Climate Change Impacts to Turneffe Atoll

Turneffe Atoll Trust

2018

Author: Julio Benavides, PhD. Affiliated Researcher University of Glasgow. Postdoctoral researcher/Universidade Estadual Paulista (UNESP)
Cite as: Benavides, 2018. Climate change impacts to Turneffe Atoll. Turneffe Atoll Trust.

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SUMMARY

Climate change, a direct consequence of human activities, is already impacting Caribbean ecosystems. Scientific consensus exists that the Caribbean will continue to experience increases in air and sea temperatures, sea-level rise, ocean acidification and an increase in the frequency of hurricanes of high magnitude over the next decade.

Turneffe Atoll, located east of Belize city, supports the most diverse ecosystems of the Caribbean including coral reefs, mangroves, seagrasses and littoral forest. This Atoll is also critical habitat for many species of conservation and commercial interest including the Queen conch, the Caribbean spiny lobster, bonefish, permit, tarpon, marine mammals and several turtle species. This biodiversity provides important revenue for Belize's fishing and tourism industries as well as ecosystems services such as protection from wave surge and carbon sequestration.

This report summarizes the current and potential impacts of climate change to the ecosystems and key species of Turneffe Atoll. A review of the scientific literature highlights the immediate risk of an increase in the frequency of coral bleaching events and potential changes in the composition of mangrove forests, favouring mangrove species that are more resilient to sea-level rise.

Currently, mangroves, seagrasses and littoral forests are critically threatened by human disturbance including coastal development and pollution. This limits their possibilities for adapting to climate change and magnifies the negative effects of climate change by removing these important natural barriers.

Overall, there are major knowledge gaps about the impacts of climate change on Caribbean ecosystems. Very limited research has been done on the impacts to Queen conch and spiny lobster, how multiple effects of climate change will simultaneously impact each ecosystem, and the adaptation capacity of each species. Despite these uncertainties, climate change will continue and impacts to Turneffe Atoll are likely to accelerate when new thresholds of temperature are reached.

Managers and decision makers need to act now. Mitigations strategies for the Atoll must include better monitoring of changes in variables affected by climate and increased awareness of the critical ecosystem services provided by Turneffe Atoll.

Further destruction of key coastal habitats such as mangroves, sea grasses and littoral forest, which mitigate the negative effects of climate change, should be avoided. Likewise, other anthropogenic effects which destroy these important areas including pollution, unsustainable fishing and oil exploration, must be minimized. The inevitable and potentially devastating consequences of climate change for Turneffe Atoll and Belize can be significantly reduced by preservation of key mitigating habitats. Conversely, further destruction of these key habitats will magnify the impending negative effects of climate change for Belize.

I. INTRODUCTION

Climate change, a direct consequence of the increase in atmospheric C02 linked to human activities, is already impacting the globe and the Caribbean ecosystems [1,2]. The last century has witnessed a global increase in air temperature of 0.7°C, an increase in sea-level of 18cm, and increases in atmospheric C02 and ocean acidity by 26% since the industrial revolution [3,4]. Since the 1990s, the number and intensity of storms has also increased in the Atlantic ocean [4]. There is uncertainty about the extent and rate of future changes based on different simulation scenarios of carbon emissions and responses to these emissions [1,2]. However, there is consensus that, given current trends, temperatures in the Caribbean should rise between 1.4 and 3.2°C by 2100, that sea-level rise in the Caribbean will range from 0.18 to 0.59 m [5,6], and that there will be an increase in droughts and extreme rainfall events including more frequent hurricanes of category 4 and 5 [1,4]. Turneffe Atoll, located 32km out east Belize city, is considered the largest and most biologically diverse coral atoll in Belize and the Mesoamerican Reef ecoregion [7]. The Atoll includes a diversity of corals, mangroves and seagrasses ecosystems that serve as habitat for keys species including the Queen conch, the Caribbean spiny lobster, sport and commercial fishes, turtles, crocodiles and manatees. The Atoll is of high economic value for the fishing and tourism industry of Belize and it provides important ecosystem services such as protection from wave surge, shoreline protection from hurricanes and carbon sequestration [7,8]. Therefore, identifying and mitigating the current and future impacts of climate change to Turneffe is critical for the economy and welfare of Belize. The Caribbean region is already severely impacted by human activities including coastal development, unsustainable fishing practices and water pollution. Thus, challenges to Turneffe Atoll related to climate change will depend on an interaction between these immediate threats and changes related to climate. In this report, we summarize the expected impacts of climate changes to the ecosystems of Turneffe Atoll, highlighting local strategies that can help mitigate a global threat.

II. STUDY OBJECTIVE:

To identify the specific challenges of Turneffe related to climate change.

III. IMPACT OF CLIMATE CHANGE FOR TURNEFFE'S ECOSYSTEMS

This section identifies the specific impacts of climate change predicted for the four main ecosystems of Turneffe Atoll including coral reefs, mangroves, seagrasses and littoral forest (summarized in Table 1).

1- Coral reefs

Several effects of climate change are already impacting, or are expected to impact, the coral reefs of Belize [9]. Among them, the most likely impacts are related to increases in water temperature, sea acidification as well as sea-level rise and the frequency of hurricanes of category 4 and 5.

