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Effects of Climate Change on Seagrasses and Seagrass Habitats Relevant to the Pacific Islands

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EXECUTIVE SUMMARY

Due to anthropogenic pressure, seagrass habitats are declining by over 7% annually worldwide, with approximately 29% of the world seagrass stock having already been destroyed. Losses in seagrass habitats for the tropical Pacific by the year 2100 are estimated to be between 5 to 35%, but a lack of knowledge on the extent and area cover of seagrass resources in Pacific Island Countries and Territories (PICTs) does not allow accurate assessments of resource status, or losses and gains in seagrass cover to be made.

Low human resource capacity and little awareness by the general public and business community of the economic value and importance of seagrass ecosystem services, including a lack of inclusion of seagrass habitats at a regional policy level, is severely hampering conservation efforts. Seagrasses and seagrass habitats provide at least 24 different service benefits in the Indo-Pacific region. These include coastal protection, provision of food, cultural value and exceptional carbon storage ability beyond terrestrial forests. If properly managed, seagrass habitats could provide a highly significant carbon mitigation service in a high-CO_2 world through a net influx of organic carbon both above and below-ground.

Massive seagrass carbon storage losses have recently been recorded in Australia after a period of elevated seawater temperature, and increased oceanic temperature will be one of the most important environmental stressors on seagrass habitats. Different tropical seagrass species show different tolerances to increased seawater temperatures, but thermal tolerance has not been well studied in seagrass in PICTs. Increases in seawater temperature also translate into stronger extreme weather events such as heavy rainfall and tropical cyclones and storms, which put additional stress on seagrass habitats through direct physical damage, increase in turbidity causing reductions in photosynthetic rates and growth, and a general loss of ecosystem resilience and productivity.

Both gains and losses to seagrass resources will result from climate change, with increases in productivity due to higher CO_2 levels being buffered by the negative consequences of higher seawater temperatures and most importantly additional anthropogenic factors such as "polluted" land runoff. These factors are very likely to be currently resulting in increasing losses of vital ecosystem services in the Pacific islands.

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With the population of many Pacific Island countries projected to almost double by the year 2050, this will exert huge pressure on already stressed coastal seagrass ecosystems, threatening their survival particularly in rapidly expanding densely-populated urban areas. Poor catchment management and unplanned coastal development will also lower the ability of seagrass habitats to be resilient and lessen adaptation to rising sea-levels for example by restricting their landward migration. Over-harvesting or environmental pollution, is likely to result in changes to seagrass community diversity and in turn reduce any associated ecosystem services.

The need for building local research capacity in seagrass ecosystems is high, particularly in the independent Pacific Island developing countries. Although indigenous communities in these countries have understood the management of their natural resources for centuries, the modern pressures of climate change and extremely high rate of human population growth makes it very positive that local communities and resource owners are being increasingly supported to effectively monitor and manage their own coastal resources which includes seagrass habitats. In partnership with local communities, NGOs and education organisations, education and capacity building is occurring with respect to awareness, resource mapping, training for monitoring of ocean acidification and an increased understanding of seagrass reproduction, role in carbon storage (blue carbon) and coastal protection.

Management of seagrass resources on islands should be focused on reducing anthropogenic impacts to prioritized coastal areas to ensure resilience levels of local seagrass populations remains high, because this will provide the best possible chance of mitigating the predicted impacts of climate change.

Introduction

This report card discusses seagrass and seagrass habitats in 22 Pacific Island Countries and Territories (PICTs) in the context of current and expected future climate change impacts across local, regional and global levels as dictated by available data. There is an overall comparison of climate change impacts in respect to other human-induced threats to seagrass resources. Locational emphasis has been placed on seagrass and seagrass resources in the fourteen independent Pacific island countries (Table 1) as these are predominantly developing countries with arguably the greatest need for economic support to effectively manage their vital coastal resources.

Although most seagrasses in the tropical Pacific are found in waters shallower than 10 m PICT seagrass habitats can be identified and divided into five broad types “estuary”, “bays and lagoons”, “barrier and patch reefs”, “island fringing reefs” and “deep water” Waycott *et al*. (2011). The dominant processes in each of these locational seagrass habitat types influences the seagrass assemblage present, its growth, survival and exposure to potential disturbance. Each of these habitat types may be influenced in different ways by both climate change impacts and other human related disturbances such as land run-off. Therefore, the role seagrasses, and seagrass habitats, play in providing resilience and lessening climate change impacts may vary from location to location depending on the seagrass habitat type and the nature of adjacent environments (Guannel *et al*. 2016).

Currently there is a “beyond-exponential” growth rate in human population globally, and providing for this increased population is adversely driving climatic change and environmental degradation at a functional planet level (Rockstrőm *et al*. 2009). It is clear that if this trend continues as predicted there will be a further highly significant increase in human population globally and within the large independent Melanesian Pacific island countries. In Papua New Guinea, Solomon Islands and Vanuatu for example, human population numbers are expected to almost double by 2050 (SPC 2016). Thus human-related threats to coastal environments, particularly in sheltered locations where seagrass resources are naturally found and urban human populations are significantly increasing (e.g. Fiji Bureau of Statistics 2018), are expected to increase substantially via non-sustainable resource use, pollution and overharvesting to cater for basic human needs such as food, water and shelter.

Classification and Distribution

Seagrass comprises at least three independent lineages of monocotyledonous flowering plants that have each returned to a marine environment, possessing a unique suite of morphological and reproductive characteristics that enables them to survive in brackish to saltwater habitats throughout the temperate and tropical regions of the world (Waycott *et al*., 2004).

Table 1. The comparative species richness of PICTS in alphabetical order and by governance type as per Gillett (2016). Where reference sources disagree on species number a range is provided.

