Article
Application of Reflectance Ratios on High-Resolution Satellite Imagery to Remotely Identify Eucalypt Vegetation

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Abstract: The scale and accessibility of passive global surveillance have rapidly increased over time. This provides an opportunity to calibrate the performance of models, algorithms, and reflectance ratios between remote-sensing devices. Here, we test the sensitivity and specificity of the Eucalypt chlorophyll-\(a\) reflectance ratio (ECARR) and Eucalypt chlorophyll-\(b\) reflectance ratio (ECBRR) to remotely identify eucalypt vegetation in Queensland, Australia. We compare the reflectance ratio values from Sentinel-2 and Planet imagery across four sites of known vegetation composition. All imagery was transformed to reflectance values, and Planet imagery was additionally scaled to harmonize across Planet scenes. ECARR can identify eucalypt vegetation remotely with high sensitivity but shows low specificity and is impacted by the density of the vegetation. ECBRR reflectance ratios show similar sensitivity and specificity when identifying eucalypt vegetation but with values an order of magnitude smaller than ECARR. We find that ECARR was better at identifying eucalypt vegetation in the Sentinel-2 imagery than Planet imagery. ECARR can serve as a general chlorophyll indicator but is not a specific index to identify \textit{Eucalyptus} vegetation with certainty.

Keywords: Eucalypt chlorophyll-\(a\) reflectance ratio; Eucalypt chlorophyll-\(b\) reflectance ratio; vegetation identification; Sentinel-2; Planet Dove

1. Introduction

Vegetation communities with greater biodiversity offer benefits for ecosystem services, resilience against degradation, food security, drug development, and the natural sustainability of habitats [1–3]. However, the strength created by mixed communities can also lead to challenges for categorizing the extent of individual species and the management of vulnerable species in these ecosystems. Knowing the location and extent of individual species’ ranges can aid in the conservation and survival of key species. To inform the targeted management of woody vegetation species vulnerable to pests, plant pathogens, and invasive species, it is critical to know the locations and connectivity of susceptible hosts [4,5]. Likewise, as climate change affects rainfall, temperature, and atmospheric CO\(_2\) levels, identifying where species already exist at the edge of their tolerances will aid in the conservation of these species against local extinctions [6,7]. Ground-level approaches would require years of data collection to amass this knowledge, so many researchers look to remote-sensing techniques and modeling to identify species distributions across the landscape.

Modeling approaches often estimate species extents with population viability analyses [8], species distribution modeling, or dynamic range models [9]. Each model uses various biotic and abiotic factors important for the species’ phenology, but all of these models require some data parameter that
relates to the known occurrences of the species. Some remote-sensing platforms have been successful in mapping vegetation distributions, such as the Queensland Herbarium’s Vegetation Management Regional Ecosystem (VMRE) mapping series. This series leverages remote-sensing data with ground surveys and environmental maps to show biannual vegetation dynamics from 1997 to the present in Queensland, Australia [10,11]. However, this dataset represents years of extensive work and effort on the ground to create its high-quality maps.

Remote-sensing approaches alone have not been enough to identify species’ distributions with certainty. Mixed vegetation communities muddle the spectral signal from an individual species [12], so reflectance has not been characterized for many species. Multispectral vegetation indices, such as the Normalized Difference Vegetation Index (NDVI), have been developed to gauge the chlorophyll properties of vegetation remotely but do not provide species-specific information. The NDVI utilizes the difference in the reflectance of light between the red and near-infrared (NIR) channels to provide a proxy for the vegetation’s “greenness” [13]. Most vegetation indices are general and identify chlorophyll broadly, but some have been developed to measure the chlorophyll of specific types of vegetation.

Reflectance ratios were previously developed to remotely estimate the amount of chlorophyll-\(a\), chlorophyll-\(b\), chlorophyll-\(a+b\), and total carotenoids in Eucalyptus leaves [14]. The correlation between chlorophyll content and the reflectance of single wavelengths of light was measured using a hand-held spectroradiometer. Two sets of algorithms were derived to estimate the chlorophyll levels of Eucalyptus leaves, one based solely on reflectance values and one adjusted to account for the different species and maturity of leaves [14].

Remote Estimation of the Eucalypt Chlorophyll algorithm where \(R\) represents the reflectance value at that wavelength of light:

\[
\text{Eucalypt Chlorophyll} - a \text{ Reflectance Ratio (ECARR)} = 0.0161 \times [R_{672}/(R_{550} \times R_{708})]^{0.7784} (1)
\]

\[
\text{Eucalypt Chlorophyll} - b \text{ Reflectance Ratio (ECBRR)} = 0.0337 \times [R_{672}/R_{550}]^{1.8695} (2)
\]

Remote Estimation of the Eucalypt Chlorophyll Scatter-Adjusted algorithm:

\[
\text{Eucalypt Chlorophyll} - a \text{ Reflectance Ratio} = 0.0008 \times [R_{860}/(R_{550} \times R_{708})]^{1.2403} (3)
\]

\[
\text{Eucalypt Chlorophyll} - b \text{ Reflectance Ratio} = 0.00005 \times [R_{860}/R_{550}]^{3.5168} (4)
\]

These algorithms have been applied by others on imagery collected by different sensors [15–17], but each of these studies had limitations. Coops et al. [15] showed a weak correlation using a modified index [18] to estimate chlorophyll-\(a\) in general eucalypt species but showed stronger correlations in individual species rather than mixed-species stands. Giles et al. [16] used Eucalypt chlorophyll-\(a\) reflectance ratio (ECARR) values from MODIS MCDA434A imagery as a model parameter. These images have a moderate spatial resolution of 500m, and the spectral bands do not closely match the correlated wavelengths in the original algorithm, in which they applied Equation (1).

