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On the relationship between continuous measures of canopy greenness derived using near-surface remote sensing and satellite-derived vegetation products

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ABSTRACT

Over the last two decades, satellite-derived estimates of biophysical variables have been increasingly used in operational services, requiring quantification of their accuracy and uncertainty. Evaluating satellite-derived vegetation products is challenging due to their moderate spatial resolution, the heterogeneity of the terrestrial landscape, and difficulties in adequately characterising spatial and temporal vegetation dynamics. In recent years, near-surface remote sensing has emerged as a potential source of data against which satellite-derived vegetation products can be evaluated. Several studies have focussed on the evaluation of satellite-derived phenological transition dates, however in most cases the shape and magnitude of the underlying time-series are neglected. In this paper, we investigated the relationship between the green chromatic coordinate (GCC) derived using near-surface remote sensing and a range of vegetation products derived from the Medium Resolution Imaging Spectrometer (MERIS) throughout the growing season. Moderate to strong relationships between the GCC and vegetation products derived from MERIS were observed at deciduous forest sites. Weak relationships were observed over evergreen forest sites as a result of their subtle seasonality, which is likely masked by atmospheric, bidirectional reflectance distribution function (BRDF), and shadowing effects. Temporal inconsistencies were attributed to the oblique viewing geometry of the digital cameras and differences in the incorporated spectral bands. In addition, the commonly observed summer decline in GCC values was found to be primarily associated with seasonal variations in brown pigment concentration, and to a lesser extent illumination geometry. At deciduous sites, increased sensitivity to initial increases in canopy greenness was demonstrated by the GCC, making it particularly well-suited to identifying the start of season when compared to satellite-derived vegetation products. Nevertheless, in some cases, the relationship between the GCC and vegetation products derived from MERIS was found to saturate asymptotically. This limits the potential of the approach for evaluation of the vegetation products that underlie satellite-derived phenological transition dates, and for the continuous monitoring of vegetation during the growing season, particularly at medium to high biomass study sites.

1. Introduction

Vegetation is a major component of the biosphere, and the amount and dynamics of vegetation influence a range of biogeochemical processes. Systematic estimates of the biophysical variables that describe vegetation condition are therefore required by the numerical models that enhance our understanding of the environment and climate system (Myneni et al., 2002; Sellers et al., 1997). Such understanding is fundamental to the development of successful environmental policy, and plays a critical role in informing effective climate change mitigation strategy. Estimates of biophysical variables are also essential in the monitoring of forest resources, of which a net loss of 13 million ha per year is estimated to have occurred globally between 2000 and 2010 (FAO, 2010). Similarly, these estimates are highly valuable in the management of agricultural practices, a particularly important consideration in the context of an increasing global population (Foley et al., 2011; Godfray et al., 2010). As a result, parameters such as the fraction of absorbed photosynthetically active radiation (FAPAR) and leaf area

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index (LAI) have been designated essential climate variables (ECVs) (GCOS, 2012).

The consistent monitoring of vegetation at regional to global scales was first facilitated by the Advanced Very High Resolution Radiometer (AVHRR), which records coarse spectral resolution data at red and near-infrared wavelengths. Over the last two decades, instruments such as the Moderate Resolution Imaging Spectroradiometer (MODIS), Medium Resolution Imaging Spectrometer (MERIS) and Vegetation (VGT) have provided improvements in radiometric, spectral and spatial resolution (Barnes et al., 1998; Maisongrande et al., 2004; Rast et al., 1999). From these data, a range of satellite-derived vegetation products have emerged, providing users with spatially explicit estimates of various biophysical variables. Examples include the CYCLOPES and MOD15 products, which provide estimates of FAPAR and LAI derived from VGT and MODIS respectively (Baret et al., 2007; Knyazikhin et al., 1999; Myneni et al., 1999), in addition to the MERIS Global Vegetation Index (MGVI), which corresponds to FAPAR (Gobron et al., 1999), and the MERIS Terrestrial Chlorophyll Index (MTCI), a surrogate of canopy chlorophyll content (Dash and Curran, 2004). Over the coming years, the continuity of these products will be ensured by new instruments such as the Ocean and Land Colour Instrument (OLCI), Sea and Land Surface Temperature Radiometer (SLSTR), and Visible Infrared Radiometer Suite (VIIRS) (Donlon et al., 2012; Justice et al., 2013).

To be of real use in environmental decision making, it is vital to ensure that satellite-derived vegetation products are of high quality and consistency. This is a particularly important consideration as we enter the era of operational use, in which an increasing number of products will be routinely made available through initiatives such as the European Commission's Copernicus programme (EC, 2005). Scientists, decision makers, and service providers will be provided with an unprecedented volume of data from which to choose, supporting activities such as agricultural monitoring and food security, forest management, numerical weather prediction, and climate modelling. By quantifying the uncertainties associated with satellite-derived vegetation products, their performance can be better understood, enabling users to assess their fitness for purpose and select those data that are most appropriate for their needs (Baret et al., 2005; Justice et al., 2000; Morisette et al., 2002, 2006). The importance of product evaluation is increasingly well recognised, and in recent years initiatives such as the Quality Assurance Framework for Earth Observation (QA4EO) have been established with the endorsement of the Committee on Earth Observation Satellites (CEOS), providing a formal structure for these activities (QA4EO, 2010).

