THE OCEANS ARE CHANGING:
Global and regional impacts of climate change on marine ecosystems

LOS OCÉANOS ESTÁN CAMBIANDO:
Impactos globales y regionales del cambio climático en los ecosistemas marinos

LES OCEANS CHANGENT:
Impacts mondiaux et régionaux du changement climatique sur les écosystèmes marins

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PLENARY ADDRESS

The Anthropocene, the newest Geological Epoch, is one in which human activity has been the dominant force for environmental change on Earth. The effects of human activity are visible everywhere: in cities, farmlands, national parks, forests and oceans. The oceans cover 71% of the Earth's surface and regulate our climate as well as providing us with basics such as food, materials, energy, transportation and recreational opportunities (Visbeck, 2018). More than 40% of the global population lives in areas within 200 km of the ocean and 12 out of 15 mega cities are coastal. Climate change, non-sustainable resource extraction, land-based pollution, and habitat degradation are threatening the productivity and health of the ocean (Visbeck 2018).

Human influence on Climate Change has been clearly demonstrated – recent anthropogenic emissions of greenhouse gases (carbon dioxide, methane, nitrous oxide) are the highest in history and the warming of the Climate System is unequivocal (IPCC 2014). Ongoing Climate Change has had the following global impacts:

i) The atmosphere has warmed,
ii) The ocean has warmed and sea level has risen,
iii) The ocean has become more acidic, and
iv) The amounts of snow and ice have diminished. The impact of climate change has already had widespread impacts on human and natural systems (IPCC 2014).

GLOBAL IMPACTS OF CLIMATE CHANGE

The following are brief summaries of the principal impacts of Climate Change on the world's oceans:

Ocean Warming

◊ More than 90% of the energy which has accumulated in the climate system in the last four decades is stored in the ocean (IPCC, 2014); only about 1% of the energy is stored in the atmosphere.
◊ On a global scale, ocean warming is largest in surface waters; the upper 75 m has warmed by approximately 0.44° C. over the past four decades.

The effects of ocean warming on marine organisms include, but are not restricted to, the following:

i) Migration patterns and species range extensions – Pelagic species e.g. tunas, swordfish, marlins, may change migration patterns or frequent new areas in range extensions which could affect fishing operations.
ii) Trophic dynamics – Ecological impacts on predator-prey relationships and competition can lead to altered trophic webs.
iii) Spawning seasonality – Spawning seasons may change or shift due to changing patterns of water temperatures. For example, spawning aggregation sites for groupers and snappers which are under management may require time/area adjustments to meet changing spawning patterns.
iv) Growth rates – Water temperature and growth rates are closely linked and thus changes in growth rates will affect stock assessments and biological parameters, e.g. size-at-age..

Ocean Acidification

◊ Carbonic acid is produced when carbon dioxide (CO_2) is absorbed by seawater thus lowering the pH.

- ◊ Since the beginning of the Industrial Revolution, the average pH of global ocean surface waters has fallen from 8.2 to 8.1, a decrease of about 26% making the oceans more acidic (IPCC 2014). This decrease has happened mainly in the past 30 - 40 years.

The effects of ocean acidification are most readily observed in a variety of calcifying species including bivalve mollusks, sea urchins, starfish and calcareous zooplankton e.g. pteropods. It has also been demonstrated to reduce the ability of hermatypic corals to produce their skeleton although tropical corals appear to be more sensitive than cold-water corals. In a recent study (Bach et al. 2017), ocean acidification has been shown to affect marine life across all groups although to varying degrees (e.g. clams and gastropods appear to be more sensitive than crustaceans) and early life history stages are generally more affected than adults. These differential responses can have possible cascading effects through changes in trophic webs.

Sea Level Rise

- ◊ Over the past century, the global mean sea level has risen by about 20 cm and about 5 cm for the period 1993 - 2010.
- ◊ Ocean thermal expansion due to ocean warming is considered to be a major factor in this rise (IPCC 2014).
- ◊ Since 1992, the Greenland and Antarctic ice sheets have been losing mass and glaciers have continued to shrink almost worldwide. This ice melt will likely have significant effects on future sea level rise.

