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The application of ecosystem thresholds in the management of tropical coral reefs: a review and synthesis

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Abstract

A review and synthesis was carried out on the extensive literature concerned with ecosystem thresholds on tropical coral reefs to collate research carried out globally, and highlight gaps in the existing knowledge. This study aims to inform the future management of ecosystem thresholds of tropical coral reefs. Information was gathered from existing literature concerning ecosystem thresholds at named tropical coral reef locations and the distribution of studies was mapped in order to draw conclusions about the state of threshold research on coral reefs, and to make recommendations for future research and management. The synthesis highlighted the negative influence of removing herbivorous grazers, and the need for quantitative measures for the resilience of reefs to anthropogenic stress. It was also found that previous research sites predominantly focused on two main areas; The Great Barrier Reefs, and Caribbean reefs.

Introduction

The growing importance of efficient ecological management through the understanding of specific ecosystem thresholds (Samhouri et al 2010) combined with global concern for the long-term degradation of tropical coral reef ecosystems (Pandolfi et al 2003; Halpern et al 2007) makes this review appropriate and timely. An ecosystem threshold is considered to be a sudden and abrupt change in the state of an ecological system (Scheffer et al 2001) at the point a critical value is reached (Muradian 2001), a change that in many cases is irreversible (Petraitis et al 2009). There is an extensive body of existing literature that discusses the existence and techniques for detection of thresholds in a wide range of ecological systems, comprehensively reviewed by Muradian (2001) and Anderson et al (2009), and interest has increased substantially in recent years, **Fig 1.1** showing the increasing number of citations from 1994-2011. Previous research has shown that the concept of thresholds can be a particularly useful tool for ecological management as they provide measureable reference points, and can be a source of motivation for management decision making (Groffman et al 2006; Samhouri et al 2010). Whilst numerous, much of the literature is widespread across a number of disciplines and categorised under multiple terminologies, hindering the efficient, unified use of the existing knowledge base.

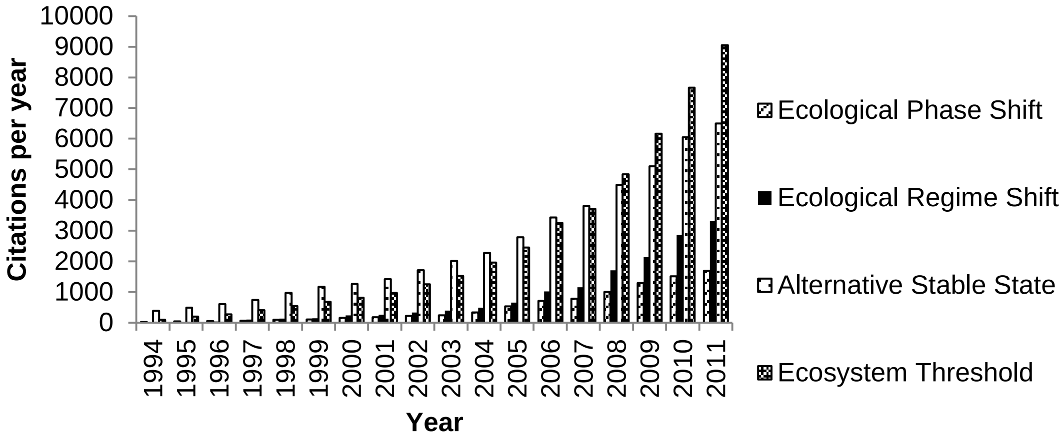

Fig 1.1 Citation Reports

Shows a citation report taken from Web Of Science, providing data on the number of citations for terms relating to 'Ecological Thresholds' showing the number of citations per year.

The aim of this review is to draw together this cross-discipline literature in order to enhance the management of tropical coral reef ecosystems in the context of their thresholds. A synthesis was carried out in order to identify key causes and consequences of reaching thresholds for coral reef ecosystems, the dominant locations of previous studies. This information is used to identify the gaps in knowledge for coral reef ecosystem thresholds, and to make recommendations for future management.

