PACE OCI Vegetation Indices (LANDVI)

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Abstract

Vegetation indices (VIs) are surface reflectance ratios which use typical spectral features of vegetation to describe some aspect of the surface. These metrics have been used for decades in the monitoring of terrestrial ecosystems and have historically represented more general aspects of the environment, such as vegetative health or stress. The Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission provides a suite of VIs using hyperspectral surface reflectance data from the Ocean Color Instrument (OCI). This product, termed LANDVI, contains VIs commonly produced with heritage multispectral instruments, extending the data record of these indices through to the present. Beyond these legacy indices, LANDVI also includes four hyperspectral-enabled VIs, which use narrowband reflectance measurements to attain detailed information about the pigment content within leaves. Foliar pigments, namely chlorophyll, carotenoids, and anthocyanins, are key to the photosynthetic and photoprotective capabilities in vegetation; their presence or absence explains much about the status of the environment. Determining these parameters from space requires those narrow bandwidth surface reflectance measurements, meaning these pigment indices cannot be calculated with multispectral instruments. By combining these two categories of VI, OCI's LANDVI suite contributes to the time series of heritage VIs while providing new insights into how vegetation responds to changing environmental conditions on a global scale.

Plain Language Summary

No content available.

Version description

This is the first version of the algorithm theoretical basis document (ATBD) for the LANDVI suite produced with data from the Plankton Aerosol Cloud ocean Ecosystem's (PACE) Ocean Color Instrument (OCI), implemented in the most recent Ocean Biology Processing Group (OBPG) data processing scheme. The algorithm descriptions below correspond to Version 3 of PACE OCI's LANDVI product, and maybe updated upon future reprocessings.

1. Introduction

Terrestrial environments have been monitored with remote sensing for decades through platforms like Landsat and Moderate Resolution Imaging Spectroradiometer (MODIS). PACE is in a unique position not only to continue the observations made by many previous sensors, but also to expand the data record using hyperspectral measurements to further understand the dynamics of vegetation on a global the scale. The LANDVI suite accomplishes these goals - it contains 10 products, including both heritage multispectral vegetation indices (VIs) as well as novel hyperspectral-enabled (narrowband) VIs. VIs are surface reflectance ratios which compare specific bands to tease out distinct features of the Earth's surface. Multispectral VIs provide information on general vegetation characteristics, such as greenness or water content, while narrowband VIs yield more detailed information on pigment dynamics. The LANDVI product suite is produced at both regional (Level 2) and global (Level 3) scales.

2. Context / Background

2.1. Historical Perspective

The use of vegetation indices to assess vegetation health is well documented in terrestrial remote sensing. This began with the simple ratio (SR; Jordan, 1969), which took advantage of the magnitude of vegetation reflectances in the red and NIR ranges of the spectrum. Later, the same principles were used to create a normalized version of SR, the Normalized Difference Vegetation Index (NDVI), which has a consistent range of -1 to 1 (Deering, 1978) and is used to quantify the "greenness" or health of vegetation. NDVI has a long history of use from missions like the Advanced Very High Resolution Radiometer (AVHRR) and MODIS, generating time series data from which seasonal and annual activity has been well characterized; Huang et al., 2021 provides a review of the use of NDVI from its inception to the present in both satellite and unmanned aerial system remote sensing. A multitude of other indices have been developed in addition to NDVI to assess other aspects of vegetation, such as water content (Normalized Difference Water Index, NDWI; Gao, 1996), the balance of certain pigments within the plant canopy (Chlorophyll-Carotenoid Index, CCI; Gamon et al., 2016), and even the presence of snow in a given pixel (Normalized Difference Snow Index, NDSI; Hall et al., 2001). The majority of these VIs leverage the capabilities of MODIS-like sensors, meaning they take multispectral band measurements as input for their calculations.

A subset of VIs have been developed to target the relative concentration of certain foliar pigments. These pigments, most importantly chlorophyll, carotenoids, and anthocyanins, play essential roles in photosynthesis and photoprotection (Blackburn, 2006). Photoprotection refers to the capacity of pigments to mitigate damage to photosystems due to environmental stressors such as excessive light or low temperatures. Unlike the VIs mentioned above, the spectral signatures required for foliar pigment analysis come from very narrow regions of vegetation spectra. The studies which developed these pigment indices did so through use of in-situ hyperspectral reflectance measurements and laboratory pigment concentration analysis (Gitelson et al., 2001 & Gitelson et al., 2002), and with specific site data collected by radiometers on mounted platforms (Gitelson et al., 2005). From a remote sensing perspective, multispectral instruments do not have the necessary spectral characteristics to compute pigment indices due to their broad bandwidths or the omission of necessary wavelengths. Seeing these minute shifts in reflectance from space is capable only with hyperspectral bandwidths, which PACE OCI provides.

