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Spatially detailed retrievals of spring phenology from single-season high-resolution image time series

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ABSTRACT

Vegetation indices derived from satellite image time series have been extensively used to estimate the timing of phenological events like season onset. Medium spatial resolution ($\geq$250 m) satellite sensors with daily revisit capability are typically employed for this purpose. In recent years, phenology is being retrieved at higher resolution ($\leq$30 m) in response to increasing availability of high-resolution satellite data. To overcome the reduced acquisition frequency of such data, previous attempts involved fusion between high- and medium-resolution data, or combinations of multi-year acquisitions in a single phenological reconstruction. The objectives of this study are to demonstrate that phenological parameters can now be retrieved from single-season high-resolution time series, and to compare these retrievals against those derived from multi-year high-resolution and single-season medium-resolution satellite data. The study focuses on the island of Schiermonnikoog, the Netherlands, which comprises a highly-dynamic saltmarsh, dune vegetation, and agricultural land. Combining NDVI series derived from atmospherically-corrected images from RapidEye (5 m-resolution) and the SPOT5 Take5 experiment (10m-resolution) acquired between March and August 2015, phenological parameters were estimated using a function fitting approach. We then compared results with phenology retrieved from four years of 30 m Landsat 8 OLI data, and single-year 100 m Proba-V and 250 m MODIS temporal composites of the same period. Retrieved phenological parameters from combined RapidEye/SPOT5 displayed spatially consistent results and a large spatial variability, providing complementary information to existing vegetation community maps. Retrievals that combined four years of Landsat observations into a single synthetic year were affected by the inclusion of years with warmer spring temperatures, whereas adjustment of the average phenology to 2015 observations was only feasible for a few pixels due to cloud cover around phenological transition dates. The Proba-V and MODIS phenology retrievals scaled poorly relative to their high-resolution equivalents, indicating that medium-resolution phenology retrievals need to be interpreted with care, particularly in landscapes with fine-scale land cover variability.

1. Introduction

Vegetation phenology is the timing of seasonal developmental stages in plant life cycles (Kimball 2014). The study of spatial and temporal variability of vegetation phenology contributes to a wide range of application fields, including climate change analysis (Cleland et al., 2007), agricultural monitoring (Duncan et al., 2015; Meroni et al., 2014a), and ecological research (Pettorelli et al., 2014). For example, phenology is proposed as one of the "Essential Biodiversity Variables" (Pereira et al., 2013) that can be monitored from space next to variables like land cover and vegetation height (Skidmore et al., 2015). Although ground-based networks, for example using human observers (Elmendorf et al., 2016) or

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digital repeat cameras (Nasahara and Nagai 2015; Sonnentag et al., 2012), provide detailed location-specific information on vegetation phenology, satellite imagery is the only data source that can synoptically assess phenological parameters at the landscape scale. Because the spatial resolution of this imagery generally fails to detect individual plant species but instead observes a combined signal of a larger surface, 'land surface phenology' is the common term used for such assessments. Phenological parameters include among others the onset of green-up, the moment of maximum green vegetation cover, and season length (Vrieling et al., 2011). The identification of phenological parameters from satellite data is made by analyzing the temporal evolution of a remote sensing indicator of vegetation greenness such as the Normalized Difference Vegetation Index (NDVI) with various methods (for a review, see de Beurs and Henebry 2010). A common requirement to generate robust estimates of phenological parameters is that the evolution of vegetation growth and decay is observed with an adequate frequency.

To meet the high-frequency time series requirement, satellite studies of phenology have traditionally focused on spectral vegetation indices derived from medium-resolution (250 m to 8 km) optical imagery that is acquired at daily or near-daily intervals (e.g., Justice et al., 1985; Moulin et al., 1997). Vegetation optical depth retrievals derived from passive microwave brightness temperatures have also been used but less frequently (e.g., Jones et al., 2011), as these are only available at a coarse resolution of 25 km. The short observation interval offered by optical instruments such as the Moderate Resolution Imaging Spectroradiometer (MODIS), the Advanced Very High Resolution Radiometer (AVHRR), or the Satellite Pour l'Observation de la Terre (SPOT) VEGETATION, allows sufficient cloud-free observations to estimate phenological parameters. Clouds are often suppressed through the use of temporal composites that retain the best cloud-free observation within a fixed temporal interval (Cihlar et al., 1994), while temporal filters can further reduce remaining atmospheric effects in the vegetation index series (Atzberger and Eilers 2011). Although 250 m and coarser-resolution phenology retrievals provide excellent contributions to regional and global studies, they cannot reveal fine-scale variability. This is because the temporal signal of different vegetation patches within a medium-resolution pixel is combined into a single temporal trajectory, which then becomes difficult to disentangle.

