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A physically based vegetation index for improved monitoring of plant phenology

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ABSTRACT

Using a spectral vegetation index (VI) is an efficient approach for monitoring plant phenology from remotely-sensed data. However, the quantitative biophysical meaning of most VIs is still unclear, and, particularly at high northern latitudes characterized by low green biomass renewal rate and snow-affected VI signals, it is difficult to use them for tracking seasonal vegetation growth and retrieving phenology. In this study we propose a physically-based new vegetation index for characterizing terrestrial vegetation canopy green leaf area dynamics: the plant phenology index (PPI). PPI is derived from the solution to a radiative transfer equation, is computed from red and near-infrared (NIR) reflectance, and has a nearly linear relationship with canopy green leaf area index (LAI), enabling it to depict canopy foliage density well. This capability is verified with stacked-leaf measurements, canopy reflectance model simulations, and field LAI measurements from international sites. Snow influence on PPI is shown by modeling and satellite observations to be less severe than on the Normalized Difference Vegetation Index (NDVI) or the Enhanced Vegetation Index (EVI), while soil brightness variations in general have moderate influence on PPI. Comparison of satellite-derived PPI to ground observations of plant phenology and gross primary productivity (GPP) shows strong similarity of temporal patterns over several Nordic boreal forest sites. The proposed PPI can thus serve as an efficient tool for estimating plant canopy growth, and will enable improved vegetation monitoring, particularly of evergreen needle-leaf forest phenology at high northern latitudes.

1. Introduction

Remote sensing from satellites can contribute to better understanding of vegetation phenology and its relations with the climate system (Keenan et al., 2014; Myneni, Keeling, Tucker, Asrar, & Nemani, 1997). However, the current methods for deriving this information from spectral vegetation indices (VIs) still face many problems. This is particularly true for evergreen needle-leaf forests over high northern latitudes, characterized by relatively low turnover of coniferous needle biomass, frequent clouds, and long periods of snow (Delbart, Le Toan, Kergoat, & Fedotova, 2006; Jönsson, Eklundh, Hellström, Bärring, & Jönsson, 2010). To overcome these problems we have developed a new vegetation index based on radiative transfer theory. Presenting and explaining the index, and testing it against canopy reflectance models and empirical data, are the aims of this paper.

Phenology is the study of climate-dependent periodical phenomena of organisms (Abbe, 1905), and the science field focuses on the timing, causes, and interrelations of those phenomena (Lieth, 1974). Recent climate warming has altered vegetation phenology, in particular the timing of spring events, has resulted in large changes at high latitudes (IPCC, 2014; Menzel et al., 2006), and may consequently have profound implications for agriculture and forest productivity. Since our understanding of mechanistic phenological processes is still limited (Chuine, Kramer, & Hänninen, 2013; Richardson et al., 2013), more observational data are needed for development of phenological models, and for understanding and predicting climate change impacts on phenology. Phenology data can be collected in a variety of ways (Schwartz, 2013), however, remote sensing is of primary choice for large-area estimates, owing to the large spatial coverage of Earth observation satellites, the high temporal sampling interval, and the availability of 30 + years of global data (Myneni et al., 1997; Zhou et al., 2001).

One of the most widely used vegetation indices for satellite phenology is the Normalized Difference Vegetation Index (NDVI, Tucker, 1979; Rouse, R.H.H., Deering, & Schell, 1973). The index is popular because of its robustness against noise and variations of sun-sensor geometry, and the availability of long-term global time series (Chen, Xu, & Tan, 2001; Heumann, Seaquist, Eklundh, & Jönsson, 2007; Høgda, Tømmervik, & Karlsen, 2013; Justice, Townshend, Holben, & Tucker, 1985; Karlsen et al., 2008; White & Nemani, 2006). However, in conifer-dominated boreal biomes, NDVI is sensitive to snow and rather insensitive to growth of dense forest canopies; hence, difficulties have been encountered in NDVI-based phenology retrieval in these regions (Delbart et al., 2006; Jönsson et al., 2010).

