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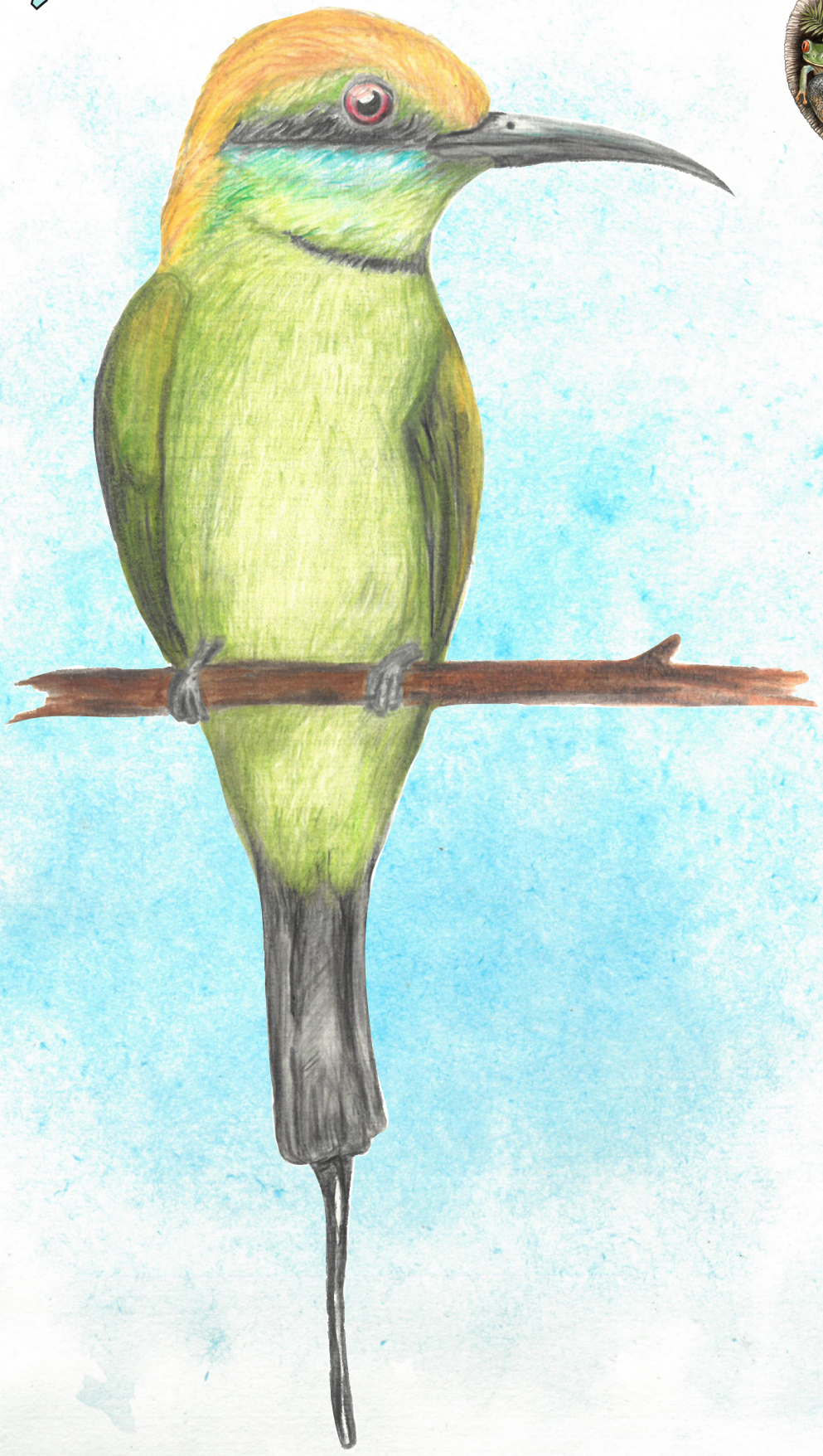

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Registered Office: 3A2 Varadarajulu Nagar, FCI Road, Ganapathy, Coimbatore, Tamil Nadu 641006, India
Ph: +91 9385339863 | www.threatenedtaxa.org
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Cover: Green Bee-eater with colour pencils and watercolor wash by Elakshi Mahika Molur.

