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NOTE

Rapid expansion of the invasive-like red macroalga, *Chondria tumulosa* (Rhodophyta), on the coral reefs of the Papahānaumokuākea Marine National Monument

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Abstract

A cryptogenic, invasive-like red macroalga, *Chondria tumulosa*, was first observed in 2016 forming thick mats on the forereef of Manawai Atoll within Papahānaumokuākea Marine National Monument. Subsequent expeditions revealed an increased abundance of this alga. In 2021, unattached *C. tumulosa* was observed forming a network of dark, meandering accumulations throughout the atoll's inner lagoon. High-resolution satellite imagery revealed that these accumulations became visible in 2015 (length: ~0.74 km; area: ~0.88 km^2) and increased 56-fold in length and 115-fold in area by 2021 (length: 41.32 km; area: 101.34 km^2). An exponential expansion rate of ~16.02 $km \cdot y^{-1}$ (length), ~44.75 $km^2 \cdot y^{-1}$ (area). This study presents the comprehensive temporal and spatial expansion of *C. tumulosa* accumulations for Manawai Atoll since its discovery, providing ecologist and resource managers with a proxy to gauge the overall abundance trend of this invasive-like alga.

KEYWORDS
algae, alien invasive species, *Chondria tumulosa*, Hawaii, satellite remote sensing

Papahānaumokuākea Marine National Monument (PMNM; Appendix S1: Figure S1 in the Supporting Information) is recognized by the United Nations Educational, Scientific and Cultural Organization as the only American World Heritage Site with a dual designation for its global cultural and natural importance and is comprised of 10 remote atolls with near-pristine reef ecosystems (Friedlander et al., 2005). These subtropical reefs are often dominated by macroalgae, in contrast to the mostly coral-dominated tropical reefs (Bruno et al., 2014; Vroom & Braun, 2010). The Hawaiian Archipelago, including PMNM, supports approximately 658 macroalgal species of Rhodophyta, Chlorophyta, and Phaeophyceae (Huisman et al., 2007; Sherwood & Guiry, 2023).

The newly described cryptic red alga, *Chondria tumulosa*, was first observed in 2016 and resighted in 2019 at Manawai (also known as Pearl and Hermes) in PMNM (Paiano et al., 2021; Sherwood et al., 2020). Researchers found this alga covering extensive areas of the forereef and the northern backreef, smothering other algae, corals, and sessile invertebrates on the substrate. It was observed in a tightly woven mat-like morphology on the forereef with unattached pieces having "tumbleweed-like" characteristics (Sherwood et al., 2020). The *C. tumulosa* displayed invasive

Abbreviations: CT, *Chondria* Trail; PMNM, Papahānaumokuākea Marine National Monument; WV-2, World View 2; WV-3, World View 3.

traits similar to those of *Kappaphycus* spp. (Conklin & Smith, 2005) and *Gracilaria salicornia* (Smith et al., 2004) in that it appeared to be fast-growing, friable, able to regrow from remnant fragments, and not preyed on by native herbivorous fishes (Conklin & Smith, 2005). *Kappaphycus* spp. and *G. salicornia* have negatively impacted the coral reef ecosystems of the Main Hawaiian Islands, outcompeting native benthic species and resulting in costly mitigation, while reducing ecosystem services (Conklin & Smith, 2005; Smith et al., 2004). *Chondria tumulosa* appears to be well established at Manawai and has since been identified in isolated areas at Kuaihelani (also known as Midway Atoll; K. H. Lopes personal observation, July 2022; Appendix S1: Figure S2). Costs may prohibit its manual removal at these remote locations, so it is imperative to understand its distribution and rates of expansion to effectively manage and avoid spreading this extremely concerning alga.

In a 2021 field survey of the inner lagoon of Manawai, unattached *Chondria tumulosa* was observed drifting on the surface of the ocean and beneath (Figure 1a,b), accumulating at the base of steep bathymetric changes from ~1 to ~5 m depths in sandy areas of the atoll's lagoon (Figure 1c). These accumulations formed an expansive, meandering network, referred to as the *Chondria* "trails" (CTs hereafter; Figure 1d). The stark contrast of the dark alga with the white sandy lagoon bottom made it easily identifiable from boat, uncrewed aerial systems (drones; Figure 1c–e), and high-resolution satellite imagery (Figure 1f), which permitted visual assessment of the CTs. Recently, Fraiola et al. (2023) demonstrated the detectability of *C. tumulosa* on the forereef and the backreef in high-resolution satellite imagery.

