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The Sensitivity of Multi-spectral Satellite Sensors to Benthic Habitat Change

Jiwei Li, Nicholas S. Fabina, David E. Knapp and Gregory P. Asner *

Center for Global Discovery and Conservation Science (GDCS), Arizona State University, Tempe, AZ 85281, USA; jiweili@asu.edu (J.L.); nfabina@asu.edu (N.S.F.); dknapp4@asu.edu (D.E.K.); gregasner@asu.edu (G.P.A.)

* Correspondence: gregasner@asu.edu

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Abstract: Coral reef ecosystems are under stress due to human-driven climate change and coastal activities. Satellite-based monitoring approaches offer an alternative to traditional field sampling measurements for detecting coral reef composition changes, especially given the advantages in their broad spatial coverage and high temporal frequency. However, the effect of benthic composition changes on water-leaving reflectance remains underexplored. In this study, we examined benthic change detection abilities of four representative satellite sensors: Landsat-8, Sentinel-2, Planet Dove and SkySat. We measured the bottom reflectance of different benthic compositions (live coral, bleached coral, dead coral with algal cover, and sand) in the field and developed an analytical bottom-up radiative transfer model to simulate remote sensing reflectance at the water surface for different compositions at a variety of depths and in varying water clarity conditions. We found that green spectral wavelengths are best for monitoring benthic changes such as coral bleaching. Moreover, we quantified the advantages of high spatial resolution imaging for benthic change detection. Together, our results provide guidance as to the potential use of the latest generation of multi-spectral satellites for monitoring coral reef and other submerged coastal ecosystems.

Keywords: Landsat-8; Sentinel-2; Planet Dove; coral reef; benthic habitat; coastal region

1. Introduction

Coral reef and shallow coastal ecosystems provide habitat for thousands of species, maintain benthic organisms, and deliver a variety of goods and services (e.g., seafood, coastal storm protection, recreation) to millions of people living in coastal regions [1–3]. For instance, Jennings and Polunin (1996) estimated that more than 300 people could be solely supported by 1 km² of healthy reefs. Unfortunately, coral reefs, especially in tropical regions, have suffered a major decline in diversity, richness, and structure [5]. With growing coastal population densities, coral reef ecosystems are under significant stress due to overfishing, pollution, and coastal development [6–11]. Moreover, global environmental changes, such as sea-level rise and increases in ocean temperature and acidification, are applying increasing stress to coral reef ecosystems [12–18]. New techniques in coastal ecosystem monitoring and protection are critically needed to increase the resilience of coral reefs in the coming decades.

Although the total extent of reef is relatively stable over time, reef composition (live coral, bleached/dead coral, macroalgae, etc.) is changing globally [16,18,19] and expected to continue to change with projections of global sea surface temperature change [13,20–22]. Unfortunately, large-scale reef monitoring is difficult via traditional field sampling methods, which are limited in spatial and temporal resolutions [23,24]. However, remote sensing technologies can provide alternative approaches to monitor changes in reef composition at high spatial and temporal resolutions [25,26], and to facilitate monitoring in remote or inaccessible regions [27].

Remote sensing technologies have been used in numerous coral reef studies, including classification of coastal benthic habitats [3,24,25,28–34], detection of changes in reef composition [35–40], retrieval of benthic (bottom) reflectance [2,23,41–43], and estimation of coastal water bathymetry [44–49]. These studies are often limited by available field data and therefore their analyses are restricted to specific field sites, which often cause biases in the ranges of observed water optical properties. For instance, there may be an overrepresentation of shallow water samples or a lack of turbid water samples. This is problematic because reflectance at the water surface is determined by the combination of properties like depth and water turbidity and there exists a wide range of conditions in nature. Moreover, previous modeling studies were often designed for monitoring by hyperspectral instruments [50–54], while existing satellite sensors have not been thoroughly examined. An analytical modeling study is therefore needed to examine the detection capabilities of multi-spectral satellite images on spectral changes in benthic composition, especially for the new satellite sensors that provide global coverage and high spatial (3.7 m) and temporal (daily revisit) resolutions (Planet Dove) [55].

Coral reef habitat composition can be derived from multi-spectral satellite images, including mid-resolution data (e.g., Landsat-8, Sentinel-2) [29,32,56,57] and new high spatial resolution data (e.g., Planet Dove, SkySat) [25,28,58]. These satellite images have a variety of spatial resolutions, image acquisition frequencies, and center wavelengths, often resulting in analytical trade-offs for end-users. In the case of reef monitoring, it is still unclear how these characteristics affect efforts to reliably and accurately identify changes in benthic composition.

To facilitate reef monitoring efforts, this study explored coral reef composition detection capabilities of four representative multi-spectral satellite sensors: Landsat-8, Sentinel-2, Planet Dove, and Planet SkySat. We combined newly-measured benthic field spectral data, which includes live coral, bleached coral, dead coral covered with algae, and sand, with an analytical radiative transfer model. We examined how these satellite sensors can be effectively applied to monitor potential changes in benthic composition in both spatial and temporal dimensions, across a range of water optical properties. Our research presents a comprehensive study for illustrating how the current satellite sensors can be applied to monitor bottom reflectance variations.

2. Materials and Methods

2.1. Benthic Reflectance Field Measurements

Benthic spectral measurements (400–700 nm) were collected from reefs in the Hawaiian Islands and Great Barrier Reef, Australia (Appendix A, Figure A1). Bottom reflectance data were measured for different benthic compositions, including live coral, bleached coral, dead coral with algae cover, and sand. Field spectra were measured using an ASD® HandHeldPro-2 spectrometer with an underwater housing and tungsten halogen light source at a distance of 10 cm from the benthic targets (live coral, bleached coral, etc.) (Appendix A, Figure A2). The resulting in-water radiance data were converted to at-target reflectance using a white calibration panel (Spectralon; LabSphere Inc.). We calculated mean values of the bottom reflectance from 100 to 150 spectral measurements of each benthic type as the inputs for the radiative transfer model.

2.2. Bottom-up Water-Column Radiative Transfer Model

We simulated remote sensing reflectance (R_{rs}) at the water surface through an analytical bottom-up radiative transfer model. The model inputs are our field-measured bottom reflectance for different endmembers ($r_b(\lambda)$). In the model, we input a wide range of Depth (H) and chlorophyll-a ($Chl-a$) to simulate the water column attenuation conditions. We vary depth from 0 to 20 m at a 0.1 m interval and chlorophyll-a from 0 to 5.0 mg m⁻³ at a 0.1 mg m⁻³ interval. Model outputs are water leaving remote sensing reflectance (R_{rs}) of different benthic compositions in a variety of water conditions. Water attenuation conditions were determined by water inherent optical properties (IOPs) which include water (w), phytoplankton (ph), and colored dissolved organic matter ($cdom$) [44,59]:

$$a_t(\lambda) = a_w(\lambda) + a_{ph}(\lambda) + a_{cdom}(\lambda) \quad (1)$$

$$b_b(\lambda) = b_{bw}(\lambda) + b_{bp}(\lambda) \quad (2)$$

where $a_t(\lambda)$ is the total absorption coefficient and $b_b(\lambda)$ is the total backscattering coefficient. Both $a_w(\lambda)$ and $b_{bw}(\lambda)$ are known values of pure water [60,61]. The phytoplankton absorption coefficient ($a_{ph}(\lambda)$) was modeled as [42]:

$$a_{ph}(\lambda) = [a_0(\lambda) + a_1(\lambda) \ln(a_{ph}(440))]a_{ph}(440) \quad (3)$$