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COMMUNICATION

Occurrence of opportunistic invasive macroalgal genus *Caulerpa* and *Halimeda opuntia* in coral reefs of Gulf of Mannar

Chatragadda Ramesh [1], Koushik Sadhukhan [2], T. Shunmugaraj [3] & M.V. Ramana Murthy [4]

[1–3] National Centre for Coastal Research (NCCR), Ministry of Earth Sciences (MoES), Mandapam Field Research Centre, Mandapam Camp, Ramnathapuram, Tamil Nadu 623519, India.

[4] National Centre for Coastal Research (NCCR), Ministry of Earth Sciences (MoES), Pallikaranai, Chennai, Tamil Nadu 600100, India.

[1] chrameshpu@gmail.com (corresponding author), [2] sadhukhan.1985@gmail.com, [3] raj@nccr.gov.in, [4] mvr@nccr.gov.in

Abstract: Investigations on indigenous and non-indigenous invasive flora and fauna of a certain geographical area are always important to assess their impact on native biodiversity and control their spread by making conservation strategies to protect biodiversity. In this study, we have encountered overwhelming growth of six seaweed species, *Caulerpa racemosa*, *C. serrulata*, *C. sertularioides*, *C. taxifolia*, *C. peltata,* and *Halimeda opuntia* on the reef flat. These algal covers on reef area appear to compete with coral polyps and restrict their settlement and resilience. Our concern on invasive species distribution in Gulf of Mannar revealed these overgrowing invasive species, which can become potential threats to coral reefs, benthic diversity, and reef assemblage. These observations will help us to develop multidisciplinary management approaches related to the expansion, mitigation, and control of these opportunistic invasive species. Further seasonal monitoring on these algal species is under process to investigate their spatial shift patterns on various coral forms.

Keywords: algal blooms, algal cover, coral-algal interactions, reef conservation, reel flat, reef resilience, reef restoration, reef threats, seaweed, seaweed utilization.

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Competing interests: The authors declare no competing interests.

Author details: Dr. Ramesh Chatragadda has been working on different aspects of coral reefs, such as coral diseases, coral restoration, coral reef monitoring, and reef diversity. His research is aimed at molecular taxonomy of reef communities and microbial ecology of coral communities for drug discovery and reef conservation. Dr Koushik Sadhukhan has been working in NCCR since 2018. He has experienced with eight years of R & D work on coral reef monitoring and coral restoration programme in India. His research interest lies in the area of marine biology, taxonomy and ecology. Dr T. Shunmugaraj is the senior scientist of NCCR (scientist-G) and he has excellent research experience of 27 years in the field of marine biology and mariculture. His research is focused on marine biodiversity assessment in Indian Ocean. He has also worked on stock enhancement and sea ranching programme of cultivable marine species in India. Dr M.V. Ramana Murthy serves as scientist-G and director of NCCR who has been engaged in R & D work for 30 years in the field of offshore and coastal hydrodynamics, coastal conservation and Information service programme in India.

Author contributions: RC conceived the study, conducted the fieldwork, and prepared the manuscript. KS helped in feild work, wrote and edited the manuscript. TS designed the study, assisted in the field study, corrected the draft manuscript, and supervised the project. MVRM coordinated the study and gave technical advice.

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INTRODUCTION

Invasive species belonging to flora and fauna can lead to adverse effects such as altering the biodiversity and community structure (Antolić et al. 2008), and can even invade or cause mortality to flora (de Villèle & Verlaque 1995) and fauna (Žuljevic et al. 2011). A study on the impact of invasive *Caulerpa taxifolia* on seagrass beds of *Posidonia oceanica* has revealed degradation of seagrass beds in the west of Menton, France (de Villèle & Verlaque 1995). Various authors have also reported the distribution of indigenous invasive species, including *Ulva fasciata*, *Cladophora sericea*, and *Dictyosphaeria cavernosa* in the Hawaiian Islands (Smith et al. 2002), and non-indigenous invasive algae, including *Caulerpa verticillata* in the Gulf of California (Perez-Estrada et al. 2013), *Lophocladia lallemandii* (Kersting et al. 2014), *Caulerpa racemosa* var. *cylindrica* and *C. taxifolia* in Mediterranean region (Žuljevic et al. 2011), and *C. racemosa* in the Gulf of Arzew, Algerian coast (Bouiadjra et al. 2010). Currently, the genus *Caulerpa* has been indicated as an invasive species by the International Union for Conservation of Nature (IUCN) Centre for Mediterranean Cooperation (Otero et al. 2013).