Here, we used high-resolution WorldView-2 (WV-2) and WorldView-3 (WV-3; <3 m resolution) satellite images from the years 2011 through 2021 and investigated the temporal and spatial dynamics of the *Chondria tumulosa* accumulations to answer the following questions: (1) What is the current spatial extent of the CTs? (2) When did the CTs first become visible? (3) How fast have they expanded? Satellite remote sensing was the only means to study the CT phenomenon in this remote area on large spatial and temporal scales.

We used WV-2/-3 cloud-free images for August 2011, January 2015, April 2017, September 2018

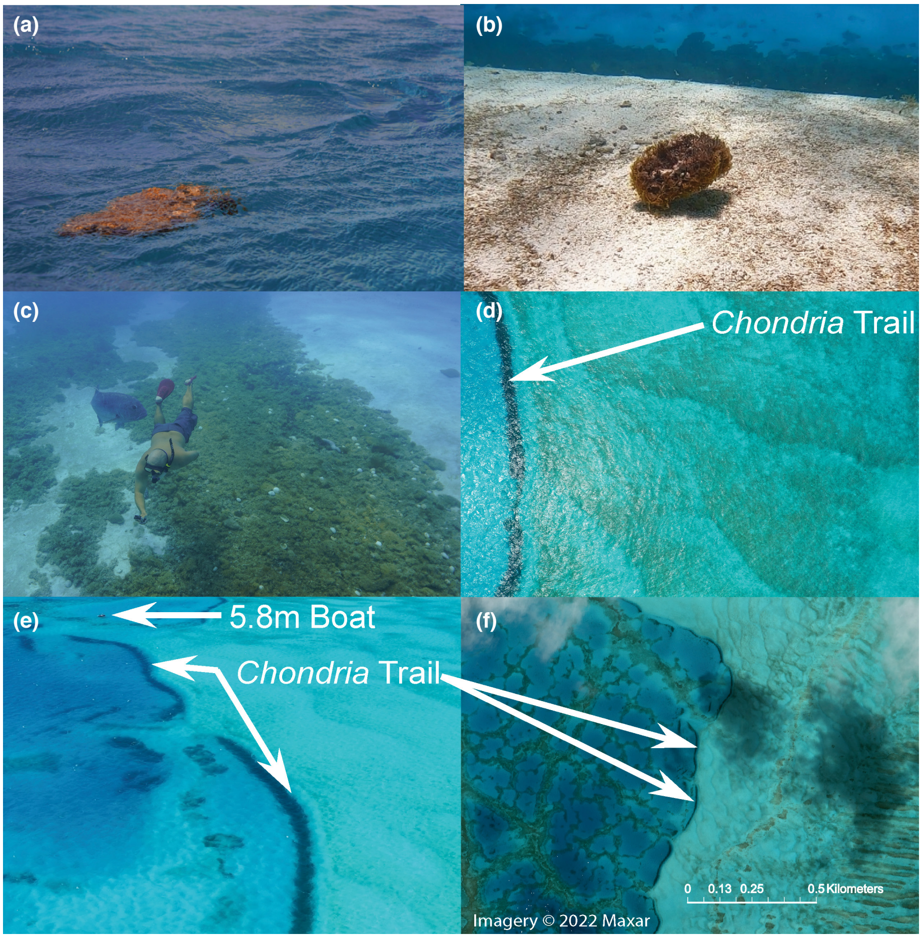

FIGURE 1 (a) Dislodged *Chondria tumulosa* rafting, (b) drifting along the lagoon floor, (c) accumulated at the foot of sandy slopes, (d, e) drone images collected on July 7, 2021, and (f) the satellite image of the study site (acquisition date, September 5, 2021). [Color figure can be viewed at wileyonlinelibrary.com]

(1 month prior to Hurricane Walaka), December 2019 (13 months after Hurricane Walaka), May 2020, and September 2021, to create red, green, and blue color composites. The CTs were hand annotated from each yearly image using ArcGIS software (Environmental Systems Research Institute, 2022) with methods adapted from Burns et al. (2016) and Levy et al. (2018). We used in situ and drone photos from July 7, 2021, collected in the eastern portion of Manawai lagoon (27.843° N, 175.762° W), to verify the hand annotation (Appendix S1: Figure S3). We calculated the characteristics of the CTs for each satellite image including (1) length, defined here as the overall distance spanned by the CT (small gaps were linearly interpolated) and (2) area, defined as the sum of the individual polygons around the CT features. All images for this study were licensed through the NextView governmental agreement.

No CT was observed in 2011 and one only became visible beginning in 2015 (Figure 2; Appendix S1: Table S1). The length of the CT in 2015 was ~0.736 km covering an area of ~0.881 km^2. It continued to increase in 2017 (length: 2.92 km; area: 4.26 km^2) and 2018 (length: 16.56 km; area: 57.40 km^2). The CT subsequently decreased in 2019 to a length of 16.02 km and area of 44.75 km^2. The CT resumed its expansion in 2020 (length: 34.91 km; area: 60.69 km^2) and 2021 (length: 41.32 km; area: 101.34 km^2; Appendix S1: Figure S4). The average rate of expansion between 2015 and 2021 was ~6 $km \cdot y^{-1}$ in length and ~16 $km^2 \cdot y^{-1}$ in area. The spatial extent of the CT is bounded within the inner lagoon (Figure 2; Table S1).

