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List of publications
A. In Journals


The article highlighted in *Science* and *Nature*


B. In Book Chapter

Publications in Journals
Bioinvasion of *Kappaphycus alvarezii* on corals in the Gulf of Mannar, India

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*Kappaphycus alvarezii* (Doty) Doty (Rhodophyta: Solieriacae) is a Philippine-derived macroalga introduced into the Gulf of Mannar Marine Biosphere Reserve, South India for mariculture in 2000. Here we report its bioinvasion on branching corals (*Acropora* sp.) in the Kurusadai Island. Qualitative data collected using underwater photography clearly indicated its invasion and establishment on live and dead corals as well as coral rubble and pavements. It specifically invaded *Acropora* sp. as monospecific beds with extraordinary phenotypic plasticity in the form of thallus, thickness of its major axis and lateral branching. It shows remarkable shadowing and smothering effects over the coral colonies. The primary and secondary branches are much reduced in the invaded algal colonies. Quantitative data on its live cover on corals and biomass production are also reported. These observations are discussed with available limited information on bioinvasion of *K. alvarezii* on coral reefs. Our findings disprove all arguments and misapprehensions reported earlier about this species as coral-friendly and as a safe candidate for mariculture for the production of carrageenan\(^5,6\), which is widely used in many industries. It was first introduced into the Gulf of Mannar Marine Biosphere Reserve (GoM), South India for commercial cultivation in 2002. It has been reported earlier that the species has successfully invaded and established on coral reefs in Hawaii islands, where it was initially introduced for mariculture\(^7,11\). It is provisionally qualified as an invasive species due to many unique features such as vegetative propagation, adaptation to low and high-wave energy environments, extraordinary phenotypic plasticity, high growth rate and chemical defence against herbivores\(^5,6\). The ecological danger associated with its commercial cultivation in the GoM was first indicated by an alarming report\(^12\) in 2005 and latter in some newspaper articles\(^13,14\). Reports presumed that once invaded in the wild, it would destroy the biodiversity of the GoM, especially corals. Even after eight years of its introduction into the GoM, there is no field study to evaluate this presumption made by the earlier reports\(^12-14\) on the invasive-ness of this alga. A recent review\(^15\) on coastal and marine biodiversity of India has emphasized that evaluation of its impacts on native species is a matter of concern. In this article, certain qualitative and quantitative data on the bioinvasion of *K. alvarezii* on corals in the Kurusadai Island of the GoM have been reported.

**Methods**

The study area, Kurusadai Island (9°15′N; 79°12′E) is located in the GoM, southeast coast of India (Figure 1). Qualitative and quantitative data on the bioinvasion of *K. alvarezii* on corals were collected from the two sampling sites that are approximately 50 m (site 1) and 100 m (site 2) away from the shore. Qualitative data were collected at different depths from August to September 2007 using underwater photography (Sony DSC-W5 model with di-capac waterproof case WP-400) during high tide as well as from the water surface during low-tide conditions. Quantitative data were collected by sampling three transects, running 10 m onto the reef (0.25–2 m depth) at the reef crest. Estimates of coral cover, sandy cover, live cover of other algae and live cover of *K. alvarezii* on cor-

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**Keywords:** *Acropora* species, bioinvasion, coral reef, *Kappaphycus alvarezii*, mariculture.

**Invasive** species invade, colonize and destabilize ecosystems in new geographical locations, which are not their native habitats. Such bioinvasion is usually prohibited by quarantine procedures, but may happen either accidentally or intentionally because of human beings for definite purposes. These invasive species are the greatest and significant threat to marine biodiversity and marine-derived bioresources\(^1-3\). India has recorded 14 invasive species, including four species of macroalgae in her marine territories\(^4\). Among these, *Kappaphycus alvarezii* (Doty) Doty ex.P.Silva (Rhodophyta: Solieriacae) is a Philippine-derived rhodophyte which has been intensively introduced into the coastal ecosystems of 26 countries, mostly in the tropics for commercial production of carrageenan\(^5,6\), which is widely used in many industries. It was first introduced into the Gulf of Mannar Marine Biosphere Reserve (GoM), South India for commercial cultivation in 2002. It has been reported earlier that the species has successfully invaded and established on coral reefs in Hawaii islands, where it was initially introduced for mariculture\(^7,11\). It is provisionally qualified as an invasive species due to many unique features such as vegetative propagation, adaptation to low and high-wave energy environments, extraordinary phenotypic plasticity, high growth rate and chemical defence against herbivores\(^5,6\). The ecological danger associated with its commercial cultivation in the GoM was first indicated by an alarming report\(^12\) in 2005 and latter in some newspaper articles\(^13,14\). Reports presumed that once invaded in the wild, it would destroy the biodiversity of the GoM, especially corals. Even after eight years of its introduction into the GoM, there is no field study to evaluate this presumption made by the earlier reports\(^12-14\) on the invasive-ness of this alga. A recent review\(^15\) on coastal and marine biodiversity of India has emphasized that evaluation of its impacts on native species is a matter of concern. In this article, certain qualitative and quantitative data on the bioinvasion of *K. alvarezii* on corals in the Kurusadai Island of the GoM have been reported.

**Methods**

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Results

It was observed that K. alvarezii had successfully invaded and established on both dead and live corals in Kurusadai Island. It had specifically invaded the Acropora sp. and destroyed them by shadowing and smothering effects. Taxonomic analysis of invaded coral samples revealed that they are A. nobilis and A. formosa. The invaded populations occur as either monospecific beds or mixed with other marine communities on live and dead corals, coral rubble and pavement. They are prominently visible even from the water surface during low-tide conditions as most conspicuous fluorescent green (light green) patches of different sizes (Figure 2a and b). An extraordinary phenotypic plasticity is observed in terms of distinct variations in colour and shape of the thallus, thickness of its major axis, morphological features, and frequency of primary and secondary branching (PSB). The alga invaded continuously as green mats over the top (Figure 2c and d) and lateral sides (Figure 2e) of colonies of Acropora sp., coral rubbles and pavement between the colonies. No part of the coral reefs was visible in most of invaded sites, where it doomed the entire colonies and occupied almost all ridges and valleys (Figure 2f and g) of the ‘coral landscape’. This complete shadowing is due to smothering effect in which the major axis extends like an elastic rubber sheet and covers maximum surface area of the corals (Figure 2h). Observations on pieces of alga-invaded dead and live corals and coral rubbles revealed that the major axis closely adhered with the rough surface of the corals (Figure 3a and b). Reduction in PSB results in wart or lump-like appearance on the surfaces of major axes, which covered both intact coral colonies (Figure 3c and d) as well as pieces of broken dead and live corals. Such a reduction in PSB in invaded colonies is also well witnessed when morphologically compared to the thallus of cultivated alga from Mandapam (Figure 3e) with samples from the study site (Figure 3f). The PSB are reduced only on the upper surface of the algal colonies, while considerable PSB is recorded on the lower surface. These branched thalli at the lower surface are relatively dark green in colour (Figure 3g and h) compared to light green, unbranched thallus on the upper surface. Moreover, the invaded corals had lost their skeletal integrity, stability and rigidity and could be easily detached from the reef matrix.

Table 1 presents quantitative data on bioinvasion of this alga on corals in the study site. Its maximum mean live cover was recorded at site 2 rather than at site 1. The former is located 100 m from the shore, suggesting an increase in its growth towards open sea. There are statistically significant ($P < 0.05$) differences between the two sites in live cover of K. alvarezii as well as other algae on the corals. But they do not differ significantly with reference to areas covered by corals as well as sand. It produces maximum mean biomass at site 2 than at site 1 (Figure 4).