Temperature rise and coral bleaching

A strong correlation exists between high sea temperature and events of coral bleaching [6]. Coral reefs of the Caribbean Sea already lie near their threshold of temperature tolerance, and their reproduction and growth capacity is affected by increases in sea surface temperatures [10]**.** Coral reefs are expected to suffer severe degradation if temperatures exceed a warming mean temperature of 1.5°C, and widespread mortality is expected if warming exceeds 3°C [10,11]. Coral bleaching events associated with elevated temperatures have already occurred in Belize in 1995, 1998, 2005, 2010, 2015 and 2016. The mass bleaching event of 2005 was related to the highest sea temperature ever recorded [4]. A recent UNESCO report predicts that bleaching threshold temperatures will be exceeded by 2100 and that, given the current C02 emission's trajectory, severe bleaching heat stress events could occur twice a decade by 2028 and annually by 2036 [11]. Other effects of an increase in sea temperature are less studied, but they could also contribute to the decline of corals. For example, a decline in the coral coverage will increase habitat for macroalgae, which compete with coral reefs and suppress coral recruitment through several mechanisms including shading and production of anti-fouling compounds [12,13]. Pollution and habitat destruction have already contributed to more than doubling the surface of fleshy macroalgae in Belize to 21% in the last decade [9]. Warmer temperatures could also result in a higher frequency of coral disease outbreaks, with thermal stress and warmer temperatures associated to an increase in coral disease outbreaks such as White Syndrome or plague both in the Australia's Great barrier Reef and the Dominica [14,15]. The symbiotic relationship between algae and coral could also change with higher temperatures by becoming a parasitic relationship [16]. Overall, several negative effects of rising sea temperatures have already started, and the frequency of bleaching will increase in the following decades if temperature keeps rising.

Ocean acidification

Ocean acidification also has a negative impact on corals by reducing calcification and growth [11,12]. Thus, the predicted increase in levels of C02 and subsequent sea acidification will cause reef erosion. Coral calcification rates have already dropped by around 15% in Caribbean coral reefs since the Industrial revolution [3]. Corals response to reduce calcification are all expected to be detrimental, and could include reduced skeleton density and reproduction [12]. Coral reefs in Belize and throughout the Caribbean have alarmingly low rates of calcification, with only 26% of corals having positive carbonate production rates, and the large majority having rates below historical values [17]. The predicted rise of C02 will likely further degrade coral structure, making them more fragile to mechanical damages such as those produced by waves and storms [4].

Sea-level rise (SLR)

Sea level has increased by 1-3 mm per year since the 1960s and it is predicted to rise another 18-59 cm by 2100 [5,6]. The positive or negative impact of SLR on coral reefs seems to be dependent on the speed of the rise. Corals can keep up with SLR to a limit of around 10 mm/year [18]. If the SLR is too fast, a direct consequence of SLR is the possibility that deeper coral reefs will 'drown' by 2100 [3], which occurred 10,000 years ago in Maui when SLR was an average of 15 mm/year [19]. Increase waves generated by SLR could also cause mechanical damaged to corals [18]. However, several studies also show that corals could adapt to current SLR under certain conditions. For example, corals benefitted from an increase in cover after a SLR produced by an earthquake [20], while undisturbed corals in the Indian ocean recovered after a bleaching event, and are expected to grow within the SLR predicted to occur by 2100 [21]. Overall, coral reefs will struggle to keep up with SLR by increasing growth, and thus, detrimental effects are expected.

Increase in hurricane intensity

Although the overall frequency of Atlantic tropical cyclones is expected to decrease with a warmer climate, climate models project a 80% increase in the frequency of category 4 and 5 hurricanes over this century [4,22]. This will increase mechanical damage to corals and thus, negatively impact their survival. However, other more complex effects of storms could prove beneficial to stressed corals, because waves caused by hurricanes can remove excess heat from shallow water during bleaching events [6].

Corals at Turneffe

Turneffe Atoll is considered the largest and most biodiverse coral atoll in the Mesoamerican Reef region, and it is inhabited by several critically endangered and endangered species of coral such as the Staghorn coral (*Acropora cervicornis*) and the Elkhorn coral (*Acropora palmata*) [7]. It also has the highest cover of star coral in the region at around 18% [9]. While the 'Reef Health Index' (RHI) of Belize coral reef in 2018 was estimated as 'FAIR' (16% cover with and overall increase from 2006 to 2016), corals at Turneffe were evaluated as 'POOR' (5-10% coral cover) [9]. The state of the coral is also highly variable according to its location on the Atoll with a 'critical' RHI (<5% coral cover) in several sites in the North, while the South of the atoll has mostly a 'poor' RHI. The rich variety of coral reefs at Turneffe provides both commercial fishing and tourism benefits for Belize, along with coastal protection to attenuate waves. A large tourism industry exists due to derived benefits from coral reefs associated with scuba diving, snorkelling, ecotours, and sport fishing. The overall economic value of the Turneffe Atoll has been estimated to be at least US37M annually in tourism, US0.5M in fisheries and US38M in shoreline protection, for a total of US75.8M [8].

Consequences of climate change for corals at Turneffe

Given the substantial biodiversity of Turneffe's coral reef ecosystem and its major socio-economic value, the current and future negative impacts of climate change described above could have severe consequences for the livelihoods depending on these corals. An increase in the frequency of coral bleaching, and particularly of mass-mortality events, will directly reduce the tourism value of the Atoll and the fish diversity associated to this ecosystem. So far, the Atoll experienced only one mass coral bleaching of 1995, when sea surface temperatures reached a 12-year high of 31°C. Predicted water temperatures and high anomalies have been derived from satellite remote sensing, and were made available for Turneffe Atoll at a 1km resolution [7]. This monitoring will prove crucial when evaluating the risk of bleaching in the area. The complexity of the coral reef is one of the most important factors in determining their ability to protect from waves under current rising sea-levels [23]. Thus, eroded reefs by sea acidification and bleaching can reduce their role in mitigating wave damage for Belize city. Although the number of hurricanes of category 5 are relatively rare on the Atoll (e.g. 1 in the last 20 years, [7]), an increase in frequency of these events could further damage corals, which will in turn reduce their ability to protect coastal populations from waves generated by hurricanes. Local variations of different abiotic and human factors will modulate impacts of climate changes to the coral reefs surrounding Turneffe. Thus, monitoring of these factors are essential when estimating the speed of changes and the magnitude of their effect for corals at Turneffe.

