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Vegetation phenology from Sentinel-2 and field cameras for a Dutch barrier island

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A R T I C L E I N F O

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A B S T R A C T

Remote sensing studies of vegetation phenology increasingly benefit from freely available satellite imagery acquired with high temporal frequency at fine spatial resolution. Particularly for heterogeneous landscapes this is good news, given the drawback of medium-resolution sensors commonly used for phenology retrieval (e.g., MODIS) to properly represent the fine-scale spatial variability of vegetation types. The Sentinel-2 mission acquires spectral data globally at 10 to 60 m resolution every five days. To illustrate the mission's potential for studying vegetation phenology, we retrieved phenological parameters for the Dutch barrier island Schiermonnikoog for a full season of Sentinel-2A observations in 2016. Overlapping orbits resulted in two acquisitions per 10 days, similar to what is achieved globally since the launch of Sentinel-2B. For eight locations on the island's salt marsh we compared greenness chromatic coordinate (GCC) series derived from digital repeat RGB-cameras with vegetation index series derived from Sentinel-2 (NDVI and GCC). For each series, a double hyperbolic tangent model was fitted and thresholds were applied to the modelled data to estimate start-, peak-, and end-of-season (SOS/PS/EOS). Variability in Sentinel-2 derived SOS, when taken as the midpoint between minimum and peak NDVI, was well-explained by camera GCC-based SOS ($R^2 = 0.74$, MSD = 8.0 days, RMSD = 13.0 days). However, EOS estimates from camera GCC series were on average almost two months before NDVI-based estimates. This could partially be explained by the observed exponential relationship between GCC and NDVI, as well as by the combined effect of viewing angle differences and the presence of non-photosynthetic elements in the vegetation canopy. A two-layer canopy radiative transfer model incorporating reduced chlorophyll levels in the upper layer provided a physically-based explanation of the viewing angle effect. Finally, we applied the phenology retrieval approach to NDVI series for all pixels of the island in order to map spatial patterns of phenology at fine resolution. Our results demonstrate the potential of the Sentinel-2 mission for providing spatially-detailed retrievals of phenology.

1. Introduction

The timing of periodic events in plants, like budburst or flowering, is generally referred to as plant phenology. Food availability for animals is affected by this timing, and as such plant phenology impacts on animal migration and breeding patterns (Durant et al., 2007; Miles et al., 2017; Shariati Najafabadi et al., 2015). Plant periodic events have a strong relationship with seasonal changes in moisture availability, temperature, and radiation (Stöckli et al., 2008), but are also affected by extreme weather events (Jentsch et al., 2009). To better understand how climate change may impact on plant and animal populations, accurate monitoring of plant phenology in space and time is important (Cleland et al., 2007).

The traditional approach of monitoring plant phenology uses frequent visual observations to detect the timing of specific events like flowering, for example by trained personnel in phenological gardens (Schnelle and Volkert, 1964) or by volunteers (Newman et al., 2012; Schwartz et al., 2012; van Vliet et al., 2014). An alternative approach,

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requiring less frequent field presence, is the use of fixed-position digital cameras that take several photographs of the vegetation each day. This so-called digital repeat photography has been implemented in various networks in Australia (Moore et al., 2016), Europe (Wingate et al., 2015), Japan (Nasahara and Nagai, 2015), and North America (Klosterman et al., 2014). Besides identifying discrete events, analysis of temporal changes in the relative brightness of red, green, and blue (RGB) channels allows for a more continuous tracking of canopy greenness (Richardson et al., 2009). Studies showed that this can be achieved effectively with relatively cheap consumer-grade RGB cameras (Nijland et al., 2014; Sonnentag et al., 2012), even if an additional near-infrared spectral band may provide complementary information similar to satellite-derived vegetation indices (Petach et al., 2014). In the past ten years, greenness series from digital repeat photography have been used extensively for assessing phenology and its relationship with primary productivity and climate, predominantly in forests (e.g., Klosterman et al., 2014; Menzel et al., 2015), but also in other ecosystems like alpine grasslands (Migliavacca et al., 2011), tropical savannahs (Alberton et al., 2014), or Arctic vegetation (Anderson et al., 2016).

Even if tower-mounted or mountain slope-viewing cameras may observe larger areas, landscape-scale observation of phenology can only be achieved from satellites. Because this equally requires frequent observation, satellite-based phenology studies mostly relied on medium- to coarse-resolution (250 m to 8 km) optical imagery from sensors like the Moderate Resolution Imaging Spectroradiometer (MODIS) that is acquired at daily intervals (Reed et al., 1994; Vrieling et al., 2011; Zhang et al., 2003). The high frequency is needed to ascertain a sufficient number of cloud-free observations throughout the growing season. Since at the medium spatial resolution individual plants cannot be discerned, we generally refer to “land surface phenology” to describe the aggregate temporal behaviour of the multiple plant species and vegetation communities present within a grid cell (de Beurs and Henebry, 2005). Although regional and global patterns of land surface phenology can be effectively captured by these medium-resolution sensors, such sensors may not properly represent the actual phenological variability, particularly in areas with heterogeneous land cover (Melaas et al., 2013; Vrieling et al., 2017).