Despite its importance, the evaluation of operational satellite-derived vegetation products is particularly challenging as a result of their moderate spatial resolution, which typically ranges from 300 m to 1 km. The in-situ observations that act as reference data are point-based, making direct comparison possible only in areas of high homogeneity (Fernandes et al., 2014; Morisette et al., 2002). Because such homogeneity is uncommon in the terrestrial landscape, particularly at the spatial resolutions of instruments such as MODIS and MERIS, logistically challenging field campaigns are required to adequately characterise spatial variability over a study site. Unfortunately, these activities are constrained by financial resources, reducing their frequency to, at best, a handful of dates per year, thus limiting the extent to which seasonal vegetation dynamics can be characterised.

In recent years, near-surface remote sensing has emerged as a potential source of data against which satellite-derived vegetation products can be evaluated, providing potentially valuable information about their performance. Digital cameras provide an inexpensive means by which the greenness of a vegetation canopy can be characterised at a high temporal resolution (Keenan et al., 2014; Richardson et al., 2007; 2009; Sonnentag et al., 2012). By making use of the red, green and blue bands of the image, vegetation indices such as the Excess Green Index (EGI) and Green Chromatic Coordinate (GCC) can be calculated, providing a measure of canopy greenness. Importantly, because the field-of-view (FOV) of a digital camera can incorporate an entire canopy, near-surface remote sensing can provide a greater degree of spatial integration than traditional in-situ techniques, better reflecting the moderate spatial resolution of the satellite-derived vegetation products themselves (Hufkens et al., 2012; Keenan et al., 2014; Richardson et al., 2007, 2009).

The phenological research community have adopted near-surface remote sensing as an alternative to traditional in-situ observations of events such as bud-burst and leaf opening, which are limited in terms of their spatial extent and species diversity. By analysing time-series of near-surface remote sensing data, phenological transition dates can be determined (Ide and Oguma, 2010; Richardson et al., 2007, 2009; Sonnentag et al., 2012). Recently, near-surface remote sensing has been used in the continuous monitoring of vegetation condition, and has formed the basis of models of plant function (Hufkens et al., 2016; Migliavacca et al., 2011; Toomey et al., 2015). The Phenological Camera (PhenoCam) network is the largest near-surface remote sensing initiative, and is comprised of 440 sites, each equipped with a digital camera that is mounted above or within a vegetation canopy (Richardson et al., 2007, 2009). Of these 440 sites, 299 adhere to a common protocol, whilst 262 record data at both visible and near-infrared wavelengths. Although the majority of PhenoCam sites are located in North America, similar initiatives have more recently been established in other parts of the world (Morra di Cella et al., 2009; Wingate et al., 2015).

Making use of near-surface remote sensing data provided by initiatives such as the PhenoCam network, several studies have focussed on the evaluation of satellite-derived phenological transition dates (Baumann et al., 2017; Coops et al., 2012; Hufkens et al., 2012; Keenan et al., 2014; Klosterman et al., 2014; Nijland et al., 2016). In these studies, it is only the timing of phenological transition dates that is considered in most cases, whilst the shape and magnitude of the underlying time-series are largely neglected. By focusing on phenological transition dates, rates of change, which can be affected by a range of meteorological and biogeochemical factors, are overlooked. Accurately capturing and representing these dynamics is vital for the continuous monitoring of vegetation condition, and for the modelling of plant function. Recently, several authors have observed features in near-surface remote sensing data that appear unrelated to vegetation dynamics, including a spring peak and summer decline (Keenan et al., 2014; Toomey et al., 2015; Yang et al., 2014). Although previous work has attributed the spring peak to the non-linear relationship between leaf chlorophyll concentration and the GCC (Wingate et al., 2015), the factors responsible for the summer decline remain unclear. If the entire time-series is to be successfully made use of, an increased understanding of these discrepancies is required.

In this paper, we examine the relationship between continuous measures of canopy greenness derived from PhenoCam data and a range of vegetation products derived from MERIS, an instrument with similar characteristics to OLCI on-board the European Space Agency's (ESA's) recently launched Sentinel-3 mission (Donlon et al., 2012; ESA, 2012). In doing so, we hope to answer the following questions:

- How do continuous measures of canopy greenness derived using near-surface remote sensing relate to satellite-derived vegetation products, and what factors are responsible for observed discrepancies?
- Can near-surface remote sensing be used as a means to operationally and systematically evaluate these satellite-derived vegetation products?

2. Materials and methods

2.1. Study sites

14 study sites were selected based on the availability of at least