The principal impact of sea level rise will be on coastal communities and cities with attendant impacts on a wide range of issues including maritime commerce, fishing operations (both industrial and artisanal), mariculture operations, coastal development, etc.

Ocean-atmosphere Interactions in the Western Atlantic - Precipitation and Salinity

The global ocean is the planet's largest water reservoir and contributes 85% of the evaporation and experiences 77% of the precipitation worldwide (Schmitt 1995). The net difference between evaporation and precipitation is balanced by moisture flux out of the ocean.

- ◊ Observations of changes in ocean surface salinity (OSS) provide indirect evidence for changes in the **Global Water Cycle** over the oceans. Moisture originating from the subtropical northwest Atlantic Ocean (Sargasso Sea) feeds precipitation throughout the Western Hemisphere. This ocean-to-land moisture transport has an effect on OSS.
- ◊ As a result, OSS over the subtropical oceans can be used as an indicator of terrestrial precipitation. It has been demonstrated that springtime OSS over the Sargasso Sea is significantly correlated with summertime precipitation over the U.S. Midwest (Li et al. 2016).
- ◊ On a global basis, in regions of high salinity (where evaporation dominates), oceans have become more saline and in regions of low salinity (where precipitation dominates), they have become fresher.

Pelagic Ecosystem Structure and Function

The physiological responses of organisms to climate-induced environmental changes and subsequent changes in ecological interactions can be complex. The mechanisms that link changes in populations and communities to alterations in ecosystem-level properties such as trophic structure, food-web dynamics, energy flow, and biogeochemical cycles are diverse (Doney et al. 2012). Existing biological interactions can be disrupted through:

- i) Shifts in the seasonality of interacting predator and prey populations,
- ii) Biogeographic range alterations, leading to changes in community composition and biodiversity, and
- iii) Loss of functionally important species e.g. keystone species (Doney et al. 2012).

These processes can be expressed through bottom-up impacts such as declines in water-column primary production and/or shifts toward smaller cells in planktonic communities. Alternatively, top-down impacts can occur that have cascading effects due to the losses or gains of ecologically dominant consumer species. Changes in seasonal migration patterns related to climate-induced changes in zooplankton productivity can have subsequent effects up the trophic chain to apex predators, e.g. tuna species (Doney et al. 2012). Global warming results in a shift in abundance and distribution (both latitude and depth) of fish species thus directly affecting species interactions and fisheries. Fisheries have altered the trophic relationships in open-ocean communities, generating trophic cascades that can lead to ecosystem-level impacts and regime shifts (Crespo et al. 2016). Open-ocean fisheries have been shown to reduce pelagic predator biodiversity (Worm et al. 2005) and ecosystem resilience. Importantly, the ecological impacts of open-ocean fisheries and climate change can act synergistically to induce profound transformations of ecosystem dynamics (Crespo et al., 2016).

In relation to commercial fisheries, climate model predictions and observations reveal regional declines in oceanic dissolved oxygen (DO) which are probably influenced by global warming (Stramma et al. 2011). Pelagic predators such as tropical tunas and billfishes have a high performance physiology and, as obligate ram ventilators, they require large amounts of DO. They start to exhibit physiological stress at DO concentrations of about 3.5 ml/L (Brill 1994), which is the approximate hypoxic threshold determined for these pelagic predators. Warming ocean temperatures have lowered DO thus potentially increasing physiological stress. In the tropical northeast Atlantic Ocean (TNEA) (Figure 1), where major tuna fisheries occur, studies indicate ongoing DO depletion and vertical expansion of the oxygen minimum zone (OMZ). The shoaling of the OMZ may restrict the usable habitat of pelagic apex predators to a narrow surface layer (Stramma et al. 2011). This habitat restriction makes them more vulnerable to surface fisheries operations such as longlines and purse seines as catchability is increased (Figure 2). In the TNEA, there has been a decrease of about 1m in depth per year in the upper ocean layer where DO concentrations exceed 3.5 ml /L. This has confined these pelagic predators to a progressively narrower surface zone and this amounts to about a 15% loss of suitable habitat over the period 1960–2010 (Stramma et al. 2011).

