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PHENOLOGICAL TRENDS OF VEGETATION IN SOUTHERN ENGLAND FROM ENVISAT MERIS TERRESTRIAL CHLOROPHYLL INDEX (MTCI) DATA

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Abstract

Given the close association between climate change and vegetation response there is a pressing requirement to monitor the phenology of vegetation and understand how its metrics vary over space and time. This paper explores the viability of the Envisat MTCI dataset for monitoring vegetation phenology via its estimates of chlorophyll content. The MTCI was used to construct the phenological-profile of and to extract key phenological dates from mixed woodland in Southern England. Woodland phenological cycles for the time period 2003 to 2007, a period with known temperature anomalies forcing variability in the phenology of the vegetation, were derived from MERIS MTCI data. Comparisons were made with ground indicators of phenology, and furthermore, cross-comparisons with other vegetation indices, namely the NDVI and EVI derived from MODIS data were conducted. Close correspondence between MTCI and canopy phenology as indicated by ground observations was evident. Also observed was a difference between MTCI-derived phenological transition curves and key transition dates and those derived from the NDVI and EVI. Overall the research presented in this paper supports the use of the Envisat MTCI for monitoring vegetation phenology, principally due to its sensitivity to canopy chlorophyll content, a vegetation property that is a useful proxy for the canopy physical and chemical alterations associated with phenological change.

1. Introduction

There is mounting evidence to suggest that climate change will have many impacts on terrestrial ecosystems [1]; including changes in ecosystem productivity, shifts in the distribution of species (including migration of the tree line towards the polar regions) and variation in the natural timing of phenological phases.

It is widely accepted that global climate change could alter plant phenology significantly because temperature influences the timing of leaf development, both alone and through interaction with other climate variables, such as photoperiod [2]. In temperate and higher latitudes, temperature is a limiting factor to vegetation growth, and precipitation and photoperiod have a less pronounced effect on phenology [3]. The effects of temperature alone on phenology are difficult to isolate, as both leaf development and senescence occur during seasons where air temperature, day length and rainfall, often change at the same time [4]. Therefore, an ability to couple vegetation phenology with climatic variation over large areas is vitally important to predict and manage the impact of climatic change on ecosystems. Higher spring temperatures have been shown to trigger both growth and early leafing in deciduous trees [5,6], whilst autumnal temperature decrease is one of the triggers for the onset of senescence [7]. Analysis of long term phenological trends and meteorological data suggest that enhanced plant growth and the duration of the growing season in northern high latitudes since the 1980s increased as a result of elevated global temperatures [8]. Therefore, the forecast change in climate is likely to have consequences for ecosystem productivity [9].

Traditionally, phenological networks rely on volunteers collecting *in situ* observations related to vegetation growth, such as first leaf and leaf fall, to determine change in the physiological development of vegetation. Most of these networks are located in populous regions in Europe and North America and therefore are focused on temperate ecosystems [2]. For example long-term point-based observations, by the UK Phenology Network (UKPN), are

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crucial in developing an understanding of the factors that influence vegetation phenology. Research utilising remote sensing shifts the emphasis from point observations, to regional and global scales and provides an opportunity to couple climate variables with the mechanics of vegetation phenology [10].

Vegetation indices (e.g., NDVI) that are correlated with green leaf area and total green biomass have been the most popular method for inferring vegetation phenology [11]. NDVI saturation at relatively low levels of biomass will limit its use as a tool to monitor vegetation phenology [12]. In recent years a new generation of remote sensing data sources have become available that greatly improve the potential to identify changes in ecosystem phenology [10]. MODIS, at spatial resolutions of 250 m, 500 m and 1 km globally, has provided data for the study of ecosystem dynamics due to greatly improved geometric, radiometric properties and atmospheric correction when compared with AVHRR. Similarly, MERIS, with spatial resolutions of 300 m (1.2 km globally), offers great potential to monitor global vegetation dynamics.