The $a_{ph}(440)$ was calculated through the chlorophyll-a value in coastal water as [62]:

$$a_{ph}(440) = 0.06 * (Chla)^{0.65} \quad (4)$$

The $a_{cdom}(440)$ is an independent value for forward modeling. It is usually taken as 0.1 m^{-1} in coastal waters [63,64]. The colored dissolved organic matter (CDOM) absorption coefficient ($a_{cdom}(\lambda)$) was modeled from the global mean empirical value S (0.015) as: [64,65]:

$$a_{cdom}(\lambda) = a_{cdom}(440) * e^{-S(\lambda-440)} \quad (5)$$

The $b_{bp}(\lambda)$ can also be simulated from the chlorophyll-a values as [64]:

$$b_{bp}(\lambda) = \left\{ 0.002 + 0.02[0.5 - 0.25 * \log_{10}(Chla)] * \left(\frac{550}{\lambda} \right) \right\} * b_{bp}(555) \quad (6)$$

$$b_{bp}(555) = 0.6 * (Chla)^{0.62} \quad (7)$$

Below surface remote sensing reflectance ($r_{rs}(\lambda)$) was separately modeled as both the water body contribution ($r_{rsC}(\lambda)$) and the bottom contribution ($r_{rsB}(\lambda)$) [66]:

$$r_{rsC}(\lambda) = r_{rs}^{deep} (1 - e^{-D_C(a_t + b_b)H}) \quad (8)$$

D_C is used to calculate the light attenuation on water column light which was calculated as [59]:

$$D_C = 1.03(1 + 2.4 \frac{b_b}{a_t + b_b})^{0.5}$$

r_{rs}^{deep} is the below surface remote sensing reflectance for infinitely deep water:

$$r_{rs}^{deep} = \left(0.089 + 0.125 \frac{b_b}{a_t + b_b} \right) \frac{b_b}{a_t + b_b} \quad (9)$$

Below surface remote sensing reflectance of the bottom contribution ($r_{rsB}(\lambda)$) is [59]:

$$r_{rsB}(\lambda) = \frac{1}{\pi} r_b(\lambda) e^{-D_b(a_t + b_b)H} \quad (10)$$

D_b is used to calculate the light attenuation on bottom reflectance which was calculated as [59]:

$$D_b = 1.05(1 + 5.5 \frac{b_b}{a_t + b_b})^{0.5} \quad (11)$$

$r_b(\lambda)$ is bottom reflectance measured in the field for different benthic targets. From that, we calculate the total below-surface remote sensing reflectance ($r_{rs}(\lambda)$):

$$r_{rs}(\lambda) = r_{rsC}(\lambda) + r_{rsB}(\lambda) \quad (12)$$

Satellite detectable remote sensing reflectance (R_{rs}) was then calculated as [43,67,68]:

$$R_{rs}(\lambda) = \frac{0.52 * r_{rs}(\lambda)}{1 - 1.7 * r_{rs}(\lambda)} \quad (13)$$

2.3. Satellite Sensor Parameters

The model-generated remote sensing reflectance range was 420–680 nm. We employed parameters of four satellite sensors (Landsat-8, Sentinel-2, Planet Dove and SkySat) to explore their ability to detect coral reef compositional changes. The spatial resolutions, image acquisition

frequencies, and center wavelengths are listed in Table 1. In the model, we simulated spatial coverage and by assuming that a pixel has a given ratio of bleached area to total area, and so calculated the weighted average of the R_{rs} for both bleached and healthy areas.

Table 1. Satellite parameters of selected satellite sensors.

Satellite	Revisit time (day)	Spatial resolution (m)	Center wavelength (nm)			
			Coastal blue	Blue	Green	Red
Landsat-8	16	30	443	482	560	655
Sentinel-2	5	10	445	492	559	665
Dove	1	3.7		470	540	610
SkySat	5	0.8		482	555	650

3. Results

3.1. Bottom Reflectance Field Measurements

The four benthic types have distinct spectral signatures, with different mean values at almost all wavelengths and unique shape characteristics (Figure 1). Sand has the highest reflectance across the spectrum in all four compositions. It represents the brightest target in shallow coastal environments. Bleached coral reflectance is nearly 75% of the sand reflectance, and is the second-highest value, higher than live coral and algae-covered dead coral. Bleached and live corals have distinct spectral shapes and values. Bleached coral reflectance is nearly three times as high as live coral from 410 to 540 nm, and nearly two times as high as live coral from 580 to 640 nm. Plateau values of bleached coral are from 540 to 660 nm. Dead coral covered with algae is the darkest target, with a reflectance nearly five times lower than the bleached coral. Its reflectance is closer to the live coral than the other two compositions, especially from 600 to 680 nm.

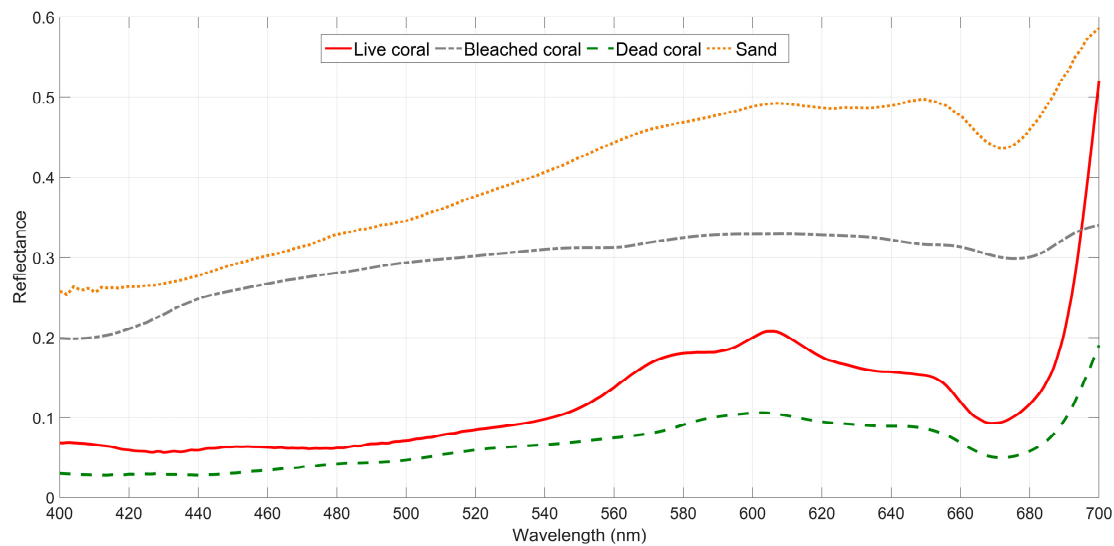


Figure 1. Full spectral reflectance data of benthic types measured in the field. Lines represent the mean spectral value for benthic types.

3.2. Remote Sensing Reflectance Variations in Different Water Bio-optical Conditions

We compared model-generated remote sensing reflectance (R_{rs}) of different benthic compositions in a variety of water bio-optical conditions (Figures 2–3). Figure 2 shows the remote sensing reflectance under different chlorophyll-a (Chl-a) concentrations with constant depth (10 m)

and colored dissolved organic matter (CDOM) absorption (0.1 m^{-1}). Overall, differences in R_{rs} are lowest in the red band (600–660 nm) compared with the other bands. Meanwhile, the R_{rs} differences are also low in the coastal blue band ($\sim 442 \text{ nm}$). R_{rs} differences between the live coral and bleached coral are much lower in the coastal blue band than the green and blue bands. Both the blue (470–490 nm) and green bands (540–560 nm) have notable differences of R_{rs} in all four satellites. With increasing Chl-a concentration, the differences of R_{rs} decrease. For instance, the R_{rs} in the green band of bleached coral is nearly 130% higher than live coral in low Chl-a concentration (0.1 mg m^{-3}) while it is nearly 40% higher than live coral in high Chl-a concentration (5.0 mg m^{-3}).