Discussion

Many events of marine bioinvasion on animals have been reported from India. This article reports the bioinvasion of an exotic alga on coral reefs in the GoM. It was cultivated experimentally in 1997 at the Pamban Pass, Mandapam, South India. At present, it is being commercially cultivated at Pamban pass. It is presumed that these cultivation trials, both past and present, could be the root cause for its bioinvasion at the sampled site. These colonies could be established from vegetative fragments, which are generated from the cultivation site by many physical forces and are dispersed through wave action that settled on the coral substratum. Other factors involved include long duration (one year) of cultivation at different depths in 1997, as well as ongoing cultivation and ideal environmental conditions such as water temperature and availability of nutrients. Detachment of the thalli from the open and raft cultures during rough weather conditions, especially during the southwest and northeast monsoon seasons and their dispersal to other areas cannot be ruled
out. Similarly, post-cultivation surveys in the Kiribati Republic\textsuperscript{16,17} and Hawaii\textsuperscript{7–11} clearly demonstrate its invasion in other areas from the initial site of introduction, particularly on corals in Hawaii. As indicated by quantitative data from earlier studies\textsuperscript{7–11}, the present study also confirms its invasion with data on its live cover on corals as well as biomass production.

The GoM is rich in diversity of corals, especially in three genera, viz. \textit{Acropora}, \textit{Montipora} and \textit{Porites}. Among these, \textit{Acropora} is the most diverse genus with 24 species of branching corals. Unfortunately, the bleaching event in 1998 destroyed most of the shallow-water corals in the GoM and left only 25\% of live coral cover in the entire reserve\textsuperscript{18}. The worst affected species were the branching corals of genera \textit{Acropora} and \textit{Pocillopora}. Its species-specific invasion on \textit{Acropora} sp. appears to be dangerous, especially in the Mandapam group of islands due to the following reasons: (1) The live cover of branching corals in the entire reserve at present is 5.30 \(\pm\) 4\% only, (2) \textit{Acropora} species has maximum live cover at present in Mandapam group (8.5 \(\pm\) 13\%), followed by Kellakkarai (6.81 \(\pm\) 13\%) and (3) \textit{Acropora} species has been already worst affected by bleaching event in the Mandapam group. Quantitative information\textsuperscript{18} on the present status of branching corals of genus \textit{Acropora}, especially in the Mandapam group of islands, together with the present observation strongly indicate that the remaining minor percentage of live coral cover of \textit{Acropora} sp., at least in the Mandapam group, is under great threat from \textit{K. alvarezii}. Quantitative data revealed no significant difference between two sampled sites in coral cover but only in live cover of \textit{K. alvarezii}, suggesting its overgrowth on corals.

Studies on invasion of \textit{K. alvarezii} on coral reefs at Hawaii islands\textsuperscript{11} revealed that it had spread from the initial site of introduction to other reefs at a rate of 250 m per year. Taxonomic data revealed that the coral species affected by its invasion included mainly \textit{Porites compressa} and \textit{Montipora capitata}. It was recorded on coral surfaces and most frequently sighted on patch reefs at less than 1 m depth. The present study shows its maximum percentage cover on corals as well as biomass at depth ranging from 0.25 to 2 m. These observations clearly disprove the earlier presumption that it would not compete with native corals for space, but restrict itself to sand-covered habitats. The time required to clear all thalli from different habitat types (live coral, coralline pavement and rubble) revealed its association with corals as a physical phenomenon. It regrows in experimental plots within one year of removal and even surpassed the pre-removal abundance at certain reef sites. Its preference for live corals is also supported by maximum biomass production on them. The present records also indicate an in-

**Table 1.** Quantitative data on bioinvasion of \textit{Kappaphycus alvarezii} on corals in Kurusadai Island

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Site 1 (50 m) from the shore</th>
<th>Site 2 (100 m) from the shore</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coral cover (sq. cm/0.5 sq. m)</td>
<td>1726.6 (\pm) 49.5</td>
<td>1257.6 (\pm) 39.6</td>
</tr>
<tr>
<td>Cover of coral with \textit{K. alvarezii} (sq. cm/0.5 sq. m)*</td>
<td>141.3 (\pm) 20.5</td>
<td>870.3 (\pm) 59.0</td>
</tr>
<tr>
<td>Other algal covers (sq. cm/0.5 sq. m)*</td>
<td>318.0 (\pm) 9.0</td>
<td>106.6 (\pm) 8.8</td>
</tr>
<tr>
<td>Sandy cover (sq. cm/0.5 sq. m)</td>
<td>313.6 (\pm) 24.9</td>
<td>265.3 (\pm) 28.4</td>
</tr>
</tbody>
</table>

* Differences between two sites are significant at \(P < 0.05\).
increase in its biomass production towards the open sea zone. Woo also observed that it is able to coalesce into the tissue of the corals in order to achieve strong attachment, and thus acquire the ability to thrive in high wave-energy environment. He showed that even smallest fragments (0.05 g) attain complete growth in the wild and demonstrated such growth on live corals by time-series photographs. According to Smith et al., it is capable of spreading laterally, but does not appear to be able to spread long distances or between islands. However, the latter part of their conclusion was disproved by an earlier report. The two official websites of the Department of Botany, University of Hawaii, reported that it begun to reproduce sexually under cultivation in the wild.

Our conclusion on its invasion through vegetative propagation of fragmented and dispersed thallus is based on a strong belief that this species will not reproduce sexually through spores. Earlier studies confirmed low survival of germings and mass mortality of spores within 2–4 days of release under in vitro conditions. Conversely, it has been also shown that the average carpospore production from fertile branches is 279,000 spores per gram wet weight of the thallus. The growth rate of germings from its carpospore was highest in more nutrient-enriched medium under in vitro conditions. Bulboa et al. have also recently reported that tetrasporophyte green strains of K. striatum introduced and cultivated in the Sao Paulo, Brazil produced tetraspores. Under in vitro condition, they showed high viability of spores, 79% germination and growth into robust plantlets. Even though these contradictory facts are based on laboratory studies, one cannot assure prolonged vegetative reproduction in the wild. One can equally expect its sexual reproduction by spores in the GoM in future, when environmental conditions unanimously favour this alga. A recent report has revealed that K. alvarezii started to reproduce sexually through spores in Hawaii Island.

The smothering and shadowing impacts of this alga on dead corals cannot be simply ignored as impacts only on dead corals from the view of resilience and recovery of corals. The resilience of corals highly depends on functional groups of coral communities, which erode dead corals, expose the reef matrix for settlement of propagules of corals and reduce algal shadowing by grazing. In the absence of precious data on taxonomy and the above-stated functions of such functional groups in the GoM, we presumed that their activities could be prevented by such smothering and shadowing effects. Its uncontrolled growth on dead corals may reduce the possibilities of coral resilience. This shifting of coral-dominated ecosys-
tems after invasion into algal-dominated ecosystems is referred as ‘phase shift’, which is a clear indication of reef degradation\textsuperscript{24,25}. The occurrence of settling surfaces remains of prime importance in the macroalgal invasion phenomenon\textsuperscript{26,27}. From this viewpoint, Acropora sp. may offer ideal settling surfaces for its drifted fragments in the Kurusadai Island. One can also interpret its absence on massive corals in the study site from this viewpoint.

Invasion by an exotic species depends on suitable ecological conditions in the recipient environment\textsuperscript{13}. The following ecological conditions in the GoM may aggravate its invasion throughout the reserve in the near future. They briefly include dynamic wave energy and motion to disperse both vegetative fragments and spores (if produced in future), occurrence of dense fringing reefs, both live and dead, as ideal settling surfaces, nutrient enrichment of water by coastal pollution and generation of fragments of various sizes by mariculture activities, grazers and physical forces. Its better growth and biomass production in open and raft culture at Thonidurai, Mandapam was also attributed to such environmental factors of the GoM, viz. warm-water temperature (25–28°C) and influx of nutrients from the Palk Bay during the northeast monsoon season\textsuperscript{28}. The GoM also experiences significant variations in climatic factors across two monsoon seasons, which may also enhance the detachment and dispersal of vegetative fragments from the culture systems.

The remarkable shadowing and smothering effects exerted by it on live and dead corals have been reported earlier\textsuperscript{3,5,6}. Smothering could be an adaptation to escape from dislodgement during rough sea conditions. The reduction in PSB in the shallow areas of the study site can be interpreted as an adaptation against wave action to reduce the loss of thallus by breakage as recorded for many intertidal algae\textsuperscript{29}. In this context, it is notable that it branches well within polyethylene bags in bag culture when protected from wave action. It may also depend on depth; it grows as fleshy mats in deeper water with intricately tangled branches, while as gnarled forms with few branches in shallow areas\textsuperscript{5,6}.

