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

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***Kappaphycus alvarezii* (Doty) Doty (Rhodophyta: Solieriaceae) 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 rubbles 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 under wild conditions in the Gulf of Mannar. Our observations underscore the need for urgent reconsideration of its cultivation in a biologically diverse ecosystem, the Gulf of Mannar.**

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: Solieriaceae) 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 invasiveness 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 dicapac 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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als at the two study sites are based on 30 randomly placed 0.5 sq. m quadrats[11] along the transect (n = 10 per transect). The biomass of *K. alvarezii* was estimated by sampling 30 (0.25 sq. m) randomly placed quadrats along the transect in sites 1 and 2 (n = 10 per transect). The harvested samples were blotted, weighed in the field and expressed in g/sq. m/wet wt. Mean values of selected parameters were tested for differences between the two sites using Student's *t*-test.

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 2 *a* 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 2 *c* and *d*) and lateral sides (Figure 2 *e*) 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 2 *f* 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 2 *h*). 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 3 *a* 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 3 *c* 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 3 *e*) with samples from the study site (Figure 3 *f*). 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 3 *g* 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).

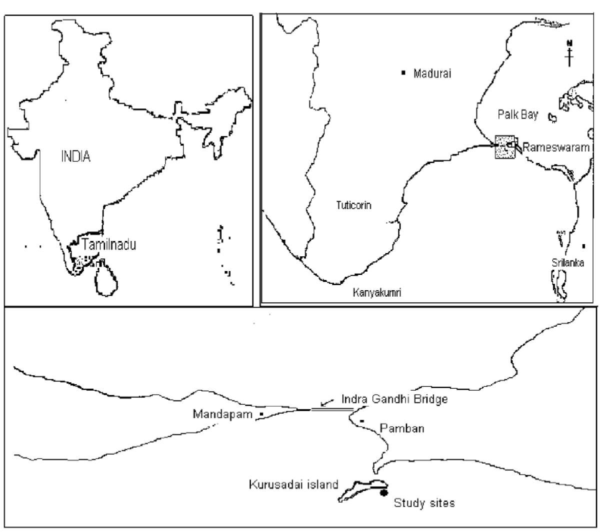

Figure 1. Map of the Gulf of Mannar Marine Biosphere Reserve (GoM) showing the Kurusadai Island and sampled sites.

Discussion

Many events of marine bioinvasion on animals have been reported from India[2]. 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, Mandabam, 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

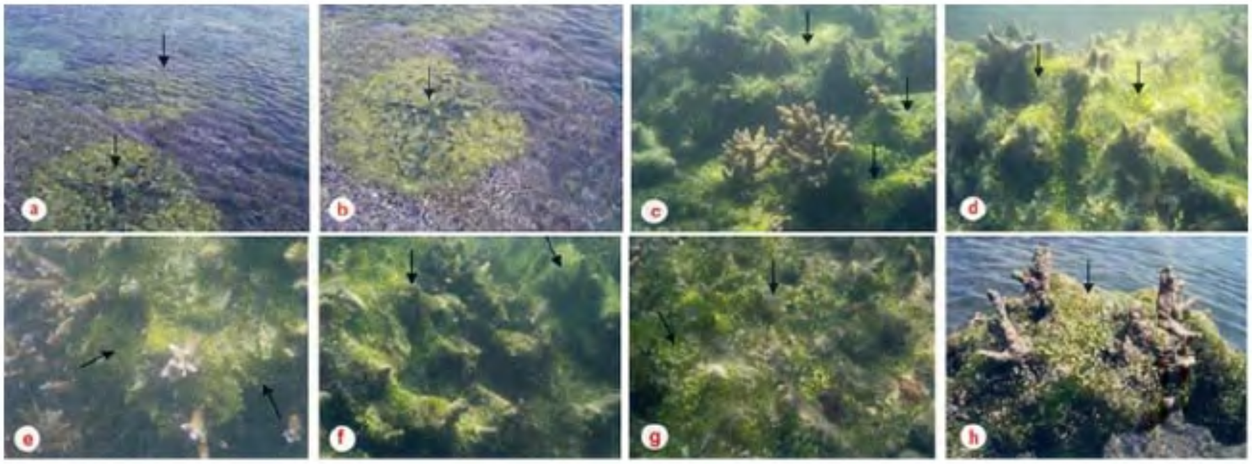

Figure 2. ***a*** and ***b***, Invaded colonies of *Kappaphycus alvarezii* in Kurusadai Island as observed from the water surface during low-tide conditions. ***c*** and ***d***, Overgrowth of *K. alvarezii* on top of colonies of *Acropora* sp., as green mate. ***e***, Growth of *K. alvarezii* on lateral sides of colonies of *Acropora* sp. ***f*** and ***g***, Ridges and valleys of coral colonies invaded and doomed by *K. alvarezii*. ***h***, Complete covering of coral surface by rubber-like major axis (smothering) of *K. alvarezii*.