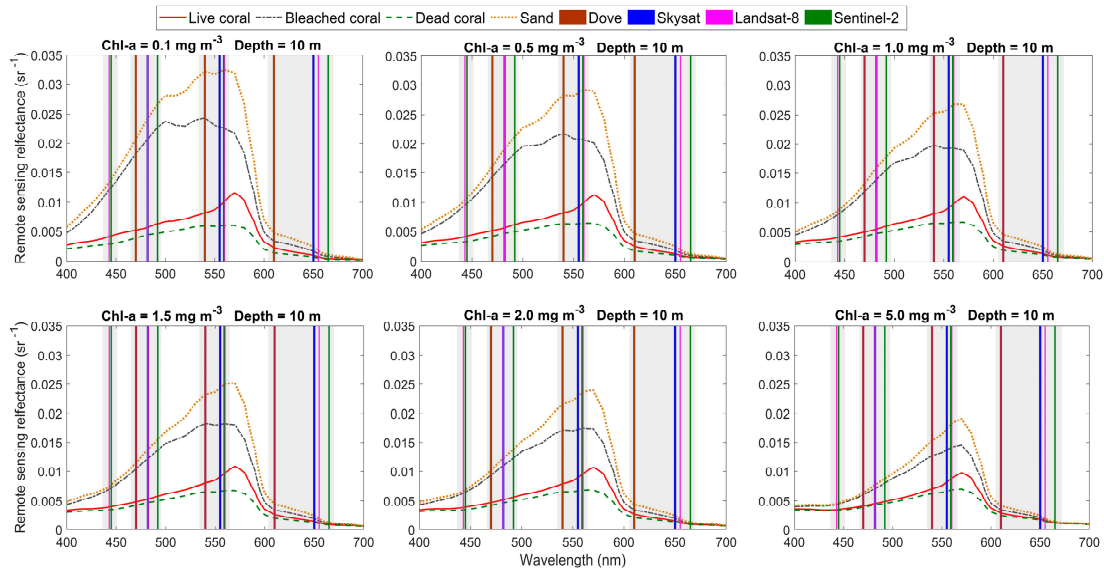


Figure 2. Model-generated remote sensing reflectance at different chlorophyll-a concentrations with constant depth.

Figure 3 shows the remote sensing reflectance at different depths with constant Chl-a concentration (0.5 mg m^{-3}) and CDOM (0.1 m^{-1}) (Figure 3). Depth determines the portion of bottom reflectance in the total water leaving reflectance. Overall, differences in R_{rs} are lowest in the red band (600–660 nm) compared with the other bands at all depths. Differences in the red and coastal blue bands are only appreciable at depths shallower than 6 m. Both the blue (470–490 nm) and green bands (540–560 nm) have notable differences of R_{rs} in all four benthic compositions when the depth is shallower than 14 m. Differences in R_{rs} decrease sharply as depth increases beyond 10 m and become negligible at 20 m, with values less than 0.005 sr^{-1} . In the comparison of bleached coral versus live coral in the green band, the R_{rs} of bleached coral is almost 0.02 sr^{-1} higher than live coral at shallow depth (4 m), while it is only 0.01 sr^{-1} higher at greater depth (14 m). In comparing benthic compositions, R_{rs} differences between sand and live coral are larger than differences between bleached coral and live coral.

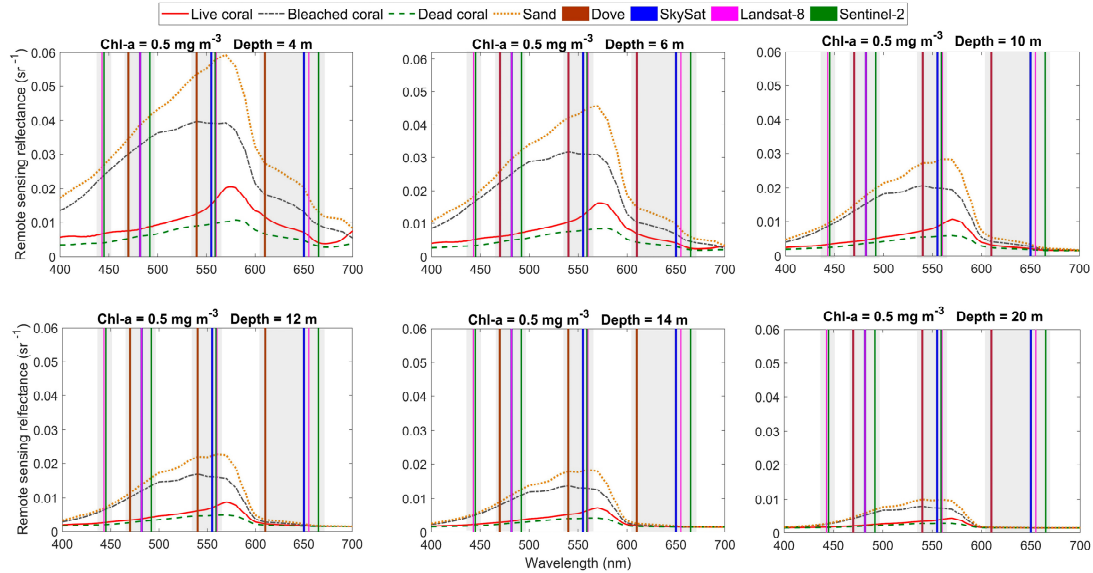


Figure 3. Model-generated remote sensing reflectance at different depths with constant chlorophyll-a concentration.

3.3. Coral Bleaching Detection in a Single Satellite Band

We explored the ability to detect coral bleaching by using a single band from four sensors. The differences in remote sensing reflectance (R_{rs}) between the bleached coral and live coral [$R_{rs}(\text{bleached coral}) - R_{rs}(\text{live coral})$] were calculated with depth ranges from 0 to 20 m, and Chl-a ranges from 0 to 5 mg m^{-3} . Downstream analyses are more likely to identify distinct signals when bleached and live corals have greater differences in their reflectance values. Thus, we quantify the absolute remote sensing reflectance (R_{rs}) differences between the two types. The center wavelengths in the blue (Figure 4) and green bands (Figure 5) of four satellite sensors were used (Table 1). Overall R_{rs} differences show decreasing detection capabilities with increasing depth and Chl-a concentrations. For instance, the blue band R_{rs} differences of Landsat-8 sensor are higher than 0.01 sr^{-1} in the shallow and low turbidity water (depth < 7.3 m and Chl-a < 1.0 mg m^{-3}). Furthermore, the green band R_{rs} differences of Landsat-8 sensor are higher than 0.01 sr^{-1} when depth is shallower than 11.2 m and Chl-a is lower than 1.0 mg m^{-3} . All the plots show higher detectability in the upper left (red), with shallower and less turbid water, and lower contrast in the lower right (blue).

Bleaching detection abilities are different across four satellite sensors in the blue band. These are represented by variation in blue band R_{rs} differences (Figure 4). Sentinel-2 satellite shows slightly higher detection abilities than the other three satellite sensors (Landsat-8, Dove, and SkySat). As shown in Figure 4, the blue band R_{rs} differences of the Sentinel-2 sensor are higher than 0.01 sr^{-1} when depth is shallower than 8.1 m and Chl-a is lower than 1.0 mg m^{-3} . While the green band R_{rs} differences of the other satellites are higher than 0.01 sr^{-1} in the shallower waters (depth < 7.3 m, Chl-a < 1.0 mg m^{-3}). This result is illustrated as the larger red to yellow color area for Sentinel-2 compared to the others (Figure 4). However, bleaching detection abilities are similar across the four satellite sensors in the green band (Figure 5).