Few datasets with the quality and detail of the Queensland VMRE are maintained and updated. However, leveraging the vast amount of passive global surveillance could help increase the availability of these types of data. Applying these methods would be particularly beneficial in areas where the vegetation classification and extent are not documented in a detailed, systematic way. The longitudinal time range of satellites can also help us understand the dynamics and changing biodiversity of vegetation. Here, we test the applications of the scatter-adjusted Eucalypt chlorophyll-\(a\) reflectance ratio (Equation (3)) and Eucalypt chlorophyll-\(b\) reflectance ratio (Equation (4)) on three different vegetation communities of varying abundance of eucalypt trees. Using high-resolution satellite imagery from Planet and Sentinel-2, we test the sensitivity and specificity of these reflectance ratios to remotely identify areas of known vegetation composition in Queensland, Australia.
1.1. Satellite Selection

We compared data on spectral bands, spatial resolution, and capture rates from several satellite sensors for the closest possible match to the original algorithm developed by Datt [14]. Due to the physical constraints of the sensor and trade-off between spectral and spatial resolutions [19], satellites aggregate information from ranges of the electromagnetic spectrum into a single band. Therefore, it is not always possible to isolate reflectance values at a precise wavelength. Therefore, satellites with spectral bands that centered wavelengths close to the reflectance values with high correlations were used. By comparing 12 different satellite sensor types, we identified Planet and Sentinel-2 products that collected bands with center wavelengths proximal to the reflectance values in the scatter-adjusted algorithms of Equations (3) and (4).

Sentinel-2, available beginning in 2015, collects data across thirteen spectral bands with a resolution of 10–60 m. Two different instruments collect imagery, the Sentinel-2A and Sentinel-2B [20]. The central wavelengths of both instruments are within one nanometer of each other (Table 1), so both instrument types were used for analyses. Planet Doves collect nearly daily imagery of the globe with three-m resolution across four bands: red, green, blue, and near-infrared [21] (Table 2). They collect data with two different types of satellites, one PS2 sensor with a “two-stripe” filter separating the red, green, and blue channels from the NIR channel and the other a PS2.SD sensor with a butcher block-style filter, where the four channels are stacked [22]. The PS2.SD sensor has been collecting data since 2019. We chose the PS2.SD sensor for this analysis due to the range of the NIR spectral band whose center wavelength more closely matched the R860 value in the scatter-adjusted algorithm (Equations (3) and (4)). Additionally, this sensor matches more closely with and is interoperable with Sentinel-2 imagery [22].

| Table 1. Planet PS2.SD instrument spectral band description [22]. |
|---------------------------------------------------------------|
| Band | Spectral Range (nm) | Approximate Center Wavelength (nm) | Spatial Resolution |
| Band 1 | 464–517 | 490 | 3 m |
| Band 2 | 547–585 | 566 | 3 m |
| Band 3 | 650–682 | 666 | 3 m |
| Band 4 | 846–888 | 867 | 3 m |

| Table 2. Sentinel-2A and Sentinel-2B instrument spectral band description [20]. |
|---------------------------------------------------------------|
| Band | Center Wavelength (nm) Sentinel-2A | Center Wavelength (nm) Sentinel-2B | Spatial Resolution |
| Band 3 | 559.8 | 559.0 | 10m |
| Band 4 | 664.6 | 664.9 | 10m |
| Band 5 | 704.1 | 703.8 | 10m |
| Band 8 | 832.8 | 832.9 | 10m |
| Band 8A | 864.7 | 864 | 20m |

1.2. Area of Study

We selected locations by first associating vegetation community information from the Regional Ecosystem Description Database with the 2017 Queensland Herbarium’s Vegetation Management Regional Ecosystem (VMRE) map [11]. We chose four sites of different vegetation compositions with respect to eucalypt abundance and vegetation density structures (Figure 1). We define “eucalypt” as a species belonging to the tribe Eucalypteae (genera: *Eucalyptus*, *Corymbia*, and *Angophora*). We compared two sites dominated by eucalypt tree species, one site that included areas dominated by eucalypt tree species and other areas dominated by non-eucalypt tree species, and one site was dominated by
non-eucalypt tree species. Three sites are between 105–108 km² in size and contain protected areas where the vegetation communities are very likely to be the same composition in 2020 as described in the 2017 VMRE map [10]. The fourth site is an area 70 km² in size of mid-dense eucalypt vegetation. There are no comparable areas of dense or mid-dense all-eucalypt vegetation in the 2017 VMRE map.

The large all-eucalypt site is in Carnarvon National Park in Southern Queensland and contains mostly sparse and mid-dense areas of trees that contain any of the following species: Corymbia citriodora (lemon-scented gum or spotted gum); Eucalyptus melliodora (yellow box, honey box, or yellow ironbark); E. melanophloia (silver-leaved ironbark); E. laevopinea (silver-top stringybark); and E. tereticornis (forest red gum, blue gum, or red irongum) (Figure 1c). We selected a second all-eucalypt site of higher density to account for the sparseness in the first all-eucalypt site. The second all-eucalypt site is in Blackdown Tableland National Park and contains mid-dense areas of Eucalyptus sphaerocephala (blackdown stringybark), E. cloeziana (Gympie messmate or dead finish), E. melanoleuca (yarraman ironbark or nanango ironbark), and various Eucalyptus and Corymbia species. The mixed eucalypt site is near Pelion State Forest in Northeastern Queensland (Figure 1c). This site was chosen, because it contains areas dominated by eucalypt tree species and areas dominated by non-eucalypt species, agricultural fields, and human settlements. The vegetated areas contain sparse-to-dense areas of trees, with the eucalypt area containing species such as Corymbia intermedia (pink bloodwood), E. platyphylla (poplar gum or white gum), E. resinifera (red mahogany or red messmate), and E. tereticornis, amongst others, and the non-eucalypt area containing evergreen to semi-evergreen notophyll, microphyll, and mesophyll vine forests, with species such as Argyrodendron actinophyllum subsp. diversifolium (blackjack, macky tulip oak, or crowsfoot elm); Argyroderon polyandrum (staweedow, brown tulip oak, or brown crowsfoot elm); Cryptocarya macdonaldii (cooluola laurel); or Araucaria cunninghamii (hoop pine). The non-eucalypt site is in Woorooroonoran National Park in Northeast Queensland and is comprised of dense notophyll vine forests and mesophyll forests containing species such as Araucaria bidwillii (bunya pine or false monkey puzzle tree); Acacia celsa (brown salwood); and Allocasuarina littoralis (black sheoak, black she-oak, or river black-oak), with small, nonvegetated areas. The South Johnstone River passes through this site, and it contains a very small, cleared area. The VMRE map description of the sites is shown in Figures S1–S4 and Tables S1–S4.

