrounded by silt; e) extensive staghorn *Acopora* thickets on a clear-water reef; f) fine-branching *Anacropora puertogalerae* thicket on a clear-water reef; g) extensive beds of *Pavona cactus* on a deeper reef slope; h) evidence of recent predation by crown-of-thorns starfish on an open tabular colony of *Acropora paniculata*.

and p = 0.006, accounting for 47.1% and 18.5% of variability, respectively). The model contains four statistically significant explanatory variables: Turf algae, species richness, dead coral and macro-algae (details in Table S5). A biplot of this model reveals a similar aggregation of coral communities (Fig. 8b). The nearshore Kimbe Bay W group is strongly associated with dead coral and inversely associated with species richness. The offshore Kimbe Bay W group is associated with hard coral and coralline algae. The third 'intermediate' Kimbe Bay W group shows a weaker association with dead coral, hard substrate and coralline algae. The Mullins Harbour group is isolated from the three Kimbe Bay W groups and shows affinity for soft coral, macro- and turf algae, and is inversely associated with the variables associated with the offshore Kimbe Bay W group, with no particularly strong association with silt.

3.2. Coral communities

In both db-RDA models coral species at the 16 reef locations in Kimbe Bay W were differentiated into three coral communities in response to

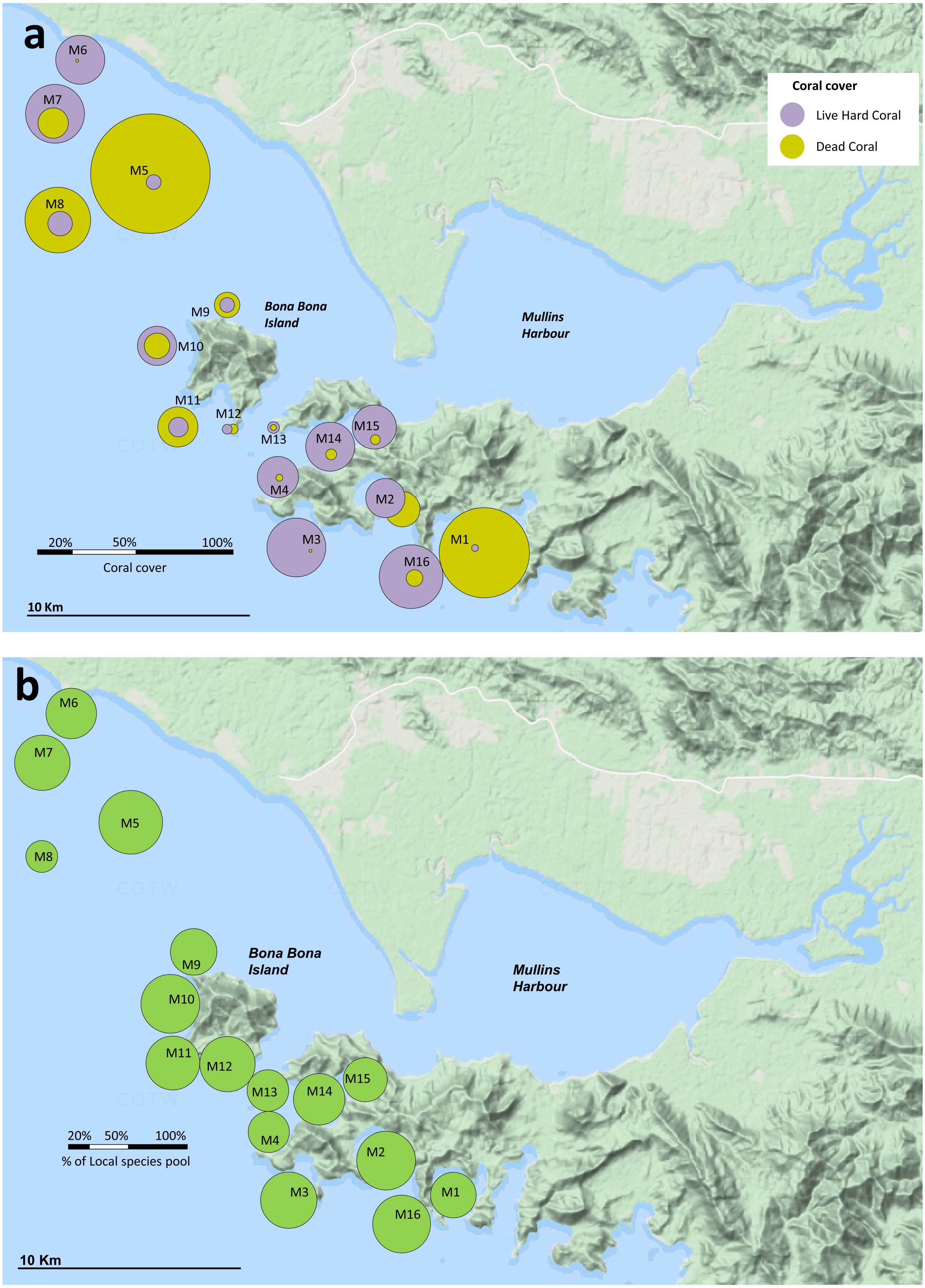

Fig. 5. Mullins Harbour. Bubble plots of a) percent cover of living and dead hard coral; b) local coral species richness, where green shading indicates a different coral community type to those in Kimbe Bay W (see later). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