2- ***Mangroves***

Mangroves are well studied resilient organisms and the possible impacts of climate change on this ecosystem have been extensively studied in the last decade [24]. The current highest threat to mangroves is human-induced destruction due to coastal development and pollution. This has resulted in a 24% decline in mangroves throughout the Caribbean over the last 25 years [24,25]. The impact of climate change on mangroves varies greatly according to their location. For example, mangroves are expected to expand their range in higher latitudes due to warmer and more suitable habitat, while negative effects are expected for mangroves in the Caribbean [25]. A recent report stated that 'the cumulative impacts of climate change - especially sea level rise, decreasing rainfall, an increase in extreme weather and loss of protection from waves and storms provided by coral reefs - are expected to cause a significant decline of mangrove ecosystems' in the Caribbean' [25].

Sea-level rise (SLR)

SLR is likely the most immediate and studied impact of climate change to mangroves [24]. An essential question is whether mangroves can sufficiently adapt to current and future sea rise by either increasing their accumulation of peat and mud or migrating landward. Accumulation depends on the sediment input, the rate of soil accretion, and local variations of sea level and topography [26]. The location and growth state of mangroves within a mangrove forest will also affect their response to SLR. Transition and interior zones, with low root production, will struggle to keep up with current SLR, while fringe mangroves could keep up with rates of 4mm/year of SLR. Higher rates will likely submerge mangroves [26]. Migration of mangrove landward will largely depend on available space, which will be impacted by limited sediments, poor environment or limited topography due to coastal development [24,26]. Since Caribbean islands have little or no upland space to colonize, SLR is predicted to cause more negative effects on mangroves in these islands [27].

Increase of atmospheric C02, air and water temperature

The effects of rising atmospheric C02, air temperature, and water temperature on Caribbean mangroves are complex, dependent on the mangrove species and locality, and require further research [24,27]. Overall, these factors should increase the productivity and soil accretion of mangroves and thus, benefit this type of forest [24,27,28]. However, these effects are species-specific. For example, experiments have shown negative effects for White Mangroves (*Laguncularia racemose) and* increase productivity for Red Mangroves *(Rhizophora mangle)* [28]. Interactive effects of increased CO_2 with salinity, nutrient availability and temperature imply that location will also be important in mangrove responses [27]. It is expected that mangrove growth will increase, plateau and then decline with increasing temperature when a critical lethal temperature threshold is reached and exceeded [27]. Although rates of leaf photosynthesis for most mangrove species peak at temperatures of 30°C and leaf assimilations decreases if temperature increases from 33 to 35°C (Ball, 2012), the critical temperature at which mangrove functionality plateaus and then decreases remains uncertain [27]. Although temperature increases alone are likely to result in increasing growth and reproduction in some geographical areas, mangroves in the tropics might already be close to their temperature tolerance threshold and thus, could be more vulnerable to negative effects of rising temperatures [24,27].

Reduced rainfall

A predicted decrease in rainfall is reported to have a more straightforward negative decline on mangroves by increasing salinization. Climate scenarios predict a decrease of precipitation in the Caribbean region with ‘medium confidence’ and thus, a decline of mangroves [24]. The combined effects of higher temperatures and reduced rainfall could lead to more detrimental consequences for mangroves because increasing pore water salinity and decreasing water availability should reduce mangrove's productivity, growth, and seedling survival [28].

Increase in hurricane intensity

Mangroves in the Caribbean have often suffered from degradation caused by extreme weather events such as hurricanes and tropical storms [24]. Increasing extreme weather events will lead to physical damage that will be exacerbated if mangroves are weakened by the formation of hypersaline waters or pollution. Storms may cause tree defoliation, making them more vulnerable to pests and soil erosion, which could be compensated by younger trees after several decades [28].

Mangroves at Turneffe

Turneffe Atoll has extensive stands of mangroves providing ideal nursery habitat for juvenile commercial fish species, and absorbing large amounts of C02 [7]. Mangroves also provide nesting structure for bird colonies including the osprey. Mangroves cover approximately 11,000 hectares of Turneffe. This includes three types of mangrove forests according to UNESCO classification: coastal fringe mangrove, mixed mangrove shrub and basin mangrove [7]. Coastal fringe mangrove is the larger terrestrial ecosystem of the Atoll with approximately 6,250 hectares, (62% of the overall land area), and it is dominated by the Red mangrove. These mangroves act as an important fish and invertebrate nursery and provide storm surge protection. Mixed mangrove scrub includes three mangrove species: Black (*Avicennia germinans*), White and Red mangrove, associated with other trees. Mixed mangrove scrub, occurring on soils that are not permanently inundated, is the second most extensive terrestrial ecosystem of the Atoll covering approximately 2,955 hectares (29% of the overall land area) [7]. Basin mangrove, occurring on water-logged and generally peaty soils at sea level, covers approximately 686 hectares (6.8% of the overall land).