2.2. Additional information

No content available.

3. Algorithm Description

3.1. Scientific Theory

The spectral shape of a pixel containing vegetation can vary immensely with the qualities of that vegetation. The presence (or absence) of pigments can cause shifts in the visible wavelength regions of the spectrum, while the structural qualities of the plant causes variance in NIR wavelengths. VIs are developed empirically by analyzing components of typical leaf reflectance for these shifts. For example, indices like NDVI rely on healthy vegetation's high reflectance in the NIR compared with the relatively low reflectance in red wavelengths (Huete et al., 2002). There are of course species of vegetation with spectra that deviate from a typical leaf's spectral shape; however, the spectral signals of pigment concentration and cell structure is similar, enabling global use of these indices in a variety of ecosystems.

There are 10 vegetation indices in OCI's LANDVI suite. The first six are heritage indices, which use wide bandwidth surface reflectance measurements to attain the value of interest: NDVI, detailing vegetation health based on greenness, the Enhanced Vegetation Index (EVI), which is similar to NDVI but accounts for saturation at high leaf area locations and for atmospheric influences by including a subtraction of blue band measurements (Jiang et al., 2008); the Normalized Difference Water and Infrared Indices (NDWI, NDII), both of which quantify water stress in vegetation by using shortwave infrared (SWIR) band measurements (Gao, 1996; Hardisky et al., 1983); CCI, providing information on the balance of chlorophyll and carotenoid pigments (Gamon et al., 2016); and NDSI, quantifying the amount of snow present in a pixel (Hall et al., 2001). These indices have well-documented use from instruments like MODIS and Landsat's Thematic Mapper/Operational Land Imager (Wang et al., 2020; Huang et al., 2021; Dos Santos et al., 2019).

The last four indices in the suite are pigment indices, requiring very narrow bandwidths to monitor shifts in relative foliar pigment content. The Photochemical Reflectance Index (PRI) quantifies changes in xanthophyll cycle pigments that can be interpretated as stress responses (Grace et al., 2007). The Chlorophyll Index Red Edge (CIRE) is a measure of relative canopy chlorophyll content, describing potential photosynthetic productivity (Gitelson et al., 2005). The Carotenoid Content Index (Car) and the Modified Anthocyanin Reflectance Index (mARI) measure relative canopy carotenoid and anthocyanin content, respectively, providing information on the photoprotective capabilities of vegetation (Gitelson et al., 2002; Gitelson et al., 2001). The effects of changes in these pigments occur in specific spectral regions that often get missed or averaged out of multispectral reflectance measurements, and so require hyperspectral surface reflectances to be accurately characterized.

3.1.1. Assumptions

No content available.

3.2. Mathematical Theory

As relatively simple band ratios, the algorithms to produce VIs are straight forward. However, for PACE OCI's LANDVI suite, the two categories of VI (multispectral and hyperspectral-enabled) have slightly different processes by which they are calculated.

For the heritage VIs, presented in Table 1, OCI's narrow 5 nm bandwidths are aggregated to simulate wide band measurements. While it is possible to calculate these VIs with "single" OCI surface reflectances, that method would leave out information historically included in the much broader bandwidths of legacy multispectral VI calculations. To preserve continuity with heritage sensors, the first step in calculating these six VIs is a band aggregation as below:

$$\rho_{agg} = \frac{\sum_{\lambda_n}^{\lambda_i} \rho_\lambda}{N} \tag{1}$$

Where ρ_λ is the spectral surface reflectance at wavelength λ and ρ_{agg} is the average surface reflectance for a bandwidth from λ_n to λ_i. The bandwidths used in this aggregation are those for the MODIS instrument (Table 1). Notably, MODIS's relative spectral response (RSR) is not used to weight the band averages. While maximizing continuity with previous multispectral sensors is a primary goal for OCI, that does not mean mimicing results from those sensors. The LANDVI suite is not meant to directly reproduce MODIS measurements, but rather to calculate VIs from OCI using as much relevant spectral information as possible, considering this subset of VIs was created with multispectral sensors in mind.

Table 1: Table 1: LANDVI suite heritage VIs. The color or spectral range given corresponds to the relevant MODIS band. OCI's SWIR bands are multispectral, and as such the specific wavelength is given where necessary. Bandwidths are as follows: NIR (MODIS Band 2), 841 - 876 nm; red (MODIS Band 1), 620 - 670 nm; $Green_1$ (MODIS Band 11), 526 - 536 nm; $Green_2$ (MODIS Band 4), 545 - 565 nm; Blue (MODIS Band 3), 459 - 479 nm.