The relationship between MTCI and phenology

The MTCI is calculated using the ratio of the band difference in reflectance between band 10 and band 9 and the difference in the reflectance between band 9 and band 8 of the MERIS standard band setting. Although very easy to calculate, it is sensitive to all and notably high values of chlorophyll content [13]. Given that the MTCI is the only available chlorophyll index from a spaceborne sensor there is now a real opportunity for monitoring vegetation function and condition.

Vegetation growth cycles can be characterised through changes in chlorophyll concentration and leaf area index, which determine chlorophyll content [14]. The start of vegetation growth (i.e., greenup) will lead to a rapid increase in either or both chlorophyll concentration and LAI (species dependant), therefore increasing foliar chlorophyll content. Similarly, autumnal senescence, and the associated breakdown in photosynthetic pigments, reduces leaf chlorophyll content. The ability of a vegetation index to monitor phenological change is reliant on its sensitivity to changes in LAI and chlorophyll concentration alike.

Spectroscopy on fresh deciduous leaves during the transition from late summer to autumn senescence has shown a significant shift in REP to shorter wavelengths, whilst numerous vegetation indices, including NDVI, only exhibit a slight decrease. As discussed in previous chapters, the REP is correlated strongly to the content of foliar photosynthetic pigments [15] and can be used to indicate the onset of senescence before structural changes (e.g., in LAI) are evident [16]. As the MTCI is designed to exploit the spectral reflectance in red edge wavelengths, the MTCI should be sensitive to the early decrease in chlorophyll content at senescence. Therefore, it is expected that estimating growing season length using the MTCI will yield different results to EVI or NDVI, which are primarily sensitive to variation in LAI.

The MERIS archive allows continual phenological observations to be made from the start of the 2003 growing season to date. The analysis of the temporal variability of MTCI to date will provide an insight into the possible effects of predicted climate variation on phenology in terrestrial ecosystems located in mid latitudes, where temperature can be a limiting factor to vegetation growth.

2. Data and methods

The New Forest study Area

The New Forest in southern England (0°56' N, 01° 5' W) covers 571km^2 and comprises of ancient semi-natural and ornamental woodlands and managed coniferous plantations (223km^2) and adjacent open heath and grassland covered in heather and low scrub (164.5km^2). The deciduous woodlands were dominated by white birch (*Betula pubescens*), oak (*Quercus robur*) and beech (*Fagus sylvatica*), whilst coniferous areas were dominated by scots pine (*Pinus sylvestri*) corsican pine (*Pinus* nigra var. *Maritima*), weymouth pine (Pinis strobus), sitka spruce (*Picea sitchensis*) and Douglas fir (*Pseudotsuga menzieii*). The woodland study areas were composed of ancient semi-natural and ornamental woodlands and managed coniferous plantations. In addition, the site was chosen for its topography. The site was essentially flat, minimising the effects of terrain in the remotely sensed data.

Woodland study sites were selected across the National Park using true colour aerial photographic imagery of the area, acquired during July 2005 and re-sampled to a spatial resolution of 5 metres. Site visits validated study sites' extent and vegetation type present. GPS co-ordinates were taken in the field at the boundaries of homogenous woodland. GPS co-ordinates from the field visits and high resolution imagery were used to refine study area boundaries in ArcGIS. Field surveys of the study area and theit percentage cover revealed that species composition at the MERIS 1 km^2 'reduced resolution' pixel level (of the MERIS sensor) meant that individual woodland study areas consisted of both deciduous and coniferous species and their understory vegetation. In total six woodland areas were used in this study, totalling 23.3km^2.

Remotely sensed data

Since 2003, Level 3 8-day composites of Level 2 geophysical data have been generated by the UK Multi-Mission Product Archive Facility (UK-MM-PAF) at Infoterra Ltd., accessed through NEODC. Gaps in the time series (2005 and for January – May 2006) are were filled using by processing downloaded 'reduced resolution' Level 2 cloud free imagery from ESA EOLI server to produce 8-day composites that batch processed using the same method as the UK-MM-PAF. Together, both sources of MTCI composites provided a complete time series from February 2003 to December 2007.

