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First report of *Acanthophora spicifera* (Rhodophyta, Ceramiales) from the Papahānaumokuākea Marine National Monument (Northwestern Hawaiian Islands)

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Abstract

The red alga *Acanthophora spicifera* is the most common invasive marine species occupying intertidal and subtidal habitats within the Main Hawaiian Islands. Despite regular surveys since 1989, *A. spicifera* has not previously been recorded within the Northwestern Hawaiian Islands, which are within Papahānaumokuākea Marine National Monument. This report describes the first record of *A. spicifera* within the Papahānaumokuākea Marine National Monument, at Kuaihelani (Midway Atoll).

Key words: marine algae, alien invasive species, Hawaiian Islands, molecular analysis, Pacific Ocean

Introduction

Acanthophora spicifera [(Vahl) Børgesen] is a species of red seaweed native to the Caribbean and Southern Atlantic (Taylor 1972; Tabb and Manning 1961; Wynne 1986; Guiry and Guiry 2022) that has since spread throughout tropical and subtropical seas across the globe (Kilar 1984; Abbott 1999). This species is common in habitats within subtidal and intertidal waters of sheltered bays and along open coasts below the mean low tide level (Rao and Sreeramulu 1974; Kilar 1984; Carlton and Eldredge 2009). *Acanthophora spicifera* is typically found in areas with moderate to strong wave action at depths of 1–8 m, though it has been found at depths of up to 22 m (Kilar 1984). It grows on a wide range of substrata including rock and coral, sand, artificial structures, as an epiphyte on other algae, and in free-floating mats (Abbott 1999; Russell 1992; Knapp et al. 2011). Growth of *A. spicifera* shows seasonal variability with the peak growing season occurring in the summer months (Weijerman et al. 2008). It produces carpospores and tetraspores, but can also reproduce asexually via fragmentation (Smith et al. 2002).

Acanthophora spicifera was introduced to the Hawaiian Islands from Guam in the early 1950's via fouling on large vessels (Doty 1961). It was first detected at Pearl Harbor in 1952, and subsequently spread to all the Main Hawaiian Islands (MHI) by 1960 (Doty 1961; Carlton and Eldredge 2009). Since its introduction, this species has become the most common of the 21 invasive macroalgal species in the MHI (Doty 1961; Smith et al. 2002). Its ability to reproduce both asexually via fragmentation and sexually, and its broad preference in habitat type are traits that have allowed this species to become a highly abundant invasive marine alga in Hawaiian waters (Kilar 1984; Russell 1992; Abbott 1999; Smith et al. 2002). In 2008, *A. spicifera* was detected at Palmyra Atoll, which lies ~ 3,000 km southeast of Kuaihelani (Midway Atoll) or ~ 1,800 km to the south of Honolulu, Hawai'i, having been most likely introduced from the MHI via vessel hull fouling (Knapp et al. 2011). It has also been found in the Marshall Islands ~ 2,600 km southwest of Kuaihelani, where it has been observed covering and subsequently killing coral (Tsuda et al. 2008). The MHI are a potential source for hull fouling invasive species to surrounding Pacific Island areas based on their proximity to other atolls and vessel movements often originating from the MHI ports (Godwin et al. 2006). However, despite its ubiquitous presence in the MHI and in subtropical seas, no previous records of *A. spicifera* have been documented in the Northwestern Hawaiian Islands (NWHI), which lay within the boundaries of the Papahānaumokuākea Marine National Monument (PMNM) and National Marine Sanctuary, until now.

Materials and methods

In early July 2022, *Acanthophora spicifera* was incidentally detected within the sand and coral rubble shallows of Kuaihelani, PMNM by one of the authors while snorkeling from shore. Photographs taken were shown to visiting NOAA staff and university researchers who confirmed identification morphologically on site and later validated through DNA analysis. The majority of the survey areas were accessed by small boat on July 13–27, 2022. Observations were made by divers using snorkel and scuba equipment. Visual estimations of percent cover were made by haphazardly estimating a 10 m^2 area surrounding a target specimen. Voucher specimens were collected with ambient water and transported to a shore-based laboratory where they were photographed and categorized before being preserved by emersion in silica gel and being transported back to the University of Hawai'i for DNA analysis (Figure 1a). The identification of *A. spicifera* was confirmed through DNA sequencing of the mitochondrial COI DNA barcode region, following the protocols of Sherwood et al. (2010).