2. Materials and Methods

We retrieved 13-band Sentinel-2 imagery courtesy of the U.S. Geological Survey through the USGS Earth Explorer [23] and 4-band Planet imagery from the Planet Explorer tool [24]. We selected...
imagery that had high coverage of the area of interest and less than 5% cloud cover from the Australian winter and late-spring/summer months (Table 3) to assess seasonal variation patterns in detectability due to growth. The spring/summer imagery analysis was only performed on the three large sites. All Sentinel-2 imagery used was collected by Sentinel-2A instruments, except for the winter images of the all-eucalypt mid-dense and non-eucalypt sites, which were collected by a Sentinel-2B instrument. A cloud-free Sentinel-2 image of the non-eucalypt site was not available in the winter of 2019, so an image from 2018 was used. Additionally, full-area coverage images of the non-eucalypt site in the winter months and a large all-eucalypt site in the summer in Planet imagery were not available, as capture over these areas just began in June 2019. Therefore, we used images with 98% coverage of the area (Table 3). We processed all imagery using ESRI’s ArcGIS Pro Version 2.5 [25] and analyzed all layers in the WGS84 UTM Zone 55S projection.

| Site               | Bounding Box Coordinates | Winter Imagery Date | Spring/Summer Imagery Date |
|--------------------|--------------------------|---------------------|----------------------------|
| Large All-Eucalypt | –24.985, 148.193         | 7 May 2019          | 1 May 2019                 |
| All-Eucalypt Mid-dense | –23.786, 149.074      | 17 May 2019         | 6 May 2019                 |
| Mixed Eucalypt     | –20.982, 148.759         | 7 May 2019          | 8 November 2019            |
| Non-Eucalypt       | –17.620, 145.800         | * 24 July 2019      | 10 November 2019           |

* These images comprise 98% of the area of interest.

Bands 3, 4, 5, 8, and 8A in the Sentinel-2 imagery were scaled by a factor of 0.0001 to convert pixel values to surface reflectance. Corrected bands 4 and 8 were used to calculate the NDVI values using Equation (5). Corrected bands 3, 5, and 8A were used to calculate the ECARR and ECBRR with Equations (6) and (7):

\[
\text{NDVI} = \frac{(\text{Band}8 - \text{Band}4)}{(\text{Band}8 + \text{Band}4)} \quad (5)
\]

\[
\text{ECARR} = 0.0008 \times [\text{Band}8A / (\text{Band}3 \times \text{Band}2)]^{1.2403} \quad (6)
\]

\[
\text{ECBRR} = 0.00005 \times [\text{Band}8A / \text{Band}3]^{3.5168} \quad (7)
\]

The resulting 20-m resolution ECARR and ECBRR rasters were then clipped down to the area of interest and exported as a GEOTIFF. This process was repeated for the Sentinel-2 imagery at each site and each season. The spectral bands used in the NDVI calculations (Table 2) resulted in a 10-m raster, which we resampled up to 20 m for comparison to ECARR and ECBRR.

Bands 2, 3, and 4 in each Planet scene were individually multiplied by their respective Top of Atmosphere (TOA) reflectance coefficients and band coefficients to convert pixel values to the TOA reflectance and harmonize the bands to other Planet scenes [22]. The TOA-corrected bands 3 and 4 were then used to calculate the NDVI to assess the area of living green vegetation using Equation (8). Corrected bands 2, 3, and 4 were used to calculate the Eucalypt chlorophyll-\(a\) reflectance ratio (ECARR) and Eucalypt chlorophyll-\(b\) reflectance ratio (ECBRR) with Equations (9) and (10):

\[
\text{NDVI} = \frac{(\text{Band}4 - \text{Band}3)}{(\text{Band}4 + \text{Band}3)} \quad (8)
\]

\[
\text{ECARR} = 0.0008 \times [\text{Band}4 / (\text{Band}3 \times \text{Band}2)]^{1.2403} \quad (9)
\]

\[
\text{ECBRR} = 0.00005 \times [\text{Band}4 / \text{Band}2]^{3.5168} \quad (10)
\]
The resulting 3-m resolution raster was clipped down to the area of interest and exported as a GEOTIFF. This process was repeated for Planet imagery at each site and each season.

The resulting rasters from all sensors and seasons were then converted into points and intersected with the 2017 VMRE map of each site to associate pixel values with the related vegetation information. Pixel level results were visualized in R [26]. Values in areas of nonvegetation according to the 2017 VMRE map (i.e., rivers and cleared areas) were removed from the analysis. The results presented here and in the SI (Figures S5–S24 and Tables S5–S16) are based on the winter imagery (Table 3). The late-spring/summer imagery analysis is shown in SI (Figures S25–S32, Tables S17–S27).

3. Results

3.1. ECARR Results

ECARR values ranged between 0 and 1 across all sites and sensors (Table 4). Planet imagery had consistently higher ECARR values (site max: 0.708) than the Sentinel-2 imagery (site max: 0.264). The highest ECARR value was found in the mixed eucalypt site and the lowest values in the large all-eucalypt and non-eucalypt sites (Table 4). While eucalypt vegetation was positively identified in both all-eucalypt sites and the mixed eucalypt site (Figure 2a–c,e–g), it was also falsely detected in the non-eucalypt site (Figure 2d,h and Table 4). The Sentinel-2 data showed similar trends to the Planet imagery with ECARR but with narrower ranges of values. The narrowest range of values was found in the all-eucalypt mid-dense site Sentinel-2 image, with the lowest maximum ECARR value of any site (Table 4).