Within ENVI software MTCI composites were stacked chronologically to produce a time series for each growing season. Vector shapefiles defining the study area boundaries permitted the extraction of pixels corresponding to woodland areas from each growing season 2003 – 2007. Pixels corresponding to woodland study areas were aggregated (to reduce noise in the phenological profile), producing a single value for each 8-day composite within each growing season.

MODIS vegetation (MOD13A2) 16-day product, including both MODIS EVI and NDVI vegetation at 1km spatial resolution, was accessed through the NASA Warehouse Inventory Search Tool (WIST) (accessed at https://wist.echo.nasa.gov/api/). MODIS-VI products are made from the level 2 daily MODIS surface reflectance (MOD09), corrected for molecular scattering, ozone absorption, and aerosols. Layer stacks were produced from the 16-day composites for both EVI and NDVI to span the 2006 and 2007 growing seasons. Therefore a direct comparison between the MODIS VI and MTCI can be made.

Although cloud contamination was minimised by compositing noise was added as a result of both compositing and re-sampling. Data smoothing was used to remove noise in time series data whilst maintaining phenological information. Harmonic analysis (specifically using Fourier series) has been shown to produce an accurate representation of a single year phenology across a range of land cover [17]. In this study, the MTCI and MODIS VI phenological profiles were smoothed using Discrete Fourier Transformation (DFT). The DFT method decomposes the complex waveform into individual sinusoids, and omits noise introduced in the compositing procedure [18]. Amalgamating the sinusoids inversely using the first five harmonics removes noise from the phenological profile and produces a smoothed MTCI time series (Figure 2). This approach has been used successfully to remove noise in the composite data whilst preserving phenological information.

The inflection point method was used to derive the phenological transition dates. Dates were identified using the rate of change in the curvature of the cumulative curve derived from the DFT smoothed data (Figure 1). Transition dates correspond to the location in time where the rate of change in the MTCI phenology profile exhibits local maxima or minima [10].

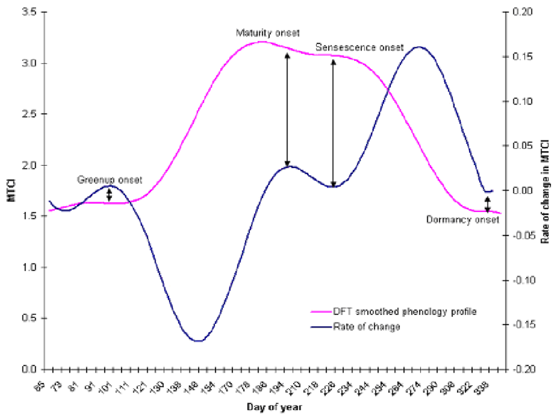

Figure 1. *Phenology transition dates were determined using maximum and minimum values in the rate of change of the (DTF smoothed) MTCI phenology profile.*

Ground data

The UK Phenology Network (UKPN), run jointly by the Woodland Trust (UK) and the Centre for Ecology and Hydrology (CEH) (UK), provides point based phenological ground observations from sites around the UK (http://www.naturescalendar.org.uk/). The UKPN records first leaf and leaf fall dates of several indicator species, including the oak, birch and beech that were abundant in the woodland sites in the New Forest study area. For the purpose of this investigation, mean first leaf and leaf fall dates have been calculated for the pre-mentioned species. Data were used to compare and support the phenological trends inferred from the MTCI time series.

Climate data

Climate data, local to each study area, were obtained from the Meteorological Office UK weather station network. Weather station observations within 25 km of the study area were provided by the Meteorological Office (UK). Average daily temperature was calculated as a mean of the daily maximum and the daily minimum. Eight day average temperatures were derived from the daily temperature dataset for each weather station to correspond with the temporal format of the MTCI composites.