Country or Territory Name	Seagrass Species Richness & Comments	Reference Source
Independent Countries		
Cook Islands	No seagrass recorded as present	Waycott *et al*. 2011
Federated States of Micronesia	10 species	Waycott *et al*. 2011
Fiji	5 species; plus 1 sub-species, molecular analysis in progress to confirm status	Tuiwawa *et al*. 2014
Kiribati	1-2 species, lacks recent survey data	Ellison 2009, Waycott *et al*. 2011
Marshall Islands	3 species	Tsuda & Sukhraj 2016
Nauru	0 but lacks survey data	Ellison 2009, Waycott *et al*. 2011
Niue	0 but lacks survey data	Ellison 2009, Waycott *et al*. 2011
Palau	8-10 species	Ellison 2009, Waycott *et al*. 2011
Papua New Guinea	12-13 species	Ellison 2009, Waycott *et al*. 2011
Samoa	3 species (including one subspecies in common with Fiji & Tonga)	Skelton & South 2014
Solomon Islands	9-10 species	Ellison 2009, Waycott *et al*. 2011
Tonga	4 species including one subspecies in common with Fiji & Samoa	Waycott *et al*. 2011, Tuiwawa *et al*. 2014
Tuvalu	0-1 species, requires new survey data beyond Funafuti	Ellison 2009, Waycott *et al*. 2011, Job & Ceccarelli 2011
Vanuatu	13 species	McKenzie & Yoshida 2017
Territories		
American Samoa (USA)	2-4 species	Skelton 2003; Waycott *et al*. 2011
French Polynesia (France)	2 species	Waycott *et al*. 2011, Hily *et al*. 2010.
Guam (USA)	4-5 species	Ellison 2009, Waycott *et al*. 2011
New Caledonia (France)	11 species	Waycott *et al*. 2011, Hily *et al*. 2010
Northern Mariana Islands (USA)	4 species	Waycott *et al*. 2011
Pitcairn Islands (Britain)	No seagrass species recorded	Irving & Dawson 2012
Tokelau (New Zealand)	No seagrass species recorded	Passfield, 1998, Waycott *et al*. 2011
Wallis & Futuna (France)	3 species	N'Yeurt & Payri 2004, Hily *et al*. 2010.

Possessing true flowers and producing seeds through both underwater and above-water pollination, seagrass are grouped into one order (Alismatales) with 14 families including Cymodoceaceae, Hydrocharitaceae, Posidoniaceae, Potamogetonaceae, Ruppiaceae and Zosteraceae (Chase *et al*. 2016). Present on all continents except Antarctica (Green & Short, 2003) seagrass comprise approximately 70 species worldwide, with 14 species and one subspecies reported from the tropical Pacific region (Ellison 2009, Table 3; Waycott *et al*. 2011).

Seagrass Species Richness

The species richness of seagrass within PICTs is highly variable (Table 1) depending on island size, topography and distance from the Indo-Pacific centre of biodiversity. The highest number of seagrass species in the region are reported from Papua New Guinea (12-13 taxa), Vanuatu (13 taxa), New Caledonia (9-11 taxa), the Solomon Islands (9-10 taxa) and Palau (8-10 species). The lowest seagrass species richness is found in Tuvalu (0-1 species), Kiribati (1-2 species) and French Polynesia (2 species). No seagrass is currently reported from Nauru, Niue, the Cook Islands, the Pitcairn Islands and Tokelau. Reports for Tuvalu are uncertain with Job and Ceccarelli (2011) including seagrass as a habitat in their non-Funafunti survey data sheet. We infer that there may be insufficient sampling and a lack of seagrass focused surveys in some parts of Tuvalu and perhaps Nauru and Niue. Based on morphology, a subspecies of *Halophila ovalis* ssp. *bullosa* is known from Fiji, Samoa and Tonga and molecular analysis is currently in progress to determine if this subspecies is genetically valid. There are also records of important biogeographical consequence in the literature that have not yet been verified through voucher specimens or new collections, such as that of *Thalassia hemprichii* from Fiji by Littler & Littler (2003). Reports of seagrass habitat in Kiribati (Tebano 2004; Awira *et al*. 2008; Peters Figure 1) suggest that new surveys to update occurrence are needed.

Seagrass Area Coverage

Expected seagrass area coverage for PICTs is also likely to be highly variable, but reliable estimates are currently unknown for all countries except for New Caledonia and Wallis (Hily *et al*. 2010). Hence meaningful comparisons of the extent of seagrass resources across PICTs, or the gain or loss of seagrass cannot yet be made. The seagrass area cover estimates, by nation, provided in Waycott *et al*. (2011) should be treated with caution, particularly for Fiji where the coverage estimate is low.

Figure 1. *Thalassia hemprichii* seagrass habitat, Tarawa Island, Kiribati. Photograph M. Peters.

Seagrass Environmental Requirements

Wherever seagrass colonizes marine sediments, they profoundly affect the physical, sedimentology, physio-chemical and biological characteristics of that area (Larkum *et al*., 2006). Habitats colonized by seagrass range from shallow coastal flats that become exposed at low tide, to permanently submerged lagoon habitats up to 60m deep (Duchêne *et al*. 2010). As previously mentioned, Waycott *et al* (2011) describe five main categories of seagrass habitat across the PICTs and within that context consider water clarity, nutrient availability and exposure to wave action as the three major influencing factors for variability within seagrass habitats.

Water clarity greatly influences light availability and different seagrass species vary in their ability to tolerate low light intensities, which also affects the vertical distribution of species. Generally speaking, smaller broad-bladed species such as the genus *Halophila* are more tolerant to lower levels of light availability due to water depth or turbidity from high sediment loads resulting from land runoffs and anthropogenic pollution (Nordlund *et al*. 2016). Hence the species composition of a seagrass community can be a direct reflection of the water quality and degree of disturbance in coastal regions. Nutrient availability and water temperature not only influence seagrass growth (Lee *et al*. 2007) but also stimulate the growth of algae (Mosley & Aalbersberg 2003) and epiphytes on seagrass blades, which in turn reduce light reaching seagrass blades (Burnell *et al*. 2014). As sea levels rise, the deepening of water over reefs is expected to reduce the absorption of wave energy from the open ocean, this may fundamentally alter the sheltered lagoonal conditions where seagrasses currently flourish (Saunders *et al*. 2014).

Seagrass Value & Ecosystem Services

Seagrass habitats are nearshore ecosystems considered as one of the world's most financially valuable natural ecosystems (Baker *et al*. 2015). In Melanesia the value of seagrass has recently been estimated at 151.4 billion $USD, which is 42 billion more than mangroves and 5.7 billion more than coral reefs in the same region (Hoegh-Guldberg & Ridgway 2016). In the tropics, seagrass, along with mangroves and coral reefs, contribute significantly to the health, welfare and daily livelihoods of the majority of the 1.3 billion people estimated to live within 100 km of the coast, particularly in developing countries (Sale *et al*. 2014; Saunders *et al*. 2014). The vulnerability of these coastal ecosystems and their contribution to tropical Pacific fisheries and aquaculture is well documented in by Bell *et al*. (2011).