OMZ expansion is evident in all tropical ocean basins and throughout the subarctic Pacific (Whitney et al. 2007) making habitat compression an increasingly global issue. The prevalence and continued expansion of the OMZ across the tropical Atlantic presents a critical issue regarding the habitat compression phenomenon and management of tropical pelagic fisheries (Prince et al. 2010). In the light of continued ocean warming, the impact of habitat compression is likely to be exacerbated.

Impacts of Climate Change in the Caribbean on Fisheries and the Marine Environment

In the wider Caribbean region, the majority of the population inhabits the coastal zone, and there is a very high dependence on marine resources for livelihoods from fishing and tourism, particularly among the small island developing states (SIDS) (Monnereau and Oxenford 2017). The fisheries sector supports the socio-economic viability of coastal communities by providing direct employment, livelihood, and benefits to the people in the region. The Caribbean fishery sector is important in terms of food security in the region as well as providing employment in post-harvest processing and marketing. The negative impacts of climate change on the fishery sector are already obvious in the region. These include coral bleaching (damaging critical fish habitat) and

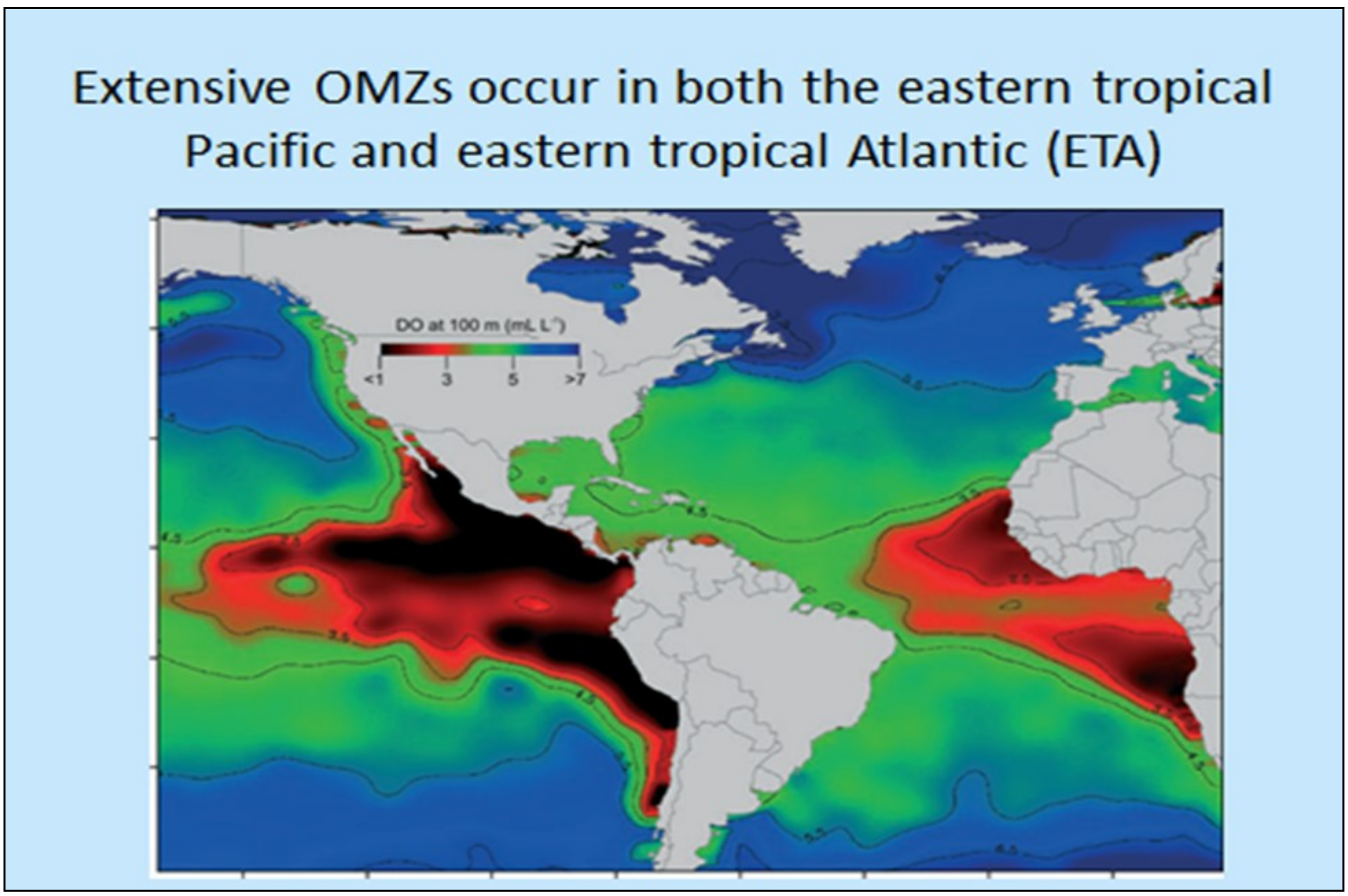

Figure 1. Oxygen minimum zones (OMZ) cover large areas of the eastern tropical Atlantic (ETA) and eastern Pacific. The color scale represents DO (dissolved oxygen) at 100 m depth. They have considerable impact on surface fisheries for tunas in both oceans. The tuna fisheries in the ETA are managed by ICCAT (International Commission for the Conservation of Atlantic Tunas).

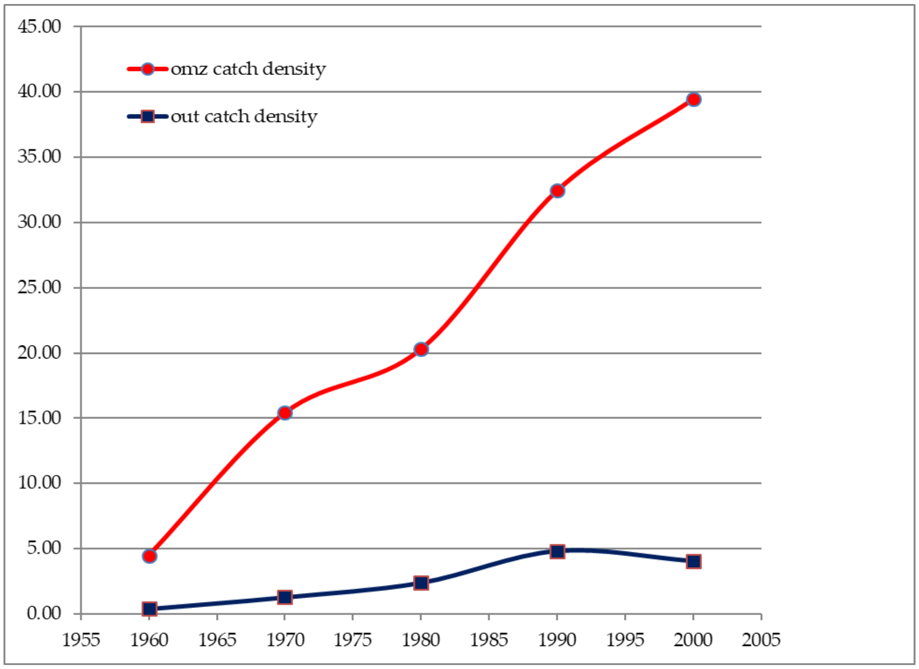

Figure 2. Bigeye tuna (*Thunnus obesus*) reported longline landings (1000's mt per km²) in tropical eastern Atlantic (1960-2000). The red line indicates catch density inside the OMZ where catchability is higher. From Stramma et al. (2011).

increased intensity of storms together with rising sea level (damaging fish habitats, fishery access and assets) (Monnereau and Oxenford 2017). In addition, *Sargassum* influxes to the eastern Caribbean which began in 2011 (Johnson et al. 2012), disrupt fishing operations and communities, affect the catchability of some pelagic species, and have significant impacts on tourism. The prediction for 2018, based on satellite imagery of the Caribbean and the central West Atlantic (University of South Florida) is for a major bloom year. Outbreaks have already been reported in several countries in the region.