The Threshold Concept

The term ecological threshold is used to describe an abrupt, non-linear change in an ecological state (Lintz et al 2011; With and King 1999b) and often requires only a small environmental change to trigger a significant response (USCCP 2009). **Fig 1.2** displays a schematic representation of how an ecosystem can move between different states under stressors, or pressures. In the majority of studies in this field, ecosystem stress can be fully or partially attributed to anthropogenic activity (McManus and Polsenberg 2004) making informed management decision-making highly important.

Previous research has highlighted the influence of site history, including long-term ecosystem health (Hughes et al 2005) on the vulnerability of an ecosystem to reaching a critical threshold. It is known that thresholds can occur at a range of spatial scales, form individual organisms (Huggett 2005) to planetary systems (Cairns 2004), however in terms of management, ecosystem based spatial scales are frequently recommended in the literature (Samhouri et al 2010; McClanahan et al 2011).

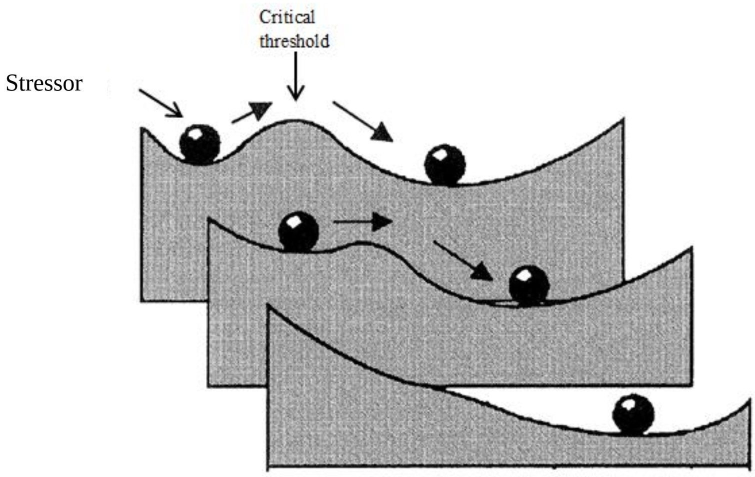

Fig 1.2 Schematic representation of ecosystem thresholds
This figure is adapted from (Gunderson 2000) Where the sphere represents the current ecosystem state, the slope represent the resilience of the ecosystem, and the three images show how resilience alters over time under stress until the point when a critical ecosystem threshold is crossed, and a new ecological state becomes established.

Unravelling Threshold Terminology for Coral Reefs

The term ecosystem threshold, while the most popular key term in the related literature, is only one of the terms used to describe this sudden shift in ecological state. Three other terms included in the search criteria of this review, giving a total of four search terms to ensure relevant literature was captured, include; alternative stable state, considered as the establishment of a stable, alternative community composition (Dudgeon et al 2010), after the crossing of an ecological threshold (Petraitis and Latham 1999); phase shift, and regime shifts, which are often used interchangeably with ecosystem thresholds, and used to describe similar abrupt changes in an ecological system (Collie et al 2004; Done et al 1992). Additional terms do exist in the literature but are less frequently occurring and so were omitted from the search criteria.

Several terms are intimately associated with ecosystem thresholds, which this paper will briefly define for clarity; ecosystem resilience, which describes the level of disturbance which an ecosystem can withstand, and still maintain its original state (Holling 1973; Gunderson 2000). When resilience is reduced the potential for crossing a threshold is increased (Scheffer et al 2001) (**Fig 1.2);** the feedback loop, which includes both negative and positive feedbacks, which can reinforce or undermine change in states once an alternative stable state has become established (Knowlton 2004).

A preliminary literature search was carried out in order to ascertain the prominence given to ecosystem thresholds in the context of tropical coral reefs compared to other ecosystems. Papers that referred to a specific location and ecosystem type were selected, and the system studies recorded. **Fig 1.3** shows the results for this search in which 60 papers were considered, of which tropical coral reefs dominated the search results. This dominance highlights the need for a targeted review to establish what has been learnt about ecosystem thresholds in this highly studied and equally vulnerable system to adequately inform beneficial future management.