Consequences of climate change for mangroves at Turneffe

Given the limited possibility for mangroves of the Atoll to respond to SLR by migrating inland, these mangroves are more vulnerable than mainland mangroves [24]. Although fringing mangroves are the most directly affected by SLR and could rapidly decline with drastic changes in sea-level, they also show the fastest resilience to recover from those events and the highest soil accretion rates [20,26]. Red mangrove seems to be more positively impacted by increasing C02 than other species, while white mangrove could be the most negatively impacted. If a decrease in precipitation is confirmed over the years, the subsequent increase in salinity could particularly affect mixed mangrove scrub, located in soils that are non-permanently inundated, as well as mangroves located in areas with the highest saline content. Overall, changes in species composition could be expected related to species-specific responses to localized changes in SLR, salt and mangrove productivity. Cascade effects towards fish, bird and other species hosted by the mangrove ecosystem could have major consequences to the tourism and fisheries industry. Changes in species composition and mechanical damage can affect the mangrove's capacity to protect the mainland from wave surge (estimated to US38M in shoreline protection by mangroves and corals) but also their ability to capture atmospheric C02, which could in turn accelerate climate change. The study of past events has shown, however, that mangroves are highly resilient organisms that have been able to adapt or recover to drastic changes in SLR and climate as the one predicted for the next few decades [20,27]. However, this will be mainly determined by the interaction between climate change effects and human-induced degradation [28]. It is noted that several knowledge gaps persist when predicting how mangroves will respond to climate change in the Caribbean. These gaps include the need for studies exploring a range of factors simultaneously, as well as their interactions, on mangrove response [24]. Given local variations in many of the factors affected by climate change, studies assessing the impact on mangroves need to be site-specific. More research is also needed on the biological processes that result in vertical accretion and changes in mangrove elevation, which will directly impact their ability to adapt to SLR [24].

3- Seagrass

Seagrass ecosystems are already experiencing a drastic global decline due to human disturbance [29–31]. For example, the seagrasses of Placencia, Belize, suffered a 46 % cover reduction in 2 years, consequence of eutrophication generated by coastal and tourism development [30]. Therefore, additional impacts of climate change to this decline could have dramatic consequences for this ecosystem [32]. Some studies report that overall, recent increases in global temperature, SLR and C02 could result in more favourable environments for seagrass species [32,33]. However, the rate of these changes are much faster than in previous evolutionary history and thus, seagrasses might not be able to adapt fast enough [29]. Other studies suggests that increase sea temperature, SLR (generating a loss of light) and increase storms of high severity should have detrimental or no major effects on seagrass in the next few decades [32,34]. Response of seagrasses to predicted changes are still unknown, which is most likely due to a limited magnitude of changes experienced to date. It is very difficult to disentangle this from local anthropogenic disturbances, and the lack of long-term monitored sites increases this difficulty [34].

Temperature rise

The response of seagrass species to predicted increases of temperature will depend on the rate of increase, the thermal threshold for species' survival, and their optimum temperature for photorespiration and growth [32]. Optimal temperatures for photosynthesis on tropical seagrass ranges from 27 to 33°C [33]. Some species can increase photosynthesis with increasing temperatures that remain below their thermal threshold, although this is regulated by light saturation [33]. While increased temperatures can enhance the reproductive function of some species, an increase in the duration of heat waves will likely exceed temperature thresholds of survival, with consequent mortality of some species [35]. The response to thermal stress will be species-specific, with some species coping to large variations in temperature while others, including turtle grass (*Thalassia testudinum)*, showing a negative impact on productivity with increasing temperatures [35,36]. The effects of an increase in temperature will also depend the species' response to increase C02, since both of these factors affect photorespiration simultaneously [33]. Higher temperatures can also indirectly reduce light availability by increasing algae populations, which will negatively impact seagrass growth [32].

Ocean acidification

Overall, an increase in C02 should result in more photosynthesis and growth for seagrasses [32,33]. However, the magnitude of these effects remains poorly understood, and should also depend on temperature. In fact, it has been shown that the effects of temperature and light could outweigh the benefits of higher C02 for some species [35].

Sea rise level, storms and reduced precipitation.

Seagrasses require some of the highest levels of light availability of any plant group [29]. Thus, they are particularly sensitive to any alteration on water clarity and light availability with extreme reductions of light reducing their growth [37]. The predicted SLR might negatively impact seagrasses by reducing light or increasing turbidity. In contrast, inundations of coastal land by SLR could open new surfaces for seagrass colonisation [32]. More hurricanes of category 4 and 5 could damage seagrasses by causing a long-lasting increase in turbidity. Reduced precipitation could also increase hypersaline environments, which has been shown to reduce manatee seagrass (*Syringodium filiforme)* in lagoons [38].

Seagrasses at Turneffe

Seagrass is the most extensive water ecosystem of Turneffe Atoll, covering approximately 67% of the shallow Atoll platform and supporting extensive meadows dominated by turtle grass [7]. Three species of seagrass have been identified within Turneffe Atoll: turtle grass, manatee grass, and shoal grass (*Halodule wrightii)*, along with algae such as *Halimeda* spp. [7]. Seagrass meadows are highly diverse habitats, providing nutrient cycling, sediment stabilization, C02 sink and habitat for many fish and invertebrates. It is a nursery area for the Queen conch (*Strombus gigas*), many commercial fish and parrotfish. It also provides corridors between habitats for juvenile's lobster and habitat for the West Indian Manatee (*Trichechus manatus*) and marine turtles. Aside from those areas which have been dredged for development, seagrass areas of Turneffe Atoll are considered to be in 'very good condition, with minimal human impact' (BFD 2012; Blanco and Cho-Ricketts 2015).

