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Given the close association between climate change and vegetation response, there is a pressing requirement to monitor the phenology of vegetation and understand further how its metrics vary over space and time. This article explores the use of the Envisat MERIS terrestrial chlorophyll index (MTCI) data set for monitoring vegetation phenology, via its estimates of chlorophyll content. The MTCI was used to construct the phenological profile of and extract key phenological event dates from woodland and grass/heath land in Southern England as these represented a range of chlorophyll contents and different phenological cycles. The period 2003–2008 was selected as this was known to be a period with temperature and phenological anomalies. Comparisons of the MTCI-derived phenology data were made with ground indicators and climatic proxy of phenology and with other vegetation indices: MERIS global vegetation index (MGVI), MODIS normalized difference vegetation index (NDVI) and MODIS enhanced vegetation index (EVI). Close correspondence between MTCI and canopy phenology as indicated by ground observations and climatic proxy was evident. Also observed was a difference between MTCI-derived phenological profile curves and key event dates (e.g. green-up, season length) and those derived from MERIS MGVI, MODIS NDVI and MODIS EVI. The research presented in this article 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

Vegetation productivity is coupled closely with interactions between the terrestrial biosphere and the climate system. Recent radiative (e.g. by atmospheric CO_2) and non-radiative forcing (e.g. land cover change) of the climate system has led to a rise in the global mean temperature. Eleven of the 12 years between 1995 and 2006 were among the warmest years in the instrumental record of global surface temperatures

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since 1850 (IPCC 2007). This has implications for a range of vegetation properties and related dynamics (Nigh 2006) that in turn affect the climate through a variety of biophysical, biogeochemical and biogeographical pathways over a range of spatial and temporal scales (Zhou *et al*. 2001, Arora and Boer 2005). Accordingly, one aspect of vegetation dynamics that has received increasing attention recently is that of phenology, which refers to the timing of plant development phases, such as leaf onset, flowering, leaf senescence and leaf offset, so-called phenological events (Menzel and Fabian 1999, Morisette *et al*. 2009).

1.1 *Vegetative phenological events*

The timing of vegetative phenological events indicates the impact of both short- and long-term climatic changes on the terrestrial biosphere (Reed *et al*. 1994, Chuine and Beaubien 2001, Brügger *et al*. 2003). The timing of the onset and eventual loss (offset) of leaves regularly alters land-surface boundary conditions by changing surface albedo, roughness, and surface water and energy fluxes (Hogg *et al*. 2000, Wilson and Baldocchi 2000, Molod *et al*. 2003). Moreover, change to the associated length of the growing season and increase in primary productivity directly influences the amount of radiatively active gases (particularly CO_2 and H_2O) in the atmosphere (White *et al*. 1997, Schwartz 1999, Cleland *et al*. 2007, Richardson *et al*. 2010). An extension in the growing season leading to increased canopy longevity and carbon gain may provide an increased sink for atmospheric carbon (Lucht *et al*. 2002), conversely an extended growing season may contribute to warming due to a decrease in surface albedo (Betts 2000). Phenological events also have implications for competition between plant species and interactions with heterotrophic organisms. In addition to these direct effects, alteration in the timing of phenological events is implicit in ecosystem services to humans, such as the production of food, fibre and extractable chemical substances, as well as the seasonal suitability of landscapes for recreational activities (Badeck *et al*. 2004). More recently, links have been postulated between changing vegetation phenology and disease transmission (Barrios *et al*. 2010).

Contemporary climatic perturbations have been associated with recent changes to phenological event timing (Hovenden *et al*. 2008). At temperate and higher latitudes, air temperature is thought to be the principal limiting factor to vegetation growth, whereas in regions such as humid and dry ecosystems, it is rainfall (Chen *et al*. 2005, Zhang *et al*. 2010). In recent years much attention has focused on phenological event alteration as a result of temperature anomalies; Myneni *et al*. (1997) observed that terrestrial vegetation between 45° and 70° N had 'greened' between 1981 and 1991, and Lucht *et al*. (2002) confirmed a high northern latitude greening trend over the past two decades. Many others report that recent warming trends in the northern hemisphere (Europe, North America and China) are seen clearly in phenological time-series records with earlier spring and later autumn dates (Menzel 2000, Roetzer *et al*. 2000, Defila and Clot 2001, Parmesan and Yohe 2003, Root *et al*. 2003, Piao *et al*. 2004, Studer *et al*. 2005). In higher latitudes elevated spring temperatures have been shown to trigger both tree growth and early leafing (Sparks *et al*. 2005, Fisher *et al*. 2006) and growth in grasslands (White *et al*. 1997, Stöckli and Vidale 2004, Steinaker and Wilson 2008), whilst autumnal temperature variation influences the onset of senescence (Busetto *et al*. 2010). These resultant changes in phenological events may have implications for pollination and herbivory. However, given the mix of pollinator services and herbivorous activity, the exact impact of phenological event change on trees

and their communities have proved difficult to predict (Fabina *et al*. 2010). Since the magnitude of change varies with species, location and investigation period (Walther *et al*. 2002, Chmielewski *et al*. 2004, Hovenden *et al*. 2008), a systematic and scientifically credible global monitoring programme of the state of the world's ecosystems is required (Millenium Ecosystem Assessment 2005, Morisette *et al*. 2009). Given the pivotal role of this aspect of vegetation dynamics, there is a pressing requirement to monitor the phenology of vegetation and understand further how its events vary over space and time.