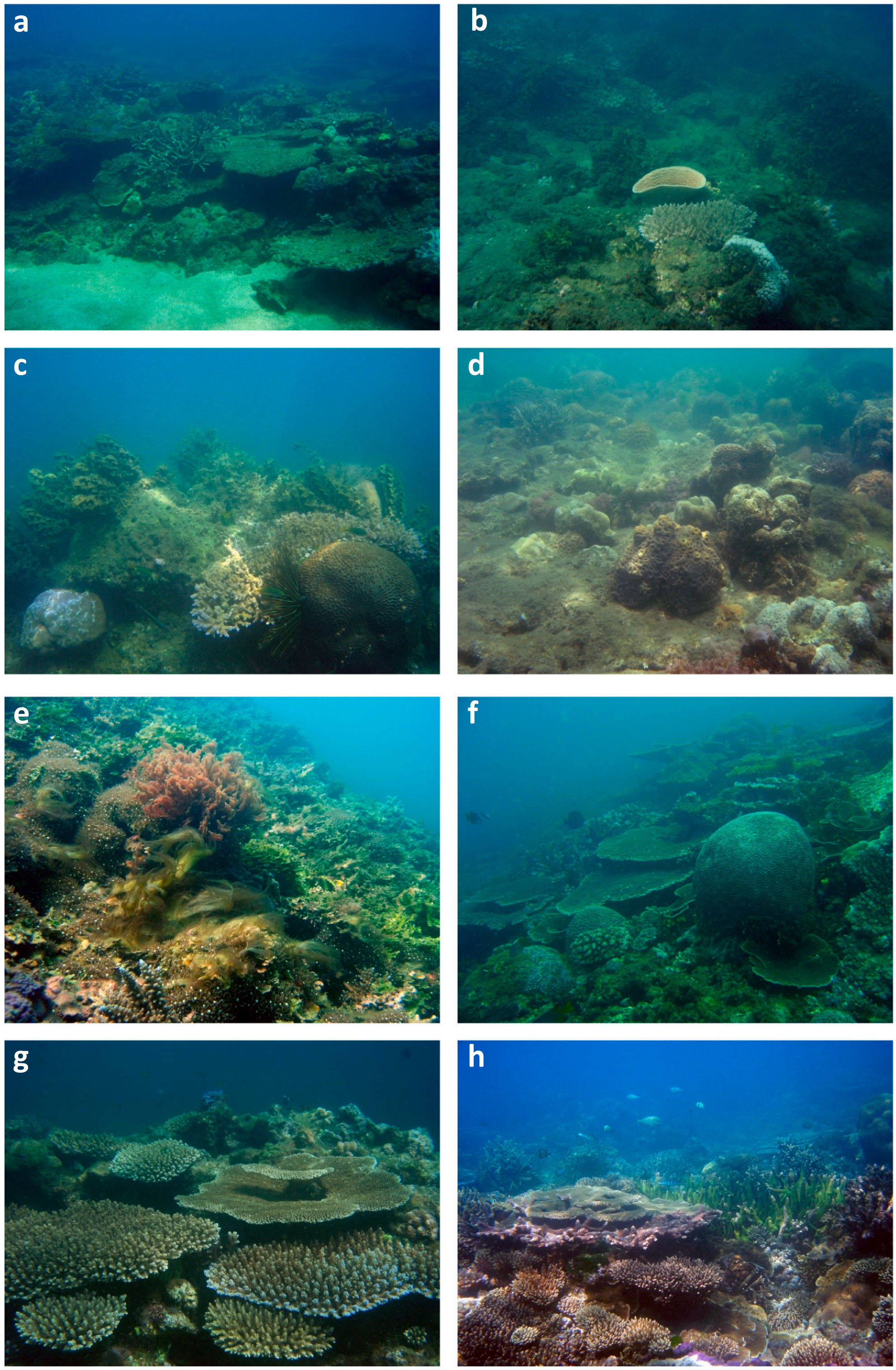

Fig. 6. Photos illustrating some of the range in coral condition at Mullins Harbour, a–d) silt covering dead standing corals, including tabular *Acropora*; e) algae and zoanthids covering dead corals; f) silt-impacted coral assemblage on reef slope; g) high cover of *Acropora* spp. corals, h) diverse assemblage of *Acropora* and *Montipora* spp. corals.

the explanatory variables (Fig. 8a, b). Some corals, notably in the genus *Porites*, were widespread across all communities (Table S6), and thus were not suitable as indicator taxa. One community, occurring on nearshore reefs (Fig. 8a), was characterized by the corals *Turbinaria* spp., *Galaxea* spp. and *Psammocora contigua* (Table S6a) and the fleshy algae *Padina* (Fig. 4b). Large colonies of the typically very hardy massive coral *Diploastrea heliopora* were also common (Table S6a), although most were either severely damaged or dead (Fig. 4c). Corals in the speciose genera *Acropora* and *Montipora* were rare. Cover of dead corals and silt were both high (Figs. 3a,b, 8a, Table S1a), and there was considerable accumulation of litter at some nearshore locations, probably reflecting a combination of stormwater discharge and discards from ships and boat

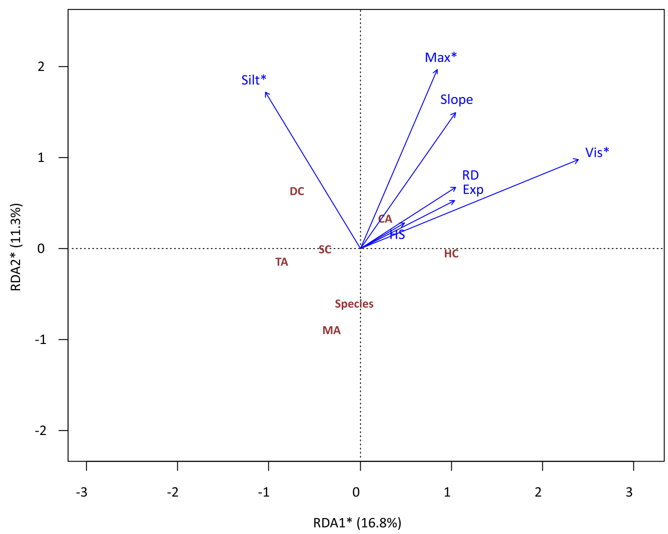

Fig. 7. Redundancy analysis biplot of relations among explanatory and response variables in Kimbe Bay W and Mullins Harbour. Explanatory variables are silt, exposure (Exp), water clarity (Vis), slope angle, reef development (RD), maximum depth (Max), hard substrate (HS, % cover). Response variables are cover of hard coral (HC), dead coral (DC), soft coral (SC), turf algae (TA), coralline algae (CA), macro-algae (MA) and species richness (Species). * denotes statistical significance ($p < 0.05$).