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A more dynamic VI, the Enhanced Vegetation Index (EVI, Huete, Liu, Batchily, & van Leeuwen, 1997), has been used e.g. for mapping global vegetation phenology (Zhang, Friedl, & Schaaf, 2006), and for identifying the growing season peak of dense evergreen forests in tropical South America (Xiao, Hagen, Zhang, Keller, & B.M. III, 2006). EVI overcomes the tendency of NDVI to saturate at high vegetation biomass, and compensates to some degree for problems like soil background variations and atmospheric aerosol influences (Huete et al., 2002). When comparing against ground observations, the index thus gives more accurate estimates than NDVI of budburst phenology (Liang, Schwartz, & Fei, 2011). However, the index is sensitive to snow (Huete et al., 2002), and has been shown to generate unreliable values at northern high latitudes in winter (Schubert et al., 2012).

Apart from NDVI and EVI, several other VIs have been investigated for phenology. A Normalized Difference Water Index (NDWI, Gao, 1996; Hardisky, Klemas, & Smart, 1983) was used by Delbart, Kergoat, Le Toan, Lhermitte, and Picard (2005) to decouple snow from vegetation spring phenology events in boreal regions. The NDWI method was found to perform well in deciduous-dominated forests, but not in evergreen-dominated forests, nor for autumn phenology (Böttcher et al., 2014; Delbart et al., 2006). Another index, the Phenology Index (PI), was formulated by Gonsamo, Chen, Price, Kurz, and Wu (2012) by using the difference of squared NDVI and NDWI. It can be shown that PI is determined by the difference between short-wave infrared (SWIR) and red reflectances, resembling another index, the Normalized Difference Snow Index (NDSI, Hall, Riggs, & Salomonson, 1995), which was formulated based on the difference of a visible band (green) and a SWIR band. However, PI was shown not to reflect canopy photosynthetic activity during the growing season (Gonsamo et al., 2012), and neither was the NDSI. It is evident that, because of the dramatic difference of snow reflectances in visible and SWIR bands, both of these indices mainly have a snow-dominated pattern over high latitudes, rather than reflecting green canopy dynamics. Therefore, we have not further considered these indices in our analysis.

In fact, all the mentioned vegetation indices are vague in quantitative biophysical meaning, and most of them were formulated to minimize the effect of non-vegetation factors on spectral data (Baret & Guyot, 1991). Their relationships with biophysical variables have mainly been derived from empirical analyses on measured or modeled data. Using regression analysis of in situ measured spectral and biomass data, Tucker (1979) showed that NDVI was significantly related to green biomass. However, with in vivo measurements, Buschmann and Nagel (1993) observed that NDVI only exhibited a weak correlation with leaf chlorophyll content, whereas the quantity of *log* (NIR/Red) seemed more promising. Using radiative transfer equations, Sellers (1985) modeled NDVI and showed that it is a good indicator of canopy-absorbed fraction of photosynthetically active radiation (FPAR), but poor for leaf area index (LAI). Asrar, Fuchs, Kanemasu, and Hatfield (1984) demonstrated a strong linear correlation between NDVI and FPAR using field data, but, using the model by Goudriaan (1977), showed that NDVI approaches a plateau level when FPAR is higher than a certain value.

A few authors have attempted to better understand VIs by analytically linking them with biophysical variables through physical derivation: Myneni, Hall, Sellers, and Marshak (1995) proved that a VI, if differentiable at wavelength, can be related to spectral derivatives and consequently related to photosynthetic energy absorption. However, a VI is usually defined for discrete wavelength bands, and the relation between a VI and spectral derivatives is not clear. Knyazikhin, Martonchik, Myneni, Diner, and Running (1998) theoretically explored the linearity of NDVI with FPAR, however, their proof was unfulfilled. Baret and Guyot (1991) used a semi-empirical exponential formula and showed that whether the relationship between FPAR and a VI is linear or not depends on how the extinction coefficient of a VI differs from that of PAR in the exponential expressions. Hence, though the indices have been shown to be clearly related to vegetation properties, their quantitative biophysical meaning is still ambiguous.