1.2 *Remote sensing of vegetation phenology*

Satellite-based observations have been used in the study of seasonal vegetation dynamics for over 30 years (Reed *et al*. 1994, Reed 2006). Due to its temporal sampling and synoptic coverage, remote sensing has become increasingly important in studies of landscape-level phenological event changes (Badeck *et al*. 2004, Cleland *et al*. 2007, Studer *et al*. 2007, Reed *et al*. 2009) and this has become generally known as land surface phenology (de Beurs and Henbry 2004). The coupling of these satellite-based observations with conventional site- and species-specific ground observations and climate data-driven phenological models is desirable but often difficult to achieve (Badeck *et al*. 2004, Fontana *et al*. 2008, Ganguly *et al*. 2010). Accordingly, work to date has focused on constructing multi-temporal records of satellite sensor data (phenological profiles), extracting key phenological event information from these and relating these to climatic variations. A key challenge in the construction of these records is decoupling change in signals that are vegetation related from those that are unrelated, notably, arising perhaps from navigation uncertainties, calibration uncertainties, atmospheric effects, variations in the viewing and illumination geometry and variations in soil background (Piao *et al*. 2003).

The use of vegetation indices, such as the normalized difference vegetation index (NDVI), that are related to green leaf area and total green biomass have been the most commonly used method of inferring vegetation phenological events from satellite sensors (e.g. Hargrove *et al*. 2009, Ganguly *et al*. 2010). Until the turn of the millennium, the National Oceanic and Atmospheric Administration Advanced Very High Resolution Radiometer (NOAA-AVHRR) suite of sensors provided the principal source of global data for this purpose (Kathuroju *et al*. 2007). The NDVI has a strong link with vegetation productivity variables such as primary productivity which in turn signals key phenological events (Myneni *et al*. 1997, Zhou *et al*. 2001, Zhang *et al*. 2004, Piao *et al*. 2006). Data sets such as the Global Inventory Modeling and Mapping Studies (GIMMS) NDVI (e.g. Heumann *et al*. 2007, Julien and Sobrino 2009) and pathfinder NDVI have been popular for studies of land surface phenology (e.g. Tao *et al*. 2008). However, radiometric data from the AVHRR sensor suffers from a lack of precise radiometric calibration, poor geometric registration and difficulties associated with cloud screening result in high levels of noise (Zhang *et al*. 2006). Seamless data continuity between satellite and sensor generations is difficult to achieve (Steven *et al*. 2003). Although, further processing of these data can minimize such discrepancies (e.g. 10-day maximum value 1 km NDVI composites in the MEDOKADAS series is compiled from the NOAA-11, NOAA-14 and NOAA-16 sensors and corrected for sensor degradation and orbital drift; Martínez and Gilabert (2009)), comparisons of the various AVHRR NDVI data sets derived as a result of different correction and processing schemes have indicated a lack of consistency (Alcaraz-Segura *et al*. 2009,

2010). The real strength of these data sets lie in the length of their temporal record (10 years +), though methods for data smoothing and extraction of key phenological events (such as green-up, dormancy) have yet to be standardized and are a source of uncertainty (White *et al*. 2009). Moreover, the spatial resolution of this record means that the contribution of the individual phenology of pixel components is missed and homogenized (Reed *et al*. 2003). The NDVI from these data also saturates at high levels of biomass (Foody *et al*. 1996).

The new generation of satellite sensors greatly improves the potential to identify changes in vegetated ecosystems (Kang *et al*. 2003). Here continuity and consistency of observations are essential in order to detect subtle tends in long-time series of data. The early NOAA-AVHRR sensors have since been joined by VEGETATION, POLDER, SeaWIFS, ATSR, MODIS, MISR and MERIS (Steven *et al*. 2003, Fontana *et al*. 2008). In particular, MODIS, at spatial resolutions of 250 m, 500 m and 1 km, globally offers enhanced geometric, atmospheric and radiometric properties (Zhang *et al*. 2003). The enhanced vegetation index (EVI) generated from MODIS data has several advantages over the NDVI for vegetation studies, having been used with some success in several phenological studies (e.g. Zhang *et al*. 2004, 2006) as it reduces sensitivity to soil and atmospheric effects and has a greater dynamic range than the NDVI (Huete *et al*. 2002).

Another satellite sensor also launched post-millennium is the Envisat MERIS. This sensor has many virtues for remote sensing ecosystem status and change; radiometrically it is the most accurate imaging spectrometer in space (Curran and Steele 2004) and unlike many spaceborne sensors, the MERIS platform has well-placed spectral sampling at visible and near-infrared (NIR) wavelengths coupled with narrow bands (15 bands selectable across range: 390–1040 nm (bandwidth programmable between 2.5 and 30 nm)) that theoretically improve the accuracy of vegetation monitoring. The sensor also benefits from a moderate spatial resolution (300 m) and 3-day repeat cycle (Verstraete *et al*. 1999). Two vegetation indices have been included in the official processing chain of the MERIS sensor: the MERIS global vegetation index (MGVI; Gobron *et al*. (1999)) and the MERIS terrestrial chlorophyll index (MTCI; Dash and Curran (2004)). Both are adopted gradually for the study of vegetation and its dynamics (e.g. Dash *et al*. 2007, Sexias *et al*. 2009, Zurita-Milla *et al*. 2009).