Overall, coral bleaching detection abilities are higher in the green band than the blue band for all four satellite sensors. For example, the green band R_{rs} differences of SkySat sensor are higher than 0.01 sr^{-1} when depth is shallower than 11.1 m and Chl-a is lower than 1.0 mg m^{-3} . While the blue band R_{rs} differences of the SkySat sensor are higher than 0.01 sr^{-1} in the shallower depth waters (depth < 7.3 m, Chl-a < 1.0 mg m^{-3}). Similar patterns can be observed for all four satellite sensors (Figure 5). Moreover, the coral bleaching detection abilities in the green band are less affected by the high CDOM absorption (e.g., river plume regions) than that in the blue band (Figure 6). For instance, the blue band R_{rs} differences of Dove decrease sharply from low CDOM waters ($\text{CDOM} = 0.1 \text{ m}^{-1}$, R_{rs}

differences $> 0.01 \text{ sr}^{-1}$, depth $< 6.2 \text{ m}$, Chl-a $< 1.0 \text{ mg m}^{-3}$) to high CDOM waters (CDOM = 0.3 m^{-1} , R_{rs} differences $> 0.01 \text{ sr}^{-1}$, depth $< 3.2 \text{ m}$, Chl-a $< 1.0 \text{ mg m}^{-3}$). While the green band of Dove still has reasonable direction ability from low to high CDOM waters (CDOM = 0.1 m^{-1} , R_{rs} differences $> 0.01 \text{ sr}^{-1}$, depth $< 10.5 \text{ m}$, Chl-a $< 1.0 \text{ mg m}^{-3}$; CDOM = 0.3 m^{-1} , R_{rs} differences $> 0.01 \text{ sr}^{-1}$, depth $< 7.0 \text{ m}$, Chl-a $< 1.0 \text{ mg m}^{-3}$) (Figure 6).

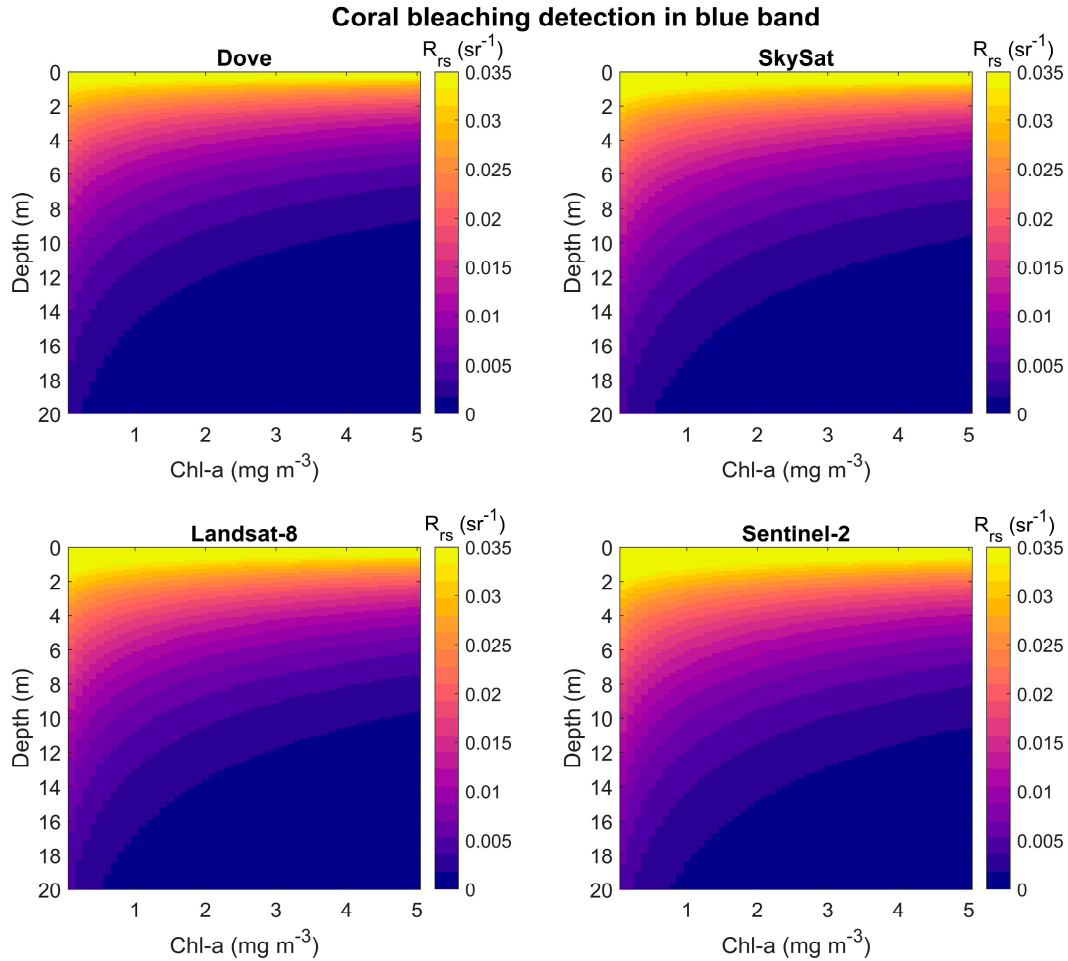


Figure 4. Differences in remote sensing reflectance between bleached and live coral in the blue spectral bands of four different satellite sensors.

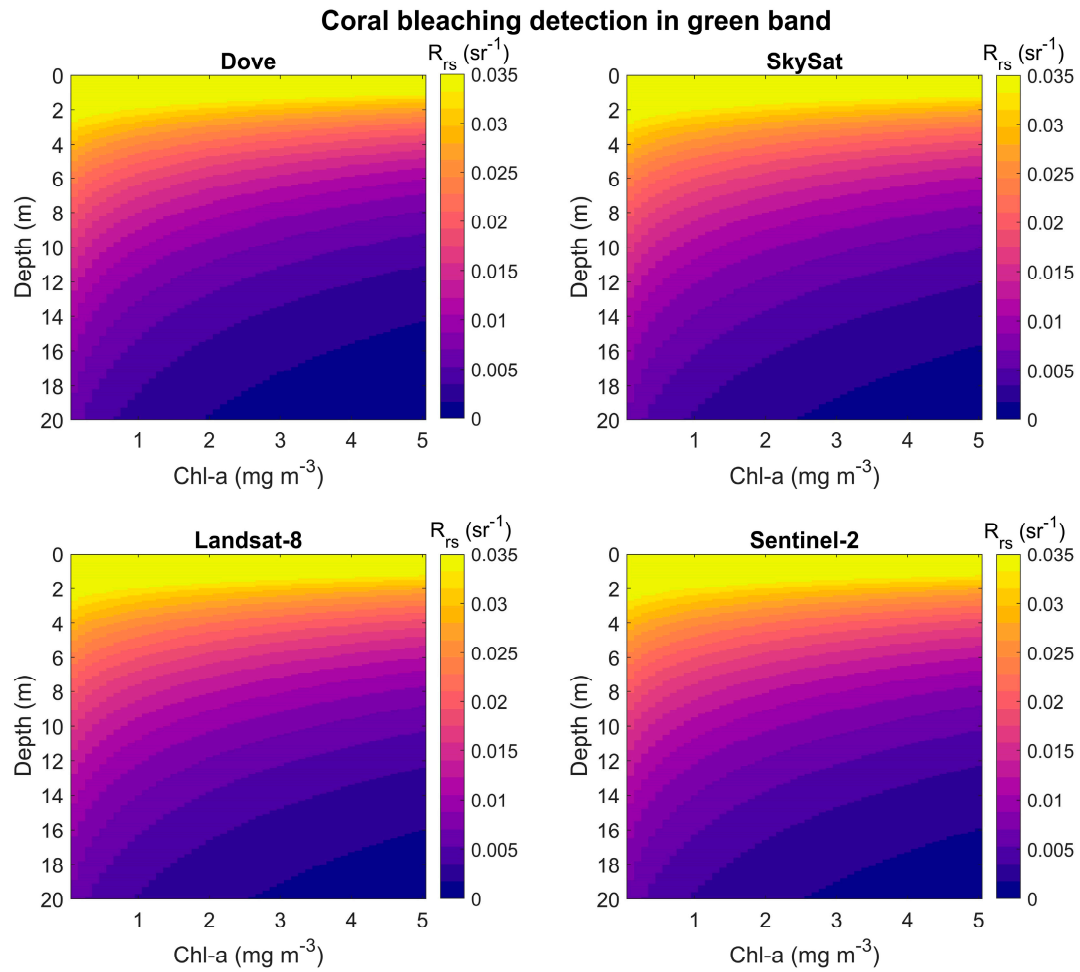


Figure 5. Differences in remote sensing reflectance between bleached and live coral in the green spectral bands of four different satellite sensors.