In the short-term, the reef-associated fisheries, which are already severely degraded, will likely be the most vulnerable to current and future climate change impacts (Oxenford and Monnereau 2017). The region is heavily reliant on reef-associated fisheries, many of which are high-value species, e.g. spiny lobster, conch, shrimp and snapper. Declining catches of these species are likely to have negative economic consequences for the fishery sector going forward.

In the short-term, oceanic pelagic species are likely to be less impacted by climate change stressors due to the following factors:

i) They are highly mobile,
ii) They have an entirely pelagic life cycle and are thus less affected by benthic habitat degradation,
iii) They have extended spawning seasons usually over broad areas, and
iv) They are generally exposed to fewer or less severe anthropogenic stressors (Oxenford and Monnereau 2017).

However, changes in ocean productivity and changes in the target pelagic species range distributions may lead to fishers having to travel further or fish longer to maintain catch rates.

Tropical Western Atlantic Coral Reef Ecosystems

Significant changes have occurred in most coral reef ecosystems in the western Atlantic over the past 40+ years. Jackson (2014) has divided these changes into three periods:

i) 1970 - 1983: The earliest data sets on coral/algal coverage in the region until the mass mortality of the black sea urchin *Diadema antillarum* throughout the wider Caribbean in 1983. Also the first reports of White Band Disease started to appear in the mid-1970s. This disease completely destroys the coral tissue of Caribbean acroporid corals, specifically elkhorn coral (*Acropora palmata*) and staghorn coral (*A. cervicornis*). These species are two of the principal hermatypic coral species in the region and their mass mortality had a major impact on reef topography (Figure 3).
ii) 1984 - 1998: From the mortality event of *Diadema* to the extreme ocean heating event in 1998 which caused extensive coral bleaching, and
iii) 1999-2011: The recent era of massive decline in the health of coral reef ecosystems.

Due to ocean warming, global coral bleaching events have occurred with increased severity and duration. The frequency of bleaching-level thermal stress increased three-fold between 1985 - 1991 and 2006 - 2012 – a trend climate model projections suggest will continue (Heron et