The MGVI is related linearly to the fraction of absorbed photosynthetically active radiation (*f*APAR) by the canopy and is computed using the top of atmosphere reflectance in blue, red and NIR MERIS bands, with the blue band being used to atmospherically correct red and NIR reflectances. The MGVI is computed as a polynomial function of the rectified red and NIR reflectances (Gobron *et al*. 2007). It was developed in order to exhibit maximum sensitivity to the presence and change in green healthy vegetation whilst limiting sensitivity to atmospheric scattering and absorption, soil colour and brightness and illumination and observation variability. As a direct estimator of *f*APAR, which has been demonstrated to constrain global models of vegetation phenology (Gobron *et al*. 2010), the MERIS MGVI is a useful but little-used source of data for phenological studies. The MTCI is the only available chlorophyll-related index from a spaceborne sensor. The index is calculated using the ratio of the difference in reflectance between bands 10 and 9 and the difference in reflectance between bands 9 and 8 of the MERIS standard band setting. It is very simple to calculate, yet it is sensitive to all and notably, high values of chlorophyll content (Dash and Curran 2004). The MTCI has limited sensitivity to atmospheric effects and also soil background and view angle (Dash *et al*. 2008). There is a rapidly growing

literature reporting the successful utility of the MTCI for vegetation studies (Dash and Curran 2006, Espana-Boquera *et al.* 2006, Dash *et al.* 2010, Foody and Dash 2010).

The ability of a vegetation index (VI) to monitor phenological event change is reliant on its sensitivity to changes in both leaf area and chlorophyll concentration. Since the red edge position (REP) of a canopy is strongly correlated to the content of foliar photosynthetic pigments (Carter and Spiering 2002), it can be used to indicate the onset of productivity and senescence before structural changes are evident (Davids and Tyler 2003). This is particularly advantageous since it has been demonstrated that changes in the chlorophyll concentration of plant species (grassland in particular) that occur as a result of elevated temperatures may not result in biomass changes (Lemmens *et al.* 2008). The start of annual vegetation growth, *green-up*, will lead to a rapid increase in either or both chlorophyll concentration and leaf area (species dependant), therefore increasing foliar chlorophyll content. Similarly, autumnal senescence, and the associated breakdown in photosynthetic pigments, reduces leaf chlorophyll content. Spectroscopy on fresh deciduous leaves during the transition from late summer to autumn senescence has shown that there is a significant shift in REP to shorter wavelengths (Cipar *et al.* 2008). Decline in chlorophyll content happens earlier in the growing season before variations in leaf area become apparent (Miller *et al.* 1991). As the MTCI is designed to exploit the spectral reflectance in red edge wavelengths, the MTCI should prove to be particularly sensitive to the changes in chlorophyll content associated with various phenological events and their associated stages of canopy development. We purport that there is now real opportunity for monitoring vegetation function and condition systemically and reliably (Gitelson *et al.* 2006, Wu *et al.* 2009) using the MTCI VI.

This article explores the viability of the MERIS MTCI for monitoring land surface phenology, through evaluation with field data and comparison with other satellite measures of land surface phenology, namely the vegetation indices of the MERIS MGVI and the MODIS EVI and NDVI. It is hypothesized that the phenological information extracted from the MERIS MTCI will be different to that from the comparison indices.

2. Materials and methods

2.1 *Study area*

The New Forest National Park in Southern England (0°56′N, 01°5′W) covers an area of 571 km^2, of which 223 km^2 is mixed and ancient deciduous forest and 164.5 km^2 is heath and grassland, with the rest of the land cover comprising marshlands, shoreland and shrubland. Meteorological data for the study period (2003–2008) revealed a clear warming trend in the central England temperature (CET) average. The CET is a long-running data set (since 1669) available from http://badc.nerc.ac.uk/data/cet/ and used in coarse spatial resolution studies to typify the English climate as it is strongly correlated ($p < 0.001$) with local station observations throughout England (Croxton *et al.* 2006). Figure 1 plots the percentage of variation between the long-term CET data set (1669–2002) monthly mean temperature and the temperatures in the years 2003–2008. A clear trend of milder winters is apparent. Also evident are several instances of elevated spring and autumnal temperatures, particularly in 2006 and 2007, an observation supported by the Meteorological Office and the Royal Netherlands Meteorological Institute which recorded from May 2006 to October 2006 as the warmest on record in the UK since 1659. These observed temperatures led
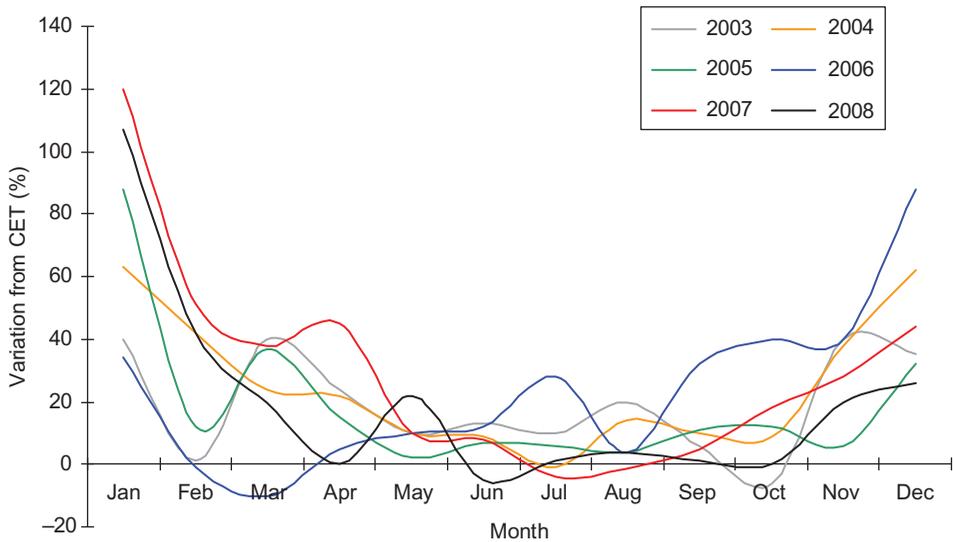
Figure 1.   Variation between the long-term CET (1669–2002) monthly mean temperature and monthly temperature during the years 2003–2008.

to reports of an extended growing season in 2006 (and delayed senescence), which was followed by a warm spring in 2007, which was also the warmest on record (http://www.naturescalendar.org.uk).