Consequences of climate change for seagrasses around Turneffe

Contrary to the global trend, the good condition of the seagrass ecosystem around Turneffe will help to mitigate the predicted negative impacts of climate effects described above. However, if temperature thresholds for species survival are reached for the turtle seagrass, the socio-economic impacts could be considerable. In fact, any major alteration of the seagrass ecosystem by any of the factors mentioned above will closely impact their ability to serve as crucial habitat for species with high economic and tourism value including the Queen conch, the spiny lobster, bonefish, commercial finfish, turtles and manatees. Furthermore, a decrease in seagrass photosynthesis and growth could affect their high value in ecosystem services such as their ability for carbon sequestration [32]. It is noted that most studies related to the effects of climate change in seagrass ecosystems are conducted in geographical areas such as Australia, Florida or the Mediterranean. Thus, there is a pressing need to study the impacts of climate change for seagrasses in the Caribbean and Belize.

4- Littoral forest

Several effects of climate change including increasing hurricanes, droughts, pathogen outbreaks and changes in forest composition are expected to disturb forests [40]. However, specific studies on the impact of climate change to Caribbean littoral forests are rare [41]. Given current rates of deforestation, tropical forests on small islands are more likely to be affected by human disturbance related to coastal development than climate change [42]. These forests could be more susceptible to reductions in soil-water availability by SLR and a decrease in precipitation than to changes in temperatures, although higher temperatures could increase pests and the intensity of fires [42]. For example, reconstruction of previous climates suggest that littoral forests in Madagascar shifted their composition during periods of combined SLR and reduced precipitation [43]. An increase in the frequency of extreme events, such as drought and hurricanes, could be the most important threat. For example, a study in mainland southern Belize show that 100% of the littoral forest was damaged after hurricane Iris in 2001, although long-term recovery was expected [44].

Littoral forest at Turneffe

The littoral forest represents Belize's most threatened ecosystem, and only 8.6% of its national coverage is protected. This ecosystem, that typically includes both 'caye forest' and 'beach thicket' with salt-tolerant trees, provides important habitat for migratory bird species, and protected nesting for crocodiles, turtles and other reptiles [7]. There are only approximately 240 hectare of this forest left on the Atoll (2.3% of land area), which has been heavily reduced by human activity [7]. Most of this ecosystem is constituted of herbaceous beach communities and shrubs, rather than the taller littoral forest. Although historically cleared for coconut plantations, it has more recently been cleared for tourism developments [7].

Consequences of climate change on littoral forests at Turneffe

Like the rest of the Caribbean, the impact of climate change on the littoral forest of Belize will probably be additive to the more direct human-induced threats such as deforestation for coastal developments. Monitoring should be given during periods of droughts and hurricanes. A negative impact of reducing littoral space will have major consequences for the reptile community hosted by this ecosystem, which could cause a cascade effect on other ecosystems and negatively impact tourism activities.

IV. IMPACT OF CLIMATE CHANGE FOR KEY ANIMAL SPECIES AT TURNEFFE

1- Commercial and sport fish

Coral reefs, mangroves and seagrasses of Turneffe Atoll support a large diversity of both commercial and sport fishes, including spawning aggregation sites for finfish. The commercial fishing sector utilizing Turneffe Atoll is part of a traditional industry that provides employment for over 2,750 fishers in Belize [7]. Finfish production has been estimated at approximately US200,000 [8]. Species of greatest value for the catch and release sport fishing industry include bonefish (*Albula vulpes*), tarpon (*Megalops atlanticus*) and permit (*Trachinotus falcatus*), and to a less extent the common snook (*Centropomus undecimalis*) and great barracuda (*Sphyraena barracuda*). Impacts of climate change for fish populations remain largely unknown, given the complexity of interactions between the impacts to fish nursery areas (e.g. mangroves and seagrasses), adult habitats (e.g. coral reefs and back-reef flats), and their subsequent effects on fish adult growth, timing of spawning, dispersal and susceptibility to diseases [45–47]. For the Caribbean, empirical information on these effects is still very limited [47]. The most immediate and expected impact is a decline in abundance and changes in community composition, which have already been observed for reef fishes such as herbivores [6,46,47]. However, this decline will be species-specific, and dependent on each species' food regime (e.g. corallivores, herbivores or omnivores) and thermal tolerance [6,48]. For example, studies have shown both an increase and decrease of herbivores after coral bleaching events [16]. Increasing sea temperatures could result in several species shifting their range to northern regions, although less mobile species would likely decline [47]. Increasing temperatures could also reduce fish size as a result of oxygen-limited growth, which could particularly affect Caribbean species [47,49]. If there is an increase in the frequency of abrupt temperature changes, such as the ones caused by hurricanes, species such as bonefish could experience the 'cold shock' phenomenon, where abrupt reductions in temperatures can cause physiological and behavioural impairment that might lead to mortality [50].

Many coral reef species often experience changes in their ecological features including wide temperature gradients, and thus, more resilient species might have the capacity to adapt to climate change [46]. Climate change could also have several negative impacts on fishermen's activities, including the destruction of fish camps by SLR and hurricanes and limited access to fishing areas due to accumulation of sargassum. Fish populations have already been impacted by the degradation of their marine environment and overfishing. Thus, further reductions in species abundance due to climate change could have large socio-economic consequences for the fisheries and fish-related tourism supported by Turneffe. As for other parts of the Caribbean, climate change could result in increasing unemployment of fishermen (with limited alternative employment opportunities), decrease in food security (and thus higher pressure on other wildlife species), and exacerbated conflict between fisherman and recreational fishers or divers [47].