Table 1. Quantitative data on bioinvasion of *Kappaphycus alvarezii* on corals in Kurusadai Island

Parameter	Site 1 (50 m) from the shore	Site 2 (100 m) from the shore
Coral cover (sq. cm/0.5 sq. m)	1726.6 ± 49.5	1257.6 ± 39.6
Cover of coral with *K. alvarezii* (sq. cm/0.5 sq. m)*	141.3 ± 20.5	870.3 ± 59.0
Other algal covers (sq. cm/0.5 sq. m)*	318.0 ± 9.0	106.6 ± 8.8
Sandy cover (sq. cm/0.5 sq. m)	313.6 ± 24.9	265.3 ± 28.4

*Differences between two sites are significant at $P < 0.05$.

out. Similarly, post-cultivation surveys in the Kiribati Republic[16,17] and Hawaii[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[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. *Acropora*, *Montipora* and *Porites*. Among these, *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[18]. The worst affected species were the branching corals of genera *Acropora* and *Pocillopora*. Its species-specific invasion on *Acropora* sp. appears to be dangerous, especially in the Mandapam group of islands due to the following resons: (1) The live cover of branching corals in the entire reserve at present is 5.30 ± 4% only, (2) *Acropora* species has maximum live cover at present in Mandapam group (8.5 ± 13%), followed by Kellakkarai (6.81 ± 13%) and (3) *Acropora* species has been already worst affected by bleaching event in the Mandapam group. Quantitative information[18] on the present status of branching corals of genus *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 *Acropora* sp., at least in the Mandapam group, is under great threat from *K. alvarezii*. Quantitative data revealed no significant difference between two sampled sites in coral cover but only in live cover of *K. alvarezii*, suggesting its overgrowth on corals.

Studies on invasion of *K. alvarezii* on coral reefs at Hawaii islands[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 *Porites compressa* and *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-

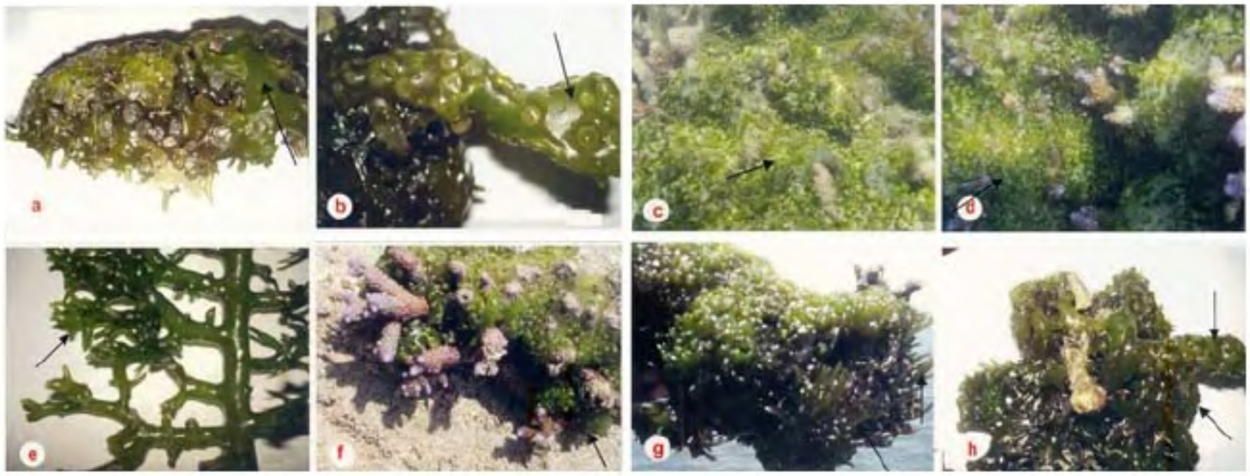

Figure 3. ***a*** and ***b***, Smothering effect of major axis on the surface of pieces of live and dead corals. ***c*** and ***d***, Wart or lump-like appearance of reduced primary and secondary branches of invaded colonies of *K. alvarezii*. ***e***, Major axis of the thallus of *K. alvarezii* from cultivation source with extensive lateral branches. ***f***, Major axis of thallus of *K. alvarezii* from the study site with reduced lateral branches. ***g***, Dark green lateral branches from the lower surface of the invaded colonies of *K. alvarezii*. ***h***, Absence of lateral branches on the dorsal surface of the invaded colonies of *K. alvarezii*.

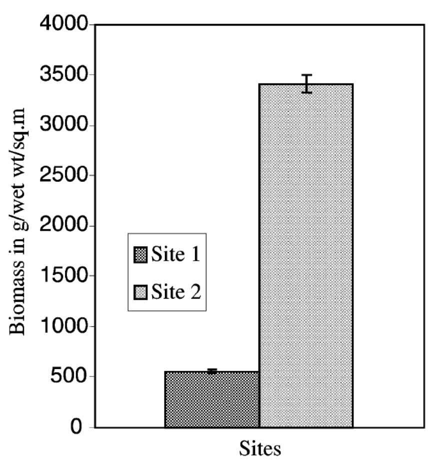

Figure 4. Biomass production by *K. alvarezii* at two sites in Kurusadai Island.

crease in its biomass production towards the open sea zone. Woo[9] 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.*[10], 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[11]. The two official websites[5,6] 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[19,20] confirmed low survival of germlings 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 germlings from its carpospore was highest in more nutrient-enriched medium under *in vitro* conditions[21]. Bulboa *et al.*[22] 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[11] 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[23], 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 ecosystems after invasion into algal-dominated ecosystems is referred as 'phase shift', which is a clear indication of reef degradation[24,25]. The occurrence of settling surfaces remains of prime importance in the macroalgal invasion phenomenon[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[3]. 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[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[5,6,9]. 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[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[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[11] on herbivorous species against this alga as biocontrol agents has met with different degrees of success and thus demand further studies. Another field study[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[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[33]. Quantitative yield of carrageenan from them may be low, but is ecologically safe for commercial cultivation 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[34] that the alga being as coral-friendly as well as suitable for commercial cultivation under wild in the GoM.

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