| Satellite | Satellite Values | Large All-Eucalypt Site | All-Eucalypt Mid-dense Site | Mixed Eucalypt Site | Non-Eucalypt Site |
|-----------|------------------|-------------------------|-----------------------------|---------------------|-------------------|
| Sentinel-2| Maximum          | 0.243                   | 0.206                       | 0.264               | 0.252             |
|           | Minimum          | 0.019                   | 0.017                       | 0.014               | 0.005             |
|           | Mean             | 0.077                   | 0.094                       | 0.148               | 0.140             |
| Planet    | Maximum          | 0.443                   | 0.255                       | 0.708               | 0.605             |
|           | Minimum          | 0.000                   | 0.000                       | 0.000               | 0.002             |
|           | Mean             | 0.160                   | 0.108                       | 0.321               | 0.271             |

Comparing ECARR values by vegetation type showed areas of non-eucalypt vegetation had higher mean values than areas of only eucalypts (Figure 3), and ANOVA tests showed that these differences in vegetation were significant (Tables S7 and S9) for both satellite types. Receiver operating characteristic (ROC) curves testing ECARR sensitivity and specificity to classify eucalypt vegetation across sensors (Figures S5 and S6) show the Sentinel-2 instrument was better at identifying eucalypt vegetation (Area Under the Curve: 0.949, Accuracy: 0.904, Positive Predictive Value: 0.949, Negative Predictive Values: 0.862) than the Planet Dove (AUC: 0.906, Accuracy: 0.872, PPV: 0.897, NPV: 0.846) (Table S5 and S6).

The distribution of ECARR values in the Sentinel-2 imagery and Planet imagery show consistent trends that non-eucalypt vegetation has higher ECARR values (Figure 4). When assessed by the vegetation density structure according to the 2017 VMRE map, the ECARR values are higher in areas with denser vegetation (Figures S8–S10), and ANOVA tests show values that were significantly different between density types \( (p = 0) \) (Table S8 and S10). The highest mean ECARR values in eucalypt vegetation were found in the mixed eucalypt site. Spatially, these “high” (>0.15) ECARR values of eucalypt vegetation cluster at the lower elevations near the bases of the Pelion State Forest hills and along boundaries with non-eucalypt vegetation communities (Figure S13).
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The resulting rasters from all sensors and seasons were then...imagery. (g) Mixed eucalypt site ECARR results Planet imagery. (h) Non-Eucalypt site ECARR results Planet imagery.

**Figure 2.** Results of Eucalypt chlorophyll-a reflectance ratio (ECARR) calculations shown with a gradient scale from white (low) to black (high). Panels (a–d) show Sentinel-2 imagery. Panels (e–h) show Planet imagery. (a) All-eucalypt site ECARR results Sentinel-2A imagery. (b) All-eucalypt mid-dense site ECARR results Sentinel-2B imagery. (c) Mixed eucalypt site ECARR results Sentinel-2A imagery. (d) Non-eucalypt site ECARR results Sentinel-2B imagery. (e) All-eucalypt site ECARR results Planet imagery. (f) All-eucalypt mid-dense site ECARR results Planet imagery. (g) Mixed eucalypt site ECARR results Planet imagery. (h) Non-Eucalypt site ECARR results Planet imagery.

**Figure 3.** Violin box plots of ECARR values across sites and sensors by vegetation type. (a) ECARR values from Sentinel-2 imagery at all sites. (b) ECARR values from Planet imagery at all sites. Plots shown with sensor-specific y-axes; see Figure S7 for plots with unified scales.
ECARR values from the summer imagery analysis are consistent with the winter imagery (Figures S25–S28). The distribution of ECARR values between vegetation types showed an increase in separation in the Planet imagery (Figure S26), while Sentinel-2 imagery showed an increase in distribution overlap (Figure S25). The ranges across all sites and sensors were smaller than that found in the winter imagery, but similarly, Planet imagery had higher ranges and means for all three large sites analyzed (Table S17). ECARR values in different density groups were also found to be significantly different from one another in ANOVA tests for both satellite types (Tables S19 and S21).

3.2. ECBRR Results

ECBRR values ranged between 0 and 0.1 across all sites and sensors (Table 5). The range of ECBRR values was greater in the Sentinel-2 imagery than the Planet imagery, with the highest mean value found in the mixed eucalypt site and lowest mean value found in the large all-eucalypt site (Figure 5 and Table 5). The ECBRR value ranges in the mid-dense all-eucalypt and non-eucalypt sites were similar between satellites, but the mixed eucalypt site showed the greatest change in range between sensors. ECBRR can identify mid-dense eucalypt vegetation (Figure 5a) in the all-eucalypt sites, but it also falsely identified eucalypt vegetation in non-eucalypt vegetation communities (Figure 5d,h), with higher values on average (Table 5 and Figures 6 and 7).

Consistent with ECARR, the ROC curves for ECBRR’s ability to classify eucalypt vegetation across the sensors show the Sentinel-2 instrument (AUC: 0.893, Accuracy: 0.855, PPV: 0.868, NPV: 0.841) had higher accuracy than the Planet Dove (AUC: 0.877, PPV: 0.868, NPV: 0.841) (Figures S15 and S16 and Tables S11 and S12). The density of the structure impacted the ECBRR values (Figures S17–S19), and the ANOVA tests showed that the density groups were significantly different from each other (Tables S14 and S16). The highest mean ECBRR value in eucalypt vegetation was likewise found in the mixed eucalypt site (Table 5). High ECBRR values are also spatially clustered in areas of lower elevations near the base of the Pelion State Forest hills (Figure S22).
Figure 5. Results of the Eucalypt chlorophyll-b reflectance ratio (ECBRR) calculations shown with a gradient color scale from white (low) to black (high). Panels (a–d) show Sentinel-2 imagery. Panels (e–h) show Planet imagery. (a) All-eucalypt site ECBRR results Sentinel-2A imagery. (b) All-eucalypt mid-dense site ECBRR results Sentinel-2B imagery. (c) Mixed eucalypt site ECBRR results Sentinel-2A imagery. (d) Non-eucalypt site ECBRR results Sentinel-2B imagery. (e) All-eucalypt site ECBRR results Planet imagery. (f) All-eucalypt mid-dense site ECBRR results Planet imagery. (g) Mixed eucalypt site ECBRR results Planet imagery. (h) Non-eucalypt site ECBRR results Planet imagery.

