Using commercial high-resolution satellite imagery to monitor a nuisance macroalga in the largest marine protected area in the U.S.A.

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Abstract

Satellite imagery is a useful tool for monitoring and mapping the distribution of invasive or nuisance algal species on coral reefs over the temporal and spatial scales needed for ecosystem management. Visual inspections of high-resolution satellite imagery were used to detect the newly discovered nuisance alga, *Chondria tumulosa*, at Manawai (Pearl and Hermes Atoll) in combination with ground-truthing surveys. Low-albedo ("dark") survey sites on spur habitats were associated with mean *C. tumulosa* cover seven times higher than adjacent high-albedo ("light") sites. There was an inverse relationship between *C. tumulosa* percent cover at ground-truthing sites and mean reflectance values. Archival satellite imagery showed that areas of high *C. tumulosa* cover (i.e., dark patches) were not evident on or before 2015 on the northeast backreef. This case study is the first to apply satellite imagery to target a nuisance red macroalgal bloom on a coral reef. The ability to use satellites for the detection of nuisance or invasive benthic species, such as expansive mats of *C. tumulosa*, provides managers with a valuable tool, especially in remote regions.

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Introduction

Marine invasive and nuisance species are important yet understudied issues faced by natural resource managers and coastal communities worldwide (Watkins et al. 2021). When managing invasive species, one of the most valuable types of data needed by managers to launch a response is the extent of invasion across the area of interest (Shaw 2005;Trueman et al. 2014;). Accurate and complete distributional data can help managers better prioritize an invasive species problem over the myriad of other competing management needs (Mack 2000). Such distributional data for reef species (nuisance, invasive, or otherwise) at large spatial scales is often unavailable due to the spatial and temporal limitations of *in situ* field survey techniques, which provide valuable data and observations but are very limited in spatial and temporal coverage in marine environments (Edmunds and Bruno 1996). Satellite remote sensing techniques have long been recognized as having the potential to resolve reef species distributions at larger spatial scales (Hedley et al. 2016).

Invasive and nuisance species of benthic macroalgae are major management challenges on coral reefs worldwide (Davidson et al. 2016). The formation of conspicuous invasive and nuisance algal beds or mats over large areas (hundreds to thousands of square meters) may provide a unique spectral signal that achieves the needed level of discrimination via satellites. Satellite imagery has been successfully applied to the targeted mapping of blooms of invasive or nuisance brown (Noiraksar et al. 2014; Hoang et al. 2016; Andréfouët et al. 2017) and green (Santos et al. 2020; Brisset et al. 2021) algae on coral reefs. These studies determined the spatial and temporal distribution of target macroalgae in specific reefs, which assisted managers with an understanding of potential drivers and the development of management actions (Andréfouët et al. 2017; Brisset et al. 2020).

In 2019, a previously undescribed red alga (*Chondria tumulosa*) was found overgrowing large areas of the reef (including live corals, Fig 1) at Manawai (Pearl and Hermes Atoll) in the Pāpāhānaumokuākea Marine National Monument (Sherwood et al. 2020). *Chondria tumulosa* forms large mounds or mats up to 20 cm in height that are loosely attached to hard substrate and composed of densely packed, tangled thalli (Sherwood et al. 2020). Currently, this alga is described as cryptogenic because its origin is unresolved. However, its rapid spread, smothering morphology, and ability to quickly overgrow native corals and algae imbue this alga with invasive-like traits that warrant its current classification as a nuisance alga.

The objectives of this study were to 1) investigate the potential of using commercially available high-resolution satellite imagery (8 bands and 2.6 m spatial resolution) to remotely detect and map *C. tumulosa* at Manawai; and 2) assess whether there is a relationship between *in situ* estimates of *C. tumulosa* cover and remotely-sensed reflectance data at photosynthetic wavelengths. We hypothesized that areas with *C. tumulosa* would have lower reflectances at those wavelengths absorbed by photosynthetic pigments.

Methods

Manawai (Fig. 2) is the second largest shallow-water area (407.2 km^2 in 0-20 m depth) in Pāpāhānaumokuākea Marine National Monument (Parrish and Boland 2004). Manawai's coral reef ecosystem has ranked second within the Hawaiian archipelago in terms of "health and value" based on factors such as reef fish biomass, total living coral cover, and endemism (Jokiel and Rodgers 2007), suggesting this is a nearly pristine ecosystem.

Visual field surveys were conducted at Manawai in August 2019 and October 2020. Field surveys were conducted by experienced SCUBA divers (2019) and snorkelers (2020), who visually estimated *C. tumulosa* percent cover in a 10 m^2 area. The 2019 survey data were collected as part of NOAA research cruise RA-19-02, which first discovered areas of high *C. tumulosa* cover. We visually inspected World View (WV2) 8-band multispectral images (2.6 m spatial resolution) from 24 March 2019 and 6 December 2019 in the vicinity of 2019 survey locations (Fig. 2a, 2b) for reflectance features (i.e., areas of low albedo) that might be associated with a high *C. tumulosa* cover. Such features were then used to visually identify suspect areas on the 29 May 2020 WV2 imagery that could be ground-truthed on the October 2020 field survey expedition. These particular images were chosen because they were the closest usable imagery to the August 2019 and October 2020 field surveys, had no cloud cover over the areas of interest, and had excellent water penetration (i.e., minimal sun glint or waves). Ground-truthing sites were on spur habitats of the forereef in the southwest region of the atoll (Fig. 2a) and chosen haphazardly. *Chondria tumulosa* cover, coral cover, and habitat complexity (Polunin and Robers 1993) were visually estimated at ground-truthing sites. The background habitat in the ground-truthing area was pavement with patches of sand.