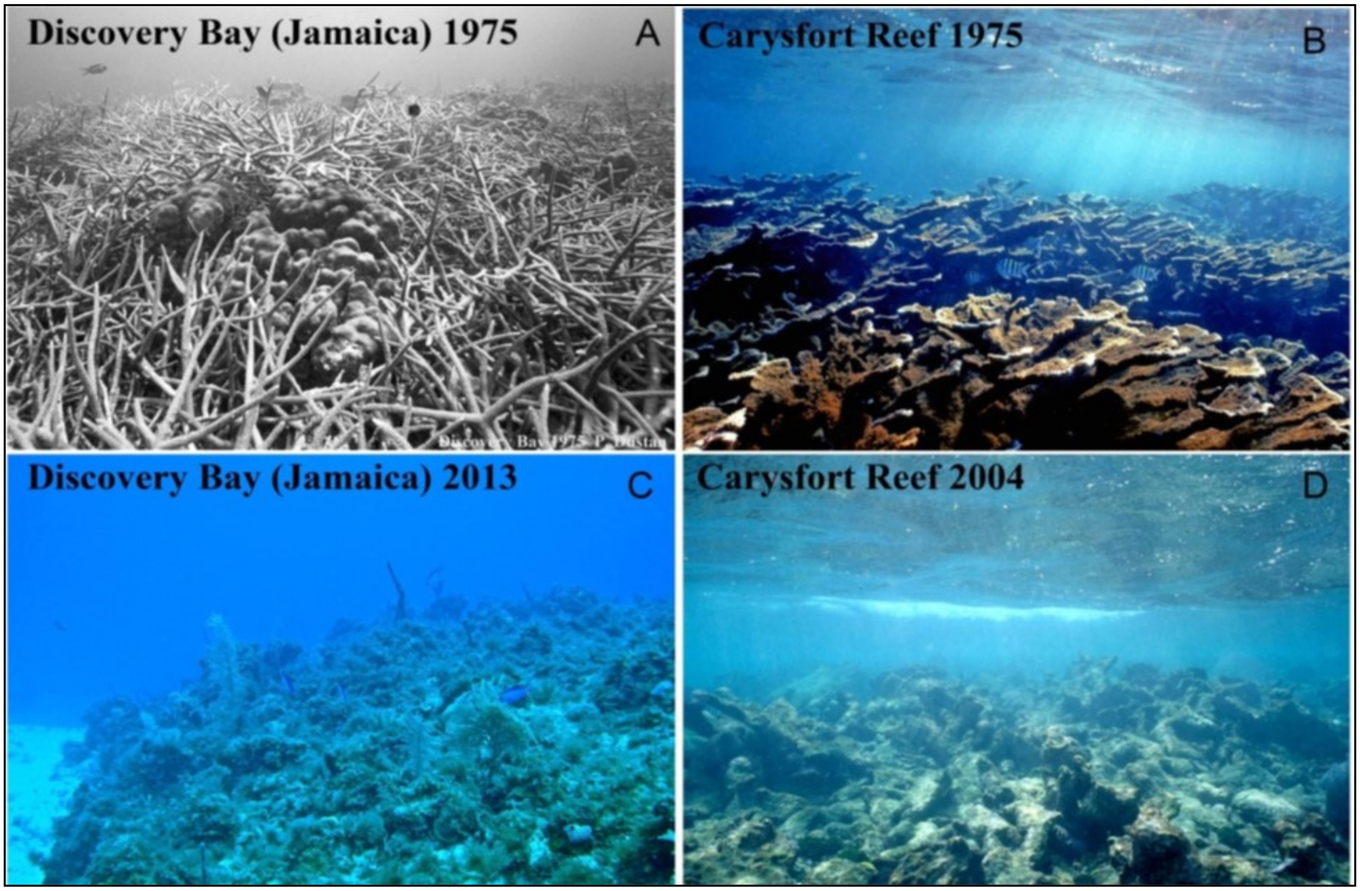

Figure 3. Staghorn coral (*Acropora cervicornis*).at Discovery Bay, Jamaica (A,C) and elkhorn coral (*A. palmata*) at Carysfort Reef, Florida Keys (B,D), from Jackson (2014). Note reduced topographic complexity after mortality.

al. 2016). The 2016 coral bleaching event, which started in 2014, was the longest and deadliest and it occurred worldwide (Heron et al. 2016). The Great Barrier Reef in Australia, the largest living structure on earth, lost 29% of its corals.

This degradation of coral reef ecosystems has occurred because of a number of anthropogenic factors in concert with climate change (Jackson 2014). These include:

i) Overfishing with traps – This has caused steep reductions in herbivore populations, especially parrotfishes (Scaridae) which regulate algal growth on reefs.
ii) Coastal pollution - Many different factors including nutrient loading, fertilizers, sewage and siltation from coastal development.
iii) Tourism - Although bringing significant economic benefits, the negative impact on the environment has been considerable.

Coral bleaching events disrupt ecosystem function and ocean acidification reduces calcification rates of corals. These global factors, working synergistically with more localized factors such as those listed above, have had a devastating impact on coral reef ecosystems (Jackson 2014).

Unless measures are taken to manage the direct anthropogenic impacts on coral reef ecosystems (e.g. overfishing with traps) with urgency, the health of these ecosystems is likely to continue to degrade. A well-documented example of coral reef ecosystem resilience, when strong management action was taken, is the banning of fish traps in Bermuda in 1990. A diver visual census program monitored the recovery of the principal herbivore groups on the reef, i.e. parrotfishes (Scaridae) and surgeonfishes (Acanthuridae) for nine years after the ban (Luckhurst and O'Farrell 2014). Parrotfish biomass increased by a factor of 3.72 and abundance by a factor of 2.46. The asymptote in scarid biomass was attained in 5 - 6 years (Figure 4). The biomass of the dominant acanthurid increased by a factor of 3.5 and reached an asymptote in only four years (Figure 4). This study provided insight into coral reef community recovery dynamics and demonstrated that when extirpated populations of herbivores are protected, the recovery of their biomass – and by inference their grazing function – can be rapid (Luckhurst and O'Farrell 2014).