traffic (see e.g. Fig. 4a). Coral species richness was low (Figs. 3d, 8b, Table S1a).

The second, 'intermediate', community, characterized by encrusting – massive *Astreopora* and plating – foliose *Merulina* spp. (Table S6b), may represent a transition assemblage between those of nearshore and offshore reefs. Cover of dead corals and silt levels were both higher than on reefs further offshore (Figs. 3a, b, 8a, b, Table S1a). The third community occurred on well developed offshore reefs with steeper slopes in clearer waters, with little or no silt, exposed to stronger wave action (Figs. 3a, b, 8a). This community was characterized by branching pocilloporids, *Isopora* and *Acropora* spp. (Table S6c, Fig. 4e), and on deeper reef slopes by extensive branching stands of *Anacropora* spp. (Fig. 4f) and foliose beds of *Pavona cactus* (Fig. 4g), developed below the influence of significant wave energy. Coral species richness was high (Figs. 3d, 8b, Table S1) and levels of dead coral cover and silt were low (Figs. 3a, b, 8a, b). Coral community structure at Mullins Harbour differed strongly from Kimbe Bay W, having higher local and regional coral richness, and cover of soft corals, turf and macro-algae, but with no clear differentiation into particular assemblage groups in response to the explanatory variables (Figs. 5a, b, 8a, b).