If it spreads to other islands, especially the Mandapam group in the near future, it cannot be cleared using any physical and chemical methods. Earlier study\textsuperscript{13} on herbivorous species against this alga as biocontrol agents has met with different degrees of success and thus demand further studies. Another field study\textsuperscript{30} at Kurusadai Island suggested that K. alvarezii was considerably grazed by fishes. However, among 11 species of red algae tested, K. alvarezii was least susceptible to grazers. In addition to the lack of taxonomic data on grazer fishes, this study failed to evaluate them separately. The overgrowing and killing of corals by macroalgal species are mainly due to lack of grazer control in the recipient system\textsuperscript{31,32}. Such conditions may exist at present in the study site. Thus there is least hope for biocontrol of this alga in the GoM. Moreover, this alga is not the one and only source of carrageenan. There are nearly nine species of indigenous red algae capable of synthesizing carrageenans. It is worth focusing on their large-scale cultivation in order to meet at least the national demand from carrageenan-dependent industries. For instance, species belonging to genera Hypnea are promising candidates\textsuperscript{14}. Quantitative yield of carrageenan from them may be low, but is ecologically safe for commercial cultivation under wild in the GoM.

**Summary**

This study provides qualitative and quantitative data on bioinvasion of *K. alvarezii* on coral reefs (*Acropora* sp.) in the Kurusadai Island of the GoM. Without immediate control measures it may likely spread to other islands, especially those included in the Mandapam group. It could specifically destroy the branching corals (*Acropora* sp.) which have already reduced to minimum live cover in the reserve due to bleaching in 1998. In future, it may also adversely affect other native marine communities (sea grasses and coral reef fishes) either directly or indirectly. Presently, it reproduces through vegetative fragmentation and may switch over to sexual reproduction by spores under favourable environmental conditions in future. Hence control efforts should be launched soon, before it endangers the marine biodiversity of the GoM. Our findings disagree with earlier arguments and assumptions\textsuperscript{3,4,9} that the alga being as coral-friendly as well as suitable for commercial cultivation under wild in the GoM.

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4. Global Invasive Data Base, Invasive Species Specialist Group (ISSG) and IUCN; [http://www.issg.org/database](http://www.issg.org/database)
RESEARCH ARTICLES


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**Turbinaria** sp. as victims to *Kappaphycus alvarezii* in reefs of Gulf of Mannar, India

The Gulf of Mannar (GoM), India, includes 21 coral islands (8°N; 79°E), covers an area of 10,500 sq. km and supports 94 species of corals belonging to 37 genera. *Kappaphycus alvarezii*, a Philippine-derived rhodophyte, has been introduced into the GoM for commercial cultivation in 2002. The ecological threat from this invasive alga to coral species in GoM was first indicated by Pereira and Verlecar (2005). After 6 years of its introduction, its bioinvasion on branching corals (*Acropora* species) in the Kurusadai island (9°15′N; 79°12′E) of GoM was reported in 2008 (Chandrasekaran et al. 2008). Consequently, commercial cultivation of this invasive alga was prohibited. A mechanical removal programme started in 2009 by the State Government at the invaded site could not deliver expected results. Thus, this alga enjoys a freedom of unrestricted spread and aggressive growth in GoM, predominantly on species of *Acropora*. On 28 April 2010, during our routine sampling visit at Kurusadai Island, unusual appearance of *K. alvarezii*, on the cup coral, *Turbinaria* sp. was observed (Fig. 1a). The space between the plates of *Turbinaria* sp. provides an ideal settlement surface for *K. alvarezii*, which protect them from the wave action and favour the profuse growth of secondary branches of *K. alvarezii* between the plates (Fig. 1b) in contrast to the smothering effect on the top of coral plates (Fig. 1c). This finding shows that *K. alvarezii* is capable of invading species of non-branching corals as reported in Hawaii for *Montipora capitata* and *Porites compressa* (Conklin and Smith 2005). Therefore, perhaps this is the first report from India on bioinvasion of *K. alvarezii* on a non-branching coral (*Turbinaria* sp.) in the GoM.

**Acknowledgments** We thank CSIR and UGC, Government of India, New Delhi, for financial assistance and Department of Forestry, Government of Tamil Nadu for encouragement. We are thankful to the topic editor and three anonymous reviewers for their suggestions and comments.

**References**


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DOI 10.1007/s00338-010-0684-4
Microbial diversity in termite nest

Status of farmers who left farming in Punjab

Watershed impact evaluation using remote sensing
Impact of removal of invasive species 

*Kappaphycus alvarezii* from coral reef ecosystem in Gulf of Mannar, India

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*Kappaphycus alvarezii* is a commercially important red alga being intentionally introduced in marine waters worldwide for the production of kappa carrageenan. Its introduction into the Gulf of Mannar Biosphere Reserve during the 1990s and its subsequent escape from cultivation sites have paved the way for its invasion into the coral reef ecosystem of Kurusadai Island. Since the report of its invasion in 2008, removal of *K. alvarezii* from the reefs has been started by means of manual removal (hand plucking). This article details the unsuccessful attempt and negative impact of the eradication programme. Regrowth of *K. alvarezii* from removal points and drifting broken fragments resulting during removal have led to further establishment in the reef environment. Variation in the morphology of *K. alvarezii* populations after their removal has been observed. A significant reduction in the cover of coral and native algae due to the increase in abundance of *K. alvarezii* was evident from the study. The need for immediate scientific control measures to eradicate the invasive alga is discussed.

**Keywords:** Coral reefs, Gulf of Mannar, invasive species, *Kappaphycus alvarezii*, manual removal.

Biodiversity is affected by the invasion of exotic species in new geographical locations. The introduction and spread of non-native species have significantly altered the ecological functions of marine ecosystems¹². Exotic marine algae which behave as invasive species have impacted the native coral communities at the sites of incursion³⁻⁵. One such alga is *Kappaphycus alvarezii* (Doty) Doty ex. P. Silva (Rhodophyta: Solieriaceae). It is one of many seaweeds being intentionally introduced for the production of kappa carrageenan worldwide⁶. The farming of *K. alvarezii* was initiated in the Philippines during 1960s with local varieties of its wild populations, and it has expanded further to other parts of the world with different cultivation technologies⁷⁻⁸. However, *K. alvarezii* poses serious threats to native corals through overgrowing and smothering⁹⁻¹⁰.

The commercial cultivation of *K. alvarezii* in India was strongly opposed due to the prediction of its likely invasiveness¹¹, as it is exotic to Indian marine environments. However, field vigilance and environmental impact assessments showed no visible harmful effects from this alga¹² and thus its cultivation continues. However, later studies had shown its smothering effect on live corals in Kurusadai Island in the Gulf of Mannar (GoM)¹³⁻¹⁴. Incidents of *K. alvarezii* invasion on corals in GoM¹³ were reported¹⁵⁻¹⁶. There were immediate remedial responses from the State Government organizations to control/eradicate the alga.

Control of *K. alvarezii* in invaded communities has been carried out by either physical or biological methods¹⁷, or both. An underwater vacuuming system, Super Sucker, has been used as a physical method to eradicate *K. alvarezii* in Kaneʻohe Bay, Oʻahu. Also, native collector urchins (*Tripneustes gratilla*) were used to control *K. alvarezii*, which clear them through grazing. However, in Kurusadai Island, the Forest Department decided to use the manual removal method to reduce the impact of *K. alvarezii* on corals. In this article, we report on the consequences of the *K. alvarezii* removal process carried out in GoM.

**Materials and methods**

**Study area**

Kurusadai Island (9°15′N; 79°12′E) is a part of Mandapam group islands in GoM biosphere reserve, Tamil Nadu (for a map of the study area see ref. 13). Study sites are part of continuous fringing reefs located on the southern side of the Island which extend up to 500 m with varying depths of 0.5–2.0 m. A survey in 2005 revealed the presence of 54.9% live coral cover in the Island¹⁸. The coral ecosystem has experienced a recent coral–algal phase shift¹⁹ due to coral bleaching in 2010.
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The present study has continued from 2007 after the preliminary report of K. alvarezi invasion on patches of corals in intertidal region of the Island\(^3\). To examine the effects of K. alvarezi invasion on native coral reef communities, we carried out subsequent monitoring with the addition of control ecosystems devoid of K. alvarezi invasion. The control ecosystems are situated west of the invaded ecosystems and they are separated by a distance of about 750–1000 m. The invaded and control ecosystems were further divided into two sites, viz. site 1 (50 m from the shore) and site 2 (100 m from the shore). Depth at site 1 varies from 0.5 to 1.0 m and that at site 2 varies from 1.0 to 2.0 m for both ecosystems. Other than depth, all other biotic and abiotic factors are common to both sites of control and invaded ecosystems, except the presence of K. alvarezi in the invaded ecosystem.