Results

Acanthophora spicifera was originally found on shallow reef flats directly downwind ~ 1.5–2 km of two historical piers (Site 1: Figure 2). Follow up surveys for *A. spicifera* were conducted around Kuaihelani in conjunction

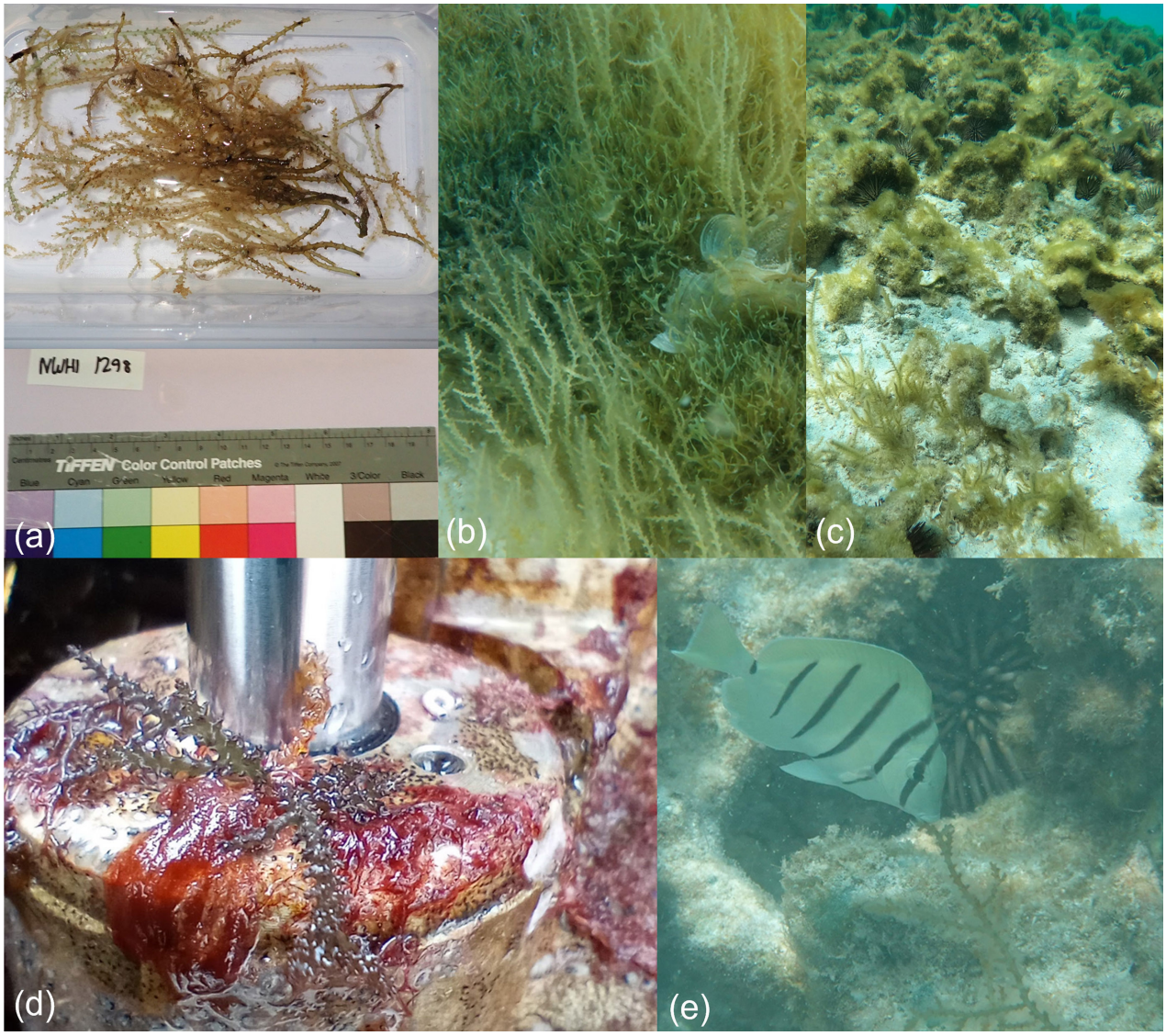

Figure 1. (a) *Acanthophora spicifera* voucher specimen being processed for later DNA analysis; (b) *Acanthophora spicifera* growing within *Padina* sp. and *Dictyota* sp.; (c) visual estimates placed highest density areas of *Acanthophora spicifera* at 50–75% cover; (d) *Acanthophora spicifera* found growing on USFWS small boat (image credit USFWS volunteer Curtis Mahon); (e) *Acanthurus trigosteus* consuming *Acanthophora spicifera*. Photos A, B, and C by Taylor M. Williams; photo E by Keegan Rankin.