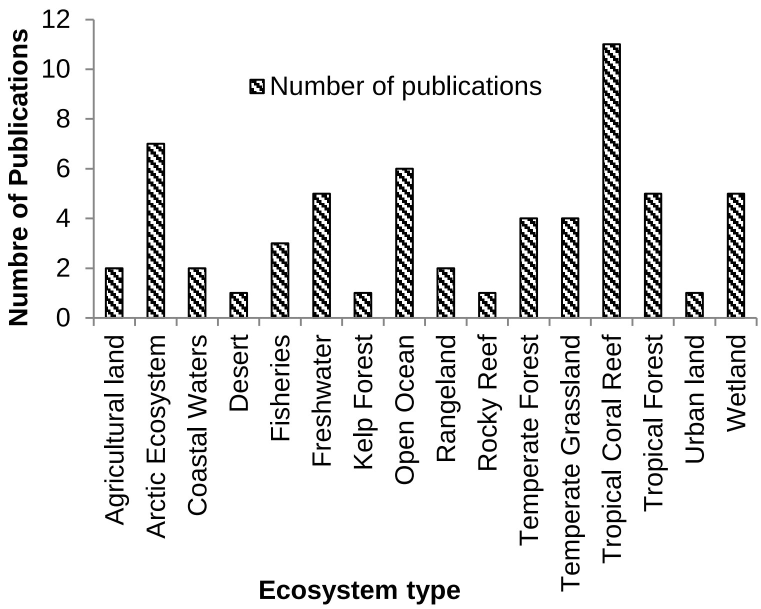

Fig 1.3 Threshold studies across different ecosystems

Bar graph showing the results of the preliminary synthesis of 60 location specific publications for an initial search of ecosystem thresholds across different ecosystem types. From the graph the priority given to coral reef publications in this context can be clearly seen.

Synthesis of Ecosystem Thresholds of Coral Reefs

A coral reef focused literature search was carried out which utilised the same search terms and criteria to explore the cumulative knowledge about the stresses driving, and consequences of, ecosystem thresholds in coral reefs. A total of 50 papers were selected that met the search criteria.

Additional data collected from the 50 papers included the geographical location of each study in order to see if historical studies had focused in specific areas, and where there were little or no publications relating to ecosystem threshold of tropical coral reefs. The locations were placed on a world map and compared with the National Oceanographic Atmospheric Administration (NOAA) global coral reef distribution map produced in 2008. On the synthesis map two different categories are used; Passive studies where the case study is based on the observation of an ecosystem threshold, and Active studies that sought to model or manage the system in some way represented by different symbols.

The cited causes and consequences (**Fig 1.4A** and **1.4B** respectively) highlight the removal of grazers as the most common stress, and the dominance of macroalgae as the most common consequence of ecosystem thresholds on coral reefs.

A comparison of the NOAA global distribution of coral reefs (**Fig 1.5 A**, with **Fig 1.5 B)**, which is a distribution of papers included within this synthesis shows that the dominant geographical areas of tropical coral reef study have been in the Caribbean and The Great Barrier Reef, Australia with a real scarcity of studies in Indonesia, West Africa, The Red Sea and the Indian Ocean where there are extensive tropical coral reefs present. The data displayed on map **Fig 1.5 B** also highlights that there is an imbalance in the number of studies simply observing the crossing of ecological thresholds (passive studies) and those trying to predict or stabilise the system (active studies), suggesting a need for more pro-active approaches to ecosystem threshold research on tropical coral reefs. One of the sites labelled on **Fig 1.5 B** was a palaeo-oceanographic study from the Tethys Ocean, where a phase shift was detected from fossil data sets, which explains its inland position.