By virtue of the area's management the National Park is composed of ancient semi-natural and ornamental woodlands and managed coniferous plantations (enclosures) of varying sizes and adjacent open heath and grassland covered in heather and low scrub. The deciduous woodlands are dominated by White Birch (*Betula pubescens*), English Oak (*Quercus robur*) and European Beech (*Fagus sylvatica*), with the coniferous forest dominated by Scots Pine (*Pinus sylvestri*), Corsican Pine (*Pinus nigra* var. *maritima*), White Pine (*Pinus strobus*), Sitka Spruce (*Picea sitchensis*) and Douglas Fir (*Pseudotsuga menzieii*) (Forestry Commission 2006). Study sites were selected across the National Park using true colour aerial imagery of the area, acquired during July 2005 and re-sampled to a spatial resolution of 5 m. The criterion for selection was that each comprised a homogenous vegetation area of at least 2 km^2 (as this could incorporate the ground area covered by two reduced spatial resolution MERIS pixels) and that they be relatively flat (to minimize topographical effects). Site visits were conducted to confirm correspondence in site extents and vegetation cover type with that on the aerial photography. GPS coordinates were taken in the field at boundaries of homogenous vegetation types. GPS coordinates from the field visits and high-resolution imagery were used to refine study site boundaries in the ESRI ArcGIS software and produce area data sets for both woodland (with a mix of coniferous and deciduous species) and mixed grassland and heathland (herein grass/heath land) in the New Forest. Field surveys of the study sites determined the species present in each study site and their percentage cover. This revealed that species composition with each study site was relatively consistent for both woodland and grass/heath land areas. In total, six study sites were deemed suitable – three woodland and three grass/heath land, totalling 34.9 km^2.

2.2 *Remote sensing data*

Vegetation phenology can be estimated with high precision from time-series data with temporal resolutions of between 6 and 16 days. This is the case even if the daily data contain some uncertainties (Zhang *et al*. 2009). This study used temporal composited VI data from the MERIS sensor (MGVI and MTCI) and the MODIS sensor (EVI and NDVI) at both 8- and 16-day resolutions. Since 2003, global and regional composite (Level 3) products of MERIS Level 2 geophysical data (sourced from the ESA MERIS MERCI dataserver) have been generated by the UK Multi-Mission Product Archive Facility (UK-MM-PAF). The Level 3 MTCI product is available from the UK's NERC Earth Observation Data Centre (NEODC; http://www.neodc.rl.ac.uk) and is processed by Infoterra (Toulouse, France). The products are generated in GEOTIFF format, on latitude–longitude geocoded grids, accompanied by an XML-metadata file and a JPEG browse image. Here the 1 km regional 8-day arithmetic mean composite product was downloaded for the growing seasons of 2003–2008. However, there were gaps in the resultant time series (i.e. the 2005 growing season and January to May 2006) and these were filled by processing downloaded Level 2 cloud-free MERIS imagery from ESA MERIS MERCI reduced resolution (1 km) dataserver to produce 8-day MTCI composites adopting the same methodology as the UK-MM-PAF. Working within the ENVI image-processing software environment, the MTCI composites were stacked chronologically to produce a time-series layer stack for each growing season. The study sites for woodland and grass/heath land were located and the MTCI value extracted from each composite image across each of the 6 years under investigation. A mean MTCI value was then computed for woodland and for grass/heath land for each composite image for analysis.

The MODIS EVI and NDVI data sets were available through the MODIS VI (MOD13A2) 16-day 1 km product and 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), which is 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, since these have known climatic anomalies. In addition, 16-day composites of MERIS MGVI were also computed from downloaded Level 2 cloud-free MERIS imagery from ESA MERIS MERCI reduced resolution (1.2 km) dataserver. Again, a mean MGVI, EVI and NDVI value was then computed for woodland and for grass/heath land for each composite image for analysis. To make valid comparisons between the MTCI, MGVI, EVI and NDVI, an averaging of two consecutive periods of the 8-day MTCI data was undertaken to conform to the 16-day period of the MGVI, EVI and NDVI data sets.

Both the 8-day MTCI and 16-day MTCI, MGVI, EVI and NDVI data sets were then smoothed, mainly to overcome any residual cloud contamination. Although cloud contamination was minimized in the compositing methods employed by selecting cloud-free images, there is associated noise as a result of the compositing and re-sampling procedures. Data smoothing is a method for removing noise, whilst maintaining phenological event information, in the time-series data. The phenological signal needs to retain its temporal pattern and detail to preserve information on vegetation condition. Therefore, careful consideration needs to be given to the smoothing method. Here, the phenological profile for each site was smoothed by Gaussian model fitting in the Timesat software programme (Jönsson and Eklundh 2004, Eklundh

and Jönsson 2009). This approach has been used successfully to remove noise in the composite data whilst preserving phenological event information (Jönsson and Eklundh 2002). Timesat has been used in a wide range of time-series studies, including characterizing phenology (Olsson *et al*. 2005, Heumann *et al*. 2007, Seaquist *et al*. 2009).

2.2.1 Estimating phenological events from time-series data. Jönsson and Eklundh's (2004) double logistic and asymmetric Gaussian function-fitting techniques were selected for use due to their improved performance over other modelling techniques (Hird and Mcdermid 2008). Seven phenological event metrics were derived either from Timesat software (Eklundh *et al.* 2009) or by determining the rate of change in curvature from the smoothed vegetation profiles. In the current version of Timesat (version 3.0) three key seasonality parameters, (1) date of the start of the growing season (green-up onset); (2) date of the end of the growing season (dormancy onset); (3) largest value (date of peak the growing season) and associated seasonal amplitude, are computed for each of the full seasons in the time series. From these, the (4) green-up duration in days and (5) growing season length in days can be calculated. Using the fitted models function to remove noise in the growing season profile provides a more stable measure of the points of phenological events. Dates of maturity onset (6) and senescence onset (7) are metrics not derived by Timesat software, therefore the rate of change in the Gaussian fitted curves was used to derive these.