Benthic community analysis

Estimates of the coral cover, live cover of K. alvarezi on corals, live cover of native algae and sand/rubble (expressed in %) were based on 80 randomly placed, 1 m\(^2\) quadrats (n = 20 per site per ecosystem). Stratified sampling was adopted to select K. alvarezi-invaded coral colonies in the study sites (sites 1 and 2) of the invaded ecosystems. Changes in abundance of K. alvarezi and native algae were estimated independently using 1 m\(^2\) quadrats without segregation of sites (n = 20 per ecosystem). Quadrats were located with a GPS (Garmin, Taiwan) and were visited periodically once in a month (between March and August) during 2008–2012. All quadrats were at least 1 m apart from each other. Parameters such as species abundance, species richness and evenness were estimated to study algal dynamics. Species abundance was calculated as the ratio between total number of individuals of a species and the number of quadrats in which the species were present. Species richness (S) was determined for each quadrat as the number of identified algal taxa. Simpson index of diversity (1 – D), which measures the probability of any two individuals randomly drawn from a community belonging to the same species, was used as a measure of species richness and evenness. For each quadrat, it was calculated as

\[
1 - D = 1 - \sum_{i=1}^{S} \frac{n(n_i - 1)}{N(N - 1)},
\]

where S is the species richness, \(n_i\) is the number of individuals in the \(i\)th species, and \(N\) is the total number of individuals of all species present in a quadrat. The value of 1 – D ranges from 0 to 1 and thus a higher value indicates greater diversity.

Though manual removal of K. alvarezi was started from 2009 (discussed below), all quadrats used for benthic community analysis in the invaded ecosystems were not affected by the manual removal process during 2009–2012. Due to mass eradication in 2012, these quadrats were not monitored further.

Assessment of manual removal impact on K. alvarezi

In early March 2009, the Tamil Nadu Forest Department initiated the removal of K. alvarezi by manual method (hand plucking) from invaded coral colonies at intertidal zone in Kurusadai Island. We did the first survey on the same day (8 March 2009). By visual survey, we selected nine removal points, i.e. reef substrates from which the alga was completely removed. Each removal point was covered by a GPS-marked quadrat (1 m\(^2\)) to analyse the K. alvarezi regrowth pattern. Prior to marking, we estimated area (cm\(^2\)/m\(^2\)) and well-drained fresh biomass (kg/m\(^3\)) of removed K. alvarezi colonies from the respective quadrats, which were noted as initial measurements. Resurvey was done at marked quadrats in early September 2009 (1 September 2009) spanning a time-interval of 175 days and estimated values were taken as final measurements. Algal colonies were removed during low-tide condition following the method of Conklin and Smith\(^{20}\). Daily growth rate (DGR) was estimated from the collected biomass using the equation given by Rueness \textit{et al.}\(^{21}\).

\[
\text{Growth rate (\% day}^{-1} ) = 100 \ln (W_t / W_0)/t,
\]

where \(W_0\) is initial weight, \(W_t\) final weight; \(t\) is the time-interval (days).

Qualitative data were taken using photographs. All observations and estimations were done during low-tide conditions.

Statistical analysis

Percentage cover data did not satisfy the assumptions of normal distribution, tested using Shapiro–Wilk’s test, even after transformations. Mann–Whitney \textit{U}-test was applied to test the null hypothesis stating that the percentage cover of each benthic component in control and invaded ecosystems, treating them as independent samples, has the same median. Since the data are non-normal, we used the median measure instead of mean for comparisons. Wilcoxon signed ranks test was used to test whether the median of each benthic variable differs significantly between successive years since 2008. However, colony area and biomass data of K. alvarezi collected for manual removal assessment were normally distributed. Hence, we used paired samples \textit{t}-test to reveal differences in their respective means between pre- and post-removal period. All statistical analyses were performed with IBM SPSS Statistics version 20.0.0.
Results

**Benthic community analysis**

We found no significant difference in the median of the studied benthic variables between successive years in both sites of control ecosystem (Wilcoxon signed ranks test: \( P > 0.05 \), \( N = 20 \), in all cases; Table 1). Compared to the control ecosystems, a remarkable decline in coral cover was observed in the *K. alvarezii*-invaded ecosystems (\( U = 4276.0, P < 0.01 \); Figure 1). In *K. alvarezii*-invaded ecosystems, median of coral cover was reduced from 64.9% in 2008 to 33.4% in 2012 and 45.6% in 2008 to 0% in 2012 at sites 1 and 2 respectively (Figure 1). A reduction in median of coral cover was significant between successive years at both sites of *K. alvarezii*-invaded ecosystems. *K. alvarezii* showed an increasing trend in its distribution at both sites of invaded ecosystem (Figure 1). Among the sites of the invaded ecosystem, median of *K. alvarezii* cover on corals had attained the maximum (97.6%) in site 2 rather than site 1 (60.9%) during 2012. It also showed significant difference in the median of *K. alvarezii* cover on invaded corals during successive years at both sites (Table 1).

During the study period, native algal species also experienced significant reduction in their cover at the *K. alvarezii*-invaded ecosystems compared to the control ecosystems (\( U = 9009.0, P < 0.01 \)). Significant reduction in median of native algal cover was observed from the year 2011 in site 1 and from 2010 in site 2 of *K. alvarezii*-invaded ecosystem (Table 1). The median number of algal species (\( S \)) per quadrat (*K. alvarezii* not included) was 7 (range: 3–11 species, \( n = 100 \)) in the control ecosystems and 5 (range: 1–8 species) in the invaded ecosystems. Median of species richness (\( S \)) showed significant difference between control and invaded ecosystems (\( U = 2031.5, P < 0.01 \)). In the invaded ecosystem, drastic decline in species richness (\( S \)) was observed during post-removal period (Table 2). Simpson diversity (1 – \( D \)) per quadrat (without *K. alvarezii*) was found to be significantly higher (\( U = 3457.0, P < 0.01 \)) in control ecosystems (median = 0.8, \( n = 100 \)) than invaded ecosystems (median = 0.7, \( n = 100 \)). Further, Simpson diversity in *K. alvarezii*-invaded quadrats reduced gradually during post-removal period (Table 2). This reduction clearly depicted the increase in dominance of *K. alvarezii* in the invaded ecosystems. Due to increase in abundance, *K. alvarezii* had shifted from lower rank (9th) during pre-removal to higher rank (3rd) and subsequently attained top rank (1st) after 2009, i.e. post-removal. Consequently, dominant native species such as *Gracilaria* sp., *Gelidiella* sp., *Caulerpa* sp. and *Padina* sp. were not recorded from the *K. alvarezii*-invaded ecosystems and other species such as *Sargassum* sp., *Turbinaria* sp., *Halimeda* sp., *Ulva reticulate* and *Hypnea* sp. had declined considerably (Table 2).