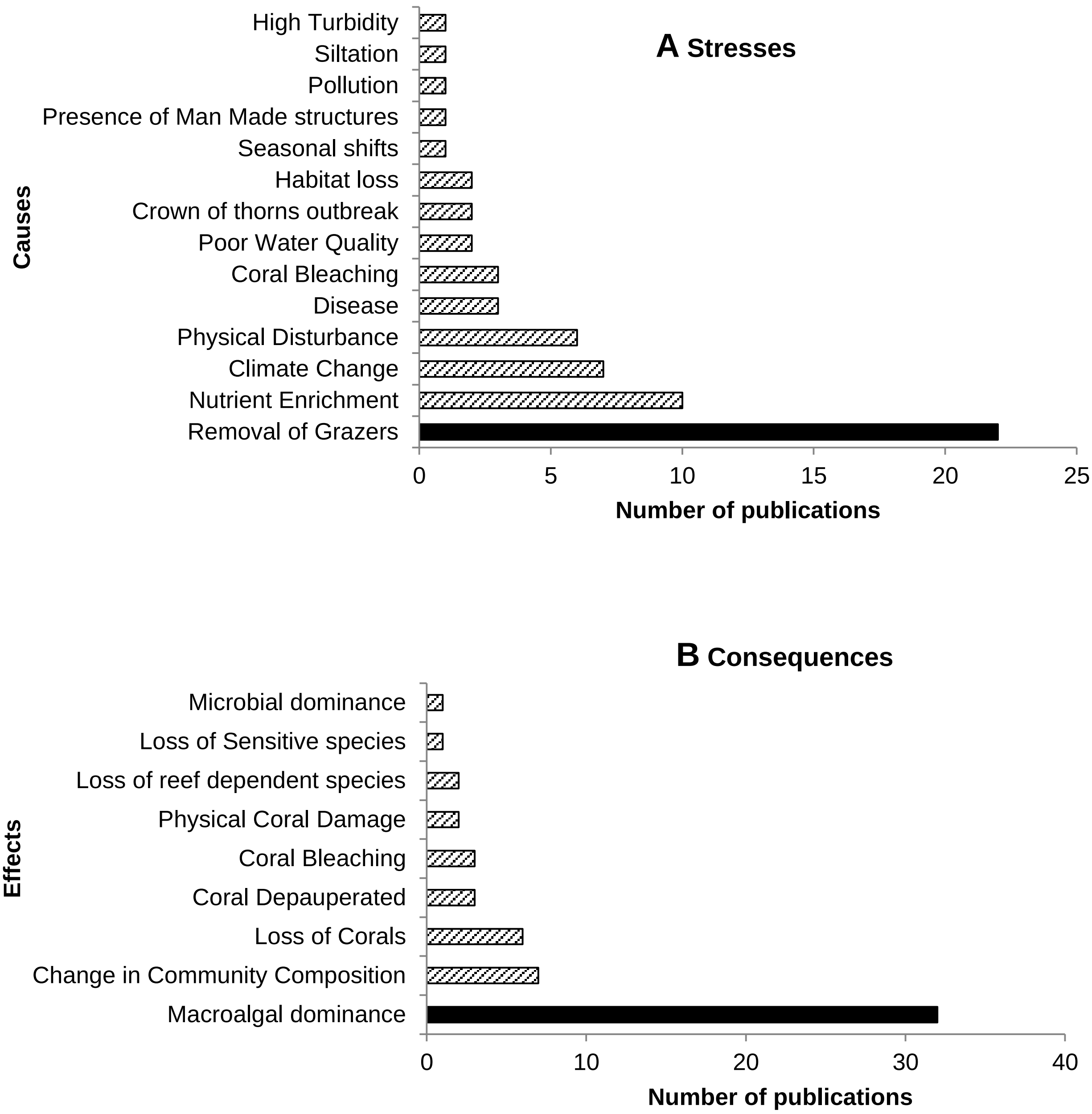

Fig 1.4 Causes and consequences of reaching ecosystem thresholds
Where **(A)** Is a bar graph showing the different causes of ecosystem thresholds reported by the 50 papers considered in the synthesis of this paper and **(B)** Is a bar graph that shows the effects reported by the same group of papers.