Increases of unattached *Chondria tumulosa* in the lagoon area of Manawai may not equate to geographic expansion. Rather, we hypothesize that the natural geomorphology and bathymetry of the atoll may increase the width and density of the CT. Evidence of increasing abundance were observations of other dark, non-linear patches distributed throughout the lagoon (Appendix S1: Figure S5). We do not have field

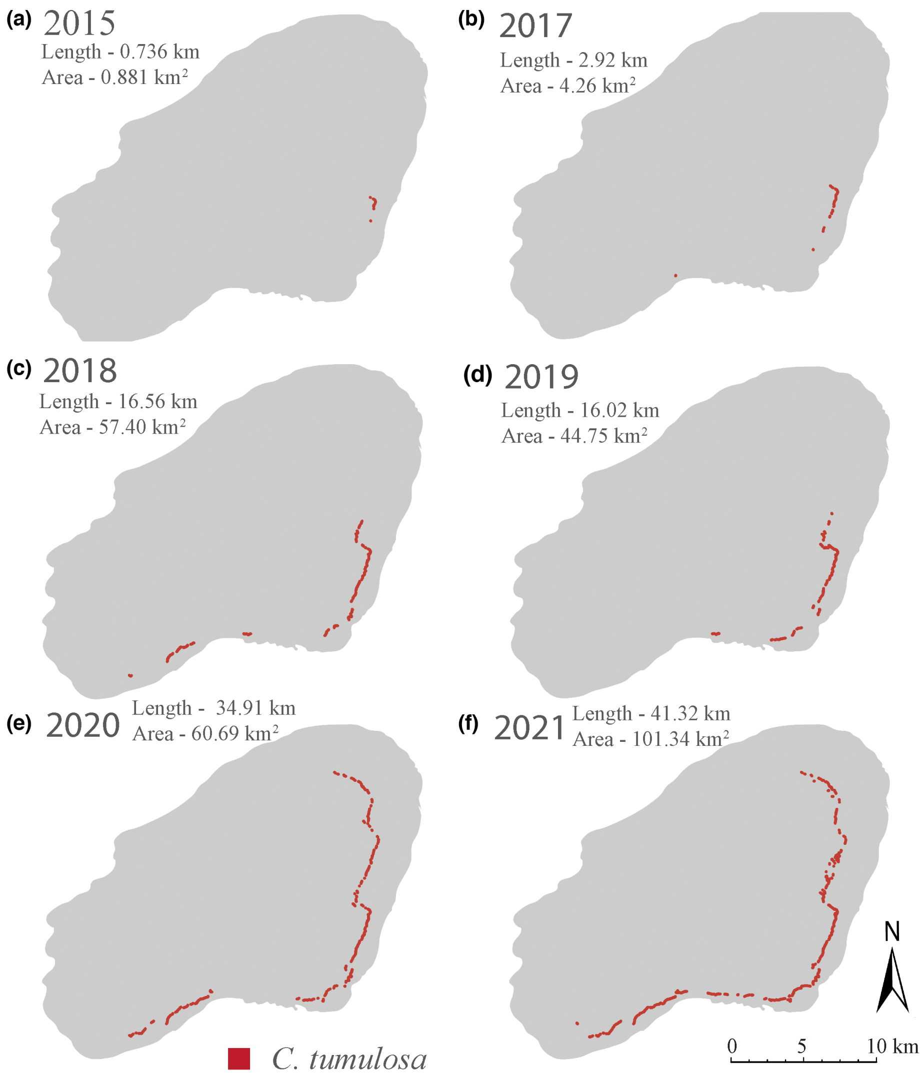

FIGURE 2 Timeseries of the *Chondria* trail (red). Gray shapes represent Manawai Atoll. No CT was found in the 2011 image (omitted). [Color figure can be viewed at wileyonlinelibrary.com]

observations to confirm that these patches are *C. tumulosa* and thus excluded them from this quantitative analysis. Future field expeditions will need to confirm the composition of these patches to achieve a more accurate characterization of the spatial distribution of *C. tumulosa* in the lagoon. Lagoon bathymetry data are necessary to investigate this hypothesis but lies outside the scope of this brief paper.