The WV2 data from the 29 May 2020 was reduced to the subsurface remote sensing (RS) reflectance by converting the digital numbers to the top of atmosphere reflectance, correcting for the atmosphere (6S model), and applying the formula of Lee et al. (2002) to the atmospherically-corrected surface reflectance. A regression analysis was used to examine the relationship between the algal cover and RS reflectance at specific bands and an index (mean of the coastal, blue, and green bands). We used this analytical approach to test the relationship between *C. tumulosa* for ease of interpretation. Correction for sun glint was unnecessary due to negligible amounts of glint (i.e., almost no reflectance in the NIR bands). We did not correct the RS reflectance (henceforth, "reflectance") for water column effects because we lacked the data on the bathymetry and inherent and apparent optical properties of water at the location of the survey sites to confidently allow for these corrections.

Archival WV2/3 imagery of the northeast backreef from similar times of year was selected to assess inter-annual variation in *C. tumulosa* cover (Fig. 2b, c). The northeast backreef area of interest (AOI) was chosen because the images from this area were less affected by the water column and variations due to relatively uniform conditions and shallow depth. Images of the northeast backreef from 21 December 2010, 24 January 2015, 13 December 2018, and 6 December 2019 were suitable for visual analyses.

Results and discussion

Visual inspection of WV2 imagery from 24 March 2019 identified dark patches (i.e., low albedo) in the vicinity of the April 2019 field survey sites identified with a high percent cover of *C. tumulosa* (Fig. 2 and 3). Ground truthing surveys found *C. tumulosa* at all ten dark survey sites (October 2020), while the alga was observed at only four of the seven light areas (Fig. 4). The mean percent cover of *C. tumulosa* at dark sites (15-35%) was seven times that of adjacent light sites (0-5%) (Table 1). In terms of habitat complexity, all sites had low to sparse relief. Average coral cover, and depth at ground-truthing sites were almost identical between dark and light survey sites (Table 1). In general, the area surveyed had relatively low densities of live coral and was dominated by pavement (Fig. 4; Table 1). The high coverage of pavement in the southwest forereef AOI provided a high albedo (higher reflectance) background that contrasted with live *C. tumulosa* mats (low albedo) that absorb more light via photosynthetic pigments. This suggests it would be difficult to distinguish *C. tumulosa* in reefs with high coral and algal cover.

The coastal band (400-450 nm), blue band (450-510 nm), green band (510-580 nm), and Index were effective in discerning patches of high *C. tumulosa* cover on the southwest backreef AOI. The average reflectance of low *C. tumulosa* cover areas (light patches) in the first three bands were 41, 30, and 24 % greater than dark patches, respectively (Fig. 5). These shorter wavelength bands penetrate deeper and have been helpful in targeting brown and green macroalgae on coral reefs (Hoang et al. 2016; Noiraksar et al. 2014; Andréfouët et al. 2017; Setyawidati et al. 2018; Brisset et al. 2021). In shallower waters, longer wavelength bands from WV satellites could improve the ability to discern *C. tumulosa*. Hoang et al. (2016) found that WV2's yellow band greatly improved the identification of *Sargassum* beds in the shallow (<4 m) waters of Rottnest Island's coral reefs (Western Australia). Reflectance values in the first three bands ranged from the ground truthing sites ranged from 0.012 – 0.054. The lack of separation in the other bands and the overall low reflectance values were not surprising given the range of depths at the ground-truthing sites due to their absorption by the water column – longer wavelengths are the more rapidly absorbed. The negative reflectance in the last three bands was likely due to the uncertainty associated with the atmospheric information.

Percent algal cover and reflectance displayed a moderate negative association (Fig. 3). Linear regressions of the reflectance versus percent *C. tumulosa* cover showed that the green band ($R^2 = 0.76$, $F(1,15) = 47.50$, $p < 0.0001$) was the best predictor of *C. tumulosa* cover, followed by the Index ($R^2 = 0.75$, $F(1,15) = 47.50$, $p < 0.0001$), blue band (R^2 = 0.67, $F(1,15)$ = 30.86, $p < 0.0001$), and lastly the coastal band (R^2 = 0.66, $F(1,15)$ = 29.32, $p < 0.0001$. Residuals were an order of magnitude smaller (0.005 to -0.005) than reflectance values, and visual inspection found linear models were relatively well suited for the regression analysis. These comparisons provide empirical support for our hypothesis that low reflectance/high absorption at photosynthetic wavelengths are a useful indicator of the presence and relative cover of *C. tumulosa* at Manawai on the forereef. The associations observed here may lead to the development of models to directly quantify algal cover and biomass (see Andréfouët et al. 2017; Brisset et al. 2021) using radiative transfer approaches in the near future.