Finer-resolution (< 30 m) satellite acquisitions usually come at the expense of longer revisit times, generally resulting in too few cloud-free observations to effectively describe seasonal changes in greenness. One option to obtain finer-resolution estimates of land surface phenology is to fuse sparse fine- with frequent medium-resolution acquisitions (generally Landsat and MODIS, e.g., Frantz et al., 2016; Walker et al., 2014; Zhang et al., 2017). Although image fusion has received much attention in recent years, it remains sub-optimal for representing rapid and subtle changes, particularly in heterogeneous landscapes (Emelyanova et al., 2013; Gao et al., 2015; Zhu et al., 2010). An alternative is to combine vegetation indices from fine-resolution data, typically Landsat, from multiple years into a single synthetic year (Fisher et al., 2006). From this, multi-annual average estimates of phenological transition dates can be made that can be adjusted annually based on sparser individual-year observations (Melaas et al., 2013; Melaas et al., 2016). This approach has proven to be successful for deciduous forests at locations where two Landsat tiles overlap, but cloud cover around transition dates limited the possibility for annual adjustment of the estimates, particularly for other land covers that have little seasonal variability in greenness and/or strong year-to-year variations its temporal behaviour (Nijland et al., 2016; Vrieling et al., 2017).

Taking advantage of new fine-resolution optical sensors with reduced revisit times, recent studies retrieved phenology directly from fine-resolution imagery without image fusion or combining data from different years. For example, Pan et al. (2015) assessed crop phenology of winter wheat and maize in central China using three years of 30-m resolution data from the two optical HJ-1 (Huan Jing) satellites. For forest sites in Vermont (United States), White et al. (2014) estimated start of season from combined Landsat TM and ETM+ imagery of two overlapping orbits and compared results with field estimates of bud burst. For the same site as the present study (Schiermonnikoog, The Netherlands), Vrieling et al. (2017) combined RapidEye and SPOT5 imagery of 2015 to retrieve spring phenology estimates. In that study, comparison with coarser resolution series (e.g., MODIS) demonstrated the additional information content of the fine-resolution retrievals, but ground data to assess the accuracy of the retrievals was not available.

This study builds on those efforts and offers a first attempt to retrieve vegetation phenology from the Multi Spectral Instrument (MSI) of the Sentinel-2 mission. This is the first mission that provides free publicly-accessible data at 10-60 m resolution (10 m in four spectral bands) every five days with global coverage (Drusch et al., 2012). Although the five-day repeat frequency is only achieved since the launch of Sentinel-2B in March 2017, for Schiermonnikoog we already obtained two acquisitions per 10 days in 2016 with Sentinel-2A using two overlapping orbits, thereby more closely simulating the Sentinel-2A and -2B configuration. The goals of this study are (1) to compare retrievals of phenology from digital repeat photography and Sentinel-2A time series for the dynamic salt marshes of Schiermonnikoog (the Netherlands); (2) to explain differences between both retrievals; and (3) to map phenology at 10 m resolution from Sentinel-2A time series.

2. Study area and data

2.1. 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). About 85% of the 40 km^2-large island is a National Park, with the remainder containing grasslands, maize, and built-up area. The National Park contains dunes, marshes, and beaches, which together host a rich fauna and flora. The island's salt marshes are regularly flooded during high tides. Small altitudinal differences affect the frequency and duration of flooding and as such the vegetation composition (Olff et al., 1988). Tides, wind, and grazing together make the natural vegetation dynamic and spatially variable. Herbs and grasses of different species and height are found across the island, while the dune area in addition contains forest and shrub vegetation.

2.2. Field camera time series

We installed eight Bushnell Trophy Cam Essential (model 119736) trail cameras across the salt marsh of Schiermonnikoog (Fig. 1) that collected 3-megapixel RGB photographs in JPEG format. White balance and exposure are determined automatically by these cameras, and cannot be adapted by the user. Despite that these cameras do not provide calibrated radiance measurements, Sonnentag et al. (2012) showed that phenology-relevant information is retained irrespective of camera choice and JPEG compression. We programmed the cameras to collect ten photos per day, i.e. every half hour between 10:30 and 15:00 CET. Six of the eight cameras (A-F) were placed along a transect from the low marshes to the higher dune area, purposively selecting relatively homogenous areas. Camera G was mounted to view a patch of reed vegetation that was not present near the transect. Cameras A–G were installed on 3 March 2016, while camera H was installed already in 2015 at a grassland site with better accessibility. Cameras A–G can only be reached by foot, and the salt marsh area is closed for public during the bird breeding season from 15 April to 15 July, hence limiting interference by humans. Fig. 2 provides sample photos for each camera.

All cameras faced north to avoid direct incoming sunlight and were mounted on poles at an approximate height of 2.2 m above the ground surface with a depression angle of ~8°, resulting in a detailed view of the area between 10 and 30 m north of the camera location. Metal pins were fixed on top of the poles to avoid disturbance by birds. We noted