The invasive *Caulerpa* species spread rapidly all along the Mediterranean countries (Klein & Verlaque 2008). Since then, the issue of invasive algae in other parts of the world was also undertaken in different countries, as mentioned above. Recently, studies on invasive flora from the Gulf of Mannar region are gaining more importance due to their reef damaging nature. A few studies showed the invasion of *Kappaphycus alvarezii* on coral reefs in Krusadai and Mulli Islands (Edward et al. 2015), *Caulerpa* sp. and *Halimeda* sp. in the Gulf of Mannar and Palk Bay coral reefs (Manikandan & Ravindran 2016), and *Turbinaria* in the Gulf of Mannar corals (Ramesh et al. 2019). However, there is very little information on the current distribution patterns of invasive seaweeds around the Gulf of Mannar Islands. Therefore, during coral reef monitoring, we investigated invasive species distribution in the Gulf of Mannar group of Islands.

MATERIAL AND METHODS

Reef monitoring surveys were carried out during August to November 2018, from Manoli Putti and Hare Islands under the Gulf of Mannar region, southeastern coast of Tamil Nadu, India. Several underwater dives on fringing reefs of these two islands revealed moderate bloom forming and overwhelming growth of four green seaweeds *Caulerpa serrulata*, *C. racemosa*, *C. sertularioides*, and *C. peltata* on live and dead corals. Underwater photographs of these bloom-forming species were documented using Nikon Coolpix underwater camera. Species identification was made using standard identification keys and AlgaeBase (Guiry & Guiry 2018).

RESULTS AND DISCUSSION

Caulerpa racemosa, *C. serrulata*, *C. sertularioides*, *C. taxifolia*, *C. peltata*, and *Halimeda opuntia* are usually seen in smaller size on corals and rubbles. Their usual occurrence on reefs or rubbles used to be within the size range <5–>30 cm. However, their bloom forming nature identified by recording their overwhelming spread on corals ranged >30 cm–>1 m. Blooms of these species overwhelming on the coral reefs of Mandapam group of Islands were recorded during our study (Image 1a–h; Image 2a–f). The favourable physicochemical conditions that promote their spread in the reef area are poorly understood. These algal species have displayed a distinct distribution in the reef environment, where *C. sertularioides* and *C. racemosa* grew on rubbles, rocky substratum, and *Porites* sp.; *C. serrulata* on dead *Acropora* corals and live *Porites* species; and *C. peltata* on live *Acropora* corals. *C. taxifolia* has formed small patches on rubbles and near reef slopes, and is also found to grow mostly on *Montipora digitata* and *Porites solida rather* than on *Acropora*. Interestingly, *C. racemosa* was observed to grow on multiple species of corals such as *Porites*, *Acropora*, and *Montipora*. *C. racemosa*, *H. opuntia*, and *C. taxifolia* grew together with no inhibition activity against each other. *H. opuntia* was found to cover a few massive *Porites* coral colonies in Manoliputti Island. While its spread in seagrass beds was also observed (Image 2a–f), its actual impact on seagrass beds is yet to be studied.

We did not observe any grazers that preferred to feed on these *Caulerpa* species. Although *C. taxifolia* was found in the reef flats but were not seen to occur profusely. These algal blooms appear to be unsuitable for the development of corals due to their proliferation, smothering the corals. Also, overwhelming algal growth inhibits light penetration required for zooxanthellae to generate energy for polyps. These reasons appear to inhibit the growth of coral polyps and restrict juvenile corals' settlement on the dead reefs or rubble in the Gulf of Mannar reefs.