Seagrasses achieve their high value by providing a wide range of ecosystem services (Nordlund *et al*. 2016, Nordlund *et al*. 2017b). These ecosystem services are natural processes and components benefiting human needs that can be classified as regulating, provisioning, supporting and cultural (Millennium Ecosystem Assessment, 2005). These services can be both proximal and distal to the habitat ranging from coastal protection and food provision to providing services to tourism and cultural practices

(Christianen *et al*. 2013, Tuiwawa *et al*. 2014, Marsh & Sobtzick 2015). Ecosystem services from seagrass habitats can also include: sediment retention leading to a decrease in exposure to pathogens in humans and invertebrates including corals (Lamb *et al*. 2017); current and hydrodynamic (wave) dampening; water filtration; and primary production. Seagrass habitats also provide a global nursery habitat for juvenile fish and other invertebrates, seeking shelter from harsh conditions and predation (Cullen-Unsworth & Unsworth 2013, Cullen-Unsworth *et al*. 2013).

Table 2. Twenty-four ecosystem services provided by seagrass genera in the tropical Indo-Pacific (adapted from Nordlund *et al.* 2016). Key: A. compost fertilizer, B. fish habitat, C. human food, D. food from seagrass associated species, E. invertebrate habitat, F: nursery (juvenile habitat) G. raw materials, H. vertebrate habitat including birds, I. carbon sequestration, J. coastal protection, K. geomorphology, L. sediment accretion, M. sediment stabilization, N. animal food, O. mariculture (as a substrate), P. seagrasses as food for animals, Q. water purification, R. bequest value, S. cultural artefacts, T. education, U. recreation, V. research, W. spiritual values, X. tourism. 1 = service present, 0 = service absent, ? = unknown, * addition error in Nordlund *et al.* 2016.

Seagrass Genus	**Ecosystem Services**																								
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**	**P**	**Q**	**R**	**S**	**T**	**U**	**V**	**W**	**X**	**Total**
Halophila	?	1	0	1	1	1	0	1	1	0	0	1	1	1	?	1	1	1	?	1	1	1	?	1	16
Ruppia	0	1	0	0	1	1	0	1	1	0	?	1	0	1	0	?	1	1	?	1	1	1	?	1	13
Halodule	0	1	0	1	1	1	0	1	1	?	?	1	1	1	?	?	1	1	?	1	1	1	?	1	15
Syringodium	?	1	1	1	1	1	0	1	1	?	?	1	1	1	1	?	1	1	?	1	1	1	?	1	17
Thalassadendron	?	1	0	1	1	1	?	1	1	1	?	1	1	1	?	?	1	1	?	1	1	1	?	1	16
Cymodocea	1	1	0	1	1	1	0	1	1	1	?	1	1	1	1	?	1	1	?	1	1	1	?	1	18
Thalassia	1	1	1	1	1	1	1	1	1	1	?	1	1	1	1	?	1	1	?	1	1	1	?	1	20
Zostera	0	1	0	1	1	1	0	1	1	1	?	1	1	1	1	?	1	1	?	1	1	1	?	?	16*
Enhalus	?	1	1	1	1	1	1	1	1	1	?	1	1	1	1	?	1	1	?	1	1	1	?	1	19
Total genera (confirmed to provide service)	2	9	3	8	9	9	2	9	9	5	0	9	8	9	5	1	9	9	0	9	9	9	0	8	
Total unknown (data required)	4	0	0	0	0	0	1	0	0	2	8	0	0	0	3	8	0	0	9	0	0	0	9	1	

Healthy sustainable ecosystems provide up to 24 different services in the tropical Indo-Pacific that contribute to human survival and well-being (Nordlund *et al*. 2016; Table 2). From this information, it is clear that ecosystem services vary considerably among seagrass genera with smaller genera such as *Halophila* having relatively low importance for coastal protection (debated by Christianen *et al*. 2013) and geomorphology (but has up to 16 other associated ecosystem services) while larger genera such as *Cymodocea, Enhalus, and Thalassia* are considered to contribute comparatively more to coastal protection. The genera *Thalassia* and *Enhalus* have the highest recorded number of currently documented ecosystem services in the tropical Indo-Pacific and are the only two genera recorded to be used as a raw material. The role of *Syringodium* and *Halodule* in coastal protection is recorded as unknown. From the same study, data is lacking for the Indo-Pacific in regard to five ecosystems services namely: use of seagrass for compost fertilizer; the role of seagrass in geomorphology; seagrass as food for animals; the use of seagrass for cultural artefacts; and spiritual value. Conservation decisions for different seagrass habitats, have different seagrass species assemblages, therefore there is a need to take into account that ecosystem service benefits may vary by location and habitat type.

With regards to climate change mitigation, seagrass habitats, along with mangroves forests, are now well-recognised globally as major organic carbon sinks, more stable and superior to terrestrial ecosystems, with the ability to absorb and store “blue carbon” over the long term (Macreadie *et al*. 2015). There are, however, knowledge gaps and untested assumptions that are considered to limit accurate valuation of “blue carbon” in terms necessary for carbon-trading (Gallagher 2017). This is particularly true in tropical Oceania where information variability on carbon storage among different seagrass habitat types is much needed (Lavery *et al*. 2013). Along with saltmarshes and mangroves, seagrass habitats are estimated globally to take in up to 70% of marine inorganic carbon (Nellemann *et al*. 2009; Githaiga *et al*. 2017; Gullström *et al*. 2017). Moreover, seagrasses alone are considered responsible for approximately 10-15% of global ocean organic carbon storage, with values ranging between 2.5 to 7.3 Mg C Ha-1 (Fourqurean *et al*. 2012). This makes seagrasses one of the planet's most efficient natural carbon capture and storage (CCS) mechanisms, with the ability to partially mitigate local increases in dissolved carbon due to their high below-ground root biomass which effectively traps and buries organic carbon for thousands of years (Russell *et al*. 2013; Macreadie *et al*. 2014). A caveat exists however, in relation to the critical nature of the ratio of inorganic to organic carbon in seagrass ecosystems to classify them as holistically carbon negative or positive, with highly productive warm tropical seagrass habitats containing a large number of organisms that release CO_2 during calcification having a net efflux of inorganic carbon offsetting biological carbon storage (Howard *et al*., 2017). This could have important implications in selecting truly carbon-negative sites for conservation, especially in tropical areas.

What is Already Happening?

