ISPRS Journal of Photogrammetry and Remote Sensing 137 (2018) 134–148

Contents lists available at ScienceDirect

ISPRS Journal of Photogrammetry and Remote Sensing

journal homepage: www.elsevier.com/locate/isprsjprs

Understanding the temporal dimension of the red-edge spectral region for forest decline detection using high-resolution hyperspectral and Sentinel-2a imagery

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ARTICLE INFO

Article history:
Received 18 September 2017
Received in revised form 12 January 2018
Accepted 23 January 2018

Keywords:
Hyperspectral
Red edge
Forest decline
Chlorophyll
Sentinel-2a
Radiative transfer

ABSTRACT

The operational monitoring of forest decline requires the development of remote sensing methods that are sensitive to the spatiotemporal variations of pigment degradation and canopy defoliation. In this context, the red-edge spectral region (RESR) was proposed in the past due to its combined sensitivity to chlorophyll content and leaf area variation. In this study, the temporal dimension of the RESR was evaluated as a function of forest decline using a radiative transfer method with the PROSPECT and 3D FLIGHT models. These models were used to generate synthetic pine stands simulating decline and recovery processes over time and explore the temporal rate of change of the red-edge chlorophyll index (CI) as compared to the trajectories obtained for the structure-related Normalized Difference Vegetation Index (NDVI). The *temporal trend method* proposed here consisted of using synthetic spectra to calculate the theoretical boundaries of the subspace for healthy and declining pine trees in the temporal domain, defined by $CI_{time=n}/CI_{time=n+1}$ vs. $NDVI_{time=n}/NDVI_{time=n+1}$. Within these boundaries, trees undergoing decline and recovery processes showed different trajectories through this subspace. The method was then validated using three high-resolution airborne hyperspectral images acquired at 40 cm resolution and 260 spectral bands of 6.5 nm full-width half-maximum (FWHM) over a forest with widespread tree decline, along with field-based monitoring of chlorosis and defoliation (i.e., 'decline' status) in 663 trees between the years 2015 and 2016. The temporal rate of change of chlorophyll vs. structural indices, based on reflectance spectra extracted from the hyperspectral images, was different for trees undergoing decline, and aligned towards the *decline baseline* established using the radiative transfer models. By contrast, healthy trees over time aligned towards the theoretically obtained *healthy baseline*. The applicability of this *temporal trend method* to the red-edge bands of the MultiSpectral Imager (MSI) instrument on board Sentinel-2a for operational forest status monitoring was also explored by comparing the temporal rate of change of the Sentinel-2-derived CI over areas with declining and healthy trees. Results demonstrated that the Sentinel-2a red-edge region was sensitive to the temporal dimension of forest condition, as the relationships obtained for pixels in healthy condition deviated from those of pixels undergoing decline.

1. Introduction

Forests worldwide are experiencing increasing levels of both abiotic stress, such as drought (Allen et al., 2010), and biotic disturbance (Macpherson et al., 2017; Senf et al., 2017b; van Lierop et al., 2015). Determining the impact of these processes on global vegetation dynamics requires the early detection of changes over time and space. Most of the standard remote sensing methods available are based on the detection of persistent structural changes in canopies due to defoliation processes, which are typical of advanced levels of disturbance in forests. The focus on structure is partly due to the ability to detect seasonal variations in the amount of fractional cover and leaf area index (LAI) over different forest types (Wang et al., 2017) with standard vegetation indices such as the Normalized Difference Vegetation Index (NDVI) (Rouse et al.,

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https://doi.org/10.1016/j.isprsjprs.2018.01.017
0924-2716/

1974). This index can be calculated using the spectral bands and bandwidths available in current satellite sensors used for operational monitoring of vegetation (de Moura et al., 2017). While short-term leaf area reductions provide a mechanism for drought tolerance, particularly in isohydric trees (McDowell et al., 2008), sustained defoliation tends to precede die-off (Dobbertin and Brang, 2001), as it might ultimately starve trees of carbon (Galiano et al., 2011). Trees under abiotic stress are also more vulnerable to pathogens, which can cause leaf desiccation and loss of leaf pigments long before they cause defoliation (Wulder et al., 2006). With the magnitude and interaction of abiotic and biotic forest disturbances expected to increase (Seidl et al., 2017), it is thus critical to further develop remote sensing indicators sensitive to progressive manifestations of tree decline to monitor the temporal dynamics of disturbances (Senf et al., 2017a). Apart from revealing structural canopy changes, such indicators should exploit spectral regions linked to specific photosynthetic pigments and thus be sensitive to physiological changes such as chlorosis that might precede leaf area reductions and mortality.

Unfortunately, the heterogeneity of forest canopies complicates the application of the pigment–sensitive indices that have demonstrated utility in uniform crops. Recent research has made significant progress in developing methods that retrieve leaf biochemical constituents and biophysical parameters in the spatial domain (Hernandez-Clemente et al., 2014a; Zhang et al., 2008). The retrieval of these photosynthetic traits has been demonstrated, among others, for chlorophyll $a+b$ (Zarco-Tejada et al., 2001), xanthophylls and carotenes (Hernández-Clemente et al., 2012, 2011), and, more recently, for quantifying chlorophyll fluorescence (Damm et al., 2015), enabling the detection of stressed tree crowns and stands exposed to abiotic stress and diseases (Hernandez-Clemente et al., 2017). Several approaches have been proposed to map variation in plant traits and stress using remote sensing imagery. However, there are few studies in which spatiotemporal data have been validated *in situ* to determine if such indicators are sufficiently robust for the temporal monitoring of early stages of forest decline. To be used in such a way, indicators must, among other things, be resistant to confounding effects generated by background and understory changes (Jonas Lambert, 2013). At the same time, scaling remote sensing-based indicators of canopy state into the temporal domain is critical if such indicators are to be used to identify forest decline processes and distinguish them from natural phenological changes.