2.3 *Ground data*

'Validation' is a key issue in remote sensing-based studies of phenology over large areas (Reed *et al*. 2009). Even if ground- and remotely sensed phenological data are spatially coincident the chance of a single point ground observation being representative of the area covered by the ground resolution element of a pixel (typically 1 km) is small (Fisher and Mustard 2007). Rather than claim validation, here two sets of ground data were used to compare with the phenological event trends inferred from each of the 8-day composited MTCI data sets.

The first was climate data, local to the New Forest National Park (measured by the weather station at Hurn, approximately 12 km away), obtained from the Meteorological Office UK weather station network. Average daily temperature (T_{mean}) was calculated as a mean of the daily maximum (T_{max}) and the daily minimum (T_{min}), a method used by the Meteorological Office (Perry and Hollice 2005). The 8-day arithmetic average temperatures were derived from the daily temperature data set to correspond with the format of both the 8-day MTCI composites.

The second ground data set was acquired through the UK Phenology Network (UKPN), which is run jointly by the UK Woodland Trust and the UK Centre for Ecology and Hydrology to provide point-based phenological ground observations from sites around the UK (http://www.naturescalendar.org.uk/). This data set provides a previously untapped opportunity to compare broad trends in satellite-sensor and ground-based phenological event measurements. The UKPN relies on thousands of volunteers who record a range of observations relating to important events in the seasonal patterns of the UK's wildlife. As part of this record three observations pertaining to this study have been archived that cover the 2003 to 2008 time period, including date of first leaf, first leaf fall and bare tree. These are recorded for a range of

indicator species, including English oak and European beech species that were abundant in the woodland sites in the New Forest National Park. For the purpose of this investigation, the date at which an observation was made in the New Forest National Park for these species was extracted from the archive. This information cannot be used as a direct comparison (i.e. date-to-date), due to the differences in geographical scale, the presence of coniferous species, a lack of ground data for grasses and heath species and a difference in the phenological event metrics. However, trends in phenology across the 2003–2008 study period are apparent and are postulated to be primarily linked to variation in seasonal temperature.

3.   Results and discussion

3.1   *MTCI-derived phenological profiles*

The smoothed MTCI phenological profiles for both woodland (figure 2) and grass/heath land (figure 3) for each year between 2003 and 2008 exhibit characteristic seasonal curves. The woodland curve was more pronounced than the grass/heath land curve, with higher MTCI values, due to the higher net primary productivity attained by this ecosystem over the growing season. Satellite sensor phenological studies of woodland at moderate to coarse spatial resolution are likely to include both deciduous and coniferous species. 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 sites, the presence of coniferous species limits the minimum MTCI value during the winter months. This was observed in the temporal MTCI profiles, where values fluctuate within a narrow range of 1.3–1.8. Coniferous trees remain
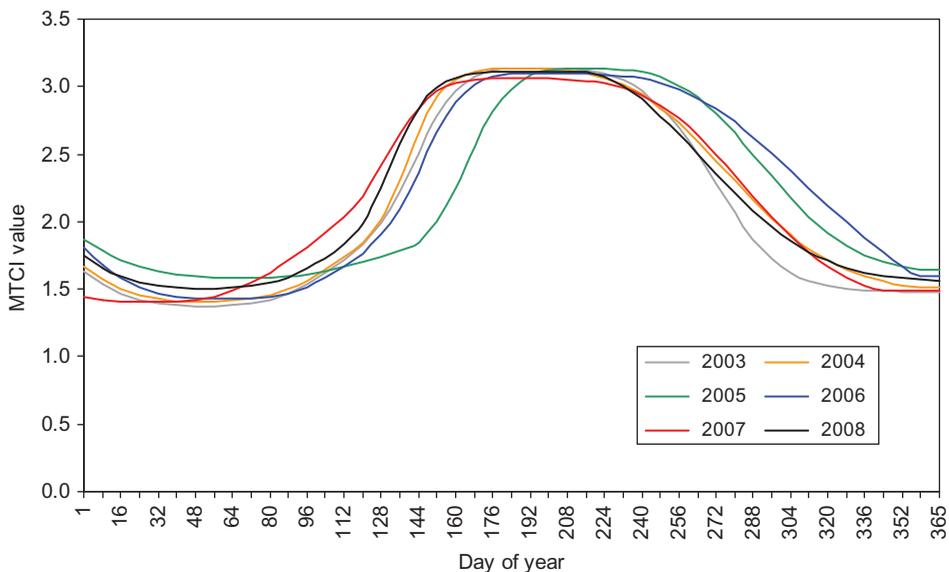