2- Lobster and conch

The spiny Lobster (*Panulirus argus*) and the Queen conch represent two of the most important commercial species for the fishing industry in Belize. Turneffe Atoll contributes to an estimated 5% of the conch and lobster of the national cooperative sales [7]. Queen Conch and lobster at Turneffe would be particularly affected by changes in seagrasses, mangrove ecosystems and coral reefs (particularly back-reef flats). Reduced nursery habitat of mangroves and seagrasses or adult habitat of coral reefs negatively impacts spiny lobster, while seagrass loss reduces critical nursery and adult habitat for the Queen conch, contributing to their ongoing decline in the Caribbean [42]. Near-future increases in water temperatures are not expected to reduce larval development for conch, although they could reduce larvae survival [51]. Although conch can be negatively impacted by an increase in acidification, with a reduction in the calcification of its shell, no reduction of calcification has been observed with current levels of C02 for the Caribbean Queen conch [51,52]. Climate change is expected to impact several aspects of lobster’s biology such as growth, reproduction, settlement and spatial distribution patterns, and lobster species with similar characteristics to the spiny lobster have been negatively impacted by increasing temperatures. However, little is known about the effects of climate for the spiny lobster [51,53,54]. A major threat to spiny lobster is the spread of highly pathogenic PAV1 virus, already reported in Belize’s cayes [55–57]. The spread of this virus could be enhanced if the hydrology of the Caribbean is affected by climate changes [58]. Climate change might also affect the spiny lobster population that is available for fishing. For example, storms can cause lobster to leave their hiding place and be more vulnerable to traps [59]. The economic losses associated with the negative impacts of climate change on conch and lobster populations could outweigh the losses related to impact on fishes. Therefore, there is an urgent need for additional studies on the impacts of climate change for these two species at Turneffe.

3- Marine mammals and turtles

Turneffe Atoll is home to a diverse population of marine mammals and reptiles which are of high touristic and conservation value. Two species of dolphins are commonly spotted, including the Atlantic bottlenose dolphin (*Tursiops truncatus*) and the Atlantic spotted dolphin (*Stenella frontalis*) [7]. The humpback (*Megaptera novaeangliae*) and pilot whales (*Globicephala macrorhynchus*) have been recorded passing in the deep waters West and East of the Atoll [7]. The abundant seagrasses in the Atoll provide habitat for the 'endangered' Antillean manatees (*Trichechus manatus manatus*), with an estimated population of 38 manatees recorded in 2002 [7]. The Atoll hosts 1 species of amphibian, 1 crocodile species, 4 sea turtle species, 1 terrestrial turtle species, 6 lizards species and 3 snakes species[7]. Sea turtles include the critically endangered hawksbill (*Eretmochelys imbricata*), the endangered green and loggerhead turtles (*Chelonia mydas* and *Caretta caretta*) which nest on the beaches of Turneffe. A single observation exists of a critically endangered leatherback turtle (*Dermochelys coriacea*) at Turneffe. Seagrasses represent high quality food for turtles, while high sandy beaches covered by littoral forest provide sea turtle nesting habitat. Turneffe is also considered a critical area for the 'vulnerable' American crocodile (*Crocodylus acutus*) with an estimated 200-300 non-hatchlings (juveniles/sub-adults) and 15-25 breeding females inhabiting the Atoll [7]. Turtle populations are highly threatened by loss and degradation of nesting sites, which are being converted into beach properties. Climate change effects on marine mammals will be species-specific and will mainly depend in changes in their food resources [60]. Learmonth et al. 2006 stated that 'the most likely direct effects of changes in water temperature on marine mammals are shifts in species ranges as species track preferred or required temperature conditions', which will also be enhanced by changes in current regimes. This is also expected for marine mammals in Belize [61]. Some species, such as the Atlantic bottlenose dolphin (*Tursiops truncatus*), the Atlantic spotted dolphin and most whales passing through the Atoll, are expected to increase in range, while effects on manatees remain unclear [60]. Shift in species distribution could result in species migrating North outside the location of the Atoll, which will reduce the Atoll's touristic value. Climate change could result in an increase of toxic algal blooms with higher temperature, which has already caused fatal poising in cetaceans and manatees [60]. Manatees have lower survival during storms [62], and are therefore vulnerable to increases in hurricanes of category 4 and 5. While SLR is not expected to cause immediate direct effects on marine mammals, the effects of other sea properties such as increase C02 are still poorly understood [60]. SLR is expected to reduce nesting sites for turtles, particularly around hotels and other narrow beaches [63]. Although turtles prefer high elevation sites which will be less affected by SLR, these sites are also the preferred locations for beach properties. The decline of seagrasses related to increasing sea temperature has been associated with a shift in regime of the green turtle, which caused its recent global decline [64]. An increase in air temperature is associated with changes in turtles sex-ratio (with higher female ratios in higher temperatures), and this has occurred in Caribbean turtles over the last few decades [65]. Higher temperatures could also reduce nesting abundance [66]. Crocodiles at Turneffe may suffer severe consequences from climate change if their capacity to migrate to deeper and cooler waters is limited. In fact, studies are showing that crocodiles lack the possibility of thermal acclimation to rising temperatures, because their diving capacities (e.g. diving to avoid predators) are reduced at predicted levels of sea temperature increase [67,68]. Both marine mammals and reptiles are highly mobile species with large home ranges. They will, therefore, be more capable of adapting than species with limited ranges. Thus, it is essential to understand the migratory options of both marine mammals and reptiles at Turneffe.