Loss of Pacific Seagrass Populations

Despite their vital social and ecological value, seagrass communities are declining yearly worldwide by over 7% (Cullen-Unsworth & Unsworth 2013), with about 29% of the world seagrass stock having already been destroyed (Waycott *et al*., 2009; Coles *et al*. 2011) mostly due to human activities, with further anticipated losses due to global warming and climate change (Short *et al*., 2016). There has been reports of massive losses in stored seagrass carbon after periods of elevated seawater temperature in Australia (Arias-Ortiz *et al*. 2018). In the tropical Pacific, seagrass habitat losses by the year 2100 are estimated at between 5 to 35% (Waycott *et al*., 2011). Knowledge of seagrass occurrence and area cover is poor or not documented for many of the independent PICTs, the therefore the extent of any loss at a national or regional level cannot currently be determined. There are however reports of seagrass maintaining status in locations with low human population (Aioi & Pollard 1993) and losses in more populated areas (e.g. Vuki 1994, Cullen-Unsworth *et al*. 2013, Short *et al*. 2014) and there is a clear need for more information.

Escalating Anthropogenic Threats

Globally, we are at a critical time in human history because we have failed over the last 25 years to make sufficient progress in solving foreseen environmental challenges, such as global warming, with the exception of stabilizing the stratospheric ozone layer (Ripple *et al*. 2017). However, climate change is not the immediate main stressor on seagrass habitats and could even be used for delaying action from more immediate localised threats such as poor catchment management, nutrient runoff and poor coastal infrastructure regulation. Coastal flooding, siltation and a lack of water clarity, for example, are much more likely once forest or other vegetation cover has been removed from water catchments. The current demographics of some of the most populated independent PICTs in Melanesia (e.g. Papua New Guinea, Solomon Islands, Vanuatu) are projected to almost double by the year 2050 (SPC, 2016), concurrently putting huge additional anthropogenic pressure on already endangered coastal habitats at these localities.

Anthropogenic threats to seagrass resources can be divided into two groups; those linked clearly to climate-change such as increased storm strengthen, sea level rise, increased temperature and CO_2 levels, ocean acidification and exposure to increased wave energy, and those not directly related to climate change such as water quality and poor catchment management practices (includes pollution, land runoff and nutrient loads), and urban expansion and poorly planned coastal infrastructure. In addition, seagrass habitats such as those of *Halodule uninervis* on coastal flats in Fiji (Figure 2) and other relatively "high" islands typically have a rich holothurian fauna (*Synapta* spp., *Holothuria* spp., Figure 3) that along with other keystone species are beneficial to sediment turnover, oxygenation and sediment production (Reise 2002). Unfortunately, in at least some coastal communities, the commercial over-fishing of these holothurian resources for Asian markets is causing change in the shallow-water sediments (Lee *et al*. 2017) which could be changing seagrass habitats through a disruption of the ecosystem balance.

Policy Gap & Lack of Awareness about Value & Ecosystem Services

Seagrass habitats and their associated ecosystems services are too often marginalised and absent from global and regional conservation agendas (Duarte, 2000; Coles *et al*. 2011). Seagrass ecosystems are still currently under-recognised and under-valued by stakeholders in the tropical Indo-Pacific particularly for their commercial, artisanal and subsistence fisheries contributions as well as for wider ecosystem services (Unsworth & Cullen 2010, Coles *et al*. 2011, Cullen-Unsworth 2014), nor is their economic importance adequately addressed in Pacific island-related coastal and marine/ocean policy frameworks. There is a very clear lack of communication of the value of seagrass ecosystem services back to local communities to justify conservation efforts, and the public perception of the value of seagrass is not strengthened with unambiguous examples that stakeholders can relate to (Nordlund *et al*. 2017).

Figure 2. Seagrass exposed at low tide on coastal flats at Naselesele Taveuni Island, Fiji. Photograph A. N'Yuert

Figure 3. *Holothuria scabra* (juvenile) a commercially significant holothurian invertebrate species found naturally in some coastal seagrass habitats. Photograph G. Brodie

Lack of Basic Information on Existing Seagrass Habitat

The impacts of climate change on seagrass can only be understood if the baseline information, on seagrass such as mapping, species assemblages present and biomass, is available. Variability within seagrass habitats, and also between different genera of seagrasses, in response to seasonal changes in environmental parameters such as water quality, dissolved oxygen (DO), carbonate chemistry (pH), salinity and water temperature is still largely unknown for many developing country PICTS. It may therefore be difficult to recognise any degradation or damaging effects of anthropogenic pressure on near-shore habitats occurring slowly over medium to long term timeframes. The size of seagrass habitats and the amount of carbon stored in different habitat types, is also largely unknown in PICTs and it is important to recognise that not all seagrass habitats are the same.

What Could Happen?

There is strong consensus that climate change impacts will significantly impact on seagrass habitat. Climate change is expected to exacerbate anthropogenic impacts on seagrasses and intertidal flats in the tropical Pacific (Waycott *et al*. 2011). Losses are expected to occur as a result of increased heat stress, increased sedimentation and turbidity due to higher rates of runoff, changes in suitable sites for growth of seagrasses due to rising sea levels, and possibly more physical damage from the combination of sea-level rise and more severe cyclones and storms. Sea level rise and the deepening of water over reefs would reduce the absorption of wave energy from the open ocean, fundamentally altering the sheltered lagoonal conditions where seagrass currently flourish (Saunders *et al*. 2014). Global mean sea level rise will continue during the 21st century, very likely at a faster rate than observed from 1971 to 2010 (IPCC 2014). For the period 2081–2100 relative to 1986–2005, the rise will likely be in the ranges of 0.26 to 0.55 m for RCP2.6, and of 0.45 to 0.82 m for RCP8.5 (medium confidence). Sea level rise will not be uniform across regions but by the end of the 21st century, it is very likely that sea level will rise in more than about 95% of the ocean area. About 70% of the coastlines worldwide are projected to experience a sea level change within ±20% of the global mean (IPCC 2014). For seagrass habitats in PICTs, this could translate into a variety of responses and influences as follows:

Human Population Increase

Predicted increases in human population in Pacific Island countries and basic issues of food security and health will become so much of a priority that issues related to ecosystems (such as seagrass habitats) not seen as valuable for sustainable development will be eclipsed. The associated challenges of providing food and health care for such increased numbers of people will be a priority for already challenged governments and detract from environmental actions that are not seen or perceived to be of direct benefit.