Figure 2.   MTCI-derived phenological profile for woodland for the years 2003–2008.
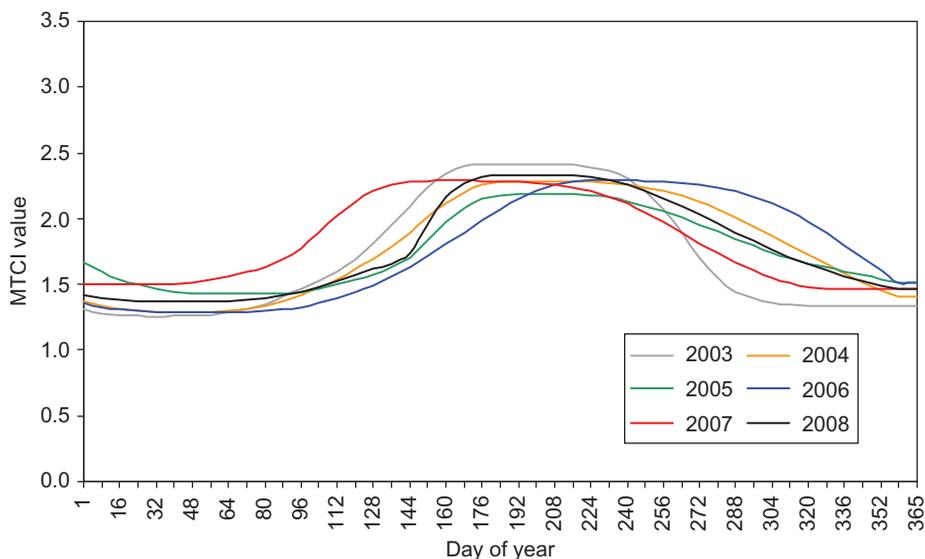
Figure 3.　　MTCI-derived phenological profile for grass/heath land for the years 2003–2008.

green during the dormancy season; however, the photosynthetic efficiency is down-regulated as a response to low demands of carbohydrates (Ensminger *et al*. 2004) as demonstrated by the low MTCI values. The aggregated woodland MTCI temporal profiles reveal a clear seasonal pattern, which is characterized by a trapezoid phenology profile. This general pattern is evident for all 6 years of data, indicating that the MTCI is a reliable tool for monitoring the phenology of the woodland study sites. In general terms, the MTCI increases rapidly from mid-April; this rapid green-up corresponds to an inferred period of increased foliar chlorophyll content mainly in the deciduous trees. The curve stabilizes during June, followed by a decrease in MTCI from the end of August, marking the onset of the autumnal senescence. The MTCI reaches a minimum during the autumn/early winter, denoting canopy dormancy.

The presence of large (greater than one 'reduced resolution' MERIS pixel) woodland enclosures permitted further examination of the MTCI-derived phenological profiles for a deciduous and coniferous wood (one MTCI pixel in each case). Figure 4 plots the phenological profiles of deciduous and coniferous canopies for the 2003–2008 growing seasons. Coniferous species maintain a minimum greenness during the winter and do not shed all of their needles each year (Fisher *et al*. 2006) accounting for the higher MTCI values during the early and later growing seasons. As a result, coniferous species do not exhibit large seasonal variation in photosynthetic biomass (Kimball *et al*. 2004), so observed changes in estimated coniferous chlorophyll content is due primarily to changes in chlorophyll concentration rather than leaf area index (LAI). Moreover, seasonal changes in photosynthetic efficiency are due to physiological changes associated with cold hardening including the clumping of chloroplasts, and cell dehydration, all of which change light absorbance and reflectance (Zwiazek *et al*. 2001). The phenological profiles show that the timing and rate of green-up is consistent between coniferous and deciduous species. This suggests that (1) leaf development in deciduous species, (2) bud burst, a period where new needles emerge in a number of coniferous species
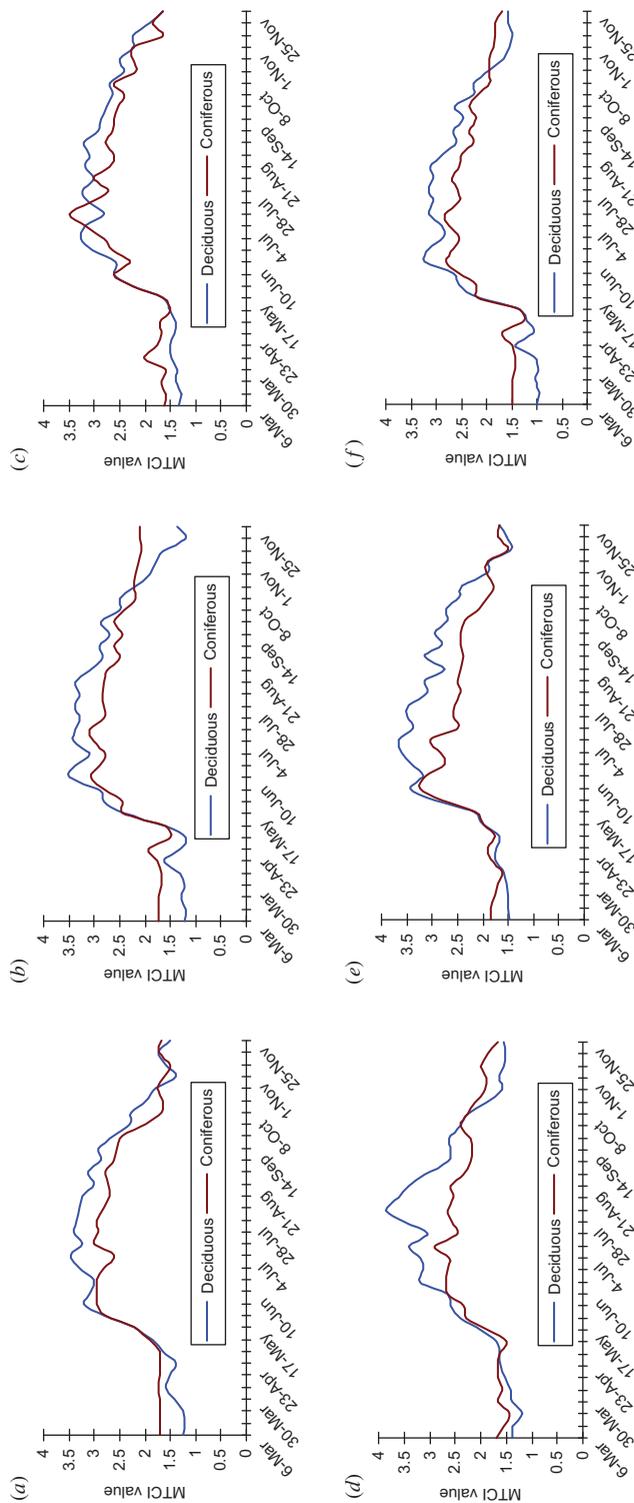
Figure 4. Comparison between deciduous and coniferous woodland MTCI profiles for growing seasons: (*a*) 2003, (*b*) 2004, (*c*) 2005, (*d*) 2006, (*e*) 2007 and (*f*) 2008.