Figure 6. Violin Box plots of ECBRR values across the sites and sensors. (a) ECBRR values from Sentinel-2 imagery at all sites. (b) ECBRR values from Planet imagery at all sites.
Table 5. Eucalypt chlorophyll-\(b\) reflectance ratio value ranges for all sites and satellite sensors from the winter imagery.

| Satellite | ECBRR Value | Large All-Eucalypt Site | All-Eucalypt Mid-Dense Site | Mixed Eucalypt Site | Non-Eucalypt Site |
|-----------|-------------|--------------------------|----------------------------|---------------------|------------------|
| Sentinel-2| Maximum     | 0.022                    | 0.019                      | 0.085               | 0.056            |
|           | Minimum     | 0.000                    | 0.000                      | 0.000               | 0.000            |
|           | Mean        | 0.002                    | 0.003                      | 0.013               | 0.009            |
| Planet    | Maximum     | 0.021                    | 0.012                      | 0.050               | 0.055            |
|           | Minimum     | 0.000                    | 0.000                      | 0.000               | 0.000            |
|           | Mean        | 0.002                    | 0.002                      | 0.007               | 0.007            |

Figure 7. Proportion of ECBRR values across all sites by vegetation type. (a) Proportion of total ECBRR values at all sites from Sentinel-2 imagery grouped by vegetation type. (b) Proportion of total ECBRR values at all sites from Planet imagery grouped by vegetation type.

The distribution of ECBRR was not significantly impacted by site (Figures S20–S21), shown by the substantial overlap of the non-eucalypt and mixed eucalypt site value distributions across both satellite types. Regardless of the vegetation attributes, there was little separation between the maximum and minimum values across all sites, sensors, and seasons.

ECBRR values from the summer imagery analysis were also comparable with the winter analysis. Areas of non-eucalypt vegetation were found to have higher mean ECBRR values than eucalypt vegetation (Figures S29 and S30 and Table S22). Planet imagery showed increased separation in ECBRR distributions between vegetation types (Figure S30), while Sentinel-2 imagery showed an increase in ECBRR’s distribution overlap (Figure S29). The ranges across all sites were similar to those found in the winter imagery. The non-eucalypt site in the Sentinel-2 image had the highest range and mean for all large sites (Table S22), and the density groups were significantly different from each other (Tables S24 and S26).
3.3. NDVI Results

All four sites had relatively high NDVI values in the Planet and Sentinel-2 imagery (Figure 8 and Table 6), showing that each site contained areas of green, healthy vegetation. In both types of imagery, the all-eucalypt mid-dense site had the lowest maximum NDVI value. The lowest mean NDVI values, similarly to ECARR, were found in the large all-eucalypt or all-eucalypt mid-dense site, depending on the sensory (Table 6). The mixed eucalypt site and non-eucalypt site showed relatively consistent NDVI values across all vegetated areas, regardless of vegetation density (Figure S24). Little difference in the NDVI ranges and means were seen between vegetation types in the mixed eucalypt site (Figure S23). Overall, the two all-eucalypt sites had the lowest mean NDVI values of all the sites analyzed. Late-spring/summer results showed similar trends to winter, with all sites having lower maximum values and means, except for the non-eucalypt site, which had nearly equivalent means for both sensors. The relationship between the NDVI and ECARR values for each site is shown in Figure 9.

Table 6. Normalized Difference Vegetation Index (NDVI) value ranges for all sites and satellite sensors from the winter imagery.

| Satellite | NDVI Value | Large All-Eucalypt Site | All-Eucalypt Mid-Dense Site | Mixed Eucalypt Site | Non-Eucalypt Site |
|-----------|------------|-------------------------|-----------------------------|---------------------|-------------------|
| Sentinel-2| Maximum    | 0.801                   | 0.789                       | 0.844               | 0.843             |
|           | Minimum    | −0.041                  | 0.185                       | 0.047               | −0.035            |
|           | Mean       | 0.513                   | 0.559                       | 0.738               | 0.719             |
| Planet    | Maximum    | 0.830                   | 0.752                       | 0.873               | 0.867             |
|           | Minimum    | 0.157                   | 0.208                       | 0.005               | −0.101            |
|           | Mean       | 0.600                   | 0.549                       | 0.754               | 0.727             |

Figure 8. Results of Normalized Difference Vegetation Index (NDVI) calculations shown with a gradient color scale from white (low) to black (high). Panels (a–d) show Sentinel-2 imagery. Panels (e–h) show Planet imagery. (a) All-eucalypt site NDVI results Sentinel-2A imagery. (b) All-eucalypt mid-dense site NDVI results Sentinel-2B imagery. (c) Mixed eucalypt site NDVI results Sentinel-2A imagery. (d) Non-eucalypt site NDVI results Sentinel-2B imagery. (e) All-eucalypt site NDVI results Planet imagery. (f) All-eucalypt mid-dense site NDVI results Planet imagery. (g) Mixed eucalypt site ECARR results Planet imagery. (h) Non-Eucalypt site NDVI results Planet imagery.
Figure 9. Mean ECARR values and mean NDVI values at all sites in the winter imagery with convex hulls of values as polygons. (a) Mean ECARR and NDVI values (points) with a convex hull represented by polygons from Sentinel-2 winter imagery at all sites and a grey dashed 1-to-1 line. (b) Mean ECARR and NDVI values (points) with a convex hull represented by polygons from Planet winter imagery at all sites and a grey dashed 1-to-1 line.

