Global Environmental Change 30 (2015) 12–20

Contents lists available at ScienceDirect

Global Environmental Change

journal homepage: www.elsevier.com/locate/gloenvcha

Evaluating the economic damage of climate change on global coral reefs

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ARTICLE INFO

Article history:
Received 17 March 2013
Received in revised form 6 October 2014
Accepted 24 October 2014
Available online 19 November 2014

Keywords:
Coral cover
Climate change
Carbon dioxide
Sea surface temperature
Meta-analysis

ABSTRACT

This paper evaluates the global economic damage arising from the effects of climate change and associated carbon dioxide concentrations on the loss of coral reefs. We do this by first estimating the effects of sea surface temperature and carbon dioxide concentrations on coral cover. We develop a statistical relationship between coral coverage and sea surface temperature that indicates that the effects are dependent on the temperature range. For example, we find that increasing sea surface temperature causes coral coverage to decrease when sea surface temperature is higher than 26.85 °C, with the estimated reduction being 2.3% when sea surface temperature increases by 1%. In addition, we find that a 1% carbon dioxide increase induces a 0.6% reduction in global coral coverage. We also estimate the resultant loss in economic value based on a meta-analysis of the recreational and commercial value of reef coverage and a crude proportional approach for other value factors. The meta-analysis shows that the coral reef value decreases by 3.8% when coral cover falls by 1%. By combining these two steps we find that the lost value in terms of the global coral reef value under climate change scenarios ranges from US$3.95 to US$23.78 billion annually.

1. Introduction

Coral reefs, known as the "tropical rainforests of the ocean", are spread over 0.2% of the global ocean (284,000 km^2), but they offer the habitat for a quarter of all marine species (Buddemeier et al., 2004). They also provide about US$30 billion annually in global goods and services that include coastal protection, building materials, fisheries, and tourism (Moberg and Folke, 1999; Hoegh-Guldberg, 2004, 2005).

Climate change threatens these reefs and the value they generate. A number of authors have asserted that temperature increases will cause coral bleaching and in turn mortality (Cook et al., 1990; Gates, 1990; Kenneth et al., 2007). Furthermore, ocean acidification gains driven by increasing atmospheric CO_2 have been argued to be reducing the ability of coral to produce its calcium carbonate skeletons. This affects the ability of the reef to maintain a balance between reef building and reef erosion and thus reduces the reef extent (e.g., see Kleypas et al., 2006; Langdon et al., 2000; Anthony et al., 2011). Collectively, this implies that the economic values of the services supplied by coral reefs will be decreased by climate change-related forces.

Several studies have examined the regional damage associated with coral reef loss. Burke and Maidens (2004) estimated that 2015 annualized Caribbean region direct economic damage ranges from $350 to $870 million a year and that induced losses from losses in fisheries, dive tourism, and needed additional shoreline protection services are $3–$4 billion a year. Becken and Hay (2007) estimated an annual loss of $91 million due to reef damage under the 1997–1998 El Niño related coral-bleaching event. Hoegh-Guldberg et al. (2000) found that the coral reef degradation caused by climate change affects tourism. However, studies have not estimated projected climate change damages on a global scale nor have they factored in ocean acidification.

This study estimates the relationship between coral reef loss, climate change and CO_2 concentrations including estimates of economic damage. The procedure we adopt is to first perform statistical analysis on the coral reef cover effects of sea surface temperature (hereafter SST), sea level change and CO_2. In turn, a

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http://dx.doi.org/10.1016/j.gloenvcha.2014.10.011
0959-3780/

meta-analysis is conducted on the value of coral reef coverage summarizing results over a wide group of non-market valuation studies. Finally, climate change scenarios from IPCC AR5 are factored into the estimated equations to first estimate the loss in terms of coral reef area, and then the loss in value.

2. Background to coral reefs

Substantial work has been done on coral reefs in terms of their value and climate change sensitivity. Here, we discuss the literature.

2.1. Coral reef value

Dalzell (1996) estimated that the annual gross value of Pacific coral reef-based fisheries was about US$260 million. Munro (1996) indicated that globally coral reef fisheries annually yield at least 6 million metric tons of fish catch.

Tourism and recreation is a major economic sector associated with coral reefs. Cesar et al. (2003) estimated that reefs generate $29.8 billion in global net benefits per year, while Jameson et al. (1995) estimated that reef and beach-based tourism were worth $89 billion to the Caribbean region. Richmond (1993) estimated that tourism on the Great Barrier Reef generates $1.5 billion per year for Queensland, Australia. Birkeland (1997) estimated that Florida's reefs produce approximately $1.6 billion annually in tourism value.

2.2. Coral reef health and climate change sensitivity

There is a broad scientific consensus that coral reef ecosystems are being rapidly degraded due to a mixture of factors including over and destructive fishing, sedimentation, pollution, climate change, and ocean acidification (Edinger et al., 1998; Hallock, 2005). Among these factors, climate change and acidification present unique challenges as the causality and effects are not easily alleviated by local action or management (Hughes et al., 2003, 2005; McClanahan, 2007).