3. Results and Discussion

Satellite sensor phenological studies of woodland stands in the New Forest at moderate to coarse spatial resolution include both deciduous and coniferous species. Site visits confirm a mixed species assemblage within the study areas. In this study, canopy dormancy is defined as the date at which coniferous species exhibit minimum estimated chlorophyll content and this date is likely to be after deciduous species have become dormant. In mixed coniferous and deciduous study areas, the presence of coniferous species limits the minimum MTCI value during the winter months as observed in the temporal MTCI profiles, where MTCI values fluctuated between 1.3 – 1.7. The aggregated woodland MTCI temporal profiles revealed a clear seasonal pattern, which was characterised by a trapezoid phenology curve. This general pattern is evident for all six years of data, indicating that the MTCI was a reliable tool for determining the phenological development of the woodland study areas (Figure 2). In general terms, the MTCI increased rapidly from mid April, this rapid greenup corresponded to an inferred period of increased foliar chlorophyll content. The curve stabilised during June, followed by a decrease in MTCI from the end of August, marking the onset of the senescence. The MTCI reached a minimum during early winter, denoting canopy dormancy.

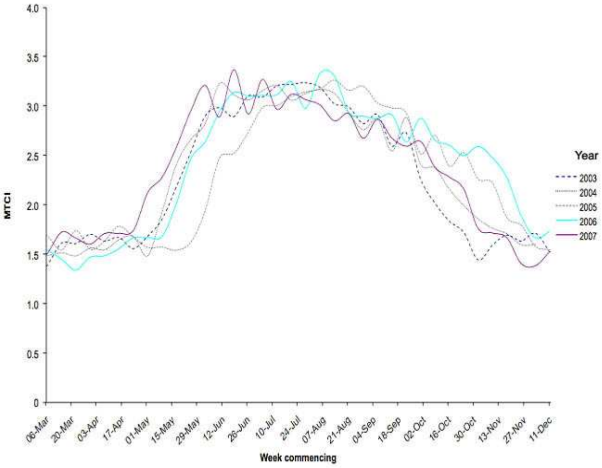

***Figure 2**. Seasonal MTCI phenological profiles for woodland study areas in the New Forest National Park; 2003 - 2007.*

Change in temperature has been shown to affect the phenology of woodland species [19], leading to earlier spring greenup in woodlands in the mid- and higher latitudes [20]. Findings in this chapter support the notion of delayed senescence due to favourable growing conditions; this was particularly evident in the MTCI growing season temporal profile for 2006.

An early greenup was observed in 2007 for woodland areas. This coincided with elevated mean temperatures (in relation to 2003 – 2006) at the local weather stations and CET. These findings support the findings of [5] and [6] who related increased cumulative temperatures to leaf development of deciduous woodland in temperate latitudes. Such changes could lead to increased photosynthetic rates, as ecosystems modify their photosynthetic capacity in relation to a change in limiting factors through changes in foliar chlorophyll content [21]. The MTCI values would suggest that foliar chlorophyll content was higher in early 2007 in comparison with previous years, indicating that higher seasonal temperatures can, indirectly, increase the photosynthetic potential of the vegetation canopy.

Variation in phenological transition dates

Changes in temperature corresponded to change in the derived phenological transition dates in the New Forest study areas. Figure 3 shows the inter-annual variability in estimated phenological transition dates derived from the inflection point methodology using MTCI temporal data from woodland study areas. Delayed senescence is shown during the 2006 growing season as a result of climatic variability. Whilst the early spring growth associated with elevated spring 2007 temperatures is indicated by an earlier estimated greenup and maturity date.