**Table 1.** Comparison of benthic cover components between successive years in control and *K. alvarezii*-invaded ecosystems of Kurusadai Island, Gulf of Mannar (GoM) during 2008–2012

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>Site 1</td>
<td>Coral</td>
<td>0.520</td>
<td>0.243</td>
<td>0.601</td>
<td>0.654</td>
</tr>
<tr>
<td></td>
<td></td>
<td><em>K. alvarezii</em> on coral</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Native algae</td>
<td>0.845</td>
<td>0.248</td>
<td>0.627</td>
<td>0.136</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sand/rubble</td>
<td>0.910</td>
<td>0.913</td>
<td>0.825</td>
<td>0.334</td>
</tr>
<tr>
<td>Site 2</td>
<td></td>
<td>Coral</td>
<td>0.918</td>
<td>0.165</td>
<td>0.856</td>
<td>0.526</td>
</tr>
<tr>
<td></td>
<td></td>
<td><em>K. alvarezii</em> on coral</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Native algae</td>
<td>0.756</td>
<td>0.070</td>
<td>0.376</td>
<td>0.433</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sand/rubble</td>
<td>0.609</td>
<td>0.983</td>
<td>0.446</td>
<td>0.765</td>
</tr>
<tr>
<td>Invaded</td>
<td>Site 1</td>
<td>Coral</td>
<td>0.010</td>
<td>0.005</td>
<td>0.013</td>
<td>0.010</td>
</tr>
<tr>
<td></td>
<td></td>
<td><em>K. alvarezii</em> on coral</td>
<td>0.001</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Native algae</td>
<td>0.388</td>
<td>0.062</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sand/rubble</td>
<td>0.209</td>
<td>0.051</td>
<td>0.008</td>
<td>0.028</td>
</tr>
<tr>
<td>Site 2</td>
<td></td>
<td>Coral</td>
<td>0.002</td>
<td>0.001</td>
<td>0.002</td>
<td>0.031</td>
</tr>
<tr>
<td></td>
<td></td>
<td><em>K. alvarezii</em> on coral</td>
<td>0.001</td>
<td>0.001</td>
<td>0.002</td>
<td>0.006</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Native algae</td>
<td>0.814</td>
<td>0.001</td>
<td>0.001</td>
<td>0.005</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sand/rubble</td>
<td>0.109</td>
<td>0.109</td>
<td>0.109</td>
<td>0.273</td>
</tr>
</tbody>
</table>

Bold values show significant difference at \( \alpha = 0.05 \) level. \( P \) values are based on Wilcoxon signed ranks test.

In the invaded ecosystem, the estimated initial (pre-removal) mean colony area of *K. alvarezii* was 1457.44 ± 113.11 cm²/m² (mean ± SE, \( n = 9 \)). Its biomass was estimated to be 4.52 ± 0.32 kg/m². We observed extensive regrowth of *K. alvarezii* at the removal points (Figure 2a). After 175 days, the mean colony area and biomass of *K. alvarezii* were found to be 3382.67 ± 192.09 cm²/m² and 12.77 ± 0.68 kg/m² respectively. Paired \( t \)-test revealed significant difference between pre- and post-removal impacts on *K. alvarezii*.
groups of *K. alvarezii* for colony area (*t* = 23.5, *P* < 0.01) and biomass (*t* = 22.1, *P* < 0.01). After removal, an increase of ca. 132% and 182% was recorded in colony area and biomass of *K. alvarezii* respectively. Estimated DGR of *K. alvarezii* for 175 days was 0.6%. Colonies of *K. alvarezii* fragmented from manual eradication attached themselves to neighbouring healthy coral colonies, and then expanded further (Figure 2b). Wave action was also responsible for the reintroduction of removed and discarded *K. alvarezii* colonies from the seashore to uninvaded corals (Figure 2c). Washed-up fragments of *K. alvarezii* colonies were observed along the seashore (Figure 2d). Twelve algal clumps with varying biomass of 150–1125 g (fresh weight) were collected along the shore of the invaded ecosystem during the study period. In addition to these observations and estimations, we observed a novel adaptation of the species after the interference of manual removal. In 2008, the growth of *K. alvarezii* was reported to be as a green mat over the top and lateral sides of the corals (Figure 2e) and the major axis of *K. alvarezii* closely adhered with the rough surface of the corals in the study region. In contrast, here we noticed unusual dome-like growth of *K. alvarezii* along the coral landscape (Figure 2f), particularly on manually damaged *K. alvarezii* colonies. The dome protruded out of the coral landscape and its height was 10 ± 0.76 cm in site 1 and
18.6 ± 1.56 cm in site 2 (n = 10 per site) of the invaded ecosystem. During our recent field visit in early March 2013, there appeared a widespread occurrence of *K. alvarezii* at both study sites of the invaded ecosystem which can be viewed clearly at low tides (Figure 3a). The number of *K. alvarezii* colonies was found to be 8.5 and 11.2 (per m$^2$; n = 10 quadrats) in sites 1 and 2 of invaded ecosystem respectively. It is significantly higher than the average number of *K. alvarezii* colonies observed in the corresponding sites of invaded ecosystem during pre-removal, i.e. 2009 (Table 3). In 2013, estimates of *K. alvarezii* colony area had ranged from 9.0 to 1716.0 cm$^2$ (mean = 502.7 cm$^2$; n = 85 colonies) in site 1 and 1.0 to 1722.0 cm$^2$ (mean = 239.3 cm$^2$; n = 112 colonies) in site 2 of the invaded ecosystems. Compared to mean *K. alvarezii* colony area during pre-removal, a significant reduction in mean colony area was observed in both sites of invaded ecosystems during post-removal, i.e. 2013 (Table 3; Figure 3b).

### Discussion

The results showed that innate benthos (such as corals, native algae) of Kurusadai Island were not altered much between sites as well as removal periods in the control ecosystems. A minimum level of reduction in coral cover of control ecosystems was observed during the study period (Figure 1). Competition between corals and native algae could be a reason for such reduction. However, such effects are common and fluctuate due to interannual variations. Absence of the invasive species *K. alvarezii* in the control ecosystems could be a specific reason for such intact ecosystem, whereas innate benthos cover was considerably decreased due to increase in the cover and abundance of *K. alvarezii* in the invaded ecosystems. Failure to restore pre-invasion status and predominant increase in *K. alvarezii* cover at invaded ecosystems could suggest that the removal has been counter-productive. Vigorous regrowth and establishment of *K. alvarezii* population has been observed after the removal process.

The reason for manual removal failure may be due to (i) biology of the invasive species and (ii) inefficacy of the method employed to eradicate *K. alvarezii*. The alga affects the corals by completely smothering them\(^{13,14}\). Consequently, there could be every possibility for leaving algal fragments within the coral tissues during removal. We observed small fragments of *K. alvarezii* firmly attached to the corals (Figure 3c), evidently detached during removal. The alga has the ability to coalesce into the tissues of corals, which provides a strong means of attachment\(^5\). Thus pieces of algal remains inside the coral tissue could facilitate regrowth under ambient natural conditions. Change in the structural form of *K. alvarezii* (i.e. dome protuberance) was observed only after manual removal. This modification may be due to non-availability of the substrate (i.e. corals) near the replenishing of *K. alvarezii*-invaded coral colonies. As a result, such algal colonies have adapted themselves to extend their colony expansion vertically. Most likely such adaptation still favours its spread by break and drift of protruding branches as fragments due to wave action. Even the smallest

### Table 2. Species abundance, richness, diversity and evenness of identified algal taxa in control and *K. alvarezii*-invaded ecosystems of Kurusadai Island, GoM during 2008–2012

<table>
<thead>
<tr>
<th>Algal species</th>
<th>Control ecosystem</th>
<th>Invaded ecosystem</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Sargassum</em> sp.</td>
<td>14.9 (4)</td>
<td>18.9 (3)</td>
</tr>
<tr>
<td><em>Gracilaria</em> sp.</td>
<td>21.8 (2)</td>
<td>22.4 (1)</td>
</tr>
<tr>
<td><em>Gelidella</em> sp.</td>
<td>22.4 (1)</td>
<td>14.8 (4)</td>
</tr>
<tr>
<td><em>Turbinaria</em> sp.</td>
<td>17.4 (3)</td>
<td>20.9 (2)</td>
</tr>
<tr>
<td><em>Caulerpa racemosa</em></td>
<td>8.0 (6)</td>
<td>3.9 (7)</td>
</tr>
<tr>
<td><em>Caulerpa taxifolia</em></td>
<td>9.5 (5)</td>
<td>2.3 (9)</td>
</tr>
<tr>
<td><em>Padina</em> sp.</td>
<td>7.0 (8)</td>
<td>3.7 (8)</td>
</tr>
<tr>
<td><em>Halimeda</em> sp.</td>
<td>2.6 (10)</td>
<td>1.0 (10)</td>
</tr>
<tr>
<td><em>Ulva reticulate</em></td>
<td>8.0 (6)</td>
<td>4.8 (5)</td>
</tr>
<tr>
<td><em>Hypnea</em> sp.</td>
<td>7.0 (8)</td>
<td>4.2 (6)</td>
</tr>
<tr>
<td><em>Dictyosphaeria cavernosa</em></td>
<td>1.1 (11)</td>
<td>1.0 (10)</td>
</tr>
<tr>
<td><em>Kappaphycus alvarezii</em></td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Species richness (S)$^a$

|                          | 5.5 (2.7) | 6.0 (2.7) | 7.0 (2.0) | 7.0 (1.0) | 8.0 (1.0) | 6.0 (1.7) | 5.5 (1.7) | 4.5 (2.0) | 4.0 (2.0) | 2.0 (1.7) |