Coral reef health requires an ecological balance of corals and algae in which herbivory is a key element thus, overfishing of herbivores, particularly parrotfish, is implicated as the major driver of reef declines in the

Caribbean to date (Jackson 2014). It is important that fisheries impacts be considered at an ecosystem level (i.e. EBFM - Ecosystem Based Fisheries Management. Even when species are not primary fisheries targets and are generally regarded as bycatch, they may still be severely affected by non-selective gears (e.g. fish traps). When species such as parrotfish perform vital ecological roles on coral reefs such as grazing, fisheries should be managed explicitly to mitigate impacts on their populations for the benefit of the coral reef ecosystems of which they are a part (Luckhurst and O'Farrell 2014).

Plastics in the Ocean

Plastic production has increased exponentially since the early 1950s and reached 322 mt in 2015; it is expected to continue to increase and will likely double by 2025 (Lusher et al, 2017). Inadequate management of plastic waste has led to increased contamination of all aquatic environments and it has been estimated that 4.8 - 12.7 mt of plastic waste entered the oceans in 2010. Abandoned, lost or discarded fishing gears are considered the main source of plastic waste generated by the fisheries and aquaculture sectors (Lusher et al. 2017). Marine turtles eat floating plastic bags which they mistake for jellyfish. This affects their ability to feed and their nutrition. Plastics are routinely found in the gut contents of sea birds. Many plastics break down in ultra-violet light and produce **microplastics (**usually defined as plastic items which measure less than 5 mm in their longest dimension). Microplastics have become ubiquitous in the marine environment and they readily enter marine trophic webs with possibly deleterious effects (Lusher et al. 2017). Microplastics contain a mixture of chemicals added during manufacture and these additives efficiently sorb (adsorb or absorb) persistent, bioaccumulative and toxic contaminants (PBTs) from the environment. As such, the ingestion of microplastics by aquatic organisms and the accumulation of PBTs have been central to the perceived hazard and risk of microplastics in the marine environment. However, adverse effects of microplastics ingestion have only been observed in aquatic organisms under laboratory conditions, usually at very high concentrations that exceed existing environmental levels (Lusher et al. 2017).