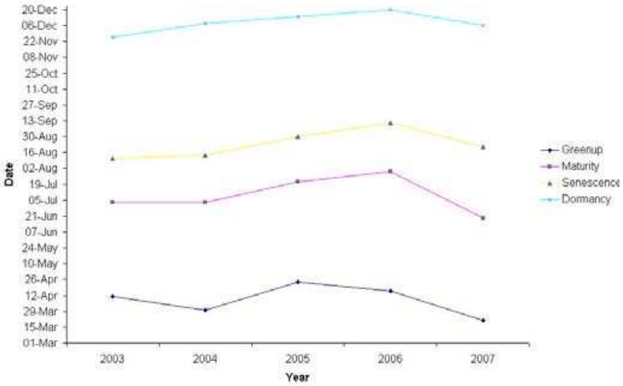

Figure 3. *Variation in key phenological transition dates through the growing season as determined by the rate of change in curvature in the MTCI profile for the New Forest woodland study areas.*

	Year				
Phenology markers	2003	2004	2005	2006	2007
Greenup	11th April	12th April	12th April	23rd April	11th April
Dormancy	23rd Nov	2nd Dec	8th Dec	3rd Dec	26th Nov
Season length (days)	226	234	240	224	229

Table 1. *Phenological transition dates derived from the UK Phenology Network.*

UKPN observations use a network of point-based ground observations around the UK to record the first leaf and leaf fall date of several indicator species, including oak, birch and beech. These species are abundant in the woodland sites in the New Forest study area. For the purpose of this investigation, greenup corresponds to the date the first leaf appeared for any of the species listed above. Dormancy relates to latest recorded leaf fall (of any species). Observations by the UKPN (Table 1) support the early onset of spring growth as inferred by the 2007 MTCI time series in woodland study areas (Table 2). Although such results cannot be used as a direct comparison, due to differences in geographical scale and the presence of coniferous species in the New Forest study area, trends in phenology are apparent and can be linked to seasonal temperature.

Comparison of MTCI and MOD13 phenological profiles

MODIS provideS daily observations of the land surface at moderate spatial resolution (250 m – 1000 m) and has been used to monitor vegetation phenology using the MOD13 vegetation indices, i.e., the NDVI and EVI [10]. The majority of satellite sensor phenological investigations utilise the NDVI vegetation index. However, the EVI has been widely used to monitor vegetation phenology due to its insensitivity to background effects. This section will evaluate the MTCI as a tool to estimate phenology in relation to the MOD13 vegetation indices.

MTCI is sensitive to variation in chlorophyll content, whereas the NDVI is principally sensitive to green biomass (LAI), therefore explaining the shape of the phenology curve. NDVI has an operational range of -1 to 1, where values which approach the upper limits correspond to dense vegetation, whereas low values indicate low vegetation densities or non vegetated surfaces [22]. However, in this study the NDVI demonstrates a small amplitude between summer maxima and winter minima compared to the MTCI temporal profile (figure 3a). Due to mixed species stands in the New Forest, pixels will contain coniferous and deciduous species. Therefore, the small seasonal variation in photosynthetic biomass demonstrated by coniferous areas results in a small change in LAI throughout the growing season compared to deciduous areas. Compared to the NDVI, the MTCI is more suited to determine phenological change in mixed tree pixels as total chlorophyll content will be more variable between seasons than LAI. The NDVI will therefore respond to the aggregated change in seasonal LAI between coniferous and deciduous species. The effect of background reflectance will be a function of vegetation phenology and linked directly to foliar development of deciduous species. Therefore, during the period, late autumn – early spring, which coincides with 'leaf off' of deciduous tree species, the positive NDVI values are the result of background reflectance (including leaf litter, understory vegetation and soil) as well as the presence of coniferous species within the study area.

Saturation in high biomass ecosystems and during the peak of the growing season where saturation occurs below typical LAI [12] limits the use of the NDVI as a tool for phenological monitoring. A number of studies have shown that the NDVI saturates at LAI of 3-4 [23], whilst LAI during peak growing season exceeds this for the study areas (this is confirmed from validation fieldwork of the same study areas completed during July 2007) [24]. The MTCI is based upon the relationship between chlorophyll content and REP, both of which have a strong correlation with green biomass [25].