4. Discussion

4.1. Eucalypt Chlorophyll-a Reflectance Ratio (ECARR)

Areas dominated by eucalypt species were correctly identified in both all-eucalypt sites and the mixed eucalypt site (Figures 3 and 4). The Planet imagery had consistently higher ECARR values than the Sentinel-2 imagery, likely due to the higher resolution of the images. This increased resolution likely lends power to ECARR’s ability to detect chlorophyll properties by reducing the variation of vegetation within a single pixel, therefore increasing the granularity of the vegetation’s reflectance signal. The highest ECARR values within the all-eucalypt site were found in the sparsely vegetated areas dominated by *C. citriodora* open forests. Similar to the location of the “high” ECARR and ECBRR values in the mixed eucalypt site, this pixel was at the base of a ridge. These soils may have higher water contents from drainage down the hillside, and vegetation grows better here, thus reflecting more chlorophyll and increasing the ECARR values. Both satellites showed they were capable of identifying eucalypts with a mid-dense canopy structure but struggled to highlight sparser vegetation in the surrounding areas (Figure 2a,d). The areas of low ECARR values (Figure 2a) correspond with areas of lower NDVI values (Figure 8a), suggesting that there is less chlorophyll reflectance from any type of vegetation in these pixels relative to the surrounding areas. Mean ECARR values from the Sentinel-2 large all-eucalypt site increased when the pixels were selected for high NDVI values (>0.5) (Figure S14). ECARR values also increased with increasing density of the vegetation canopy (Figures S8 and S9), and different density groups were significantly different from one another in the
ANOVA tests. This validates that the canopy density substantially influences the ability of ECARR to identify eucalypt vegetation remotely. The late-spring/summer imagery ECARR analysis echoes these trends but with slightly smaller ranges and lower means for the three large sites analyzed across both sensors. This could be due to the vegetation putting more energy into reproduction rather than growth during this time or biotic factors that impacted growth during these months. The spring of 2019 was the driest and the second-warmest on record for Australia [27]. The decrease in ranges and means of ECARR at all sites likely show the effects of these extreme environmental conditions.

The mixed eucalypt site (Figure 2c,g) contained the greatest ECARR value calculated across all sites and sensors (Table 4.) It was calculated in an area of mid-dense vegetation consisting of *E. resinifera* and/or *E. portuensis* (Figure S7b). Interestingly, the agricultural fields in both types of imagery had low ECARR values (Figure 2c,g), suggesting this reflectance ratio may be able to discern native vegetation chlorophylls from cultivated crop chlorophylls. The scene still contained relatively high ECARR values in areas of both eucalypt and non-eucalypt vegetation (Figure 3), but high values in the eucalypt vegetation communities were spatially clustered in areas of lower elevation (Figure S13), where vegetation likely benefits from the water drainage down these slopes. Other high eucalypt ECARR values were along boundaries between eucalypt and non-eucalypt vegetation communities (Figure 2c), which could reflect differences in vegetation boundaries between the VMRE maps and the landscape.

Mean ECARR values in the non-eucalypt site were higher than both all-eucalypt sites in both sensor types (Table 4 and Figure 3). Surprisingly, ECARR values did not differ greatly between density structures; both “dense” and “very sparse” vegetation showed similar mean values (Figure S8). However, the “very sparse” vegetation is very small in geographic extent (<0.05% of pixels) and is surrounded by dense vegetation. It is possible that the satellite resolutions were too coarse to distinguish this very small area of sparse vegetation from its surroundings. There could also be boundary discrepancies between the VMRE map and the landscape that could have allowed for “dense” vegetation on the landscape to be classified in the “very sparse” area from the VMRE map.

ROC curves for each satellite show that ECARR was sensitive enough to identify eucalypt vegetation and had higher sensitivity, negative predictive power, and positive predictive power in the Sentinel-2 imagery. This is likely due to the closer band match of this sensor’s spectral bands to the original reflectance ratio. The center wavelength of Sentinel-2’s band 5 is only 5 nm off from the original reflectance ratio, while the Planet’s corresponding band was 40 nm off. Both satellites also show ECARR has low specificity when discerning eucalypt vegetation from other vegetation types. This is corroborated by the higher mean ECARR values in the non-eucalypt site than the large and mid-dense all-eucalypt sites for both satellites (Figure 3) and seasons (Figures S25 and S26). These results demonstrate that satellite-derived ECARR values are not specific enough to discriminate between eucalypt and non-eucalypt types of vegetation.

### 4.2. Eucalypt Chlorophyll-b Reflectance Ratio (ECBRR)

The ECBRR results show similar trends to ECARR across sites and seasons, but the values were an order of magnitude smaller than the ECARR and NDVI. The lowest maximum and mean ECBRR values for both satellite types were found in the large all-eucalypt and mid-dense eucalypt sites (Table 5). Unlike ECARR, the greatest ECBRR values were detected in Sentinel-2 imagery. However, the ranges and means of the ECBRR values are very narrow, making it difficult to say with confidence whether this algorithm can discern vegetation from nonvegetation remotely.

The mixed eucalypt site similarly contained pixels with the highest ECBRR values near the slopes of the Pelion State Forest hills and along boundaries between vegetation communities. However, the agricultural fields that were readily distinguished by ECARR (Figure 2c,g) are not as easily discernable and blend in with the nearby forest due to their similarly low ECBRR values. This implies that ECBRR cannot distinguish between the chlorophyll reflectance of native vegetation and cultivated crops. The non-eucalypt site contained higher maximum values of ECBRR in both types of satellite
imagery than the large all-eucalypt site. Although the ROC curves indicated that ECBRR was sensitive enough to identify eucalypt vegetation in both types of imagery (Figures S15 and S16), the very low means and narrow ranges of ECBRR suggest other spectral indices, such as ECARR or NDVI, are better at identifying vegetation remotely and offer more separation in values between vegetation and nonvegetation in satellite imagery.

4.3. Normalized Difference Vegetation Index (NDVI)

The substantial overlap of ECARR and NDVI value ranges across sites (Figure 9) further supports that the ECARR is sufficiently sensitive to identifying vegetation, but it cannot distinguish between vegetation types. However, the NDVI values (Figure 8c,g) were relatively high and consistent between the agricultural fields and the neighboring dense forest. This further promotes that the ECARR may emphasize reflective differences between chlorophylls in native vegetation and cultivated crops. We believe the high sensitivity but low specificity in ECARR’s ability to identify eucalypt vegetation is due to differences in the wide range of spectral wavelengths collected by these sensors and the original algorithm. The lack of specificity and low values from high-resolution imagery (3–20 m) suggest ECARR should not be used on the satellite data sources considered here to assess changes in eucalypt vegetation dynamics or biodiversity over time with confidence. The ECBRR is also not readily applicable to identify eucalypt vegetation remotely with high confidence from the satellite imagery assessed here. The algorithms alone, when applied to either source of imagery, do not provide enough information to classify the eucalypt vegetation extent.