Species Simpson index of diversity (1–D)$^b$

|                          | 0.8 (0.1) | 0.7 (0.1) | 0.8 (0.1) | 0.8 (0.04) | 0.8 (0.05) | 0.8 (0.1) | 0.8 (0.1) | 0.7 (0.2) | 0.5 (0.6) | 0.4 (0.9) |

$^a$Values denote abundance (species rank); $^b$Values represent median (interquartile range; n = 20 quadrats for each year); S and 1 – D values of invaded ecosystem devoid of *K. alvarezii* data.
fragments of size 0.05 g will be able to disperse and establish themselves widely if given sufficient time. The method employed for this alga removal (i.e. hand plucking) was not well planned and was unscientific. Available field experimental data on manual removal of K. alvarezii from corals in Hawaii have shown that the process is a daunting task. In the Gulf of Mannar National Park, the park managers have attempted eradication operations and they removed K. alvarezii attached to coral colonies in a ‘pluck and throw’ manner with no proper strategy to dispose or prevent spread of broken fragments. We observed several Acropora coral fragments attached to K. alvarezii both on-site (reef substrates) and off-site (seashore; Figure 3 d and e). To date, local island managers are collecting the washed-up coral fragments with K. alvarezii and dumping them on the seashore. So far, it is considered that the species could spread or reproduce by vegetative fragmentation because sexual reproduction through spores is rare and not viable. Hence fragmentation resulting from manual removal facilitates dispersal of fragments, and such broken fragments seem to attach and re-establish in the reef ecosystem. Widespread observation of higher number as well as small-sized colonies of K. alvarezii in invaded ecosystems during our recent visit in 2013 has supported this claim (Figure 3 b). Strong regeneration ability of this species and unscientific eradication strategies have contributed to significant spread of invasion in the locality. Similar negative feedback has been accounted in physical removal of invasive alga Sargassum muticum in England.
Invasive species as ‘ecosystem modifiers’ modify, create and maintain new physico-chemical conditions for their comfortable growth and continued expansion\textsuperscript{25}. Their removal should be viewed in the whole ecosystem or community context\textsuperscript{26,27}. Hence unscientific control strategies would exacerbate existing complexities and issues.

**Conclusion and implication**

This study illustrates the negative effects of the ongoing unscientific manual removal of *K. alvarezii* from invaded coral reef ecosystem in the Gulf of Mannar Marine National Park. If the alga is not controlled properly, there could be chance for it to invade the control ecosystem which is physically separated by considerable distance from invaded ecosystem and shares similar biogeographic conditions. To eradicate *K. alvarezii* from Kurusadai Island, it is necessary to develop ecologically viable control measures such as use of native herbivores, and mechanical removal by means of sucking pumps which are non-destructive to native communities, especially corals. While it is almost impossible to eliminate established alien species in marine habitats\textsuperscript{28}, it is obvious that prevention would be the option to avoid incidents of invasion.

**Table 3.** Frequency and colony size (cm\textsuperscript{2}/m\textsuperscript{2}) of *K. alvarezii* in invaded ecosystems of Kurusadai Island, GoM during the years 2009 and 2013

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Site 1</th>
<th>Site 2</th>
<th>Site 1</th>
<th>Site 2</th>
<th>t-test**</th>
<th>P value**</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of colonies*</td>
<td>1.8 ± 0.4</td>
<td>2.2 ± 0.5</td>
<td>8.5 ± 2.0</td>
<td>11.2 ± 5.0</td>
<td>14.53</td>
<td>&lt; 0.05</td>
</tr>
<tr>
<td>Area of colonies$</td>
<td>2238.0 ± 1268.5</td>
<td>5855.0 ± 3102.2</td>
<td>562.7 ± 389.0</td>
<td>239.3 ± 349.9</td>
<td>10.77</td>
<td>&lt; 0.05</td>
</tr>
</tbody>
</table>

Data represent mean ± SD; *Number per 1 m\textsuperscript{2} quadrat (n = 20 for 2009; n = 10 for 2013); $n = 20$ colonies for site 1 and site 2 in 2009; $n = 85$ colonies for site 1 and $n = 112$ colonies for site 2 in 2013; **Unequal sample size t-test; **Significance tested at $\alpha = 0.05$ level.


RESEARCH ARTICLES


ACKNOWLEDGEMENTS. We thank the Council of Scientific and Industrial Research, New Delhi for financial assistance and Tamil Nadu Forest Department for permission to carry out this work. We thank the two anonymous reviewers for their critical comments and valuable suggestions on the manuscript. We also thank Prof. R. Kannan, Madurai Kamaraj University, Madurai and Mr N. Krishnankutty, Madurai for help during the preparation of the manuscript.
Publication in Book Chapter
Knowledge Systems of Societies for Adaptation and Mitigation of Impacts of Climate Change
Climate Change Induced Coral Bleaching and Algal Phase Shift in Reefs of the Gulf of Mannar, India

J. Joyson Joe Jeevamani, B. Kamalakannan, N. Arun Nagendran and S. Chandrasekaran

1 Introduction

Coral reefs are the most diverse and complex of all marine ecosystems which normally flourish in tropical and semitropical regions of the world where water temperatures range between 16 and 30 °C. Coral reefs are most productive and provide various goods and ecological services (Moberg and Folke 1999) to human as well as marine biota. On other hand, throughout the world, there are many threats to existing coral reefs. Global warming, over fishing, mining, sedimentation, pollution, and diseases all threaten the viability and health of coral reefs. Coral bleaching is considered one of the biggest threats to coral reefs which accompanies coral mortalities (Brown 1997; Glynn 1993). Bleaching is a natural phenomenon in which the symbiotic intracellular algae (zoanthellae) of reef-building corals is expelled under stressful environmental conditions causing corals to lose their color. Such conditions are now more frequent due to global warming (Donner et al. 2005; Hoegh-Guldberg et al. 2007). Global warming and associated increases in sea surface temperatures (SSTs) are now projected to be very likely in the coming decades (IPCC 2007; Phinney et al. 2006). Incidence of coral bleaching reports, primarily due to SST rise, has increased considerably since the early 1980s (Glynn 1993; Hoegh-Guldberg 1999; Hoegh-Guldberg et al. 2007; Hughes et al. 2003). More often, mass coral mortality due to bleaching is followed by an invasion of macro algae which ultimately results in shifted algal dominated system (Done 1992). Such shift from coral reefs to high cover of macro algae is
referred as ‘coral-algal phase shift’. Regional scale studies are highly necessary to investigate the process of coral-algal phase shift after the bleaching phenomenon. Reefs of India also experienced severe bleaching events in 1998 and 2002. Increase in SST appears to be the main stress for these events (Arthur 2000; Kumaraguru et al. 2003). The present study reports algal phase shift after a bleaching event in 2010 in reefs of the Gulf of Mannar (GoM), India.

2 Materials and Methods

Visual observations of the bleaching event were observed during April 2010 in reefs of Kurusadai Island (9°15′ N; 79°12′ E) at Gulf of Mannar, Southeast coast of India (Fig. 1). Bleaching occurred in both massive and branching forms of corals. Photographic records were taken at first and bleached coral cover was estimated using transects. Totally, 10 transects, each of 5 m in length, were laid on selected bleached locations at a depth range from 0.25 to 2 m. Transects were marked using a Geographical Position System (GPS) device and revisited periodically at least once in a month from April to July 2010. Biophysical status of coral reefs were assessed based on observation of live coral cover, bleached coral (massive and branching forms), algal mat cover (algal turfs, macro-algal cover) and sand/coral rubble. SST was measured in situ using mercury bulb thermometer. To correlate SST with bleaching, satellite SST dataset obtained from National Oceanic and Atmospheric Administration’s Coral Reef Watch (NOAA/CRW) satellite bleaching alert (SBA) system (http://coralreefwatch.noaa.gov) specifically derived for the Gulf of Mannar region from January 2001 to October 2010 was used (Gang Liu, “personal communication”). The SST data is based on the NOAA 0.5° (approximately 50 km) resolution using Advanced Very High Resolution Radiometer (AVHRR) with weekly twice time interval. The data was subjected to appropriate statistical analyses.