with another project, which was surveying for the nuisance red alga *Chondria tumulosa*. Out of nearly 150 sites surveyed, *A. spicifera* was only present at a few locations, all at depths less than 5 m (Figure 2). Voucher specimens were collected from sites 1 and 2 (Table 1, Figure 2). The resulting DNA sequence, which is available in GenBank under accession OP503542, shared 99.68% identity with a sequence of *A. spicifera* from the Main Hawaiian Islands with only 2 out of 623 nucleotides being different (GenBank accession GU223869, using the nucleotide BLAST function in GenBank (https://blast.ncbi.nlm.nih.gov/). The species was observed mostly in mixed communities of native species with a relative high abundance. It was also observed growing epiphytically on *Dictyota* sp. and *Padina* sp. (Figure 1b). Visual estimates of 50–75% cover were observed in the densest locations, although native species were still present, indicating *A. spicifera* did not have

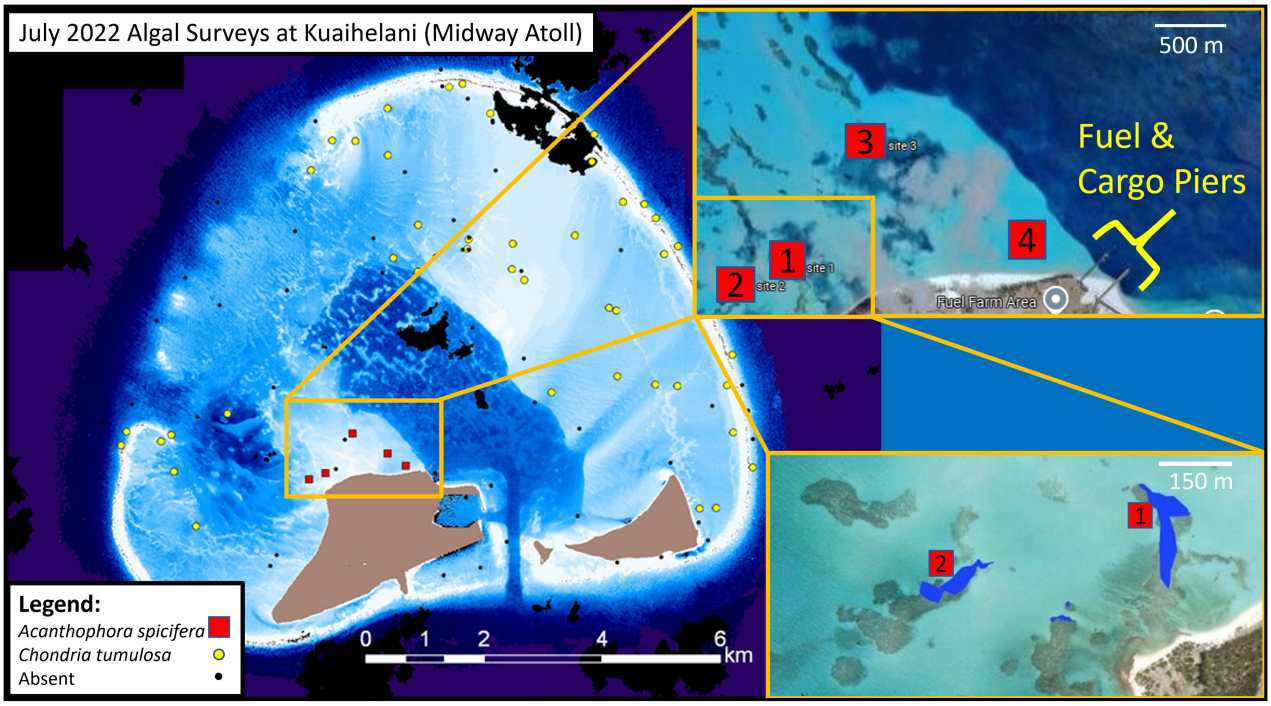

Figure 2. Alien algae distribution surveys at Midway Atoll showing *Acanthophora spicifera* sites 1–4 and their proximity to vessel piers. Areas highlighted in blue at sites 1 and 2 indicate *A. spicifera* distribution from surveys off of Rusty Bucket.