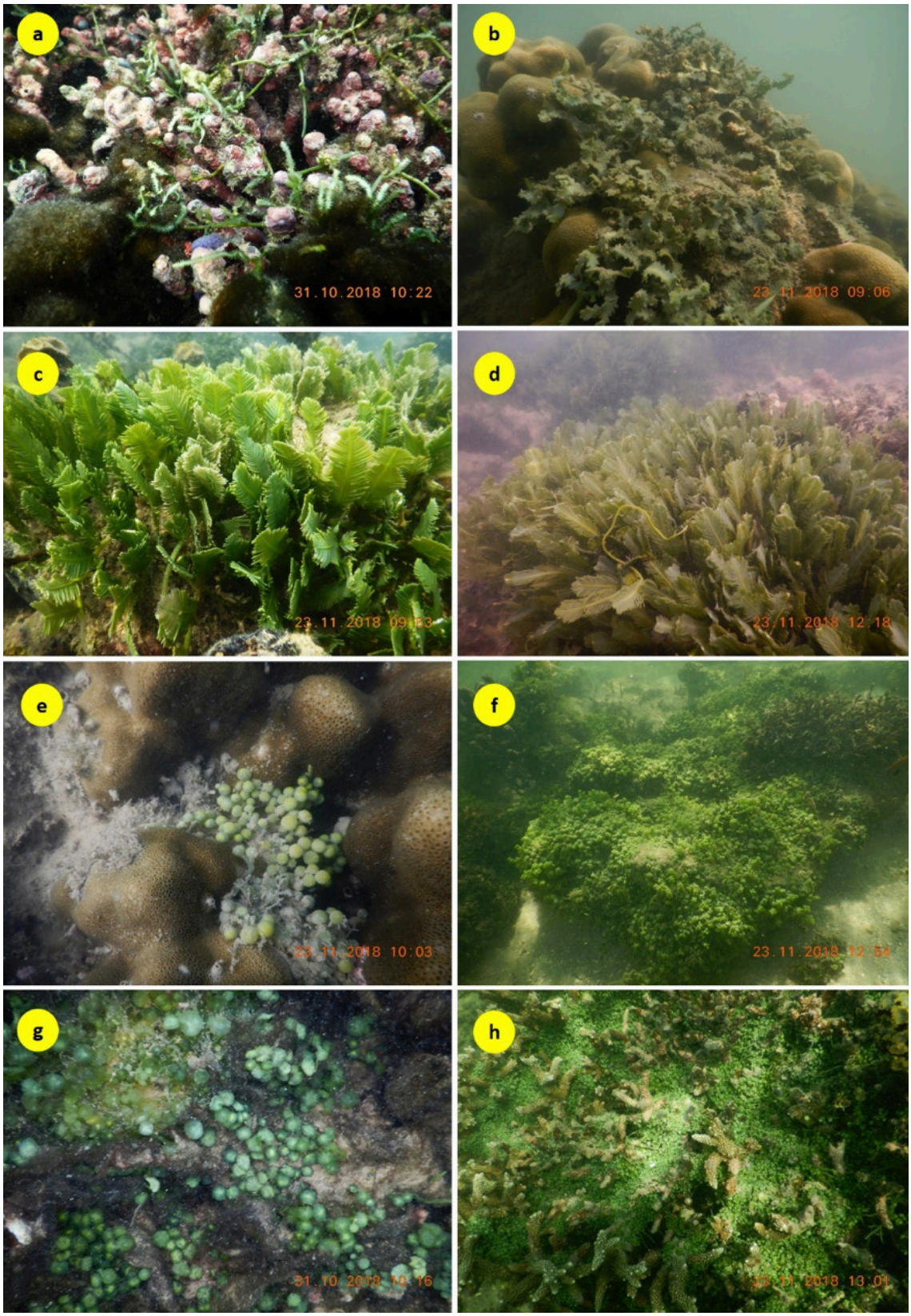

Image 1. a—Invasive and bloom-forming *Caulerpa serrulata* on dead *Acropora* reef | b—its overwhelming growth on *Porites* | c—*Caulerpa sertularioides* usual occurrence | d—canopy formation on the upper surface of *Porites* sp., dead corals and coral rubbles | e—*C. racemosa* in normal condition | f—its algal mat formation on *Porites* sp., dead corals and rubbles | g—*C. peltata* on dead *Acropora* coral | h—its algal mat formation on *Acropora* coral. © Ramesh Ch.