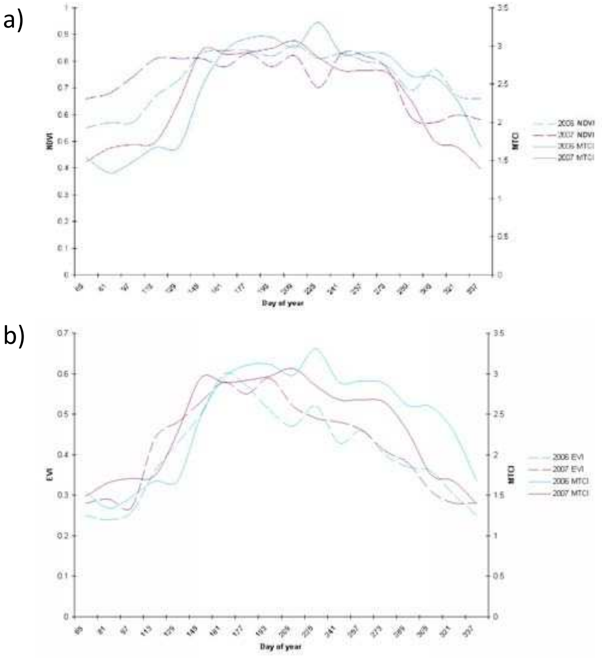

***Figure 3**. Comparison between MTCI and the phenological profiles derived from MODIS NDVI (a), and MODIS EVI (b).*

The associated decrease in MTCI from late August 2007 was considerably earlier than the observed senescence observed by the MODIS NDVI time series (Table 2). This supports the assumption that chlorophyll content declines prior to a decrease in leaf area, during autumnal senescence (Millar *et al.,* 1991).

Whereas the NDVI is chlorophyll sensitive and responds mostly to the visible or red band variations, the EVI is more sensitive to variation in near-infrared reflectance and therefore responsive to canopy structural variations, including LAI, canopy type, and canopy architecture [26].

The EVI temporal profiles reveal earlier senescence when compared with MTCI results, but does not capture the extended 2006 growing season (Figure 3b). This opposes the expected trend, which is related to earlier canopy chlorophyll decrease. Similarly, the greenup in the 2007 growing season revealed by the MTCI temporal profile, and supported by UKPN field observations, was also delayed in the EVI temporal profile. The EVI profiles of 2006 and 2007 reveal similar greenup and canopy maturatation dates, a trend that was unsupported by the UKPN and MTCI phenolgy profiles. EVI and NDVI data from MODIS utilize Maximum Value Composite (MVC) data. The MVC filter is designed to find the highest VI value (and therefore lowest noise) in a fixed time period. The MVC introduces temporal uncertainty when the acquisition period falls within a week- to month-long window (in this instance the composting period is 16 days). Such uncertainty therefore means that MVC data cannot be used to determine phenological events with an accuracy of a week or two [6].

4. Conclusions

The MTCI is sensitive to chlorophyll content, which allows first leafing as well as pigment breakdown associated with autumnal senescence to be identified. The MTCI has proven useful for estimating seasonal variation in chlorophyll content of woodland canopies. The sensitivity of the MTCI in estimating change in foliar chlorophyll during late summer, earlier than the onset of senescence as observed by changes in plant structure and physiology as determined through field observations (phenology networks) suggests that the MTCI would be useful for assessing canopy productivity and therefore changes in ecosystem productivity as a function of climatic variability.

Growing season	Greenup	Maturity onset	Senescence	End of growing season	Season length (days)	Vegetation Index
2006	22nd March	18th June	16th October	19th December	246	NDVI
	7th April	18th June	29th August	19th December	230	EVI
	7th April	12th July	14th September	21st December	232	MTCI
2007	6th March	8th June	30th September	19th November	234	NDVI
	14th March	10th June	29th August	3rd December	248	EVI
	6th March	2nd June	13th August	3rd December	256	MTCI

Table 2. *Comparison between estimated transition dates derived from NDVI, EVI and MTCI time series for the growing seasons 2006 & 2007.*

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