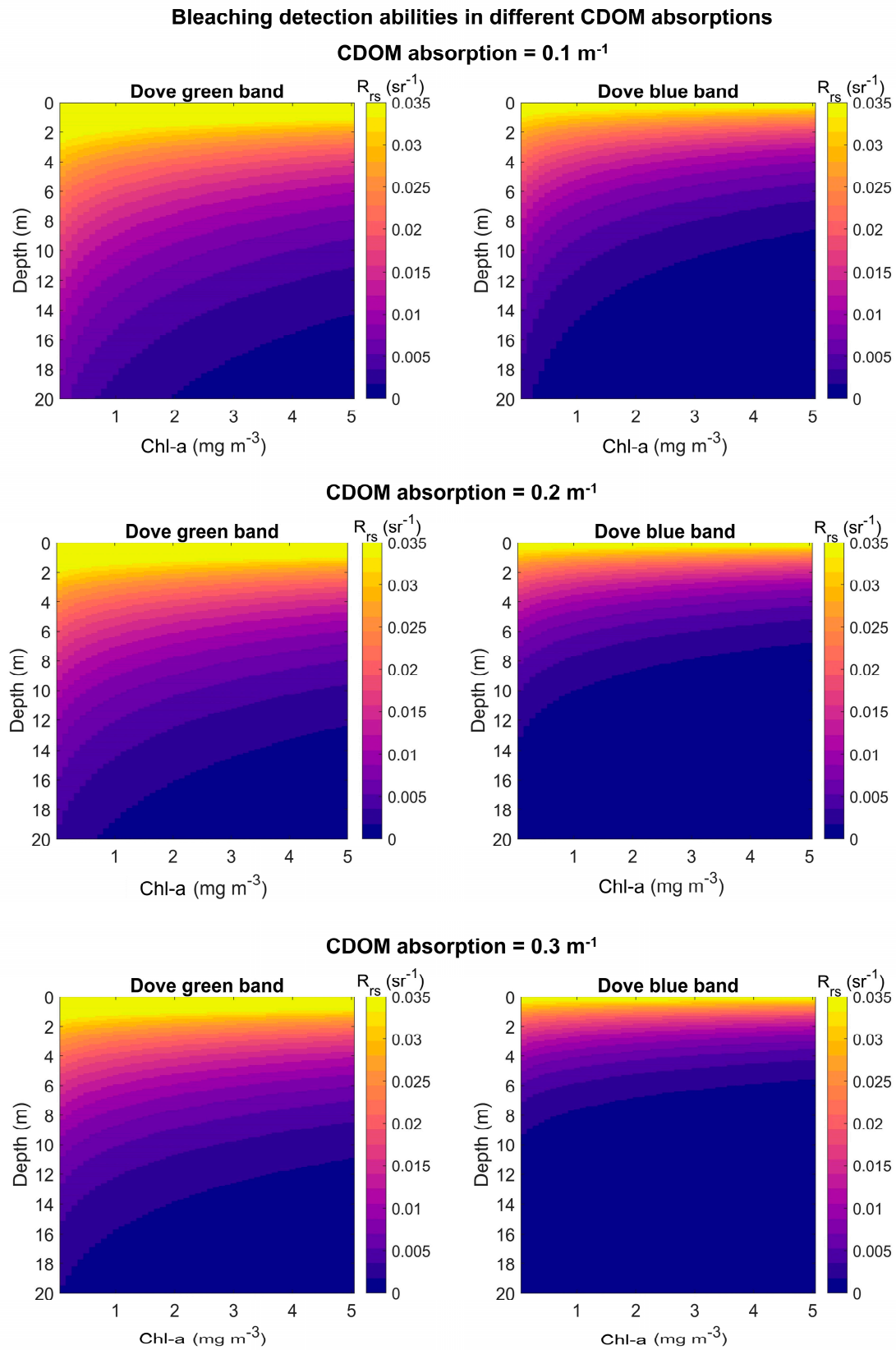


Figure 6. Bleaching detection abilities of Planet Dove satellites at different colored dissolved organic matter (CDOM) absorptions.

3.4. Bleached Coral to Algae-Covered Dead Coral Detection in a Single Satellite Band

We assessed whether single satellite bands would be capable of distinguishing a transition from bleached coral to algae-covered dead coral (Figures 7–8). We calculated the differences of R_{rs} between the bleached coral and algae-covered dead coral ($0 \text{ m} < \text{depth} < 20 \text{ m}$, $0 \text{ mg m}^{-3} < \text{Chl-a} < 5 \text{ mg m}^{-3}$) in the blue (Figure 7) and green bands separately (Figure 8). Similar to the coral bleaching detection, overall differences of R_{rs} decreased with increased depths and Chl-a concentrations.

For all satellite sensors, R_{rs} differences are larger when comparing the bleached coral and dead coral than between bleached coral and live coral. For instance, blue band R_{rs} differences of Landsat-8 sensor are higher than 0.01 sr^{-1} when the depth is shallower than 7.9 m and Chl-a is lower than 1.0 mg m^{-3} . Furthermore, green band R_{rs} differences of Landsat-8 sensor are higher than 0.01 sr^{-1} when depth is shallower than 12.2 m and Chl-a is lower than 1.0 mg m^{-3} . In Figures 7–8, the areas representing greater than 0.02 sr^{-1} (yellow to red) are larger than the coral bleaching comparisons (Figures 4–5). All four satellite sensors showed strong capabilities for detecting the change in composition from bleached coral to algae-covered dead coral.