4. Discussion

4.1. Kimbe Bay corals – history of decline

In the early 1990s, reefs in western Kimbe Bay were considered overall to be in good condition (Maragos, 1994). Two-thirds of reefs had high levels of live coral cover (mean > 50%, Fig. 3c), with extensive zones of very high coral cover (75–100%), despite low levels of coral bleaching, and sedimentation and fishing pressure nearshore (Maragos, 1994). Although nearshore reefs are naturally subjected to terrigenous sediment input, evidence from across the Indo-Pacific has shown that these reefs can sustain very high cover and species richness of reef-building corals (e.g. Done, 1982; Done et al., 2007). This was apparently the case in Kimbe Bay prior to land use change, episodic natural disturbances, notably geo-tectonics, notwithstanding (Tomascik et al., 1996). By 1993, sedimentation was starting to impact nearshore coral communities (Maragos, 1994). According to Maragos (1994), introduction of oil palm plantations and logging in the watersheds had undoubtedly increased sediment input to reefs. Hence our coral 'baseline' was already partly-shifted in the early 1990s, although much less so than in the following decade. From 1993 to 2003, 10 of the twelve reef locations resurveyed for this study had a reduction in living coral cover, declining by between 27 and 94%, with a mean decline of 55%.

In 2003, highest live coral cover and local richness, representing 46–52% of the regional species pool, occurred on reefs furthest from coastal development. There was a discernible nearshore - offshore gradient in water clarity and on-reef levels of silt. The strong relations between cover of silt and dead coral, species richness and community structure (Figs. 7, 8a) suggests that the amount of silt being transported and deposited into the nearshore environment has had a major negative impact on reef condition there (also see Cooper et al., 2007; De'ath and Fabricius, 2010). This is supported by the positive association between water clarity and cover of hard corals (Fig. 7). Given the earlier commentary from Maragos (1994), it is highly likely that expanding oil palm development and related activities have caused nearshore silt levels to increase substantially from those prior to clearance of the land. Worst impacted reefs had a low energy regime, with poor flushing, low wave action and generally still conditions.

Work in other parts of Kimbe Bay, including by one of the present authors in the eastern portion (Turak and Aitsi, 2002) also found that nearshore reefs closest to oil palm development had highest silt levels, with coral communities of similar species composition to the degraded reefs of Kimbe Bay W. Additionally, from 1996 to 2003, Jones et al. (2004) reported that live coral cover on eight reefs declined from 66% to a low of 7%. Jones et al. (2004) attributed the decline to a combination of increasing sedimentation from terrestrial run-off, repeated minor levels of coral bleaching (1997, 1998, 1999, 2000, and 2001) and predation by crown-of-thorns starfish. Similarly a decline in the abundance of acroporid corals and coral-dwelling fishes was reported from 1996 to 2003 (Munday, 2003), most severe on nearshore reefs, and again attributed to sedimentation, bleaching and predation. Conversely, cover of algae increased on the western coast of Kimbe Bay (Jones et al., 2001), potentially responding to increased space from loss of corals. Nearshore reefs had low exposure to wave action, and hence silt was not washed from corals, as presumably occurs in other parts of Kimbe Bay on reefs exposed to more wave action and/or with steeper reef slopes (Figs. 7, 8a).

Modelled estimates of sediment and nutrient loads, reinforced by anecdotal and observational evidence, suggest that the most significant additional loads of sediment, above natural, originated from logging operations and the planting stage in development of oil palm plantations (Brodie and Turak, 2004). Subsequent to our survey, dedicated water quality sampling indicated that the lower reaches of the Dagi and Lamegi Rivers, close to several of the worst-impacted reef locations, had higher turbidity levels than upstream sites and other lowland streams (Sheaves and Johnston, 2014). Much of the turbidity appeared to have resulted from conversion of natural riparian zones and steep hillsides into household gardens, areas where oil palm was not usually planted. These conversions appear, in turn, to have resulted from the planting of oil palm on all available land, a practice that displaced household gardens into less desirable locations (Sheaves and Johnston, 2014). These authors also identified other sources of turbidity as un-bridged road crossings, roadside drains, gravel extraction operations, new oil palm plantings and undefined sources upstream from plantation areas, including logging operations and roads, landslips and household gardens. Hence, irrespective of the proximal source of turbidity it was ultimately linked back to oil palm production (Sheaves and Johnston, 2014).