Carbon Dioxide and Ocean Acidification

Rising atmospheric carbon dioxide levels as a result of the anthropogenic burning of fossil fuels has led globally to a 26% increase in ocean acidity over the last 200 years, with a further drop of 0.2 to 0.3 pH units by 2100 expected (IPCC 2014). With the expected continued inputs of carbon dioxide into the atmosphere, productivity and carbon storage capacity of some seagrass habitats is likely to increase dramatically (Russell *et al*. 2013), while at the same time locally reducing ocean acidification through the intake of dissolved carbon dioxide (Unsworth *et al*. 2012). Increased CO_2 levels are likely to lead to heightened seagrass physiological performance, with increased photosynthetic activity (Rehpolho *et al*. 2017). However, the effects of long-term exposure to elevated levels of carbon dioxide (CO^2) on seagrass communities are considered to be poorly understood (Takahashi *et al*. 2015). Campbell & Fourqurean (2013) found that structural characteristics were unresponsive to CO^2 enrichment in the tropical seagrass *Thalassia testudinum* but that below ground, non-structural carbohydrates increased by 29% therefore influencing both the nutrient status and the resilience of the overall system. Although progressive ocean acidification may lead to higher seagrass cover and above and below ground biomass, the studies of Takahashi *et al*. (2015) indicate that higher CO_2 levels may also lower size-specific growth and alter species composition in tropical seagrass communities.

According to Waycott *et al*. (2011) “The greater projected productivity of seagrasses, and the changes in their species composition, under higher levels of CO^2 are expected to flow-on to increase the ecosystem services provided by seagrasses in places where other impacts are minimised. In particular, the richness and productivity of food webs supported by seagrasses may increase, and the shelter that plants provide for juvenile fish and invertebrates …. may be enhanced.”

Tropical seagrass habitats could increasingly become refugia for a range of invertebrate communities including high-value molluscs, crustaceans and echinoderms, where the increased overall productivity of the system buffers the negative effects of ocean acidification (Garrard *et al*. 2014). However, seagrass carbon storage capacity, both above and below ground, could be limited by the ability of seagrass to productively utilise any expected increase in dissolved inorganic carbon in seawater because of potential changes in water quality (light availability) via major influences like land runoff (Ow *et al*. 2016).

Seawater Temperature & Link to Extreme Weather Events

Overall, increased oceanic temperature will be one of the most important environmental stressors on seagrass habitats as clearly shown by the recent massive seagrass carbon storage losses recorded after highly elevated seawater temperatures in Australia (Arias-Ortiz *et al*. 2018). Different tropical seagrass species show different tolerances to increased seawater temperatures (Campbell *et al*. 2006) but thermal tolerance has not been well studied in seagrass in independent PICTs. However, generally speaking, tropical species have higher optimal growth rates than temperate species, with some species surviving at temperatures as high as 32°C while others begin to show shoot mortality above 26°C (Lee *et al*. 2007). In most tropical species, reductions in growth and increases in respiration rates were seen at higher temperatures (Short *et al*. 2016) and temperature extremes are known to reduce seagrass growth and lead to mortality (Collier & Waycott 2014).

Increases in seawater temperature also translate into increased disturbance via stronger extreme weather events such as heavy rainfall and tropical cyclones and storms, which put additional stress on seagrass habitats through direct physical damage, increase in turbidity causing reductions in photosynthetic rates and growth, and a general loss of ecosystem resilience and productivity.

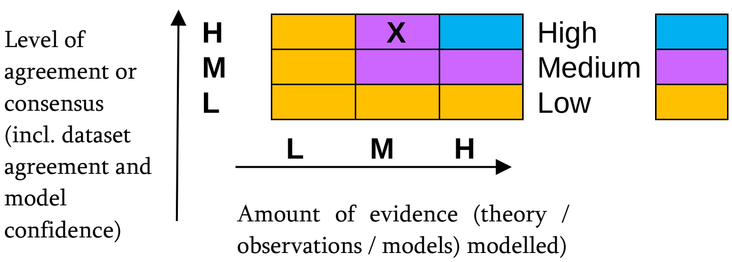
Sea-Level Rise

The effects of sea-level rise on seagrass habitats can be variable, depending on the habitat and surrounding topography. Studies have estimated that globally there may be up to a 17% loss in seagrass area through a rise in sea-level of 1.1 m by 2100 (Saunders *et al*. 2013), yet in many cases, a deepening of the water resulting in lower light intensity and photosynthetic productivity could be compensated by a landward migration of the seagrass community, if extensive shallow mudflats are present (Short *et al*. 2016). However, in areas of strong coastal development, man-made structures and land reclamation will put a stop to the landward migration of seagrass, and in such case seagrass communities could be severely reduced in size or disappear altogether, along with all their associated ecosystem services. Coastal planning would therefore need to take into account sea-level rise effects and allow for the landward migration of not only seagrass but also mangroves and their associated fauna.

Interacting Factors and Overall Prognostic
While a future increase in CO_2 could increase the photosynthetic pigments in seagrasses and hence the efficiency of organic carbon influx, this may be unable to counteract the deleterious effects on growth of increased water temperature as a result of unequivocal global warming (IPCC, 2014). This could lead to a net decrease in seagrass cover, especially in warm tropical areas. Seagrass coverage could also decline because of increases in algal epiphytes, driven by rising nutrient levels, and elevated turbidity levels reducing the light intensity required for photosynthesis reaching seagrass leaves (Burnell *et al*. 2014).
All factors being considered, gains and losses in seagrass habitat will occur but most importantly the extent of anthropogenic stress on these habitats will be the ultimate decisive variable. Thus, there is an essential need for substantially improving the sustainability of our current environmental practices and lowering our human impact on coastal ecosystems, to facilitate resilience to climate change.

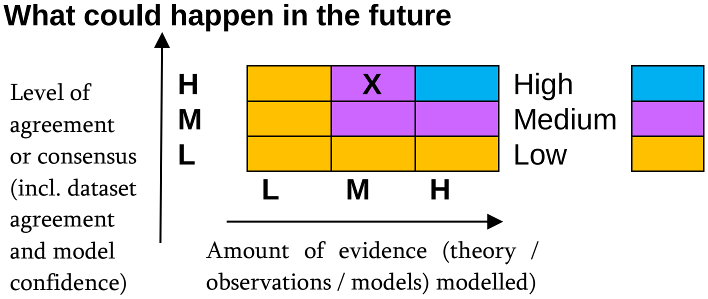
Confidence Assessment

What is already happening



It is very clear that seagrass resources are in decline globally as a result of anthropogenic impacts including climate change (Waycott *et al* 2009). It is also clear, because of evidence to support climatic change and increasing human related pressures on coastal ecosystems via land-based threats and overharvesting, that Pacific Iiland seagrass resources are highly likely to be following this trend as shown in the Western Pacific by Short et al. (2014).