The analysis has shown steady and continuous growth of the CT except for a substantial reduction between the years of 2018 and 2019. This reduction may be attributed to the Category 3/4 Hurricane Walaka, which passed ~780 km to the northeast of the atoll on October 5, 2018. This hurricane may have generated enough energy to flush both attached and unattached *Chondria tumulosa* into the open ocean. If we assume that much of the *C. tumulosa* in the lagoon and forereef was removed by the Walaka storm event, then we can postulate that the subsequent analysis for December 2019 reflects a more accurate annual growth rate of *C. tumulosa*. This would suggest that the one-year growth (2018 post-Walaka to December 2019) of the CT was ~16.02 km in length and ~44.75 km^2 in area, in contrast to the calculated average of ~6 $km \cdot y^{-1}$ in length and ~16 $km^2 \cdot y^{-1}$ in area between 2015 and 2021. Further studies are needed for a better understanding of the role of lagoon currents in the accumulation, distribution, and flushing of unattached *C. tumulosa*.

During the most recent expedition in July 2021, *Chondria tumulosa* was observed exhibiting dispersal methods that may further aid its spread. These included unattached *C. tumulosa* rafting on the ocean surface as well as the previously mentioned "tumbleweed-like" clumps rolling on the seafloor (Figure 1). We hypothesize that thicker mats may break away easily from the attachment points under high wave energy or strong currents and potentially re-grow to continue the cycle, as has been seen in mats of *Kappaphycus* spp. and *Gracilaria salicornia* in the Main Hawaiian Islands (Conklin & Smith, 2005; Smith et al., 2004). Field observations suggest that CT accumulations may be supplied by these *C. tumulosa* transport mechanisms after they have been detached from the fringing or forereef.

We report a 56-fold increase in length and 115-fold increase in area of accumulated, non-attached *Chondria tumulosa* from 2015 to 2021 at Manawai atoll. We have demonstrated that satellite-based monitoring of the CT is an effective tool to surveil this rapidly expanding algal species in remote and expansive areas with high accuracy, thanks to the distinct characteristics of the CT. The origin of *C. tumulosa* is unresolved at this time and only three studies have been published on this species to date (Fraiola et al., 2023; Paiano et al., 2021; Sherwood et al., 2020). Fraiola et al. (2023) found that satellite imagery was helpful, but not always accurate in detecting attached *C. tumulosa*, underestimating its actual abundance. We felt that detecting and mapping the CT was more accurate than detecting and mapping the *C. tumulosa* mats on the forereef and backreef. The *C. tumulosa* mats that formed on complex reef bottoms with darker substrates have reduced contrast with heterogeneous benthic bottoms. Conversely, the CT's homogeneity and dark coloration in areas of white sandy bottoms have a high contrast making it easier to identify. For the first time, this study revealed the spatial extent of the CT features throughout the atoll and their temporal evolution spanning the pre-discovery of *C. tumulosa* through 2021. By continuing to monitor *C. tumulosa* using remote sensing methods, scientists and managers can gain a better understanding of this potential threat to the coral reef ecosystems of PMNM and beyond.

AUTHOR CONTRIBUTIONS

Tomoaki Miura: Conceptualization (equal); formal analysis (equal); methodology (equal); supervision (lead); writing – review and editing (equal). **Brian Hauk:** Conceptualization (equal); formal analysis (equal); funding acquisition (equal); investigation (equal); methodology (equal); writing – review and editing (equal). **Randall Kosaki:** Funding acquisition (lead); investigation (equal); methodology (equal); resources (equal); supervision (equal); writing – review and editing (equal). **Jason Leonard:** Funding acquisition (equal); investigation (equal); methodology (equal); writing – review and editing (equal). **Cynthia Hunter:** Formal analysis (equal); investigation (equal); methodology (equal); writing – review and editing (equal). **Keolohilani H. Lopes Jr:** Conceptualization (lead); data curation (lead); formal analysis (lead); funding acquisition (equal); investigation (lead); methodology (lead); project administration (lead); resources (lead); software (lead); supervision (equal); validation (lead); visualization (lead); writing – original draft (lead); writing – review and editing (equal).

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CONFLICT OF INTEREST STATEMENT

We have no competing interests or conflicts.

STATEMENTS AND DECLARATIONS

The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the opinions or policies of the U.S.

Government; DOC; NOAA; University of Hawai'i; the DOI and the USFWS, or the National Fish and Wildlife Foundation and its funding sources. Mention of trade names or commercial products does not constitute their endorsement by the U.S. Government, or its funding sources mention of trade names and/or commercial products does not constitute their endorsement by the U.S. Government; NOAA; University of Hawai'i; the National Fish and Wildlife Foundation and its funding sources. Field work was conducted under PMNM permits PMNM-2021-001; PMNM-2021-016; and PMNM-2021-019. All satellite imagery was provided by the NextView license agreement.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Data S1.

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