(Cannell and Smith 1983, Jönsson *et al.* 2010) and (3) the associated increase in foliar chlorophyll content in both deciduous and coniferous species are triggered by similar environmental events. Similarly the timing of autumnal senescence between deciduous and coniferous woodland is similar, although during the 2004 and 2006 growing seasons, the rate at which chlorophyll content decreased was less in coniferous stands. At maturity, the deciduous woodland has a greater MTCI compared with coniferous woodland, which is maintained throughout the peak of the growing season.

Heath/grass land exhibit a distinct phenological profile and clear responses to a change in inter-annual seasonal temperatures. Such change has been observed in temperate grasslands and linked to variations in annual weather patterns (Kammer 2002, Butterfield and Malmström 2009). Although the mechanics of the relationship have not been studied, the results of this research support the notion that warm spring periods increase growth rates, chlorophyll content and photosynthetic rates (Lemmens *et al.* 2008). Since leaf phenology is correlated positively with root phenology in grassland, and therefore reflects overall system seasonality (Steinaker and Wilson 2008), the ability to track seasonal dynamics of grassland will be a particularly beneficial input to models predicting the response of vegetation to climate warming (Kramer *et al.* 2000).

With both the woodland and grass/heath land curves (figures 2 and 3), it is apparent there was an increase in MTCI (and thus inferred chlorophyll content) for the autumnal period of 2006 compared with the same period for other years in the study. Late October 2006 MTCI values were comparable with mid-September values for the years 2003 and 2004 indicating a delay in senescence of the vegetation canopies. Investigation between MTCI and CET_{mean} for the 2006 growing season and the growing seasons of 2003–2005 revealed a marked increase in temperature and MTCI. From the period July 2006 to November 2006 the high MTCI values were maintained, indicating a delay in autumnal senescence and vegetation photosynthetic potential. During mid-October the mean inferred chlorophyll content for all sites was considerably greater than the average of the previous 3 years. The 2006 MTCI profile also reveals a delay in reaching canopy maturity; evident as MTCI values are below average until early July, which can be attributed to lower mean temperatures throughout the early growing season (February to May). In addition to a late senescence in 2006, an early green-up was observed in 2007 MTCI phenological profiles for both woodland and heath/grass land areas. This coincided with elevated mean temperatures (in relation to 2003–2006 and 2008) at the local weather stations and CET. These findings support those of Fisher *et al.* (2006) and Sparks *et al.* (2005) who related increased cumulative temperatures to leaf development of deciduous woodland in temperate latitudes, particularly those of the preceding months (Menzel *et al.* 2006). Bassow and Bazzaz (1998) linked an increase in seasonal temperature with increased photosynthetic rates, as ecosystems modify their photosynthetic capacity in relation to a change in limiting factors through changes in foliar chlorophyll content (Dawson *et al.* 2003). Since air temperature is the principal limiting factor to vegetation growth at temperate and higher latitudes these findings are consistent with the observation that warming remains the most important driver of phenological event 'shifts' in the northern hemisphere (Root *et al.* 2003, IPCC 2007). The inference from MTCI data was that chlorophyll content was higher in early 2007 than in previous years and so higher seasonal temperatures can, indirectly, increase the photosynthetic potential of vegetation for the species under investigation.

A closer examination of the link between temperature and phenology was undertaken through correlations of the MTCI response from each 8-day composite for the years 2003–2008 with the corresponding 8-day arithmetic mean of the local temperature for both the woodland and grass/heath land sites (figure 5(*a*) and (*b*), respectively). In both cases a strong and statistically significant relationship exists between the local temperature and the MTCI. As temperatures altered so did chlorophyll content, with warmer temperatures associated with more chlorophyll content, and thus productivity of the ecosystem. The MTCI has usefully captured this.
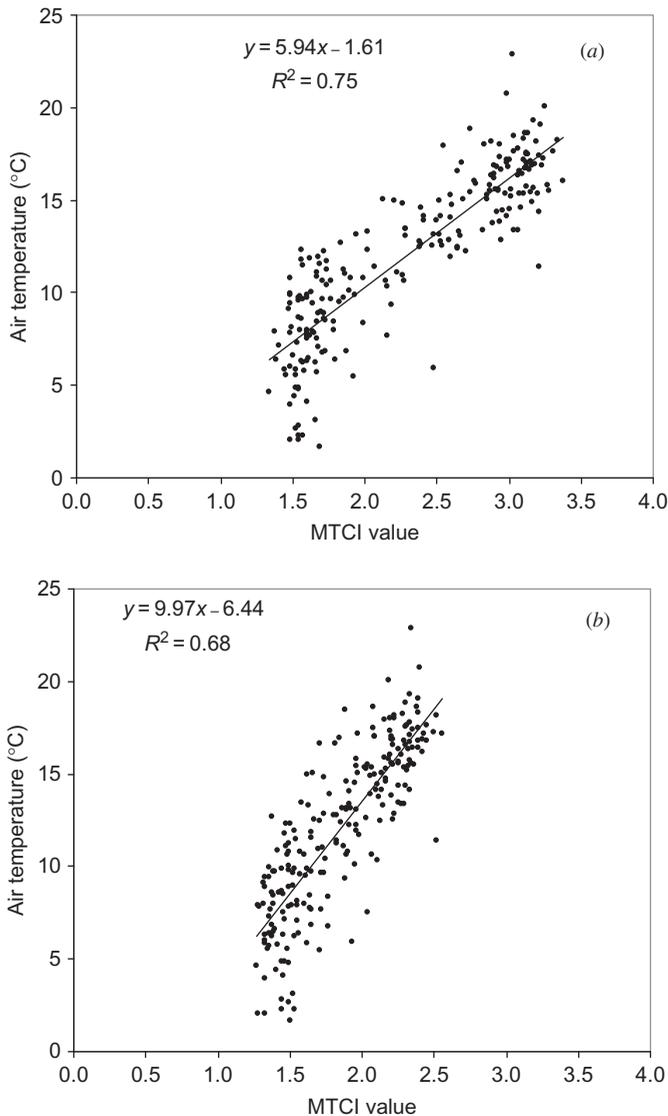