What could happen in the future



As a result of expected increasing human population and related pressure on coastal ecosystems like seagrass habitat (Orth *et al*. 2006), effective management of coastal resources such as seagrass habitats will be particularly challenging in Pacific island developing countries with low or medium Human Development Indices (HDI) and low GPD (Table 3) where marine-related options for small or remote communities to address poverty and food security are challenging (Bell *et al*. 2009).

Thus, for seagrass ecosystems in the independent developing country Pacific Islands there will be a significant increase in the vital need to focus on elements that can be controlled at a local level, such as national and community led natural resource management. There will be a vigorous need for public education and a substantial strengthening of environmental regulations, particularly focused on uniting the research and business sector. This emphasis on improving environmental health is vital so that seagrass habitats will be resilient enough to withstand the predicted impacts of future climate change as per the IPCC (2014).

Most importantly, effective management of coastal seagrass resources will not only significantly contribute to addressing poverty and human well-being via ecosystem services but have the potential to mitigate climate change pressures because of their potentially exceptional carbon storage ability.

Knowledge Gaps

Policy: Despite the vital economic importance of seagrass ecosystems, particularly in the larger, high-island independent countries of the Pacific island region (see Hoegh-Guldberg & Ridgway 2016), seagrass resources have not been explicitly included in relevant regional policy frameworks such as the Pacific Island Regional Ocean Policy & Framework for Integrated Strategic Action (SPC 2005) and the Framework for a Pacific Oceanscape (Pratt & Govan 2010). This weakness in big picture enabling environment has very likely limited capacity building and access to support and funding for research and management of developing country Pacific island seagrass resources.

Mapping & Coverage: The extent of seagrass area coverage is reliably unknown at a national level in any Pacific Island country or territory except Wallis and New Caledonia, the latter which has by far the highest

GDP per capita in the region (Table 3). Thus, estimating losses or gains at a national level or collating regional trends is almost impossible because without baseline mapping of the extent of the resource, no adequate comparisons for determining loss or gain status are possible. This lack of basic data on seagrass occurrence, area coverage and loss or gain status across the PICTs creates a considerable risk that the importance of seagrass resources in several locations will be considerably under-estimated.

Research - socio-economic: There are significant studies that compare seagrass resource use in terms of socio-economic impacts linked with ecosystem services and fisheries activities (Nordlund *et al*. 2016, Nordlund *et al*. 2017a). These studies include the value of traditional use, which varies considerably by seagrass genera and by geographical location. The study of Cullen-Unsworth *et al*. (2013) used a Fijian case study to examine seagrass meadows as coupled social–ecological systems, connecting seagrass habitat to human well-being. However, as noted by the authors, a knowledge gap exists for dedicated detailed studies connecting seagrass and human benefit and use in any of the independent PICTs. We need to clearly and explicitly document the links between seagrass and a wide variety of fisheries activities. Such studies in the future which collect new data and expand on brief comments like those of Tuiwawa *et al*. (2014) (that seagrasses are used for roofing, basket weaving and sinnet (braided cordage)) would be of considerable value. Additionally, Nordlund *et al*. (2017a) looked in detail at the purpose and method of fishing in seagrass habitats in many parts of the world. This study included New Caledonia and north-eastern Australia within the tropical Indo-Pacific bioregion, both of which have very high Human Development Indices (UNDP-HDR 2016). It would be very useful to conduct a similar detailed comparative study in several of the 14 independent PICTs which have comparatively lower HDI and low GDPs (Table 3) (such as the Solomon Islands, Vanuatu, Fiji, Samoa or Kiribati) because the economic and livelihood reliance on coastal seagrass resources for food and income is likely to be quite different in these countries than in countries like Australia or New Caledonia.

Research - Environmental: There is a severe lack of collated data in many of the independent PICTs that measures the extent of impact of land-based pollution to coastal ecosystems, including seagrass habitats. Such land-based pollution includes poorly regulated catchment management practices as well as aquatic and land-based pollution (Mangubhai *et al*. in press).

Table 3. A comparison of GDP, HDI and annual human population growth rate for the PICTs listed in alphabetical order and governance structure as per Gillett (2016).

Country or Territory Name	GDP Per capita USD as per SPC (2015)	HDI as per UNDP-HDR (2016)	% Annual Growth Rate as per SPC (2015)
Independent Countries			
Cook Islands	19,523		0.2
Federated States of Micronesia	3,056		0.3
Fiji	3,757	high	0.5
Kiribati	1,442	medium	-
Marshall Islands	3,524	-	0.5
Nauru	11,015	-	1.1
Niue	12,945		-1.1
Palau	13,835	high	0.3
Papua New Guinea	1,931	low	2.3
Samoa	4,231	high	0.7
Solomon Islands	1,643	low	2.3
Tonga	4,280	high	-0.1
Tuvalu	3,253	-	0.4
Vanuatu	2,864	medium	2.5
Territories			
American Samoa (USA)	12,584		0.3
French Polynesia (France)	22,531		0.6
Guam (USA)	27,908		0.9
New Caledonia (France)	38,100		1.5
Northern Mariana Islands (USA)	12,239		0.5
Pitcairn Island (Britain)	2,353		-
Tokelau (New Zealand)	-		0.0
Wallis & Futuna (France)	12,399		-0.9

Regulations, and compliance with regulations, in rapidly expanding urban areas where compliance to modern governance “laws” operate is often weak (Figure 4). Additionally, research is needed on the effects of changes in nutrient discharge and water temperature on seagrass epiphytes as well as fauna found in seagrass habitats. We also have very limited knowledge of the reproductive cycles of seagrass in the PICTs, which restricts our ability to effectively utilise possible mitigation methods like the regeneration of seagrass habitats from seeds. McMillan (1982) looked at the reproductive physiology of tropical seagrasses while Inglis (1999) and Orth *et al*. (2007) examined variation in the recruitment behaviour of seagrass seeds and the ecology of seagrass seeds and seagrass dispersal processes respectively. Dedicated studies in any of the 14 independent Pacific island countries that looks explicitly at seed banks or seed ecology is lacking, although Brouns & Heijs (1985) and Brouns (1987) worked in Papua New Guinea on seagrass production and biomass.

Figure 4. Septic tanker directly discharging raw sewage into a coastal estuary near fish markets in Suva, Fiji. An obvious example of blatant non-compliance to environmental pollution laws. Photograph G. Brodie.