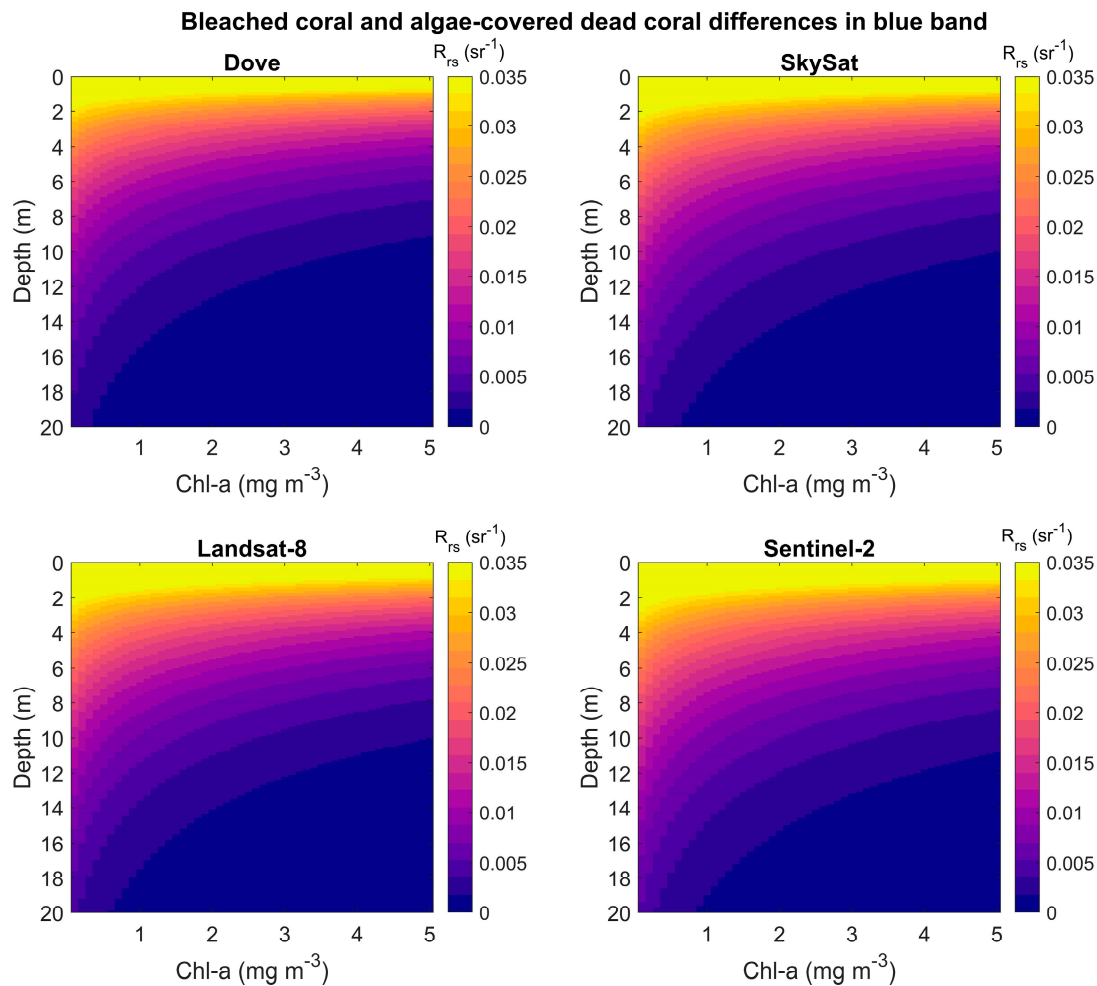


Figure 7. Differences of remote sensing reflectance between the bleached coral and algae-covered dead coral in the blue spectral bands of four different satellite sensors.

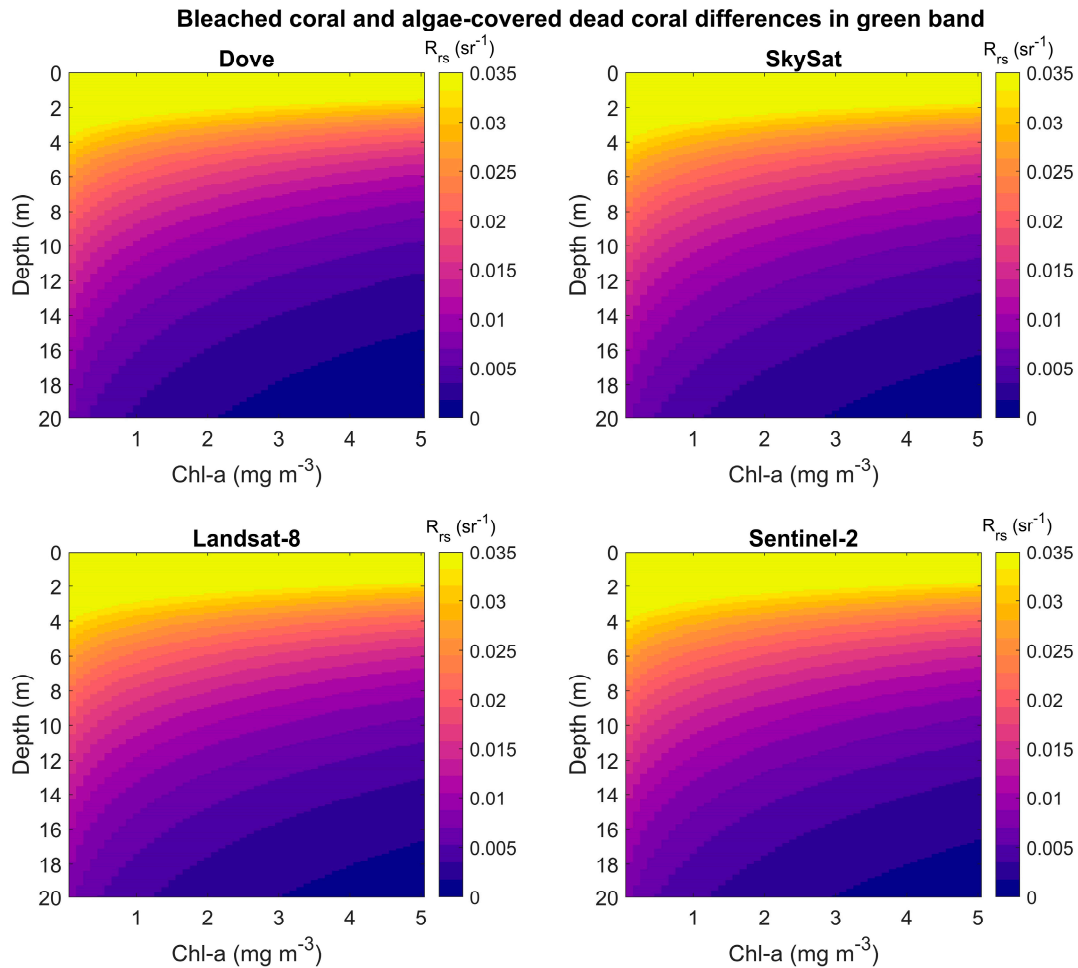


Figure 8. Differences in remote sensing reflectance between the bleached coral and algae-covered dead coral in four different satellite sensors' green bands.

3.5. Effects of Spatial Resolution on Satellite Monitoring of Coral Bleaching

We examined spatial resolution (ground sampling distance) effects on coral reef monitoring. In our simulations, the detection area was designed as 30 m × 30 m and the area of total bleached coral is 4 m × 4 m. The green band was selected to calculate the differences of R_{rs} between bleached coral and live coral. We found that the satellite detection capability of coral bleaching is heavily affected by image spatial resolution. The mid-resolution satellites (Landsat-8 and Sentinel-2) have lower detection potential than the high-resolution satellites (Dove and SkySat) in benthic habitats, which are spatially heterogeneous and highly diverse. As shown in Figure 9, the R_{rs} differences of the Planet Dove sensor are higher than 0.01 sr⁻¹ when depth is shallower than 10.5 m and Chl-a is lower than 1.0 mg m⁻³. Furthermore, SkySat has slightly better performance (R_{rs} differences > 0.01 sr⁻¹, depth < 11.4 m, Chl-a < 1.0 mg m⁻³) than the others. In contrast, both Landsat-8 (R_{rs} differences > 0.005 sr⁻¹, depth < 1.2 m, Chl-a < 0.5 mg m⁻³) and Sentinel-2 (R_{rs} differences > 0.01 sr⁻¹, depth < 4.1 m, Chl-a < 1.0 mg m⁻³) have low detection abilities when the detection area is small. High-resolution satellite images can better detect the bleaching than mid-resolution images.

We further explored coral bleaching detection ability of the green band for Planet Dove by using different total bleached coral areas (4m × 4m, 3m × 3m, 2m × 2m, 1m × 1m) (Figure 10). The ability to detect coral bleaching decreases as the spatial extent of bleaching decreases, becoming extremely challenging as the spatial extent becomes much smaller than the sensor resolution. Similarly, coral bleaching detection capabilities decrease when the detection unit becomes smaller. For instance, Dove's green band works best when the actual change covers more area: 4m × 4m: R_{rs} differences >

0.01 sr^{-1} , depth < 10.5 m, Chl-a < 1.0 mg m^{-3} ; $3\text{m} \times 3\text{m}$: R_{rs} differences > 0.01 sr^{-1} , depth < 8.9 m, Chl-a < 1.0 mg m^{-3} ; $2\text{m} \times 2\text{m}$: R_{rs} differences > 0.01 sr^{-1} , depth < 6.1 m, Chl-a < 1.0 mg m^{-3} ; $1\text{m} \times 1\text{m}$: R_{rs} differences > 0.01 sr^{-1} , depth < 1.3 m, Chl-a < 1.0 mg m^{-3} . When the detection unit size ($1\text{m} \times 1\text{m}$) is much smaller than the image resolution (3.7 m), the detection of coral bleaching becomes difficult.