4.2. Mullins Harbour corals - an unknown history

At Mullins Harbour, relations between coral species richness and cover of live and dead corals and silt (Figs. 5a, b, 7, 8a, b, Table S1), or

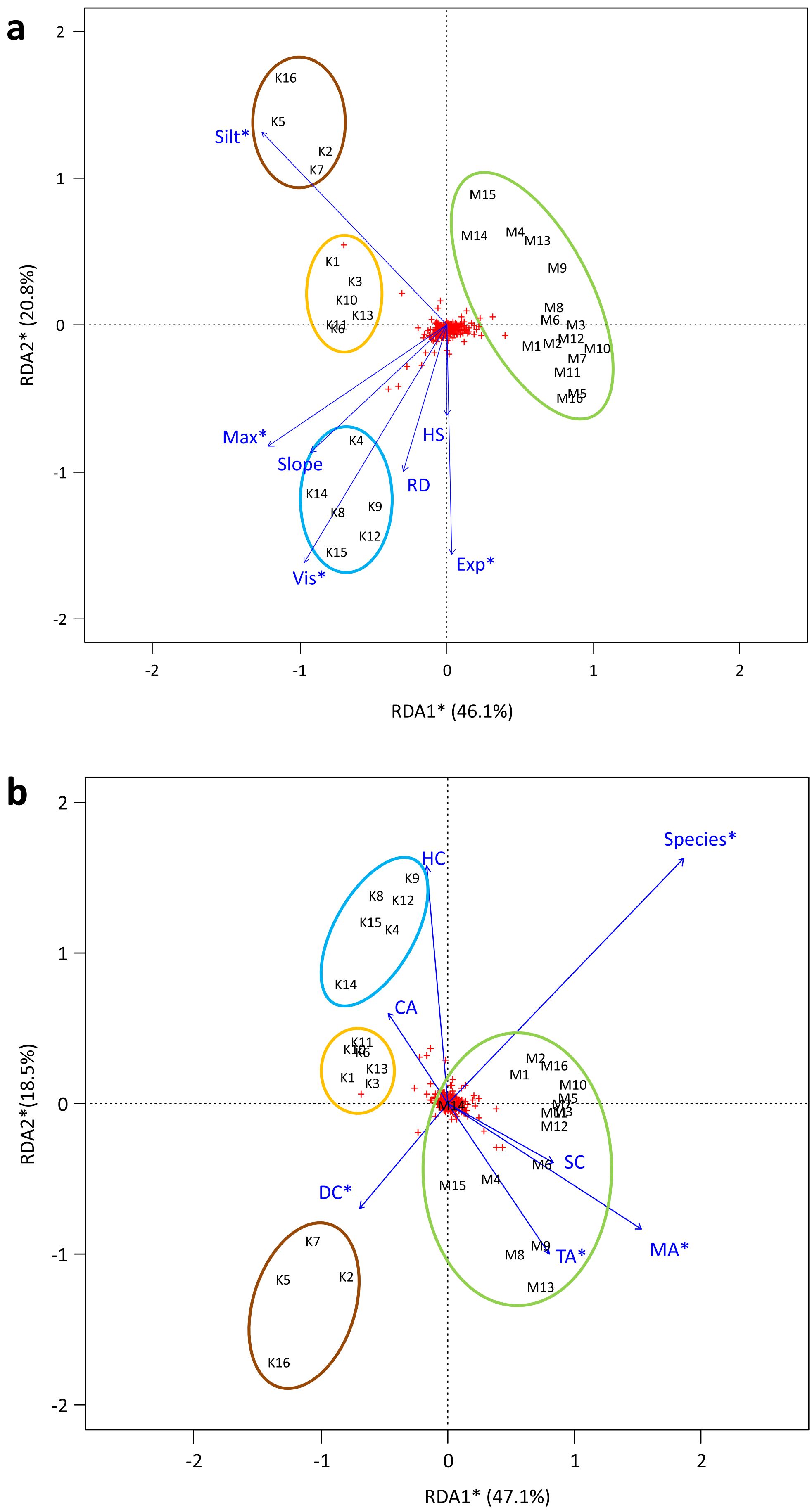

Fig. 8. Distance-based Redundancy Analysis biplots of relations among explanatory and response variables at 32 reef locations in Kimbe Bay W and Mullins Harbour. a) Explanatory variables are Silt, exposure (Exp), water clarity (Vis), Slope angle, reef development (RD), maximum depth (Max), hard substrate (HS). Response variable is species abundance; b) explanatory variables are cover of hard coral (HC), dead coral (DC), soft coral (SC), turf algae (TA), coralline algae (CA), macro-algae (MA) and species richness (Species). Response variable is species abundance. * denotes statistical significance ($p < 0.05$).

indeed most other explanatory variables, were much less clear-cut than at Kimbe Bay W. This may be related to the convoluted coastal topography and presumably more complex oceanography outside Mullins Harbour, and the effects of additional forms of coral mortality. Species richness at both local (mean of 153 spp.) and regional (374 spp.) levels was higher than at Kimbe Bay and comparable with similarly sized regions of the adjacent northern region of the Great Barrier Reef (Veron et al., 2015) or periphery of the Coral Triangle, but lower than the richest regions of Indonesia and the Philippines (DeVantier and Turak, 2017; DeVantier et al., 2020).

No information, anecdotal or scientific, was available on reef condition prior to the 2007 survey. However, a similar set of circumstances to those discussed above seems likely, with nearshore reefs impacted by siltation, whereas those further offshore had lost living coral cover to other disturbances, probably bleaching in the mid-1990s and predation. The lack of reef development immediately outside the entrance to Mullins Harbour suggests that conditions have, since the return of sea level in the Holocene Transgression, been inimical to reef-building. Sparse corals are, nonetheless, present, indicating that corals can become established there, but likely suffer episodic mortality in flood events emanating through the entrance. At those times the generally low underwater visibility (our proxy for water clarity) likely declines to near-zero from flood runoff and sediment resuspension. Episodic flood events can also introduce waters of low salinity and differences in temperature (Devlin et al., 2001).