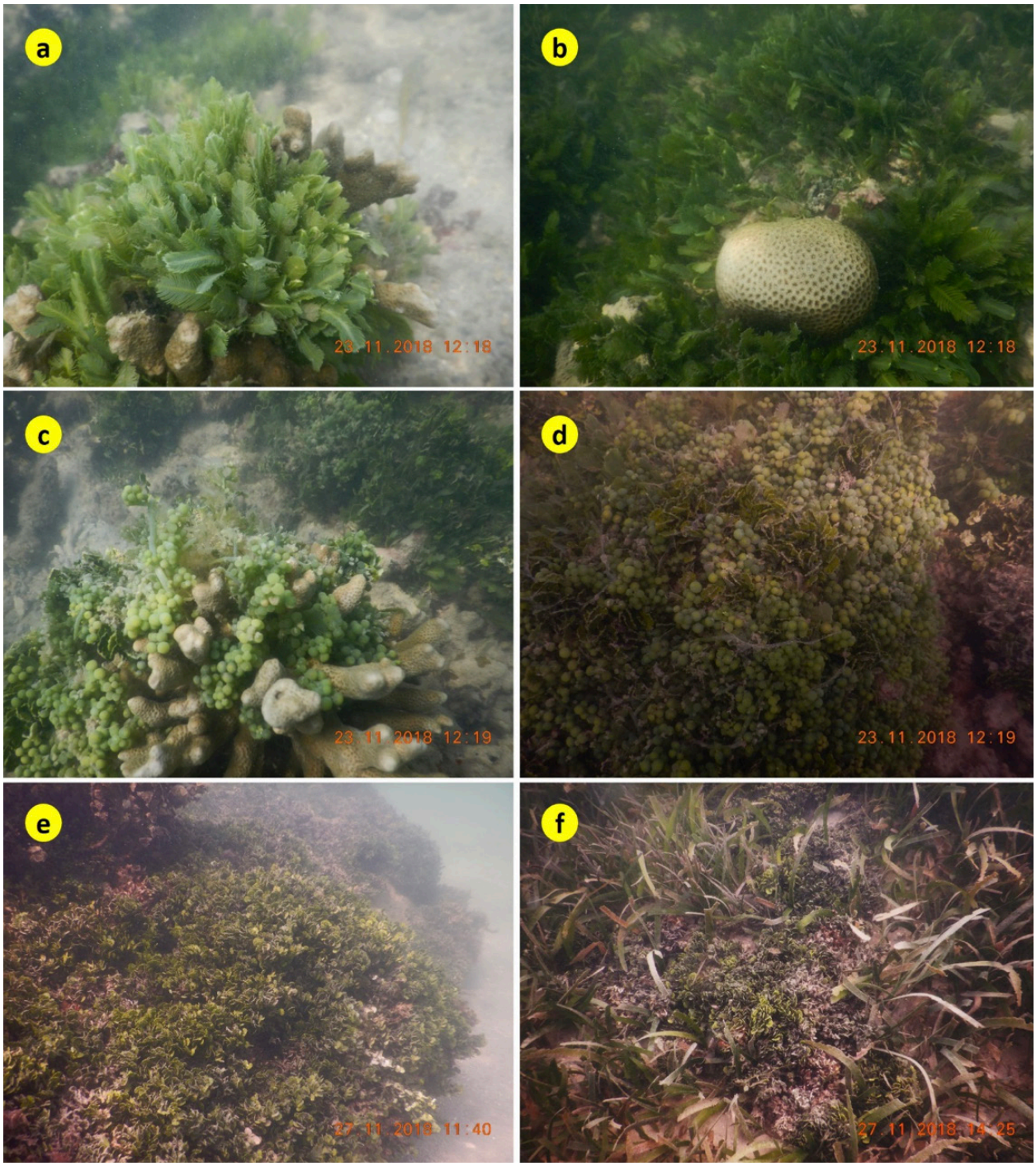

Image 2. a—*Caulerpa taxifolia* invasion on *M. digitata* | b—around a newly recruited *P. solida* | c—*C. racemosa* invading on *M. digitata* | d—its interaction with *Halimeda opuntia* and *C. sertularioides* (top left) | e—profuse growth of *H. opuntia* on *P. luteus* | f—its propagation in seagrass bed. © Ramesh Ch.