To overcome the abovementioned problems, we propose a new index, named the plant phenology index (PPI), which is derived from radiative transfer equations, is approximately linear to green LAI, and has the same unit as LAI ($m^2 \cdot m^{-2}$). We argue that green LAI is the most dynamic visible canopy variable during the phenological cycle, hence, linearity with green LAI is a fundamental property of a phenology vegetation index. The new index can be used for representing canopy green foliage dynamics for any green terrestrial vegetation, but it is particularly useful for conifers in seasonally snow-covered areas such as northern latitudes. Apart from providing an analytical expression of PPI, we demonstrate the PPI–LAI relationship in several other ways: with outdoor measurements on stacked green leaves against a soil background; through SAIL model simulations (Jacquemoud et al., 2009; Verhoef, 1984); and by comparison of satellite-derived PPI with 350 field LAI data from 46 global sites. Furthermore, using SAIL modeling with varied soil backgrounds we investigate the influence of soil brightness on PPI; and through linear mixture modeling with variable snow cover we demonstrate its robustness against snow influence. Finally, to test the performance of PPI in characterizing vegetation canopy growing dynamics, we analyze the similarity of satellite PPI time series to temporal profiles of ground observed manual phenology and gross primary productivity (GPP) over several Nordic boreal sites. All these

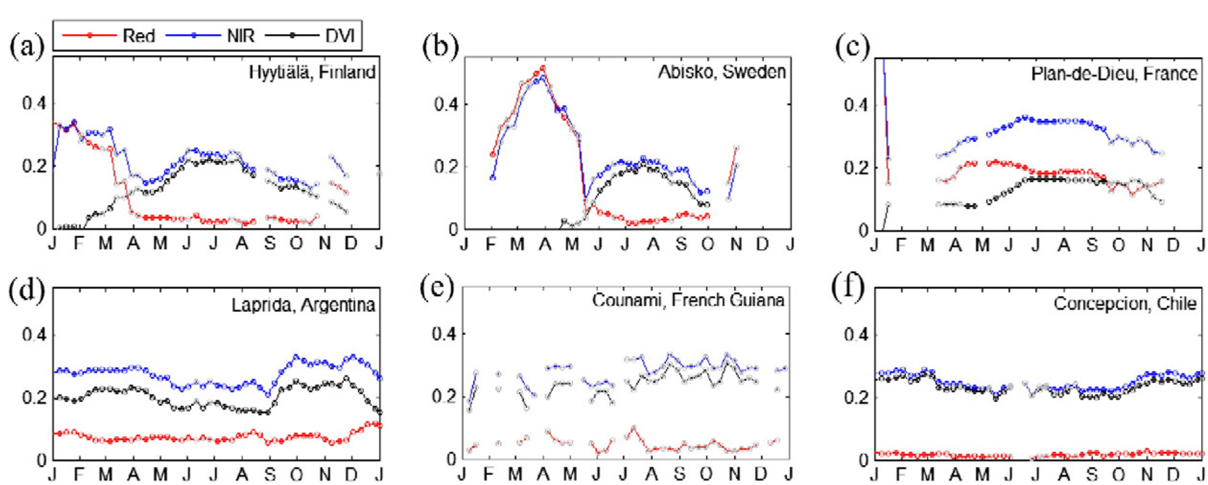

Fig. 1. Typical time series of red and NIR reflectances and DVI of 2010 from the MODIS NBAR reflectance product (MCD43A4, Schaaf et al., 2002). The data are the site pixel raw data, and gray markers indicate poor quality NBAR data. See Supplementary material for site information.