V. POTENTIAL MITIGATION STRATEGIES

Climate change is already affecting the ecosystems of the Turneffe Atoll. Although some of the negative effects of climate change are not yet readily visible at Turneffe, they are present and likely to increase in magnitude over the next decade. Local protections are imperative to mitigate the negative effects of climate change, but they will not be enough. The first scientific global assessment on the impact of climate change on corals states that 'local management is no longer sufficient to ensure the future of coral reefs' and that it 'requires complementary national and global effort to limit warming to 1.5°C' [11]. Although local actions are unlikely to stop the effects of climate change on marine ecosystems, well-managed marine reserves might still help ecosystems and people to adapt to climate change [69]. Since most of the ecosystems and key species present at Turneffe suffer from either habitat destruction due to unsustainable coastal development or over-harvesting of commercial species, reducing the magnitude of these threats is undoubtedly the most effective measure to maintain ecosystem resilience and allow species the best opportunity to adapt to climate change. For example, projects at the Atoll that include the clearing of mangroves, dredging of seabeds and production of large amounts of wastewater and sewage waste require regulations that ensure either minimal or no-impact to these ecosystems. Given the limited amount of knowledge regarding the impacts of climate change on Caribbean ecosystems and the potential serious effects, managers should closely monitor sea water temperature, ocean acidity, sea level rise, salinity and precipitation around the Atoll. This should be done in partnership with fishermen, the tourist sector, decision makers, and scientists developing cost-effective tools (e.g. satellite imaging to assess risk of elevated water temperate as previously conducted at Turneffe [7]). A list of specific actions for each ecosystem of Turneffe is presented below, summarizing the literature cited in this report (Table 1).

1- Coral reefs

- Limiting human-induced degradation that negatively impacts corals including overfishing, siltation from dredging and pollution.
- Continue the monitoring of reef health in partnership with surveillance groups such as Healthy Reef Ecosystem or 'The Network of Coral Reef Early Warning Systems (CREWS) Stations', to estimate the timing and magnitude of bleaching events.
- Follow the NOAA's predictive modelling and alert system (https://coralreefwatch.noaa.gov/satellite/index.php) that suggest where and when elevated sea surface temperatures accumulate to warning levels.
- Consider the feasibility of creating a coral nursery to plant coral species after bleaching events, with emphasis on coral genotypes that are more resistant to bleaching.
- Reduce coastal and watershed nutrient and sewage contamination to limit the amount of macroalgae that competes with corals. This can also be done using 'reef weeding', referring to the direct removal of macroalgae by trained drivers, which could involve both commercial fishermen and tourist divers.
- Restore and maintain a healthy population of herbivores, mainly parrotfish, which will contribute to maintaining low levels of algae. Evaluate the possibility of restoring populations of *Diadema*, the long-spined sea urchin, which also reduces macro-algae.

- Explore the mitigation strategies recommended by the Australia Caribbean Coral Reef Collaboration (ACCRC) (2014) in the report 'Improving the outlook for Caribbean coral reefs: A Regional Plan of Action 2014-2019, Great Barrier Reef Marine Park Authority, Townsville'.
- Apply for funding mechanisms that are specific to implementing climate change adaptation strategies, such as the 'Pilot Programme for Climate Resilience (PPCR)'.
- Increase awareness of fishermen, the public and decision makers on the impacts of climate change to Turneffe ecosystems as well as the services provided by these ecosystems that can mitigate climate change such as carbon sequestration or wave surge protection. Actions could include the establishment of a 'coral day' or the implementation of a website updating on conservation issues related to the different ecosystems of the Atoll, as well as live monitoring of key factors related to climate change (e.g. sea temperature).

2- ***Mangroves***

- Create mangrove protected areas to preserve current mangrove cover.
- Limiting human-induced degradation (e.g. coastal development) should be a priority in order to allow mangroves enough resilience to face climate change impacts [28].
- Monitor the mangrove cover using innovative technologies such satellite imagery [70] or drones (see: http://www.citizensciencegis.org/ for an example of drone's monitoring in Belize).
- Protect coastal land where mangroves are expected to migrate in response to SLR.
- Increase awareness on the role of mangroves for carbon sequestration, for maintaining fish diversity and as coastal protection. This could be achieved by implementing a 'mangrove day' and a website related to this ecosystem.
- Assess the feasibility of restoring degraded mangrove forests, which is currently been implemented using drones in Myamar by the company BioCarbon Engineering.

3- Seagrass

- Maintain the healthy seagrass population around the Atoll by limiting water pollution, eutrophication and turbidity due to coastal development.
- Implement codes of conduct for fishing and boat anchoring to reduce disturbance.
- Monitor changes in abundance and distribution of seagrass coverage, participating in networks such as SeagrassNet.
- Institute seagrass abundance in water quality management and environmental impact assessment studies.
- Increase the public awareness, and the awareness of decision makers, of seagrasses and their critical role for marine mammals and turtles, as well as carbon sequestration. The media coverage for seagrass is estimated to be 3 to 100-fold lower than for mangroves and coral reefs [29]. This could be achieved by implementing a 'seagrass day' and a website related to the importance of this ecosystem, featuring live monitoring of species such as manatees and turtles using GPS devices.

4- Littoral forest

- Protect the remaining littoral forest by creating forest protected areas, particularly in areas of turtle nesting.
- Increase forest cover by limiting further deforestation due to coastal development and promoting reforestation by creating a 'forest nursery' to populate degraded areas.
- Monitor forest coverage and assess its health, particularly during periods of drought and after storms/hurricanes using similar technologies as for mangroves.
- Increase awareness about the role of this forest for turtle nesting and other species.
- Reduce the need for using wood as fuel by replacing it with other low-technologies (e.g. solar ovens and solar energy at fishing camps).