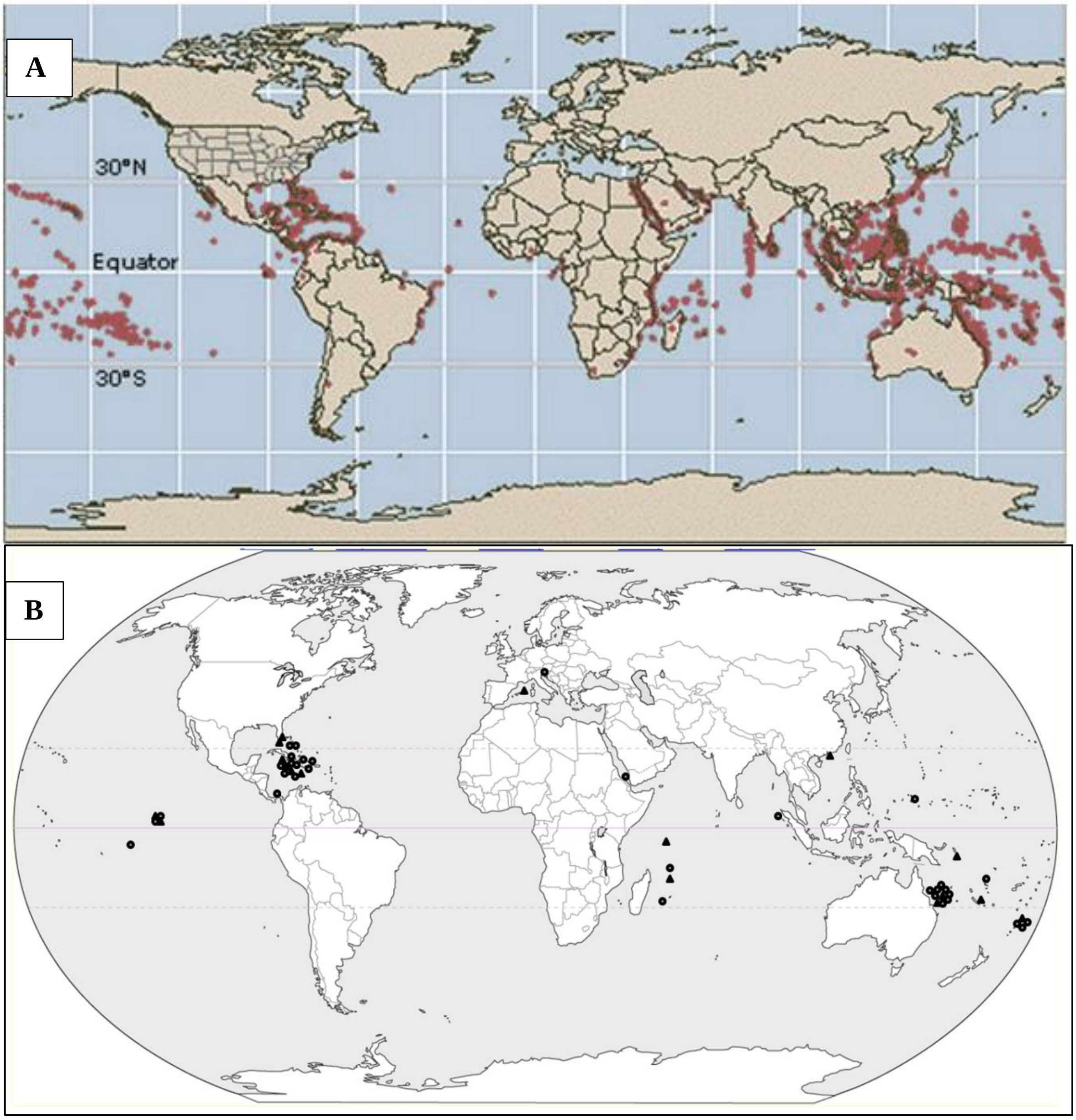

Fig 1.5 Comparison of the global distribution of reefs, and the distribution of threshold studies

Where **(A)** is adapted from the NOAA 2008 map of tropical coral reef distribution globally; this stands in contrast to **(B)** the geographical distribution of 50 papers included in this synthesis. Where ( ) represents the passive studies, and ( ) represents the active studies. Two major clusters can be seen, one in the Caribbean, and the other in and around the Great Barrier Reef.