Table 1. Distribution of *Acanthophora spicifera* across Kuaihelani Atoll, Papahānaumokuākea Marine National Monument in July 2022.

Site	Latitude (DD)	Longitude (DD)	Depth (m)
1	28.21813	−177.38728	1
2	28.21717	−177.39011	2.4
3	28.22422	−177.3826	1.8
4	28.21929	−177.37341	2.4

a complete competitive advantage at that point (Figure 1c). Subsequent surveys conducted at additional sites in August and September 2022 demonstrated that *A. spicifera* had a scattered, clumped distribution at survey locations. Abundance varied from being absent on coral rubble and sand to covering coral rubble in dense mats. It was not observed growing on sand but was found in sandy patches with holdfasts attached to hard substate below the sand, such as rubble or underlying pavement. Since the time of these original surveys, fragments of *A. spicifera* have also been found adhered to USFWS small boats (Figure 1d), on a submerged buoy offshore of the previously mentioned piers, and ~ 500 m downwind of piers in shallow waters (Site 4: Figure 2; USFWS Midway staff *personal communication*). Although *A. spicifera* is a preferred food source for herbivorous fishes and Green Sea Turtles (*Chelonia mydas*; Stimson et al. 2001; Russell and Balazs 2009), little evidence of herbivory was detected at sites where *A. spicifera* was present beyond the presence of urchins (*Echinometra* spp.) and observations of foraging Convict Surgeonfish (*Acanthurus triostegus*) (Figure 1e).

Discussion

The original discovery location is offshore of an area commonly referred to as "Rusty Bucket" because of the amount of steel remnants that reside there after allegedly being deposited off the end of the old runway upon the end of military activities. It is unknown if there is a correlation between algal presence and available iron in these nearshore waters. Future studies could look at the trace element availability as well as potential eutrophication from terrestrial sea bird sources or wastewater infiltration. More recent discoveries located downwind of piers and as biofouling on FWS small boats further strengthen the theory supporting hull fouling as a probable vector into the NWHI and that eastern trade wind direction could drive the distribution from fouled vessels at piers to adjacent reefs. If these piers were indeed the point of introduction, they are mostly surrounded by sand and thus, the hard substrate found downwind would likely be the first suitable habitat. Surveys of the algal communities within PMNM have been conducted since 1989 (Abbott 1989; Wagner et al. 2013; Tsuda 2014; Tsuda et al. 2015; NOAA 2020). As is the case in most other tropical reef systems, surveys for corals and fish are conducted more frequently than algal surveys. The logistical and financial constraints associated with conducting work within the PMNM have made it difficult for phycologists to conduct research on its marine communities. These factors, in addition to the large size of PMNM, may be one reason new introductions of potentially invasive species can go undetected. To better detect and monitor introductions of algae species, future surveys within the PMNM would greatly benefit from the regular presence of phycologists.

Authors' contribution

KR: research conceptualization, sample design and methodology, investigation and data collection, data analysis and interpretation, writing and editing; TMW: research conceptualization, sample design and methodology, investigation and data collection, data analysis and interpretation, writing and editing; AS: sample design and methodology, investigation and data collection, data analysis and interpretation, writing and editing; RK: permit approval, funding provision, writing and editing; BH: research conceptualization, sample design and methodology, investigation and data collection, data analysis and interpretation, permit approval, funding provision, writing and editing, corresponding author.

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Conflict of interest/Declaration of interests

The scientific results and conclusions, as well as any views or opinions expressed herein, are those of the authors and do not necessarily reflect the views of the U.S. Government, the Departments of Commerce and Interior, USFWS, NOAA, NFWF, or their funding sources. No potential conflict of interest was reported by the authors.

Ethics and permits

All research was conducted under PMNM Co-Manager's Permit PMNM-2022-001 and PMNM-2022-011.

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