Previous reports indicated that *C. racemosa* and *C. taxifolia* could inhabit the entire reef area, which would ultimately undermine the resilience of corals (Hoey et al. 2011). The impact of these *Caulerpa* species on Gulf of Mannar's reef environment is yet to be studied in detail. However, the present study observations are challenging the issues related to the algal destruction and conservation of corals and coral reef biodiversity from invasive algae.

A recent study revealed that a feeding deterrent activity assay on green algae *C. peltata*, *C. sertularioides*, and *C. taxifolia* species display highest deterrent

activity of >80% (Rajan & Padmakumar 2017). While *C. cupressoides* and *C. fergusonii* showed moderate deterrent activity, *C. scalpelliformis* and *C. microphysa* exhibited negligible deterrent activity (Rajan & Padmakumar 2017). Experimental studies also show that grazing on *C. taxifolia* resulted in the loss of spines and less gonosomatic ratios in sea urchin *Paracentrotus lividus* (Boudouresque et al. 1996). Later it was observed that high production of toxic and repellent chemical metabolite 'caulerpenyne' in summer causes sea urchins to avoid *C. taxifolia* (Lemee et al. 1996). The deterrent activity exhibited by *C. taxifolia* might be the reason that restricts grazers not to feed on it.

Whereas the same compound produced by *C. racemosa* had not displayed any deterrent activity towards herbivorous surgeon fish *Zebrasoma flavescens* (Wylie & Paul 1988), and it was highly preferred by both juvenile and adult rabbitfish *Siganus argenteus* (Paul et al. 1990). In this study, we have not found any grazers feeding on these *Caulerpa* species during our underwater observations. A recent study also indicated that *C. racemosa* distribution could drastically change over time by spreading from deep water to the shallow waters, as observed in the Columbretes Islands, Mediterranean Sea (Kersting et al. 2014). A study also suggested that overgrowth of *C. racemosa* via chemotropism results in smothering or even death of sponge *Sarcotragus spinosulus* (Žuljevic et al. 2011).

Caulerpa species are well known as edible seaweeds in eastern Asian countries such as China, Japan, Korea, Philippines; southeastern Asian countries like Indonesia, Vietnam; and Indo-Pacific regions (Kaliaperumal & Chennubhotla 2017). In India, *C. lentillifera* is cultured on the Gulf of Mannar coast (Mary et al. 2009). But utilization of these six species in India has not been implemented so far. Hence, they remain an untapped and unutilized food resource from the Indian Coast. Thus, *Caulerpa* species can be considered a potential natural edible seafood to the increasing population in India.

Crustose coralline algae are well known as they support the settlement of coral polyps (Tebben et al. 2015). Although we have found very few coralline algae in our surveys at Hare Island and Manoli Island, the coral recruitment was appreciable on the dead corals free from these algae. However, there is high competition for substrata between algae and corals, similar to previous reports (McCook et al. 2001). Therefore, monitoring the bloom-forming invasive seaweeds in terms of their reproductive strategies and favourable conditions that promote their propagation is essential for developing remedies. Reports evidenced that ease dispersion and spread of *Caulerpa* species is mostly due to fishing nets, anchors, boats, and aquaria (Otero et al. 2013). Studies from the Mediterranean Sea have shown the rapid spread of invasive *C. taxifolia* by fragment mechanism (Ceccherelli & Cinelli 1999; Smith & Walters 1999). Therefore, further investigations are important to understand the temporal and spatial expansion of *C. racemosa*, *C. serrulata*, *C. sertularioides*, *C. taxifolia*, and *C. peltata* in these Islands. Also, multidisciplinary approaches are essential to address issues related to invasive species distribution dynamics, impacts, management, and utilization in the Gulf of Mannar. Also, the impact of environmental factors such as light, temperature, and water quality in different seasons should be analysed in future studies to understand bloom dynamics.

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