The assessment of the temporal dimension of forest decline is potentially feasible through different methods and strategies, namely (i) using time series of spectral vegetation indices related to specific pigments and physiological traits through statistical relationships (Assal et al., 2016; Czerwinski et al., 2014; Vicente-Serrano et al., 2016); (ii) quantifying leaf biochemistry over time using *scaling up* methods (as in Zarco-Tejada et al., 2001 for C_{ab}); and (iii) applying radiative transfer model inversions through different retrieval strategies, linking leaf and canopy models (as in Houborg et al., 2007) through wavelet analysis (Ali et al., 2016) and spectral unmixing (Stagakis et al., 2016). In the latter approach, retrievable physiological traits are limited to the input part of both the leaf and canopy models. This can be problematic when specific physiological indicators linked to tree health decline are not included in the radiative transfer models (for example, in the case of xanthophyll pigments currently not modeled in PROSPECT). Each of the approaches listed above has advantages and disadvantages, which depend on the complexity of each method, the heterogeneity of the canopy, the maximum errors allowed in the retrievals, and the spectral and spatial resolution of the data available for the *scaling up* and modeling methods. Although model inversion techniques are considered to be the most advanced, they yield errors of about 10 $\mu g/cm^2$ in the best case scenario for C_{ab} (Hernandez-Clemente et al., 2014b; Yáñez-Rausell et al., 2015), reaching 15–20 $\mu g/cm^2$ and more over heterogeneous canopies. These accuracies are usually acceptable for mapping specific traits related to forest health condition at a given time, but might not be sufficient to detect small changes over time due to the inherent errors involved in the parameter retrievals. From an operational point of view, spectral indices sensitive to specific traits tend to be more robust than parameters retrieved by model inversion, which makes them potentially more suitable for temporal monitoring. This is particularly true when the changes between two consecutive dates are subtle or smaller than the inherent errors of the inversion procedures. However, individual spectral indices tend to be sensitive to multiple leaf and canopy characteristics (e.g., to both biochemical constituents and structural attributes of canopies), making it difficult to disentangle the different expressions of crown stress. Specific strategies are thus needed when using indices in the temporal domain for the monitoring of forest decline.

In this context, narrowband indices have been successfully used over crop canopies to maximize the sensitivity to chlorophyll content while minimizing structural effects. A few examples of such indices are the Photochemical Reflectance Index (PRI) (Gamon et al., 1997) used to track light use efficiency in different forest types (Zheng and Chen, 2017) and other soil-resistant pigment indices such as the Modified Chlorophyll Absorption Ratio Index (MCARI) and the Transformed Chlorophyll Absorption Ratio Index (TCARI) (Haboudane et al., 2002) normalized by the Soil Adjusted Vegetation Index (SAVI, OSAVI) (Rondeaux et al., 1996) to form the TCARI/OSAVI and MCARI/OSAVI indices (Haboudane et al., 2004; Zarco-Tejada et al., 2004). These normalizations are proposed to minimize structural effects on the indices (as in Hernández-Clemente et al., 2011 for xanthophyll pigments). Nevertheless, while these index combinations have proven to work well over uniform and closed canopies, they have failed over heterogeneous forest stands due to the effects of within- and between-crown shadows (Hernandez-Clemente et al., 2014b, 2016). This constraint of index-based pigment estimates is particularly limiting for their use in time series analyses, as diurnal and seasonal changes in within-crown illumination and shadows increase their errors.

In an effort to reduce structure-related artifacts in retrieved plant traits, the red-edge spectral region (RESR) was shown in the 1980s to be sensitive to chlorophyll content while largely unaffected by structural properties (Horler et al., 1983). Since then, the red-edge position has proven to be useful for mapping forest species composition (Zarco-Tejada and Miller, 1999) in closed forest canopies (Hernández-Clemente et al., 2016) and conifer forests (Zarco-Tejada et al., 2004) due to its sensitivity to chlorophyll irrespective of crown shadows. These earlier studies involving the RESR were carried out using hyperspectral data and later evaluated with MERIS on board ENVISAT as the first attempt to use RESR parameters for forest monitoring from a satellite sensor (Hu et al., 2008). However, it is well known that both chlorophyll and structure play a role in the shape and temporal dynamics of the RESR (Curran et al., 1990). Therefore, the red-edge chlorophyll index (CI) (e.g. R_{750}/R_{710} as in Zarco-Tejada et al., 2001) will respond to changes in C_{ab} but will be largely affected by LAI.

With the launch of the MultiSpectral Imager (MSI) on board Sentinel-2a in 2015 and Sentinel-2b in 2017, there is a potential opportunity to use the RESR at 20 m spatial resolution and 18–19 nm full-width half-maximum (FWHM) to estimate chlorophyll and nitrogen content in vegetation (Clevers and Gitelson, 2013), among other biophysical parameters (Frampton et al., 2013); (Castillo et al., 2017), and to monitor forest condition based on such parameters. In this study, we explored the temporal dynamics of forest decline using the RESR obtained from both high-