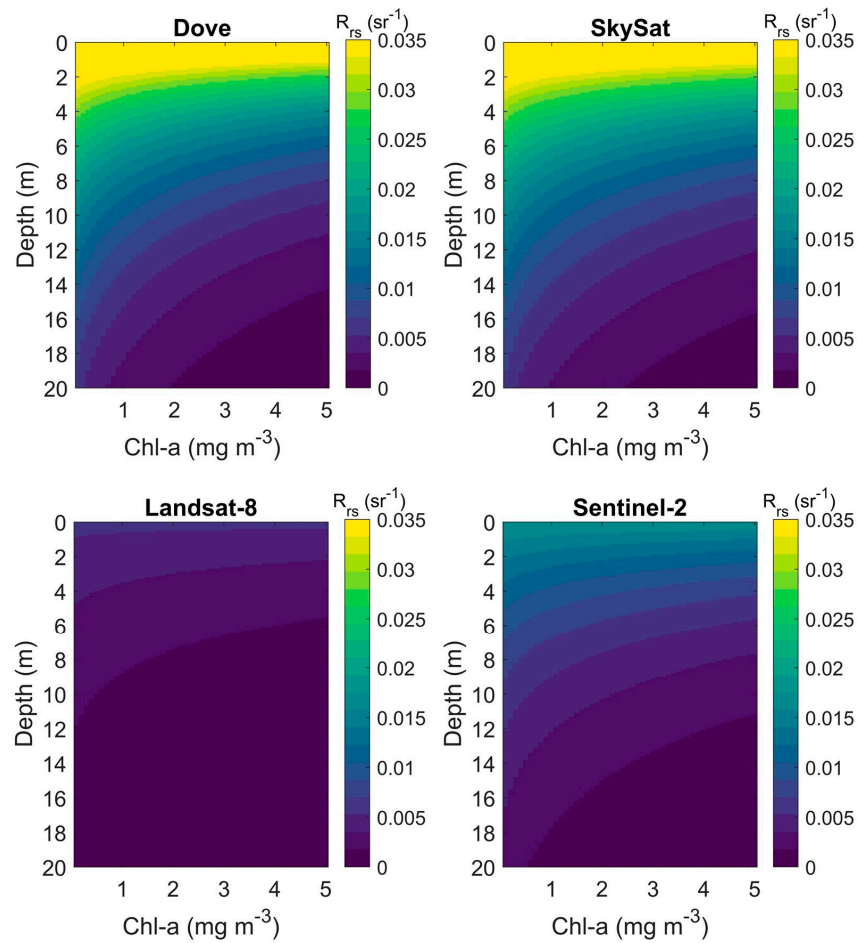


Figure 9. Differences in remote sensing reflectance between bleached and live coral at $4 \text{ m} \times 4 \text{ m}$ simulated ground sampling distance (pixel size).

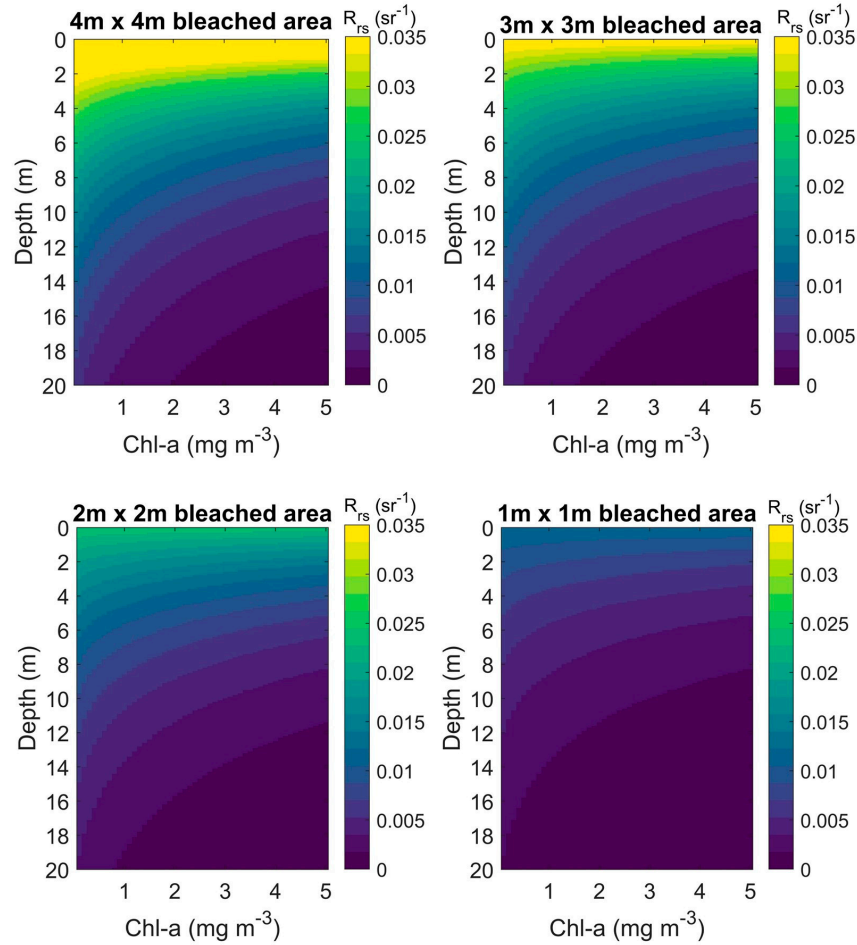


Figure 10. Sensitivity of Dove satellite imaging of sub-pixel bleaching of corals. The 4m x 4m panel indicates bleaching across the entire Dove pixel.

3.6. Multiple Benthic Change Detections in Dove's Green Band

We examined the ability of Dove's green band to detect change in different benthic components. We calculated the R_{rs} differences between various combinations of bleached coral, live coral, algae-covered dead coral, and sand (Figure 11). R_{rs} differences are large between bleached coral and live coral (R_{rs} differences $> 0.01 \text{ sr}^{-1}$, depth $< 10.5 \text{ m}$, Chl-a $< 1.0 \text{ mg m}^{-3}$) or bleached coral and dead coral (R_{rs} differences $> 0.01 \text{ sr}^{-1}$, depth $< 11.3 \text{ m}$, Chl-a $< 1.0 \text{ mg m}^{-3}$). The R_{rs} differences are slight when comparing bleached coral to sand (R_{rs} differences $> 0.01 \text{ sr}^{-1}$, depth $< 4.0 \text{ m}$, Chl-a $< 0.6 \text{ mg m}^{-3}$). Differences between live coral and dead coral are negligible across a range of depth and turbidity.