Higher spatial resolution data is needed to capture the small-scale spatial variability of phenology. However, until recently the finer spatial detail of satellite sensors was achieved at the expense of a reduced swath of the instrument, thereby limiting its temporal resolution and not allowing it to effectively capture vegetation temporal dynamics. To overcome this, several approaches have been explored, including multi-resolution image fusion and the joint analysis of multiple years of high-resolution acquisitions. Image fusion combines data from medium- and high-resolution ($\leq$30m) sensors to generate synthetic high-resolution time series with the temporal frequency of the medium-resolution dataset. This can be achieved for example with the spatial and temporal adaptive reflectance fusion model (Gao et al., 2006). The fused dataset can subsequently serve as input to a phenology retrieval procedure (Bhandari et al., 2012; Viña et al., 2016; Walker et al., 2014; Zhang et al., 2017) or alternatively fusion can take place after medium-resolution phenology retrieval (Frantz et al., 2016). Nonetheless, the fusion approach still requires the availability of high-resolution imagery at key phenological stages (Frantz et al., 2016; Möller et al., 2017; Walker et al., 2014) and may be less effective for heterogeneous landscapes (Zhu et al., 2010). The other approach to overcome data paucity is to treat high-resolution observation dates from multiple years as a single year of data. For example, Fisher et al. (2006) compiled 57 Landsat images from 1984 to 2002 for a deciduous forest site in northeast US into a single 'synthetic' year to derive 30m-resolution estimates of phenology. Potentially, this approach may also allow estimating annual deviations by determining the offset between individual-year observations around transition dates and the curve fitted to the synthetic year (Melaas et al., 2013; Melaas et al., 2016; Nijland et al., 2016). Nonetheless, multi-year data pooling is only effective for areas with a relatively stable year-to-year phenological behaviour while estimates of annual deviations are only feasible if good cloud-free observations for that year exist near average transition dates.

Given the increasing availability of high-resolution imagery acquired by satellite sensors with relatively high repeat frequency, the possibility emerges to directly estimate phenology at high-resolution from single-season imagery. This can overcome the issues inherent to multi-resolution image fusion and multi-year data pooling, which is particularly problematic for dynamic and heterogeneous landscapes. For example, the often-used software package for phenological retrieval TIMESAT is being adapted to effectively handle 10m-resolution Sentinel-2 data (Eklundh and Jönsson 2015). Nonetheless, to date few studies exist that demonstrate the use of single-season high-resolution imagery for phenology assessment (exceptions include: Pan et al., 2015; White et al., 2014). The objectives of the current study are first to demonstrate that phenological parameters can now be retrieved from single-season high-resolution time series (i.e., 5 m RapidEye and 10 m SPOT5), and second to compare these retrievals against those derived from multi-season high-resolution data (i.e., 30 m Landsat-8), as well as against single-season medium-resolution data (i.e., 100 m Proba-V and 250 m MODIS).

2. Study area

Schiermonnikoog is a barrier island located in the north of the Netherlands between the North Sea and the intertidal Wadden Sea (Fig. 1). The size of the island is about 40 km^2, of which approximately 85% is assigned as National Park and the remainder contains agriculture (pasture and maize) and a small village. The National Park consists of dune areas, marshes, and beaches, which together host a rich fauna and flora. The marshes are regularly flooded due to tidal variability, whereby the frequency and duration of the flooding depend on altitude and affect vegetation composition (Olff et al., 1988). The natural vegetation displays a strong spatial and temporal variability, particularly due to the dynamic influences of tide, wind, and grazing. Various species of herbs and grasses of different height are found across the island, while the dune area in addition contains forest and shrub vegetation. Fig. 1 displays the main vegetation communities.

3. Data

3.1. Single-season high-resolution satellite data

We combined two sources of high spatial resolution data that were acquired as part of the European Space Agency funded Innovators-III project on "remote sensing for essential biodiversity variables" (RS4EBV). These comprise 10 m resolution SPOT5 data from the Take5 experiment, and 5 m resolution RapidEye data.

The Take5 experiment took place at the end of SPOT5's lifetime and collected multi-spectral images for 150 sites around the globe from April to September 2015 with a five-day revisit time to simulate Sentinel-2 acquisitions (Béhague et al., 2016). This resulted in 14 (six fully, eight partially) cloud-free images of Schiermonnikoog over the five-month experiment. Atmospheric correction and cloud masking of the data was performed at the French inter-agency Theia Land Data Centre using the Multi-sensor Atmospheric