There are several factors in this study that may have impacted the ECARR and ECBRR results at the sites tested. When developing these ratios, the correlation factor rapidly declines just a few wavelengths around the peak wavelengths of 550 nm, 708 nm, and 860 nm [14], so it is likely the bands in the imagery used here were too far from the original bands to reprise those results. Additional errors could be due to the characteristics of the vegetation communities selected. Large areas of monogenus or monotribe eucalypt vegetation on the Vegetation Management Regional Ecosystem maps are rare in Queensland. Australia has lost nearly 40% of its forests since European colonization in roughly 1750, and areas of native forest have become increasingly fragmented over time [28]. No “dense” eucalypt vegetation patches are present on the 2017 VMRE map, so a comparison of “dense” eucalypt and non-eucalypt areas was not possible. The large all-eucalypt site, which was the only area of its size found on the 2017 VMRE map, contained mostly areas of sparse vegetation. We see this had a direct negative impact on the ECARR, ECBRR, and NDVI values from this site (Figures 2, 4 and 6).

Abiotic factors such as topography, elevation, average rainfall, and temperature also impact vegetation communities broadly. Rapid decreases in elevation were spatially correlated with higher ECARR and ECBRR values in the mixed eucalypt site. It is likely that other environmental factors not considered here also influenced the distribution of ECARR values at each site. Biotic factors such as eucalypt physiology and the spatial canopy structure may have also limited the ability to measure eucalypt chlorophylls from satellite imagery. Eucalypts have pendular leaf morphology [14,29], causing the leaves to hang downward, which can impact the appearance of the eucalypt canopy density from above-ground imagery. Lastly, as shown in a previous work, some individual species were shown to have higher correlations with a modified index [15] than when it was applied to areas of mixed species. It is possible the diversity of Eucalyptus species at these sites gave lower correlations with ECARR and ECBRR than if these Eucalyptus species were evaluated individually.

Further studies need to be done to test the use of ECARR and ECBRR on remotely collected data. These analyses should be repeated on smaller sites with uniform vegetation types and elevations to test the effect of the canopy structure on the ECARR more closely. Similarly, these could be repeated on areas of single species to categorize ECARR ranges for different eucalypt species. Additionally, high-resolution multispectral imagery with very narrow ranges of spectral bands may be able to remotely measure chlorophyll-a better than sensors with wide ranges of spectral bands. This could
reveal new or improved correlations at different wavelengths captured by satellites and may lead to the development of a version of ECARR better-suited for satellite imagery.

While the eucalypt chlorophyll reflectance ratios tested here were not able to distinguish the eucalypt tribe of vegetation from other types on previously collected imagery, the incredibly detailed VMRE maps can still benefit from newly available, high-resolution, globally comprehensive satellite imagery. These increasingly powerful sensors can help to assess the plant presence and absence and chlorophyll properties at finer spatial scales. We can assess vegetation losses in greater detail now than ever before and can apply these tools to inform reactive conservation and preservation policies as necessary on rapidly changing landscapes or on a changing climate. It is crucial to develop and refine our vegetation classification tools on satellite imagery, so we know how vegetation communities and biodiversity are being impacted in areas where no vegetation mapping products exist.

5. Conclusions

When applied to passively collected imagery of landscapes from Sentinel-2 and Planet, and, likely, other sources as well, the Eucalypt chlorophyll-a reflective ratio can serve as a general chlorophyll indicator but is not a specific index with which to identify Eucalyptus vegetation with certainty. This is likely due to the large range of wavelengths collected by the sensors and imperfect band matches to the original algorithm. Eucalypt chlorophyll-b reflective ratio values were an order of magnitude smaller than the ECARR and NDVI and should be used with caution when evaluating vegetation chlorophyll properties from satellite imagery. Further studies need to be done to reassess the correlations between eucalypt chlorophyll-a and eucalypt chlorophyll-b and the wide ranges of wavelengths collected from the many passive satellites currently imaging the globe. With improved calibrations of these reflectance ratios, it may be possible to leverage previously collected satellite imagery to classify eucalypt distribution in areas with no existing information on vegetation communities.

Supplementary Materials: The following are available online at http://www.mdpi.com/2072-4292/12/24/4079/s1:

- Figure S1: All-eucalypt site from the 2017 VMRE map colored by vegetation type where green represents areas dominated by eucalypt vegetation.
- Figure S2: All-eucalypt mid-dense site from the 2017 VMRE map colored by vegetation type where green represents areas dominated by eucalypt vegetation, blue represents areas dominated by non-eucalypt vegetation, and grey represents non-remnant areas (cleared land).
- Figure S3: Mixed eucalypt site from the 2017 VMRE map colored by vegetation type where green represents areas dominated by eucalypt vegetation, blue represents areas dominated by non-eucalypt vegetation, and grey represents non-remnant areas (cleared land).
- Figure S4: Non-eucalypt site from the 2017 VMRE map colored by vegetation type where blue represents areas dominated by non-eucalypt vegetation.
- Figure S5: ROC Curve for ECARR’s ability to detect eucalypt vegetation from Sentinel-2 winter imagery.
- Figure S6: ROC Curve for ECARR’s ability to detect eucalypt vegetation from Planet winter imagery.
- Figure S7: Violin Box plots of ECARR values in winter imagery colored by vegetation type as characterized in the 2017 VMRE map with unified scale. (a) ECARR values in Sentinel-2 imagery at all sites. (b) ECARR values in Planet imagery at all sites.
- Figure S8: Violin Box plots of ECARR values in winter imagery colored by vegetation type and separated by vegetation density as characterized in the 2017 VMRE map. (a) ECARR values in Sentinel-2 imagery at all sites. (b) ECARR values in Planet imagery at all sites.
- Figure S9: Sentinel-2 winter imagery ECARR value distribution across all sites colored by density structure.
- Figure S10: Planet winter imagery ECARR value distribution across all sites colored by density structure.
- Figure S11: Sentinel-2 winter imagery ECARR value distribution across all sites colored by site.
- Figure S12: Planet winter imagery ECARR value distribution across all sites colored by site.
- Figure S13: Mixed Eucalypt Site with a Digital Elevation Model colorized with white as the high elevations and black as low elevations and high NDVI values in eucalypt vegetation communities in green from Sentinel-2 winter imagery.
- Figure S14: Violin box plots of Sentinel-2 winter imagery ECARR values in the large all-eucalypt site selected by high NDVI thresholds of that pixel.
- Figure S15: ROC Curve for ECARR’s ability to detect eucalypt vegetation from Sentinel-2 winter imagery.
- Figure S16: ROC Curve for ECARR’s ability to detect eucalypt vegetation from Planet imagery.
- Figure S17: Violin Box plots of winter imagery ECBRR values colored by vegetation type and vegetation density as characterized in the 2017 VMRE map. (a) ECBRR values in Sentinel-2 imagery at all sites. (b) ECBRR values in Planet imagery at all sites.
- Figure S18: Sentinel-2 winter imagery ECBRR values across all sites colored by the density structure.
- Figure S19: Planet winter imagery ECBRR values across all sites colored by the density structure.
- Figure S20: Sentinel-2 winter imagery ECBRR values across all sites colored by site.
- Figure S21: Planet winter imagery ECBRR values across all sites colored by site.
- Figure S22: Mixed Eucalypt Site with a Queensland Digital Elevation Model colorized with white as high elevations and black as low elevations and high ECBRR values in eucalypt vegetation communities in green from Sentinel-2 winter imagery.
- Figure S23: Violin Box plots of winter imagery NDVI values colored by vegetation type. (a) NDVI values in Sentinel-2 imagery at all sites. (b) NDVI values in Planet imagery at all sites.
- Figure S24: Violin Box plots of winter imagery NDVI values colored by vegetation type and separated by vegetation density as characterized in the
2017 VMRE map. (a) NDVI values in Sentinel-2 imagery at all sites. (b) NDVI values in Planet imagery at all sites. Figure S25: Sentinel-2 late-spring/summer imagery ECARR values across three large sites colored by vegetation type. Figure S26: Planet late-spring/summer imagery ECARR values across three large sites colored by vegetation type. Figure S27: Sentinel-2 late-spring/summer imagery ECARR values across three large sites colored by density. Figure S28: Planet late-spring/summer imagery ECARR values across three large sites colored by density. Figure S29: Sentinel-2 late-spring/summer imagery EBCRR values across three large sites colored by vegetation type. Figure S30: Planet late-spring/summer imagery EBCRR values across three large sites colored by vegetation type. Figure S31: Sentinel-2 late-spring/summer imagery EBCRR values across three large sites colored by density. Figure S32: Planet late-spring/summer imagery EBCRR values across three large sites colored by density. Table S1: Description of all-eucalypt site vegetation communities from the 2017 VMRE map. Table S2: Description of all-eucalypt mid-dense site vegetation communities from the 2017 VMRE map. Table S3: Description of mixed eucalypt site vegetation communities from the 2017 VMRE map. Table S4: Description of non-eucalypt site vegetation communities from the 2017 VMRE map. Table S5: Sentinel-2 ECARR ROC curve specificity and sensitivity for ECARR with the "best" method. Table S6: Planet ECARR ROC curve specificity and sensitivity for ECARR with the "best" method. Table S7: ANOVA Table (type II tests) for the effect of vegetation type on ECARR for Sentinel-2 winter imagery. Table S8: ANOVA Table (type II tests) for the effect of density structure on ECARR for Sentinel-2 winter imagery. Table S9: ANOVA Table (type II tests) for the effect of vegetation type on ECARR for Planet winter imagery. Table S10: ANOVA Table (type II tests) for the effect of density structure on ECARR for Planet winter imagery. Table S11: Sentinel 2 ECBRR ROC curve specificity and sensitivity for ECBRR on winter imagery with the "best" method. Table S12: Planet ECBRR ROC curve specificity and sensitivity for ECBRR on winter imagery with the "best" method. Table S13: ANOVA table (type II tests) for the effect of vegetation type on ECBRR for Sentinel-2 winter imagery. Table S14: ANOVA table (type II tests) for the effect of density structure on ECBRR for Sentinel-2 winter imagery. Table S15: ANOVA table (type II tests) for the effect of vegetation type on ECBRR for Planet winter imagery. Table S16: ANOVA table (type II tests) for the effect of density structure on ECBRR for Planet winter imagery. Table S17: Eucalypt chlorophyll-a reflectance ratio value ranges and mean of late-spring/summer imagery for the three large sites and both satellite sensors. Table S18: ANOVA table (type II tests) for vegetation type on ECARR for Sentinel-2 late-spring/summer imagery. Table S19: ANOVA table (type II tests) for the effect of density structure on ECARR for Sentinel-2 late-spring/summer imagery. Table S20: ANOVA table (type II tests) for vegetation type on ECARR for Planet late-spring/summer imagery. Table S21: ANOVA table (type II tests) for the effect of density structure on ECARR for Planet late-spring/summer imagery. Table S22: ANOVA table (type II tests) for vegetation type on ECARR for Sentinel-2 late-spring/summer imagery. Table S23: ANOVA table (type II tests) for the effect of density structure on ECARR for Sentinel-2 late-spring/summer imagery. Table S24: ANOVA table (type II tests) for vegetation type on ECARR for Planet late-spring/summer imagery. Table S25: ANOVA table (type II tests) for the effect of density structure on ECARR for Planet late-spring/summer imagery. Table S26: Eucalypt chlorophyll-b reflectance ratio value ranges and mean of late-spring/summer imagery for the three large sites and both satellite sensors. Table S27: Normalized Difference Vegetation Index value ranges and mean of late-spring/summer imagery for the three large sites and both satellite sensors.

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