VI. DISCUSSION AND KEY RECOMMENDATIONS

This review of the current and future impacts of climate change to the ecosystems of Turneffe Atoll reveals uneven levels of threat for different ecosystems (summarized in Table 1). The coral reef ecosystem is likely the one facing the most immediate threat related to an expected increase in events of mass mortality due to coral bleaching. In contrast, mangroves and seagrasses ecosystem are currently more threatened by habitat degradation due to human activities. For those ecosystems, predicted effects of climate change will add to current human degradation with mostly unknown outcomes, including changes in community composition. Although some singular effects of climate change are well understood (e.g. higher temperature reduces coral productivity), impacts of climate change will be site-specific and multiple, with several research gaps remaining to understand and predict their impact on the ecosystems of the Atoll. Among these knowledge gaps, we lack enough understanding on (i) whether seagrasses and mangroves have enough plasticity to adapt to negative impacts of climate change, (ii) whether (or when) temperatures will increase to levels passing the thermal limit for survival of many species in the Caribbean, (iii) what the outcome of the interaction of different factors changing at the same time will be, and (iv) how fast climate-induced effects can accelerate the decline of ecosystems caused by human-induced disturbance. Cascade effects on marine ecosystems are complex, and the disturbance of key species in the ecosystems could generate negative effects for a whole community of species [71]. Despite these uncertainties, a consensus is that healthier ecosystems have a higher chance to adapt and be resilient to negative impacts caused by climate change. Therefore, priority should be given to actions that center around maintaining the overall health of the ecosystem and following 'one health' approaches including animal, human and ecosystem health. Mitigating the impacts of climate change in marine ecosystems will therefore require trans-disciplinary work from ecology, conservation and social sciences [72], which could be promoted by creating specific working groups and integrating all of these disciplines with decision makers. Mitigation strategies for the Atoll should include (i) constant monitoring of ecosystems' health by participating to regional networks, (ii) reducing human-induced disturbance to allow ecosystem resilience and (iii) increasing awareness of the ecosystem services provided by the Atoll and how they could be negatively impacted by climate change - especially for less mediatic ecosystems such as seagrasses (Table 1). Managers and policy makers should explore adaptation strategies for the fishing and tourism sectors, which will likely be negatively impacted by an increase in hurricane frequency, coral bleaching and a shift in the distribution of key species. For example, alternative activities should be explored for fishermen if climate change results in a decline in the abundance of finfish, the Queen conch or the spiny lobster. Managers will have to make decisions regarding climate change effects and mitigation plans within the uncertainty of the predicted climate scenarios. The use of adaptive management, involving decision making in uncertainty by basing actions on iterative monitoring, will be an appropriate management framework for Turneffe. This framework is currently being used in the Caribbean to mitigate the effects of climate change (Tompkins 2004, Heller 2009).

VII. REFERENCES

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VIII. APPENDIX

Table 1. Summary of climate change effects, potential socio-economic consequences and mitigation solutions for each ecosystem at Turneffe Atoll

Ecosystem	*Predicted Impacts*	*Potential Consequences*	*Mitigation Strategies*
Coral	• Increase in mass-bleaching events by 2028 • Increase in macroalgae outcompeting coral • More disease outbreaks • Coral erosion (reduce calcification) due to ocean acidification • Negative effects of SLR if rise is too fast • Mechanic damage by increased frequency of high-magnitude hurricanes	• Reduction of Turneffe's tourism value related to corals • Reduction of adult habitat for fish and of fish diversity • Reduction of adult habitat for the spiny lobster • Negative impacts on commercial and sport fishes • Reduction in wave protection for Belize city	• Limit overfishing, dredging and pollution • Monitor predictions on timing of bleaching events • Plant corals to restore populations after bleaching events • Reduce pollution and restore herbivores (e.g. parrotfish) to limit macroalgae • Increase awareness on the impacts of climate change to the populations depending on corals
Mangroves	• Impacts are species and location-specific • Overall decline is expected • Mangroves can adapt to SLR up to a threshold (e.g. 4mm/year for fringing mangroves) • Higher CO_2 and temperature can favour some species until their thermal threshold is reached • Detrimental effects of reduced precipitation and mechanical damage of hurricanes • Several knowledge gasps remain (e.g. multiple effects and adaptation capacity)	• Changes in species composition could affect fish, birds and other species • Alteration of nursery habitat for fish and nursery habitat for spiny lobster • Reduced wave protection and carbon sequestration if mangroves are damaged or fragilized • Detrimental effects on fish and tourism remain to be quantified	• Create mangrove protected areas • Limit coastal development that destroy mangroves • Monitor mangrove coverage • Protect land where mangroves could migrate in response to SLR • Increase awareness on the role of mangroves for carbon sequestration and wave protection • Explore possibilities for restoring mangrove forests
Seagrass	• Effect of climate change (positive or negative) on seagrasses is still poorly understood • Higher temperature could increase growth up to a threshold, and will depend on CO_2 concentration • Increase turbidity by SLR and hurricanes • Adaptation capacity is still poorly understood	• Changes in seagrasses will have considerable impacts on fish populations, conch and lobster. Ex: alteration of nursery habitat for fish and critical nursery and adult habitat for conch • Critical resources for turtles and manatees could be altered • Consequences for economy and tourism still poorly understood • Impacts to photosynthesis will alter rates of carbon sequestration	• Limit water pollution, eutrophication and erosion to maintain healthy seagrasses • Reduce disturbance caused by boats • Monitor seagrass coverage • Increase the low-media attention and public awareness on seagrass' rol in maintaining key species and carbon sequestration

Littoral forest	• Effects on the Caribbean littoral forest are poorly understood • Human-induced deforestation remains the major threat • Negative impacts or changes in species composition with increase in fire frequency, droughts, hurricanes and pests	• Critical nesting habitat for turtles and crocodiles could be lost • Reduction of the tourism and conservation value of Turneffe if reptile populations are affected	• Create forest protected areas • Limit deforestation due to coastal development • Monitor forest coverage and health, particularly after hurricanes and droughts • Reduce the need for wood • Increase awareness on the role of this forest for reptile populations (e.g. nesting)