3 Results and Discussion

Results show that both massive (Porites sp.) and branching (Acropora sp.) corals have been affected during the bleaching event of 2010 (Plate 1). Around 57% of corals were found to be bleached in Kurusadai Island during April to June 2010. Porites species were affected more compared to Acropora species. SST results shown that mean SST of the Gulf is 28.7 °C in 2010 with a maximum temperature of 31 °C in May and minimum temperature of 27.0 °C in February (Fig. 2). Sudden increase of temperature was observed (Fig. 2) from 29.9 to above 30.9 °C in April (16th week) and the existence of high temperature (up to 31 °C) for 7 weeks (April to May). Anomalies of mean SST for these weeks were also shows a great increase range from +1 to 2.2 °C (Fig. 3) relative to the 1950–1979 base
periods. Prolonged existence of inexperienced increased SST for nearly 50 days caused the corals to bleach. Decadal mean SST of Gulf of Mannar varied from 28.2 to 28.7 °C with a maximum temperature of 31.2 °C in 2002 and minimum temperature of 25.7 °C in 2004 (Fig. 4). The mean SST of the Gulf of Mannar has been growing at 0.02 °C per decade along with 0.1 °C increase per decade in minimum SST temperature.

Observation in July 2010 indicates that recovery was also rapid as that of bleaching. Nearly 15 % of bleached corals were found to have recovered. Recovery patterns differed between the two forms of corals. Recovery process is fast and effective in massive (Porites) rather than branching forms (Acropora). The increase in live coral cover (from 11.23 to 44.87 %) was mainly contributed by massive corals (Table 1). Significant recovery of branching corals was not observed. As a consequence, these corals were overgrown by algal mats (Sargassum sp., Turbinaria sp., Ulva sp., Caulerpa sp., Kappaphycus alvarezii) or algal turfs (Plate 1e and f) which increased the algal assemblage in branching forms from 10.9 to 18.36 %.
Similar to 1998 and 2002, the bleaching event in 2010 is driven by the increased effect of SST which was also recorded in other parts of world during the summer season (Harrison et al. 2011). Our results of this SST anomaly were also correlated with the prediction of McWilliams et al. (2005) who stated that maximum bleaching extent and intensity will occur at regional SST anomalies of less than +1 °C level. In our study, the mortality rate was high and recruitment rate was low in branch coral forms rather than in the massive and encrusting coral forms. Similar results were also reported earlier, which demonstrated that scleractinia corals with branching colony morphologies generally suffer higher rates of mortality than species with massive and encrusting morphologies (Hoegh-Guldberg and Salvat 1995; Jokiel and Coles 1990; Marshall and Baird 2000; McClanahan...
Bleaching incidence, caused by global warming, has resulted in replacement of hardier coral species by less hardy corals (Glynn and De Weerdt 1991) and corals by macro algae (Shulman and Robertson 1996). Our results synchronize with the above reported changes. Bleaching has significantly induced occurrence of phase-shift from coral to algae in the study site as previously observed in other regions of the world (Aronson et al. 2002, 2004; Hughes 1994).

Baker et al. (2008) suggested that changes in coral community structure following

$$y = 0.0212x + 73.231$$

$$R^2 = 0.04$$

$$y = 0.0199x - 11.487$$

$$R^2 = 0.1448$$

$$y = 0.0994x - 173.09$$

$$R^2 = 0.6348$$

![Graph](image)

**Fig. 4** Average minimum, maximum and mean SST at Gulf of Mannar for 2001–2010

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Life formsa</th>
<th>April 2010</th>
<th>July 2010</th>
<th>t—testb</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (SE) (n = 10)</td>
<td>Cover (%)</td>
<td>Mean (SE) (n = 10)</td>
<td>Cover (%)</td>
<td>t value</td>
</tr>
<tr>
<td>1.</td>
<td>BMC</td>
<td>2.25 (0.24)</td>
<td>45.10</td>
<td>0.57 (0.06)</td>
<td>11.43</td>
</tr>
<tr>
<td>2.</td>
<td>BBC</td>
<td>0.59 (0.06)</td>
<td>11.74</td>
<td>0.16 (0.02)</td>
<td>3.16</td>
</tr>
<tr>
<td>3.</td>
<td>AMC</td>
<td>0.40 (0.04)</td>
<td>7.95</td>
<td>0.44 (0.04)</td>
<td>9.05</td>
</tr>
<tr>
<td>4.</td>
<td>ABC</td>
<td>0.55 (0.06)</td>
<td>10.90</td>
<td>0.92 (0.10)</td>
<td>18.36</td>
</tr>
<tr>
<td>5.</td>
<td>LC</td>
<td>0.56 (0.06)</td>
<td>11.23</td>
<td>2.23 (0.23)</td>
<td>44.87</td>
</tr>
<tr>
<td>6.</td>
<td>SA</td>
<td>0.65 (0.07)</td>
<td>13.08</td>
<td>0.66 (0.07)</td>
<td>13.13</td>
</tr>
</tbody>
</table>

a BMC Bleached massive type corals, BBC Bleached branching type corals, AMC Algal assemblage over massive type corals, ABC Algal assemblage over branching type corals, LC Live coral, SA Sand area
b Paired t—test
c Bold faced values are highly significant

and Maina 2003). Bleaching incidence, caused by global warming, has resulted in replacement of harder coral species by less hardy corals (Glynn and De Weerdt 1991) and corals by macro algae (Shulman and Robertson 1996). Our results synchronize with the above reported changes. Bleaching has significantly induced occurrence of phase-shift from coral to algae in the study site as previously observed in other regions of the world (Aronson et al. 2002, 2004; Hughes 1994). Baker et al. (2008) suggested that changes in coral community structure following
bleaching can take two forms, viz., changes in the relative abundance of coral surviving *zooxanthellae* and changes in the dominance of non-coral taxa associated with reef assemblages. When bleaching long lasts with pronounced effect, coral-algal phase shift results and can lead to fundamental differences in the structure of reef communities. So it is inferred from this study that if increase in SST continues into the future, it will definitely impact the coral communities in the Gulf of Mannar and, thereby, affect the unsubstituted ecosystem services obtained from them.

**Plate 1** a Bleaching in massive corals (*Porites* sp.). b Recovered massive corals. c Bleaching in branching corals (*Acropora* sp.). d Algal turfs over bleached *Acropora* corals. e and f Algal phase shift dominated in branching coral forms
4 Conclusion

Existence of shift from coral dominance to algal dominance, following a bleaching incident in reefs of Gulf of Mannar is clear from the study. Once these communities have shifted, it will require a long time to return to their original status. Coral reefs of the Gulf of Mannar are already under serious threats like pollution, sedimentation, destructive fishing practices, biological invasion (Chandrasekaran et al. 2008; Kamalakannan et al. 2010), etc. Now coral-algal phase shift is also adding stress to the environment. Immediate mitigation measures have to be taken in order to protect the enriched coral diversity of Gulf of Mannar from recent climate change.

Acknowledgments We are thankful to the UGC and CSIR, New Delhi for the financial assistance to carry out this work. We also thank the Forest Department, Government of Tamil Nadu for providing permission and their encouragement to carry out this work. We are thankful to Mr. M. R. Anbarasan, Madurai for his valuable help in data mining.

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Seaweed Invader Elicits Angst in India

NEW DELHI—An effort in southern India to raise coastal farmers out of poverty by paying them to cultivate red algae for a food additive has gone awry. Last month, botanists reported that the alga, *Kappaphycus alvarezii*, has invaded coral reefs in a marine reserve in the Bay of Bengal. Experts are trying to establish who let the seaweed escape into the wild; a government lab, a multinational company, or careless farmers.