Vegetation Index	Equation
Normalized Difference Vegetation Index (NDVI)	$(\rho_{NIR} - \rho_{Red})/(\rho_{NIR} + \rho_{Red})$
Enhanced Vegetation Index (EVI)	$2.5 * (\rho_{NIR} - \rho_{Red})/(\rho_{NIR} + 6.0 * \rho_{Red} - 7.5 * \rho_{Blue} + 1)$
Normalized Difference Water Index (NDWI)	$(\rho_{NIR} - \rho_{1250})/(\rho_{NIR} + \rho_{1250})$
Normalized Difference Infrared Index (NDII)	$(\rho_{NIR} - \rho_{1618})/(\rho_{NIR} + \rho_{1618})$
Chlorophyll-Carotenoid Index (CCI)	$(\rho_{Green_1} - \rho_{Red})/(\rho_{Green_1} + \rho_{Red})$
Normalized Difference Snow Index (NDSI)	$(\rho_{Green_2} - \rho_{1618})/(\rho_{Green_2} + \rho_{1618})$

OCI's LANDVI suite also includes four hyperspectral-enabled VIs (Table 2). These indices necessitate hyperspectral inputs and do not have a satellite data record to preserve. As such, the aggregation scheme described above is not implemented for these VIs. Instead, the surface reflectances at each named band are used to calculate each index.

Table 2: Table 2: Hyperspectral-enabled VIs included in PACE OCI's LANDVI suite. Each corresponds to the surface reflectance measurement at specific wavelength .

Vegetation Index	Equation
Photochemical Reflectance Index (*PRI*)	$(\rho_{530} - \rho_{570})/(\rho_{530} + \rho_{570})$
Chlorophyll Index Red Edge (*CIRE*)	$(\rho_{800}/\rho_{705}) - 1$
Carotenoid Content Index (*Car*)	$[(1/\rho_{495}) - (1/\rho_{705})] * \rho_{800}$
Modified Anothcyanin Reflectance Index	$[(1/\rho_{550}) - (1/\rho_{705})] * \rho_{800}$

(*mARI*)	

3.2.1. Assumptions

The same assumptions made for the SFREFL suite apply to the LANDVI suite:

1. No aerosols are present to contribute to the TOA reflectance that would propagate through to VI calculations.
2. There is no coupling between the gas absorption and the molecule scattering.
3. The Earth is a Lambertian surface reflecting light isotropically.

3.3. Algorithm Input Variables

Name	**Long Name**	**Unit**
rho_S	Surface Reflectance	sr^{-1}

3.4. Algorithm Output Variables

Name	**Long Name**	**Unit**
NDVI	Normalized Difference Vegetation Index	unitless
EVI	Enhanced Vegetation Index	unitless
NDWI	Normalized Difference Water Index	unitless
NDII	Normalized Difference Infrared Index	unitless
CCI	Chlorophyll-Carotenoid Index	unitless
NDSI	Normalized Difference Snow Index	unitless
PRI	Photochemical Reflectance Index	unitless
CIRE	Chlorophyll Index Red Edge	unitless
Car	Carotenoid Content Index	unitless

Name	Long Name	Unit
mARI	Modified Anthocyanin Reflectance Index	unitless

4. Algorithm Availability

4.1. Location of Implemented Algorithm #1

URL **https://oceancolor.gsfc.nasa.gov/docs/ocssw/**

DESCRIPTION **Each VI algorithm is distributed with the OCSSW package. OCSSW contains all of the science processing software used within OBPG, and can function as a set of command line tools.**

Location of Implemented Algorithm #2

URL **https://seadas.gsfc.nasa.gov/**

DESCRIPTION **Additionally, OCSSW is built into SeaDAS, a software package presented as a graphical user interface (GUI) to assist users in processing data.**

5. Algorithm Usage Constraints

Table 3: Table 3: Algorithm Product names and associated L3 masks. Several masks listed above are not relevant for land processing, but are included for completion. Definitions for each flag can be found at https://oceancolor.gsfc.nasa.gov/resources/atbd/ocl2flags/. *Note that the LAND mask is inverted to mask any pixels identified as not including land.

Level 2 Product Suite	LANDVI
Level 3 Product Suite	LANDVI
Level 3 Masking	ATMFAIL, LAND*, HILT, HISATZEN, STRAYLIGHT, CLDICE, COCCOLITH, LOWLW, CHLWARN, CHLFAIL, NAVWARN, MAXAERITER, ATMWARN, HISOLZEN, NAVFAIL, FILTER, HIGLINT

The algorithms for LANDVI operate under the same constraints as the algorithm for their input surface reflectances, described in the SFREFL ATBD. Angular effects due to observation geometries may be present in the underlying surface reflectance measurements due to a lack of bidirectional reflectance distribution function (BRDF) correction in OCI data. Additionally, reflectances may contain uncorrected aerosol effects, as the surface reflectance algorithm does not currently account for their contributions. Some of these effects may be mitigated by the fact that VIs are ratios - however, time series data will exhibit these effects, as will those VIs which are not solely normalized differences.