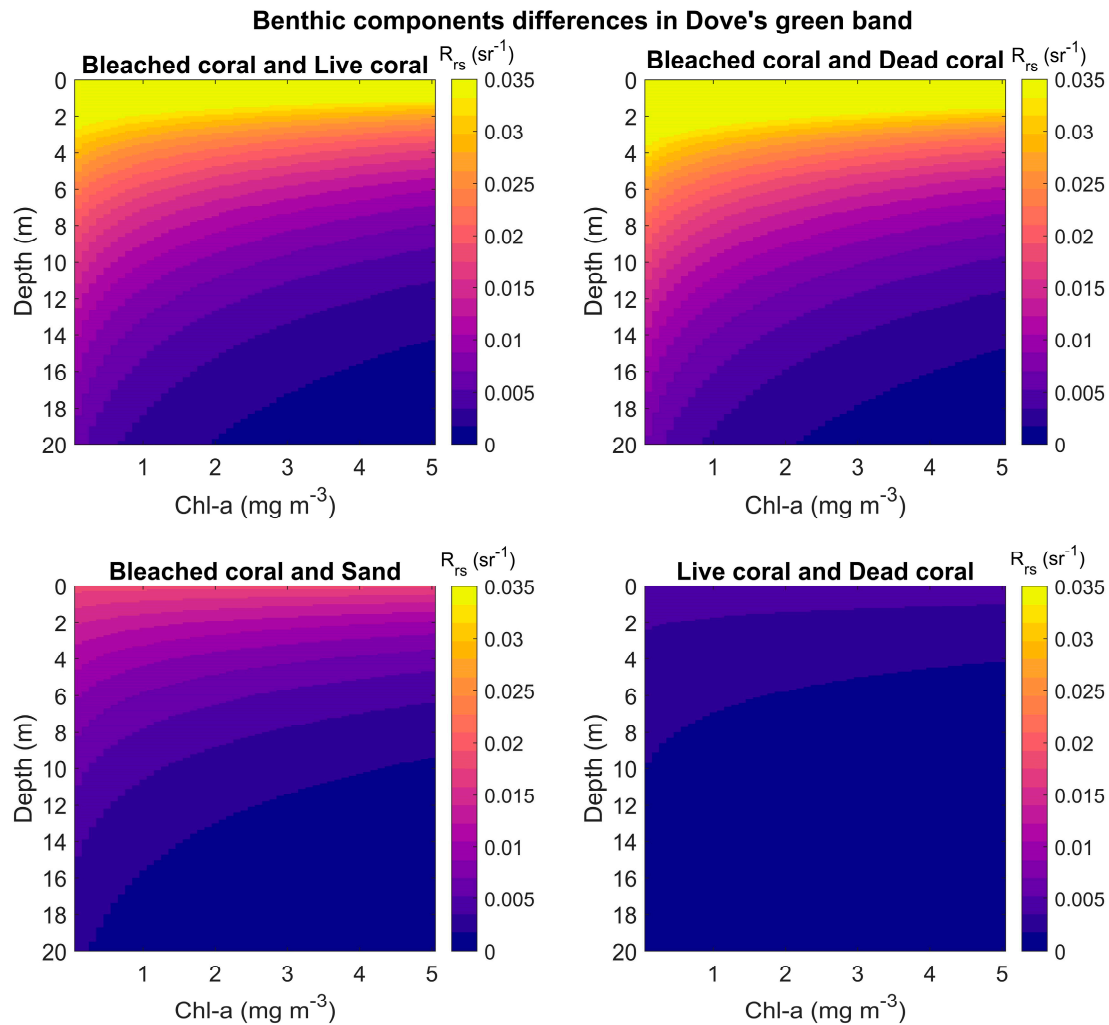


Figure 11. Differences in remote sensing reflectance of different benthic components in Dove's green band.

4. Discussion

We explored coral reef satellite bleaching detection in different water bio-optical conditions using an analytical bottom-up radiative transfer model and field-measured benthic reflectance data. We found that satellite-based, benthic composition change detection using Dove's green band can only be sufficiently applied in shallow to middle depths (depth < 14 m) and low turbidity waters (Chl-a < 1.0 mg m^{-3}). In the deeper ocean, bottom reflectance is absorbed by increasing water column attenuation [44,69,70]. Meanwhile, a significant proportion of the water-leaving radiance is contributed by the backscattering of the water column in deep waters [42,59,71]. These combined effects complicate benthic change detection, such that live and bleached corals (Figures 4 and 5) cannot be distinguished in either deep, clean waters or shallow, turbid waters [24,44]. Thus, quantitative monitoring of coral bleaching needs to consider both the depth and water turbidity.

We simulated the model-generated remote sensing reflectance of different benthic compositions based on center wavelengths of four representative satellite sensors, including Landsat-8, Sentinel-2, Dove and SkySat. We found a single band of satellite images could be applied to monitor spectral changes in benthic compositions. However, different center wavelengths of the satellite sensors have distinct detection abilities. In certain ranges of depth and turbidity, benthic reflectance signals are absorbed and scattered by water column components (e.g., water, phytoplankton, colored dissolved

organic matter, etc.) when the signals transfer back to the water surface [41,72]. These water column components have different attenuation levels in the different wavelengths [44]. The red band (> 600 nm) is not capable of detecting benthic composition change because of the strong absorption of pure water [60]. Strong absorption of Chl-a and CDOM in the coastal blue band (~ 440 nm) also affected the benthic detection abilities [73–76]. Therefore, only the blue and green bands are useful for detecting spectral changes in benthic composition (Figures 4–8). In these two bands, the green band displayed better performance in detecting benthic compositional changes.

The increased spatial and temporal resolutions of satellites such as Planet Dove and SkySat are critical to detect changes in reef environments. Benthic habitats in shallow, coastal waters are often spatially heterogeneous [2,32] and highly diverse, both in terms of species composition and bleaching resistance [77]. Moreover, the tropical coastal regions generally have dense cloud coverage. Studies found that MODIS images only have 20–30% cloud-free images over reef regions [29,78]. Thus, satellites with both high spatial and temporal resolutions are likely to be suitable for change detection with biologically-optimal sensitivities (Figure 9).

5. Conclusions

In this study, we combined newly-measured benthic field spectral data (live coral, bleached coral, coral covered with algae, and sand) with an analytical radiative transfer model to examine how multi-spectral satellite sensors can be effectively applied to monitor potential changes in benthic composition. We found that Planet Dove has an advantage in benthic monitoring (e.g., coral bleaching) given its high spatial resolution and daily revisit frequency. Among different satellite bands, the green band is best for benthic change detection.

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Appendix A

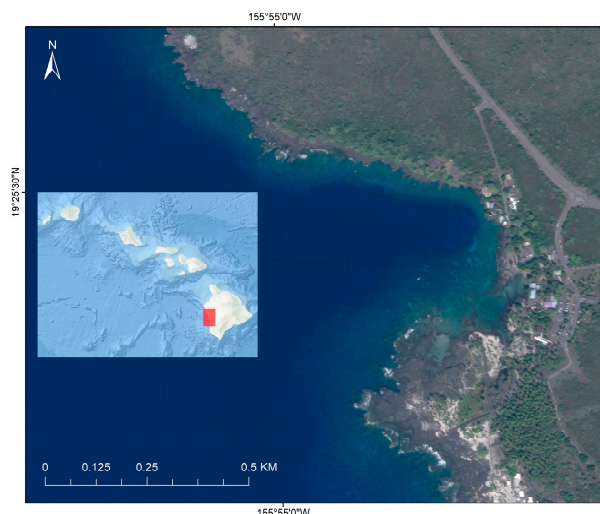


Figure A1. SkySat satellite image of study site in Honaunau Bay, Hawai'i Island.

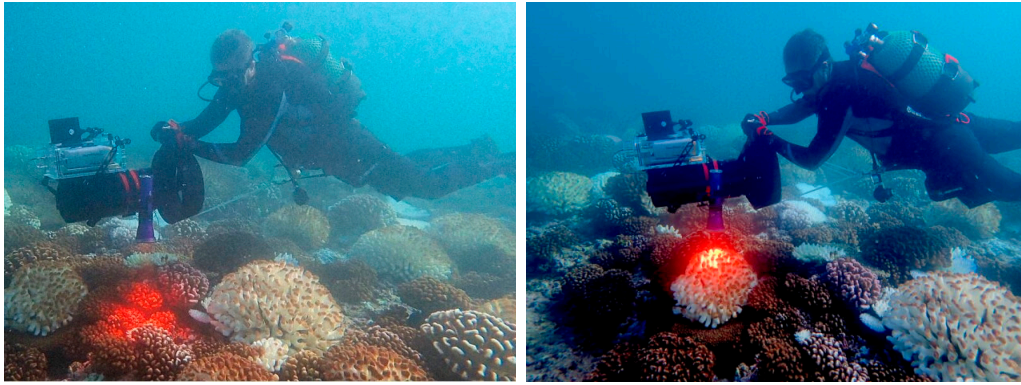


Figure A2. Benthic spectral data field measurements.

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