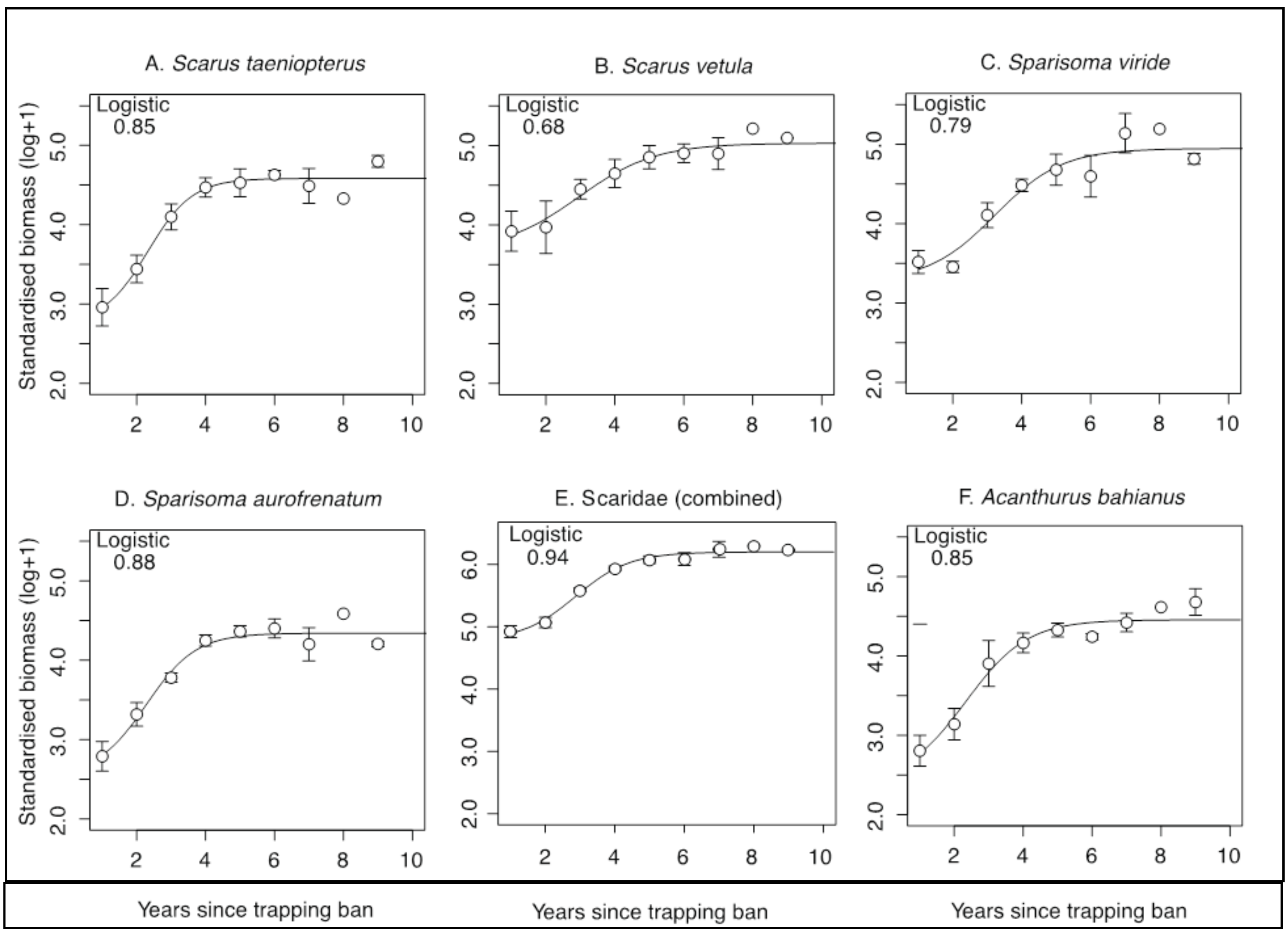

Figure 4. Growth curves fitted to four species of scarid and one of acanthurid biomass data collected over a nine-year period following the imposition of a fish trap ban in Bermuda. The X-axis is the number of years since the fish trap ban. White markers indicate mean values, and error bars show 95% confidence intervals. The best fitting growth model (logistic) for each species is plotted along with the nonlinear approximation of r² (from (Luckhurst and O'Farrell 2014).

SUMMARY

No ecosystem is unaffected by the diverse effects of rising CO_2 levels. The effects of climate change are particularly striking for the poles because of the sensitivity of polar ecosystems to sea-ice retreat and poleward species migrations. In the tropics, the sensitivity of coral-algal symbiosis to minor increases in temperature has brought about major bleaching events and subsequent mortality and ocean acidification may hasten the decline of tropical coral reef ecosystems including effects on coral growth (IPCC 2014).

Pressures on ocean ecosystems arise from coastal degradation and pollution (fertilizers and plastics), fish stock overexploitation and benthic habitat degradation (including the effects of mariculture operations). These factors interact in complex and sometimes synergistic ways. With multiple stressors on marine ecosystems—both CO_2 and non-CO_2 related—the total impact of these pressures on systems must be considered and not treated as independent issues (Doney et al., 2012).

Climate and CO_2 changes influence many levels of ocean biological organization and function. Direct temperature and chemical effects alter organism physiology and behavior, leading to population-level impacts as well as changes in population size, population growth rates, and seasonal variation.

Community-level impacts of climate change stem from altered physiology that translates to changing interactions among species such as competition, grazing, predation, and disease dynamics. These interactions may result in altered community structure and diversity, including the emergence of novel ecosystems (Williams and Jackson 2007).

Rising CO_2 and climate change may modify overall ecosystem properties such as trophic structure, food-web dynamics, and aggregated functioning such as energy and material flows and biogeochemical cycles, eventually impacting the **Ecosystem Services** upon which people and societies depend (Doney et al. 2012).

ACKNOWLEDGEMENTS

I thank Tammy Trott for helpful suggestions in reviewing the paper.

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