Inspection of archival images detected large patches of the northeast backreef AOI that darkened between 2015 and 2018 and continued to increase into 2019 (Fig. 6). This suggests the transition to a *C. tumulosa*-dominated benthic habitat in the northeast backreef AOI occurred sometime after 2015. This chronology of *C. tumulosa* spread at Manawai supports the timeline documented in benthic survey data collected over the past 20 years (Sherwood et al. 2020).

An important limitation of the application of multispectral satellite imagery to the detection of *C. tumulosa* at the reef scale is its utility in relatively shallow water (< 15 m) versus *C. tumulosa*'s observed depth range to at least 23 m depth. This limitation is due to the rapid attenuation of light (particularly in the longer visible wavelengths and near-infrared region) and its scattering by the water column. In addition, the reliance on low albedo as the diagnostic feature versus a unique spectral profile for the alga increases the possibility of confusing *C. tumulosa* with other photosynthetic organisms (e.g., corals, algal turf, and other red macroalgae) or mixtures of organisms and/or habitats. This spectral confusion is due to the WV2/3 sensors having few broad bands (ranging from 25 to 70 nm wide); a larger number of narrower spectral bands (10 to 20 nm) would be needed to discriminate among major reef bottom types (Hochberg and Atkinson 2003). Confusion is also affected by the background heterogeneity of the reef, which can result in mixed pixels depending on the complexity of the benthos (due to mixtures of habitats or organisms). While researchers were able to map target species of brown algae on coral reefs (Noiraksar et al. 2014; Hoang et al. 2016; Andréfouët et al. 2017), Andréfouët et al. (2004) could not separate the radiometric signal of an invasive brown alga from those of other habitats in a highly heterogeneous reef in Tahiti.

Analyzing images at diverse temporal scales (monthly to annually) may detect changes in albedo that could minimize confusion, improve the detection of *C. tumulosa,* and aid in the large-scale monitoring of reefs from satellite imagery. Hedley et al. (2021) used this approach to distinguish transient patches of floating *Sargassum fluitans* and *S. natans* from seagrasses and live corals in Sentinel-2 imagery. Observations from the field and studies of closely related taxa suggest that it is reasonable to suspect that some potential causes of *C. tumulosa*-related changes in albedo could include sloughing from the benthos (Sherwood et al. 2020), mat removal via high wave motion, and seasonal variation in biomass (Hay and Norris 1984). Given that seasonal variability in biomass is a characteristic of other species of red macroalgae in the tropics (Hay and Noris 1984), changes in biomass between the date the imagery was collected and the date the ground truthing surveys were conducted represent a potential source of error. This large gap in time was primarily due to the use of opportunistic archival imagery. In future work, gaps could be reduced if acquisitions were coordinated with field surveys.

High-resolution WV2/3 imagery can successfully identify areas of high *C. tumulosa* abundance (i.e., areas of low albedo) on the reefs of Manawai. The association of *C. tumulosa* with decreased albedo in WV2/3 imagery will dramatically improve our ability to map *C. tumulosa*'s spatial extent and provides satellite-based observations on the timeline of *C. tumulosa* spread at Manawai. This technology holds great potential in the early detection of new outbreaks of *C. tumulosa* within the Papahānaumokuākea Marine National Monument and elsewhere. Although many challenges remain in applying satellite remote sensing technology to monitoring invasive species on coral reefs, the ability to monitor large areas and the variety of available satellite products make it a relatively inexpensive approach worth exploring.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

These results may be presented as an oral presentation at an internal U.S. Fish and Wildlife Service seminar series.

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Figures and Tables

Fig. 1 Site with high *C. tumulosa* cover on the northern backreef (a), showing a portion of mat unattached from the reef, and another site on the eastern forereef (b) with high cover, showing *C. tumulosa* overgrowing live *Porites* sp. (Photo: Taylor Williams).

Fig. 2 The areas of interest (AOI) for this study. Close-up views of the southwest forereef AOI (a) and northeast backreef AOI (c) showing dark patches and the locations of the 2019 SCUBA algal survey (colored dots) and the 2020 ground-truthing sites (crosses). The general area of dark patches are outlined with a dashed line.

Fig. 3 The remote sensing reflectance in the coastal (a), green (b), blue (c), and Index (d) from the 2020 ground-truthing sites versus *C. tumulosa* cover (%) recorded for each site.

Fig. 4 Images of sites with low (a) and high (b) *C. tumulosa* cover from the 2020 ground-truthing snorkel surveys.

Fig. 5 Spectral profiles of light (dashed line) and dark sites (solid line) showing the mean reflectance and standard deviation of each of the satellite’s eight bands in light sites and dark sites.

Fig. 6 WV-2 and 3 false color composite images over the northeast backreef AOI, from 2010 (a) to 2019 (d). The coastal, blue, and green bands are assigned to blue, green, and red colors. The numbers in (d) represent field estimates of *C. tumulosa* % cover in the August 2019 field survey, and the yellow lines denotes the 10 m bathymetric isocline.