The file format for Level 2 and Level 3 data products is described in the Ocean Data Product User Guide (https://oceancolor.gsfc.nasa.gov/resources/docs/format/Ocean_Data_Product_Users_Guide.pdf). Each LANDVI file is distributed in NetCDF format consistent with CF conventions. Specifics pertaining to the contents of each group in a Level 2 file are described in Table 4 below:

Table 4: Table 4: Description of Level 2 LANDVI product including contents of each group.

Level 2 Group	Group Contents
geophysical_data	Retrieved geophysical parameters; Variables: ndvi, evi, cci, ndwi, ndii, ndsi, pri, car, mari, cire, l2_flags
navigation_data	Geolocation information; Variables: latitude, longitude, and tilt.
processing_control	High level summary of processing workflow used for retrievals; Variables: flag_percentages and input_parameters
scan_line_attributes	Location and observation Information for each scan line; Variables: clat, clon, csol_z, day, detnum, elat, elon, msec, mside, slat, slon, time, year
sensor_band_parameters	Information on spectral bands as applicable to the instrument; Variables: aw, bbw, F0, k_no2, k_oz, Tau_r, vcal_gain, vcal_offset, wavelength

Retrieved geophysical parameters in Level 3 products are not contained in a group, and instead are presented as data variables at the top of the data tree along with the latitude ("lat") and longitude ("lon"). The processing_control group is present in Level 3 files as well.

6. Performance Assessment Validation

6.1. Performance Assessment Validation Methods

Validation of VI data is dependent on validation of the surface reflectance data provided in the SFREFL product. Currently, an initiative to use Radiometric Calibration Network (RadCalNet) data for this purpose is underway. Railroad Valley (RRV) in Nevada, USA was the first site used for validation. Two other RadCalNet sites, Gobabeb, Namibia (GONA) and La Crau, France (LCFR), are currently being added to the validation pipeline. RRV is a clay-based playa with reflectances that are generally stable under dry conditions but can vary due to rain and snow. The GONA site is located in Namibia's gravel plains on the edge of the Namib desert and is another area of high spatial homogeniety. LCFR is a primarily pebbly site populated with sparse vegetation(Marcq et al., 2018,Bouvet et al., 2019), and thus will represent more of a mixed pixel measurment than either RRV or GONA. See the SFREFL ATBD for more detail on the validation methods.

Data from recent field campaigns will also be useful in validating surface reflectances and thus the VIs produced by PACE. The PACE Postlaunch Airborne eXperiment (PACE-PAX), a field campaign designed specifically to collect validation data for the PACE mission, was conducted in September, 2024 (Knobelspiesse et al., 2023). It included two airborne imaging spectrometers, PICARD and PRISM, which measure in the VNIR-SWIR and UV-VIS-NIR, respectively. Combining the data from these instruments covers the full PACE OCI wavelength range, and as such will provide necessary validation data points for terrestrial targets. These instruments were flown broadly over the central California region, with some coverage over Nevada to capture RRV. Several National Ecological Observation Network (NEON) sites were chosen as measurement targets in addition to RRV. NEON monitors environmental change across the United States using both in-situ measurements and airborne data from the NEON Imaging Spectrometer (NIS) (Metzger et al., 2019), all of which will be evaluated for utility as validation data for PACE overflights.

6.2. Performance Assessment Validation Uncertainties

No content available.

6.3. Performance Assessment Validation Errors

No content available.

7. Data Access

7.1. Input Data Data Access

7.1.1. Entry #1

URL **https://oceancolor.gsfc.nasa.gov/data/download_methods/**

DESCRIPTION **Input variables from Level 2 surface reflectance data can be downloaded from the ocean color website through the different methods described in the link above.**

7.2. Output Data Data Access

7.2.1. Entry #1

URL **https://oceancolor.gsfc.nasa.gov/data/download_methods/**

DESCRIPTION **The LANDVI products can be downloaded through the "File Search" method described in the link above, or on Earthdata Search as of Version 3.**

7.3. Important Related URLs

7.3.1. Entry #1

URL **https://oceancolor.gsfc.nasa.gov/docs/ocssw/get__ndvi_8c.html**

DESCRIPTION **This is a graphical description of the NDVI algorithm implementation in OBPG's processing code (l2gen). Other VIs follow this implementation with the relevant equations and averaging methods as applicable.**

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