In terms of reef degradation, Jokiel (2004) found that the living coral cover and species richness in Japan decreased by 85% and 61% respectively following the 1998 bleaching event. Gardner et al. (2003) indicated that living Caribbean coral cover has fallen by 80% in the last decade and argued that the reduction is the result of local and global environmental changes. Hoegh-Guldberg et al. (2007) predicted that hard corals may not dominate global reefs by 2050.

SST has been found to be an important determinant of coral reef presence and health. Many studies indicate that there exist appropriate but narrow ranges of SST that support living reefs (Kleypas et al., 1999; Guinotte et al., 2003; Hoegh-Guldberg, 2005). Some studies (such as Glynn, 1993; Goreau and Hayes, 1994; Glynn, 1996; Strong et al., 1998; Hughes et al., 2003; Kawai and Wada, 2007; McClanahan et al., 2007; Berkelmans, 2009; Hoegh-Guldberg, 2011; Riegl et al., 2011) indicate that coral bleaching and mortality is being stimulated by SST rises (Gates, 1990; Glynn, 1996; Bruno et al., 2007; IPCC, 2007b; Negri et al., 2011). Several studies argue that rising SSTs will cause severe damage to coral communities (Donner et al., 2005; Hoegh-Guldberg et al., 2007; Maynard et al., 2009; Selig et al., 2012). Acidification associated with increased concentrations of CO_2 has also been argued to be associated with reef declines acting through several drivers that have been identified (Wilkinson, 2004; Hoegh-Guldberg et al., 2007; Meissner et al., 2012). The ocean exchanges CO_2 with the atmosphere and absorbs about 25% of the CO_2 emitted from human activities to the atmosphere (Jury et al., 2010). The dissolution of atmospheric CO_2 in sea water forms carbonic acid and increases ocean acidification (Feely et al., 2004; Hall-Spencer et al., 2008; Doney et al., 2009; Kroeker et al., 2010; Hendriks et al., 2010; Fabricius et al., 2011; Rodolfo-Metalpa et al., 2011).

Since the Industrial Revolution began, ocean acidity has increased by 30% (IPCC, 2007a). Multiple studies (e.g., see Langdon et al., 2000, and the review in Anthony et al., 2011) have indicated that the calcification rates are decreasing due to the ocean acidification and since coral reefs are largely calcium this limits their growth. De'ath et al. (2009) showed that the calcification of corals in the Great Barrier Reef has decreased by 14.2% since 1990. Kleypas and Langdon (2002), Reynaud et al. (2003), and Raven et al. (2005) found that doubling CO_2 decreases calcification in coral reefs by between 20% and 60%. Kleypas et al. (2001) and Guinotte et al. (2003) projected that at current trends this will substantially decrease coral cover by 2070.

Increasing global sea levels is another effect of climate change (IPCC, 2007b) and has a negative effect on coral reefs (Dickinson, 1999; Gibbons and Nicholls, 2006). Tropical storms are another factor. Gardner et al. (2005), Hoegh-Guldberg et al. (2011), and Mumby et al. (2011) showed that they have a negative effect on reefs as they lead to reef relocation, shrinkage in coverage, and destruction of reef ecosystem biodiversity.

3. Estimating a coral reef cover function

We will now estimate a function that depicts the relationship between climate conditions in the form of coral reef extent. The literature reveals that the relationship between coral coverage and SST is nonlinear and may involve SST thresholds (Hoegh-Guldberg, 2005; Guinotte et al., 2003; Munday et al., 2008; Munday et al., 2012). Hence, this study employs Hansen (1999) threshold model. The climate-related factors included are SST, CO_2 and sea level.

The estimation will be carried out over coral coverage data spanning 1–15 m depth in five geographic regions: the Greater Caribbean, Florida Keys, Coral Triangle, Indian Ocean, and Great Barrier Reef with the time period based on years from 1985 to 2006. The data are drawn from numerous sources (including Causey et al., 2002; Gardner et al., 2003; Jaap et al., 2003; Keller and Causey, 2005; Bruno and Selig, 2007; Bruno et al., 2007; Jaap et al., 2008; Somerfield et al., 2008; Bruno et al., 2009; Schutte et al., 2010; Selig and Bruno, 2010; Wagner et al., 2010; Osborne et al., 2011; Soto et al., 2011; Sweatman et al., 2011; Selig et al., 2012) plus several monitoring programs (e.g., Atlantic and Gulf Rapid Reef Assessment Program; Australian Institute of Marine Science's Long Term Monitoring Program; Florida Coral Reef Evaluation and Monitoring Project; Hawaii Coral Reef Assessment and Monitoring Program; National Oceanic and Atmospheric Administration; ReefBase; and Reef Check).

In addition, data on SST, CO_2, and sea level in these five geographic regions are assembled from the following sources

- SST data from the Atmospheric Science Pathfinder Version 5.0 temperature data set specifically available through the National Oceanic and Atmospheric Administration Oceanographic Data Center. Those data are at a resolution of 4.6 km.
- CO_2 concentration data from the National Oceanic and Atmospheric Administration's Earth System Research Laboratory.
- Sea level data from the Permanent Service for Mean Sea Level at corresponding stations in five coral reef regions.

Descriptive statistics on these variables are shown in Table 1. The estimated coral reef coverage threshold equation allows coverage to vary as it crosses two thresholds. It also includes CO_2, and sea level