Research – Ecosystem Services including Blue Carbon: The inter-linkage of seagrass related ecosystems services in combination with adjacent habitats such as mangroves and coral reefs (Guannel *et al*. 2016) needs to be acknowledged and explored in a PICT context as this will better inform management decisions and the formulation of conservation priorities. Global research on the extent of past, or current, carbon storage capacity and biomass of seagrass habitats (both above and below ground) will increase awareness of the need for seagrass habitats to be valued for their significant role in climate change mitigation (Fourqurean *et al*. 2012, Lavery *et al*. 2013, Macreadie *et al*. 2014). Although research in at least some of the 14 independent PICTS (e.g. Lawrence 2012, Vierros 2017) has occurred, more is needed as it is debatable if general seagrass facts on the role of Blue Carbon in climate change mitigation discovered elsewhere are always transferable to every PICT scenario.

Monitoring Status & Government Processes: There is inadequate funding, in developing country PICTs, to support long-term seagrass monitoring coordinated at a national or regional level, so our understanding of both "natural" and human induced change in seagrass habitats is limited. Seagrass monitoring in several locations within at least two countries, i.e. Fiji and the Solomon Islands, started well over ten years ago but relatively little data has been published in the peer reviewed literature. Exceptions are Short *et al*. (2014) and Cullen-Unsworth *et al*. (2013) which include data from the Federated States of Micronesia and Palau, and a case study from Fiji respectively. We recommend that funding be sourced to place stronger emphasis on publishing data, building local research capacity and connecting monitoring to relevant local government agencies to assist with strengthening regional policy development and assisting with national obligations such as National Biodiversity Strategic Action Plan (NBSAP) processes.

Socio-economic Impacts

If well managed, seagrass resources in the Pacific Islands have the potential to substantially increase their already significant value and contribute substantially to socio-economics. Given the traditional Pacific island governance structures and very high level of "ownership" of resources by communities themselves the key to achieving successful management is to acknowledge traditional practices and reduce the risk of significant socio-economic impacts on humans. This will be inherently difficult in developing countries such as Vanuatu and the Solomon Islands, where human population numbers are predicted to increase substantially in coming years, with the number of humans needing to be fed in these two countries predicted to double by the year 2050 (Pacific Community 2016).

The relative lack of understanding of the true value of seagrass habitats and their link to human well-being (Cullen-Unsworth *et al*. 2014), their marginalization and the well-documented bias towards coral reefs, as stated by Coles *et al*. (2011) and Duarte *et al*. (2008), is perhaps one of the greatest risks to human welfare and livelihoods. Despite the estimated high value of seagrasses resources in Melanesian countries at least (Hoegh-Guldberg & Ridgway 2016), we consider value is placed more highly on marine resources such as coral reefs probably because of their visual beauty, publicly recognised connection to tourism and also their better-documented and understood connection to fish and fisheries. In addition to this imbalance it is also important to remember that perceived value in westernised societies may be very different to that perceived by Pacific island societies (Foale *et al*. 2016).

It is imperative that research efforts recognise the intimate connection between seagrass resources, mangroves, and coral reefs (Guannel *et al*. 2016) and that the functional ecological connection is understood and acknowledged in a holistic manner during policy development and resource planning at both a top down and bottom up level. Climate change, pollution and poor catchment management has, and will have in the future, major impacts on both commercial and subsistence use of seagrass habitats, the provision of ecosystem services and in turn the socio-economic welfare of coastal communities.

Climatic and environmental conditions are changing worldwide (IPPC 2014) including in Pacific island countries (Kumar *et al*. 2013; 2014) the latter particularly in coastal areas (see Mosley & Aalbersberg 2003) where seagrass resources are likely to be present. For both urban and rural communities it is sometimes difficult to separate different environmental threats that impact on the socio-economic welfare of communities. Therefore, it is a risk that communities and the general public may confuse the coastal degradation resulting from poor catchment management practices (e.g. flooding, land runoff, pollution) with those resulting from human-induced climate change (inundation, increased storm surge intensity). The former are considered to be threats under national government and land owner control and the latter being difficult for local people to change.

Reduction of coastal fisheries productivity (subsistence and commercial) and therefore a weakening in human food security and human health, as well as reduction of income and physical activity to women gleaning in nearshore coastal environments, such as seagrass habitats, is well acknowledged (Bell *et al*. 2009; Pratchett *et al* 2011). It is also known that this reduction in turn produces a reduction in the ability of communities to maintain cultural practices – see Nordlund *et al*. (2017). Exactly how much reduction is occurring as a result of climate change impacts or more localised land-based human activities on seagrass habitats in the Pacific Island region is currently unknown. However, as shown by Verweij *et al*. (2008), many important Pacific island coral reef and fisheries species have close associations with seagrass habitats, either as a food source e.g. lobsters *Panulirus* species, or as preferred habitat particularly during the juvenile stages e.g. rabbit fish *Siganus* spp. (see Lee *et al*. 2018 and references therein). For example, in Fiji eight of the 44 species highlighted as significant fisheries resources have a specific link to seagrass, while others are linked to estuarine habitats within which seagrasses are likely to occur.

Resilience-Building, Regenerative Measures and Emerging Good Practice

Resilience to change in PICTs may be covered by the seagrass resilience framework proposed by Unsworth *et al*. (2015). Tool development for inclusion of seagrass mapping in tropical marine protected areas as per Torres-Pulliza *et al*. (2013) have been targeted to build resilience, however we are uncertain if any direct regenerative measures explicitly related to seagrass and seagrass habitats in the PICT region have occurred. Seagrass monitoring and conservation of coastal seagrass areas are included by default in a large number of relatively small but significant near-shore community-based projects in the region. For example, Tetepare Descendant Association (TDA), in the western Province of the Solomon Islands, protect Tetepare Island and its surrounding marine waters (Read 2011) where seagrass monitoring (Moseby 2006, Figure 5) has been on-going for over 10 years and has expanded to 33 sites. Similar community run conservation activities operate via the Locally Managed Marine Areas (LMMA) network and there are significant cross habitat plans for big-picture long term protection of globally significant marine areas such as the Great Sea Reef in Fiji.

The role of sexual and asexual reproduction, seed bank dynamics and species composition in recovery of tropical disturbed seagrass communities has been studied along the coast of Queensland Australia by Birch & Birch (1984), Preen *et al*. (1995), Campbell and McKenzie (2004) and Rasheed *et al*. (2014) respectively.

Figure 5. Women from local Tetepare Descendant Association (TDA) communities monitoring seagrass in western providence, Solomon Islands. Photograph K. Soapi.