There are a number of limitations associated with this type of synthesis, due to the search criteria a number of papers were omitted to allow comparability between studies. It is also not possible to capture all the related literature within a synthesis, but the studies selected act as a representative sample of those available.

Gaps in the Knowledge and Future Management of Coral Reef Thresholds

The high complexity of tropical coral reefs and the interaction of multiple stressors make their management complex (Maina et al 2011). Efficient management of thresholds requires an in-depth understanding of underlying system dynamics in order to set knowledge-based reference points at which thresholds can be predicted and managed against (McClanahan et al 2011). Adaptive management holds the most potential due to the mobile nature of thresholds and system resilience both spatially and temporally (Folke et al 2004). There are a number of ways that coral reef resilience is thought to be maintained, these include but are not limited to; healthy connectivity with adjacent ecosystems for example mangrove forests (Mumby and Hastings 2008) control of anthropogenic impacts (Maina et al 2011), and the maintenance of high biodiversity(Levin and Lubchenco 2008), however there is a need to explore the strength of these relationships, and to establish coral reefs resilience to anthropogenic stress in a quantitate manner. The development of ecological stress indicators is suggested as a useful management tool in which to facilitate the measurement of resilience in specific coral reefs (Samhouri et al 2010), quantifying macroalgal cover, as it is considered a key consequence has potential for future management, but requires further study to increase understanding of this interaction.

In papers considered in this synthesis that recorded coral reef return to a previous state, recovery was frequently attributed to the presence and health of the population of herbivorous algal grazers (Bellwood et al 2006; Adam et al 2011) which matches the most common cause established in the synthesis, that the removal of grazers drives change in tropical coral reef ecosystem state (**Fig 1.3A);** and also the establishment of Marine Protected Areas (MPAs) (Ledlie et al 2006) which have historically been proven to be beneficial to the area directly under protection when rigorously enforced (Pollnac et al 2001). Concern has been voiced in the literature, that the use of thresholds in ecological management may prove minimalist (Lindenmayer and Luck 2005), and so estimates for resilience should be set conservatively.

While there is a high level of concern for coral reefs, there is an underlying lack in policy driven management that is required for international protection of coral reefs (Kushlan 2010). It is important that all management of coral reef thresholds are considered in the context of global climate change (USCCP 2009), supported by the results of the synthesis showing it to be in the top three most commonly cited stresses (**Fig1.4A)**. There is a strong likelihood that global climate change will alter existing ecosystem thresholds, trigger new thresholds, or even produce unpredictable ecological responses (Burkett et al 2005) which may affect management decisions. Additionally, resilience of ecosystems to existing or new stresses may be reduced in the presence of climate change pressures (Folke et al 2004; Travis 2003). Use of the Ecosystem-based management (EB M) technique increasingly recommended for the management of coastal resources (Browman et al 2005) and for the management of resilience (Levin and Lubchenco 2008), and as such is highly applicable to threshold management, particularly as EBM incorporates human interactions with coral reef ecosystems in order to monitor and mitigate for anthropogenic stresses identified that drive changes in state.

Conclusions

There is a rising global concern for the efficient management of tropical coral reef ecosystems, and an extensive body of literature exists which refer to coral reefs in terms of thresholds. This review highlights the stress induced by the removal of grazers from the system and the need to establish quantitative measures of specific reef system resilience.

This review suggests that past research focussing on the Caribbean and Great Barrier Reefs is transposed onto relatively unstudied geographical sites, in particular the Indonesian, Pacific Ocean reefs and those in the Arabian Sea. Research should focus primarily on past examples of recovery which suggest the maintenance of populations of herbivorous grazers to establish the effectiveness of various potential management and recovery strategies. In order to achieve this, studies should be primarily pro-active in order to benefit the future of coral reefs and the knowledge of their ecological thresholds.

There is a good case for using ecosystem thresholds in the management of tropical coral reefs. Future research needs to cover two areas; firstly, developing a greater understanding of the present reef dynamics and those in the context of predicted future climate, and secondly to establish the effectiveness of possible management strategies.

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