Fine terrigenous silt was present, particularly on the deeper reef slopes, at many of the nearshore locations (Table S1), but there was no clear trend with increasing distance away from the harbour entrance. Most reefs close to Mullins Harbour had low to moderate living coral cover (<25%), and moderate to high dead coral cover, similar to that of living corals. The coral death had likely occurred during the past decade. Cause(s) of the mortality are impossible to assign in retrospect, however the 'usual suspects' of bleaching triggered by major flooding or high temperatures, siltation or predation appear likely. An additional consideration, from the microbiological standpoint, is disease. For example, a large sponge die off in New Guinea has been attributed to bacteria isolated from dying sponge tissue (Cervino et al., 2006). These bacteria, closely related to those in use in oil palm pest management, did not occur on healthy tissue of the same colonies.

4.3. Distinguishing the effects of past disturbances

Post hoc determination of the specific impact of each of a range of recent disturbances, or even which was the principal cause of coral damage, is difficult, being largely contingent on the presence and veracity of historical knowledge (Fine et al., 2019), often anecdotal. Even when prior surveys have been conducted, differences in methodology and site selection can limit usefulness of comparisons. Adding to these constraints, impacts can be acute or chronic, occur sequentially or coincidentally, or act synergistically or antagonistically (Crain et al., 2008; Bessell-Browne et al., 2017c; Fisher et al., 2019). For example, with relevance to the present study, impacts from poor water quality are typically chronic or may be pulsed in flood plumes, whereas those from crown-of-thorns starfish outbreaks or bleaching events are usually acute (Fabricius, 2005; Wolanski et al., 2008; Fabricius et al., 2013). Such synergisms were likely to have occurred in both Kimbe Bay and Mullins Harbour.