Studies in Torres Strait Island waters, in far northern Australia, have shown that seagrass recovery varies with species and with tidal location and that sexual reproduction is most likely required for recovery from larger disturbances (Taylor *et al*. 2013). Restocking of seagrass habitats using seedlings or seeds may not be a cost effective or a successful disturbance recovery strategy as life stage survival can depend on many different factors including habitat depth, species, seed density and the ability to obtain enough viable seed (e.g. see Statton *et al*. 2017; Rasheed *et al*. 2014). However, seagrass rehabilitation or restoration through seeding (Orth *et al*. 2006) and transplantation of seedlings (Van Katwijk *et al*. 2009, McSkimming *et al*. 2016) are possible options for restoring seagrass habitat. However, it is currently unknown if restocking is needed in any area of the Pacific islands or if current environmental conditions would allow such activities to be successful. It is also relevant to note that the worldwide success rate of transplantation and restoration programs has been estimated at approximately 30% (Fronseca *et al*. 1998; Green & Short, 2003) and this would need to have a considerably lower risk to even consider Pacific island implementation.

Taylor *et al*. (2013) predicted changes to climate variables in Torres Strait and the wider Pacific region "could have far reaching consequences for local seagrass community distribution and structure, which in turn may have profound implications for local dugong, turtle and commercial fisheries species". We agree with their conclusion that the management of seagrass resources in relatively remote small island areas "should be focused on reducing any anthropogenic impacts to seagrass to ensure resilience levels of local seagrass populations remain high" because this will provide the best possible chance of mitigating the predicted impacts of climate change. To contribute to this goal, seagrass monitoring training, awareness and capacity building with youth has occurred, in partnership with local communities and youth education organisations, in the Torres Straits for many years (Mellors *et al*. 2008).

The need for building local research capacity in seagrass ecosystems is high, particularly in the independent Pacific island developing countries (Table 1). In many of these latter countries substantial marine capacity building activities are occurring for example the Coral Triangle Initiative in PNG (Maclean & Mallery 2014) and the Micronesian Challenge in FSM (TNC 2017). At the University of the South Pacific local human resource and research capacity building in seagrass ecosystems has occurred (e.g. Vuki 1994; Koshy 2001, Skelton & South 2014, Tuiwawa *et al*. 2014) and seagrass habitat surveys are part of the postgraduate curricula (Figure 6a & b). Since the University of the South Pacific is owned and operated by 12 of the 14 independent developing country governments in the Pacific region it therefore has a major role to play in research capacity building for seagrass resource management particularly via local and regional postgraduate research projects by national youth. Three such projects are currently in progress with support from external research organisations such as: University of Adelaide; University of Western Australia, Centre for Environment, Fisheries and Aquaculture Science (Cefas) in the United Kingdom; and organisations such as the Office of the Pacific Ocean Commissioner, Commonwealth Marine Economies Program, European Union and the Global Climate Change Alliance.

Substantial regional training by world-class and globally-recognised research and monitoring agencies such as NOAA's Ocean Acidification Program have also recently been hosted by the University of the South Pacific and training has been conducted specifically on building local research and associated policy capacity in understanding and monitoring ocean acidification. These hands-on training workshops organised and sponsored by many donors, such as The Ocean Foundation and New Zealand Pacific Partnership on Ocean Acidification, included experienced local scientists, researchers, education providers and policy makers from independent small island developing countries such as Fiji, Vanuatu, Papua New Guinea, Solomon Islands and Western Samoa and provided monitoring kits for establishing national ocean acidification monitoring to each of the countries involved.

Figure 6a. University of the South Pacific postgraduate students learning to appreciate and monitor seagrass in Suva Harbour during their postgraduate course work. Photo credit G. Brodie.

Figure 6b. Pacific Island youth from Nauru, Fiji and the Solomon Islands sample seagrass seeds in sheltered near-shore coastal environments. Photo credit G. Brodie.

It is very positive to see there is currently a regional program in place, the Pacific Ecosystem Based Adaptation to Climate Change (PEBACC) led by the Secretariat of the Pacific Regional Environment Programme (SPREP) with proposals and funding bids underway to progress national seagrass mapping and calculate carbon audits in the Melanesian Pacific Island countries of Fiji, Vanuatu, Solomon Islands and Papua New Guinea. These projects will include climate change modelling and in the relevant countries like Vanuatu, PNG and the Solomon Islands will also include conservation of the large seagrass feeding marine mammal *Dugong dugon* which was classified by Marsh & Sobtzick (2015) as vulnerable with a decreasing population trend on the IUCN Red List of Threatened species. Like the green turtle *Chelonia mydas,* which also feeds on seagrass, and is similarly threatened (Seminoff 2004), dugong are traditionally eaten by many Pacific Island communities and play important roles in cultural ceremonies (Butler *et al*. 2012; Marsh & Sobtzick 2015). The concept of Ecosystem-Based Management, where humans are seen as an integral part of the ecosystems they manage, is crucial if seagrass habitats are to be effectively managed and conserved in a way that is sustainable to both the marine habitats and the human populations that depend on them.

Conclusion

Currently the level of research and research funding for information generation in relation to seagrass ecosystems in the independent developing countries is inadequate to provide appropriate evidence-based decision making via both grassroots community efforts and higher policy frameworks. This is worrying considering that seagrass resources hold considerably more economic value than is currently acknowledged by the majority of stakeholders, i.e. an estimated value of $151 billion for Melanesia made in 2016 (Hoegh-Guldberg & Ridgway 2016) which is higher than both mangrove ($110 billion) and coral reef ($146 billion) resources in the same geographical area.

In some PICTs the separation of “environment” and “climate change” in national governance structures and the weak integration of planning and problem solving across ministries and across stakeholders requires considerable rethinking within an ecosystem-based framework as the current emphasis on economic development for the sole benefit of humans in a manner that is so obviously environmentally unsustainable can no longer be ignored (Ripple *et al* 2017).

In conclusion, four main directions are needed: we need to identify what seagrass resources exist; identify specific threats and vulnerable habitats/regions, including in relation to climate change; manage impacts such as water quality and coastal development to increase resilience; and then if those measures are not successful then management options such as restoration in areas where the initial reasons for seagrass habitat loss have been removed or previous threats substantially addressed could be considered.

Finally, a concerted effort needs to be made by all stakeholders to communicate the value of seagrass ecosystems and their services to local communities and governments, in a manner that is evidence-based and relevant to their lifestyle.

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