The saga began in 1996, when the Central Salt and Marine Chemicals Research Institute (CSMCRI) in Bhavnagar launched a project to grow the algae in perforated bags in the open sea and extract carrageenan, a gelatinous compound used to stabilize or add texture to products as diverse as toothpastes and mocha lattes. In 2000, CSMCRI transferred the technology to PepsiCo India Holdings Private Limited in Gurgaon, whose executive vice president, Amit K. Bose, told *Science* that since 2001 the company has been “supporting and subsidizing” local farmers to cultivate the alga offshore. The seaweed is grown on tethered rafts in shallow water; algae is harvested and dried and exported to countries such as Malaysia and the Philippines, which extract the carrageenan.

The commercial cultivation is near the edge of the Gulf of Mannar Marine National Park, a 560-square-kilometer reserve that’s home to more than 100 species of corals and mammals such as sea cows and dolphins. Off Kurusadai Island in the reserve, “no part of the coral reefs was visible in most invaded sites, where [the algae] doomed the entire colonies and occupied almost all ridges and valleys of the coral landscape,” a team led by botanist S. Chandrasekaran of Thiagarajar College in Madurai reported in the 10 May issue of *Current Science*. It’s not clear if the alga has spread to other parts of the reserve.

This isn’t the first time the alga, native to the Philippines, has invaded new turf: In 1999, it colonized coral reefs in Hawaii, according to the University of Hawaii, Manoa. For that reason, some prominent researchers, including M. S. Swaminathan, an agricultural scientist at M. S. Swaminathan Research Foundation in Chennai who now serves in Parliament, had opposed bringing the alga to India in the first place.

No one has taken responsibility for *K. alvarezii*’s escape. Whoever is deemed responsible could be prosecuted for damaging habitat under the Indian Wild Life Protection Act of 1972, says P. K. Manohar, a lawyer with Legal Action for Wildlife and Environment in New Delhi.

Bose acknowledges that PepsiCo promoted contract farming of the algae to serve the community by helping impoverished farmers. The company guarantees that it will buy all the farmers’ annual production of *K. alvarezii*, amounting to 100 to 200 metric tons of dry seaweed; all the dry seaweed is exported, Bose says. He denies that PepsiCo played a role in the alga’s escape into the marine reserve. Instead, he suggests that CSMCRI’s cultivation trials are “the root cause for its bioinvasion at [Kurusadai].”

CSMCRI’s director, Pushpito K. Ghosh, says he is “quite puzzled as to what may have happened.” He and his colleagues argue that strong currents could have swept algal twigs from commercial farms near Kurusadai or from his institute’s trial cultivation site.

“When the votes were counted, Osipov had received 52%, whereas Fortov got 39% and Valery Chershevnev 7%. “I think we are now witnessing a critical moment in the history of our academy,” says Spirin. “This is an unprecedented situation that so many people voted against the president.”

—ANDREY ALLAKHERDOV AND VLADIMIR POKROVSKY

Andrey Allakhverdov and Vladimir Pokrovsky are writers in Moscow.

US genomics leader bows out from institute

Francis Collins, the geneticist who led the US National Human Genome Research Institute (NHGRI) in Bethesda, Maryland, through the completion of the Human Genome Project and the dawn of the personal genomics era, has announced that he will leave his post on 1 August.

In a news conference last week, Collins said he has no concrete plans about his future and was leaving the NHGRI to explore posts "that would be very difficult to consider or discuss or pursue while continuing in my role as a federal employee". Many speculate that Collins could assume a leadership role in the next presidential administration, possibly as director of the National Institutes of Health or science adviser to the president. Collins also says that he would like to write a book about personal genomics for the public.

During his 15-year tenure, Collins led what many scientists see as a shift towards funding large-scale projects. He became known as a public face of the Human Genome Project and drew the wrath of some scientists for arguing that science and religious faith are compatible (see Nature 442, 114–115; 2006). See Editorial, page 697.

Merck scores victory in three Vioxx appeals

Appeals courts in two US states last week overturned verdicts favouring plaintiffs who had sued Merck, the pharmaceutical giant, over its painkiller Vioxx (rofecoxib). The drug was taken off the market in 2004 after a study showed it doubled the risk of heart attacks and strokes.

In Texas, a three-judge panel reversed a $26-million jury verdict in the first and most public Vioxx lawsuit. It said that lawyers for Carol Ernst had failed to prove that the drug caused the death of her husband in 2001 (see Nature 436, 1070; 2005). Ernst's lead attorney said they would appeal the decision.

The ruling came the same day that a New Jersey appeals court scuttled $9 million in punitive damages awarded to John McDarby in 2006 — arguing that the law under which the money was awarded is trumped by the federal law under which the Food and Drug Administration approves drugs for market.

The reversals mean that, out of 16 Vioxx cases that have completed trials so far, only three have resulted in unqualified victories by plaintiffs. The bigger picture for the company and for tens of thousands of other plaintiffs remains largely unchanged because of a $4.85-billion settlement agreed last November (see Nature 450, 324; 2007).

Indian coral islands under threat from algae

A dispute about non-native algae has broken out in India between beverage giant PepsiCo and the Central Salt & Marine Chemicals Research Institute (CSMCRI), which is based in Bhavnagar, Gujarat. Institute researchers originally imported the alga Kappaphycus alvarezii for research; in 2001 PepsiCo began cultivating it for the food thickener carrageenan in the Gulf of Mannar marine bioreserve, along India's southeastern coast. Reporting in Current Science last month, scientists from Thiagarajar College in Madurai say that corals fringing an island in the gulf are being smothered to death by the algae.

The CSMCRI suspects that the algae drifted into protected waters from PepsiCo's
The alga *Kappaphycus alvarezi* is choking coral.

Cultivation sites, whereas PepsiCo says the more likely source is the institute’s seaweed depot on the island. According to CSMCRI, that depot was closed down in 2003. Ecologists are worried that *K. alvarezi*, which is currently spreading asexually, could switch to sexual reproduction by spores. These could be carried by wind to the remaining 20 coral-fringed islands in the bioreserve.

**Donation breathes life into Fermilab’s balance sheet**

A private donor has given US$5 million to particle physics. The donation ends unpaid leaves of absence that physicists at Fermi National Accelerator Laboratory in Batavia, Illinois, have been forced to take since February because of budget cuts.

The money, from a family that wishes to remain anonymous, was given on 27 May to the University of Chicago, which in turn will hire Fermilab to do contract work on neutrinos and rare particle decay. The furloughs, scheduled to last into September, were intended to save $12 million. The $5 million gift, plus an additional $1 million of savings through early retirements, allowed the leaves to end on 31 May.

Fermilab has also reduced from 200 to 140 the number of lay-offs it expects to make starting in June.

**Researchers kidnapped near Atacama telescope**

Officials at the Atacama Large Millimeter Array (ALMA) telescope are stepping up security at its construction site in Chile after two researchers were kidnapped on a nearby road.

On 11 March, Rolf Güsten, an astronomer with the Atacama Pathfinder Experiment, an ALMA-related project, and a senior engineer were stopped by four men dressed as policemen on a highway near the site in a remote part of northern Chile. The men commandeered the vehicle and drove it into Bolivia, where a few hours later they left the pair at the side of the road. “Fortunately, none of us was injured,” Güsten says.

ALMA has since increased security by hiring more guards and adding more cameras and phones at the site, and is working with Chilean authorities.

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**Correction**

The Editorial ‘Working double-blind’ (*Nature* 451, 605–606; 2008) referred to a study that found more female first-author papers were published using a double-blind, rather than a single-blind, peer-review system. The data reported in ref. 1 have now been re-examined. The conclusion of ref. 1, that *Behavioral Ecology* published more papers with female first authors after switching to a double-blind peer-review system, is not in dispute. However, ref. 2 reports that other similar ecology journals that have single-blind peer-review systems also increased in female first-author papers over the same time period. After re-examining the analyses, *Nature* has concluded that ref. 1 can no longer be said to offer compelling evidence of a role for gender bias in single-blind peer review. In addition, upon closer examination of the papers listed in PubMed on gender bias and peer review, we cannot find other strong studies that support this claim. Thus, we no longer stand by the statement in the fourth paragraph of the Editorial, that double-blind peer review reduces bias against authors with female first names.