The low overall ratios of live: dead coral cover at Kimbe Bay W (21: 24%) and Mullins Harbour (17: 16%, Table S1) are useful indicators of general condition, with one important caveat: the ratio may be high on a long-term degraded reef with low live cover of a few tolerant species but no recent coral mortality, such that no dead standing coral is present. Hence this ratio is most useful in light of the cover scores themselves, their relations with environmental variables (Fig. 7), and also with consideration of species composition and abundance (Fig. 8b, Table S6). With these considered, the ratio was strongly positive on a couple of the shelf-edge reefs in Kimbe Bay W and offshore reefs in Mullins Harbour (Figs. 3a, 5a), where *Acropora* species were common. The low overall ratios of most nearshore reefs, contingent on higher levels of dead standing corals, are consistent with those reefs previously having higher living coral cover, as documented during the 1993 survey at Kimbe Bay (Maragos, 1994, Fig. 3c). Hence, if conditions are amenable, there is scope for recovery of coral cover and, potentially, diversity, contingent on a reduction in future disturbances facilitating recovery. On some nearshore reefs however, the high levels of deposited silt (Fig. 8a) may hinder coral settlement and/or growth.

Broad coral size distributions and occurrence of small corals more commonly at offshore locations in both Kimbe Bay W and Mullins Harbour (see e.g. Figs. 4d, 6c), indicated that recruitment had been occurring. If recovery occurs, the live: dead coral ratio will increase substantially. Conversely, a lack of recovery and/or continuing disturbance will further erode this ratio, until, potentially a shift to algal dominance may develop (see e.g. Figs. 4b, 6e). For corals, water clarity, sediment levels and substrate suitability are all crucial factors in settlement, growth to recruitment and maintenance of populations (Richmond et al., 2018).

4.4. Challenges, shortcomings and recommendations

In Kimbe Bay W, and to a lesser extent at Mullins Harbour, corals on nearshore reefs were covered or surrounded by silt, likely causing or contributing to death, and also presumably interfering with recruitment and recovery. Although no data were available that definitively linked prior land-based activities to river end loads to site-based water quality parameters, the main apparent sources were land-use changes, initially from logging and with subsequent development of oil palm plantations.

In terms of minimizing impacts from land use change, the period between initial clearing of ground and planting or replanting, where soils are highly exposed to erosion, is critical in minimizing silt delivery to streams, rivers and reefs (Brodie et al., 2009). Catchment clearing and 'hardening', and increased drainage, result in less infiltration and evapotranspiration and greater surface water runoff (Staver et al., 1991, Sheaves and Johnston, 2014). Higher runoff increases flow volumes and velocities, and causes greater levels of gully and bank erosion (Sheaves et al., 2018). The principal potential contaminants are suspended sediment, nitrogen and phosphorus, pesticides and litter, mobilised in soil eroded in runoff (Brodie et al., 2009; Kroon et al., 2012; Waterhouse et al., 2012). Dense accumulation of the macro-alga *Padina* at one location may indicate localized nutrient enrichment (D'Angelo and Wiedenmann, 2014), although we have no data to confirm this. For nearshore coral reefs to remain in good condition, and for those already degraded to recover, pressures from the catchment need to be minimized. Indeed, remaining intact forest should not be cleared, as downstream reefs crucial for both food and livelihoods are easily impacted (Wenger et al., 2020). These authors demonstrated that even at low levels of clearing using 'best management practices' to minimize the exposure of coral reefs to increased runoff, clearing would still result in 32% of the reef experiencing an increase in sediment exposure.

In conclusion, the challenges of understanding and remediating the impacts of plantation agriculture are exacerbated by a lack of appropriate baseline information on ecosystems and water quality. This directly hampers effective decision-making and limits the ability for monitoring programs to measure the success or failure of management actions. This paper has highlighted such gaps, with baselines either non-existent or already shifted by development. Nevertheless, clear trends of decline in live coral cover and comparatively low species richness were apparent on reefs closest to the major changes in land use in Kimbe Bay W. As climate change escalates in coming decades, and interacts with local impacts, measures aimed at effectively addressing local impacts, including changed land usage, as well as the 'big picture', will become increasingly important (Persey et al., 2011; Luke et al., 2020; Dutra et al., 2021). Effective, relatively simple measures include protection of natural vegetation on steep slopes most prone to erosion, expansion of stream and coastal buffer zones, and minimization of fertilizer and pesticide use. Additionally, targeted monitoring of key parameters of ecosystem condition is needed to inform reactive management that addresses impacts in a timely manner. On national- and international scales however, both supply- and demand-side interventions will be required.

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CRediT authorship contribution statement

Emre Turak: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Writing – review & editing. **Lyndon DeVantier:** Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Writing – review & editing. **Robert Szava-Kovats:** Formal analysis, Writing – original draft, Writing – review & editing. **Jon Brodie:** Conceptualization, Methodology, Investigation, Writing – original draft.

Declaration of competing interest

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

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