Figure 5. Regression analysis of the MTCI response from each 8-day composite for the years 2003–2008 with the corresponding 8-day arithmetic mean of the local temperature for both the woodland (*a*) and (*b*) grass/heath land sites.

3.3 *MTCI-derived phenological event dates*

The computed phenological event dates for both woodland and grass/heath land sites for each year of investigation as indicated by the MTCI, along with the growing season length (days) and green-up duration (days), are presented in table 1. As denoted by the phenological profiles, green-up of the woodland vegetation occurred in April or beginning of May, maturity onset in June or July, senescence onset in September or October and dormancy onset in October to December. The number of days taken for the woodland site to green-up varied between a minimum of 55 (2003 and 2004) and a maximum of 72 (2006), and the growing season length ranged between 179 (2003) and 221 (2006). Although the grass/heath land sites exhibit a longer growing season (ranging from 84 in 2003 to 237 in 2006), the interannual pattern is very similar to that of woodland.

Although direct comparison of dates with those compiled from the UKPN is not possible, the pertinent trends are consistent with those depicted by the MTCI data and with the fact that the timing of the seasons is changing in length and complexity. Noteworthy is (1) the extended green-up and late senescence onset and dormancy onset in 2006 which was a result of a warmer, non-drought year compared with the average; (2) the early green-up but average senescence and dormancy in 2007 which was the result of an exceptionally warm spring followed by cooler conditions in the latter part of the year; (3) an early senescence in 2003 which was the result of drought in the autumn coupled with slightly elevated temperatures; and (4) a late dormancy in 2005 due to warm temperatures and lack of drought. Ideally, spatially coincident phenological event dates would provide more information and this should be the focus of further study. However, for the purpose of this investigation the UKPN data demonstrate the utility of the MTCI, in that it has captured the key phenological event dates and depicts how the vegetation has responded to climatic anomalies over time. Change in temperature has been shown to affect the phenology of woodland species (Deng *et al*. 2007), leading to earlier spring green-up in woodlands in the mid- and higher latitudes (Menzel *et al*. 2006). The findings in this article support the notion of delayed senescence due to favourable growing conditions; this was particularly evident for the 2006 MTCI growing season.

3.4 *Comparison of MERIS-MTCI data sets with MERIS-MGVI, MODIS-derived NDVI and MODIS-derived EVI*

The phenological profiles for the 16-day composites of MTCI and MGVI from MERIS and NDVI and EVI from MODIS for woodland are depicted in figure 6(*a*) and (*b*) for the years 2006 and 2007, respectively; these were years with the largest climatic anomalies. Statistical intercomparison of the phenological profiles for the four vegetation indices was undertaken using a two-sample Kolmogorov–Smirnov test, which examines the difference (at 0.05 significance level) between the shape of the phenological profiles. This test indicates that for both 2006 and 2007 the MTCI curve was statistically different to the curves produced using the other indices. Also of note is that for both the years the MGVI phenological profile was not found to be different to that of the EVI curve. Furthermore, for 2006, it was found that the NDVI curve was not different to that of the EVI and MGVI; however, a difference was recorded between the phenological profiles of the NDVI to that of the EVI and MGVI for the year 2007. The phenological event dates from each curve for both years, shown in figure 7(*a*) and (*b*), indicate that all four indices depicted the late end of growing season for 2006 and

Table 1. Inter-annual variability in phenological event dates for woodland and grass/heath land derived from the MTCI time series.

	2003	2004	2005	2006	2007	2008
Woodland						
Green-up onset	30 April	1 May	10 May	7 May	8 April	29 April
Maturity onset	25 June	25 June	11 July	19 July	3 July	25 June
Senescence onset	5 September	13 September	29 September	31 October	13 September	29 September
Dormancy onset	27 October	15 November	23 November	17 December	14 November	7 November
Peak of the growing season	14 August	14 August	11 August	12 August	25 July	22 July
Green-up duration (days)	55	55	61	72	86	56
Season length (days)	179	197	197	221	220	191
Grass/heath land						
Green-up onset	1 April	9 April	1 April	28 April	17 March	19 April
Maturity onset	25 June	1 July	25 July	12 Aug	11 May	3 July
Senescence onset	21 September	7 October	13 September	8 November	28 August	7 October
Dormancy onset	13 October	12 November	10 December	11 December	9 November	29 November
Peak of the growing season	25 July	12 August	7 August	11 September	6 July	4 August
Green-up duration (days)	84	94	85	105	60	75
Season length (days)	225	217	222	237	236	223
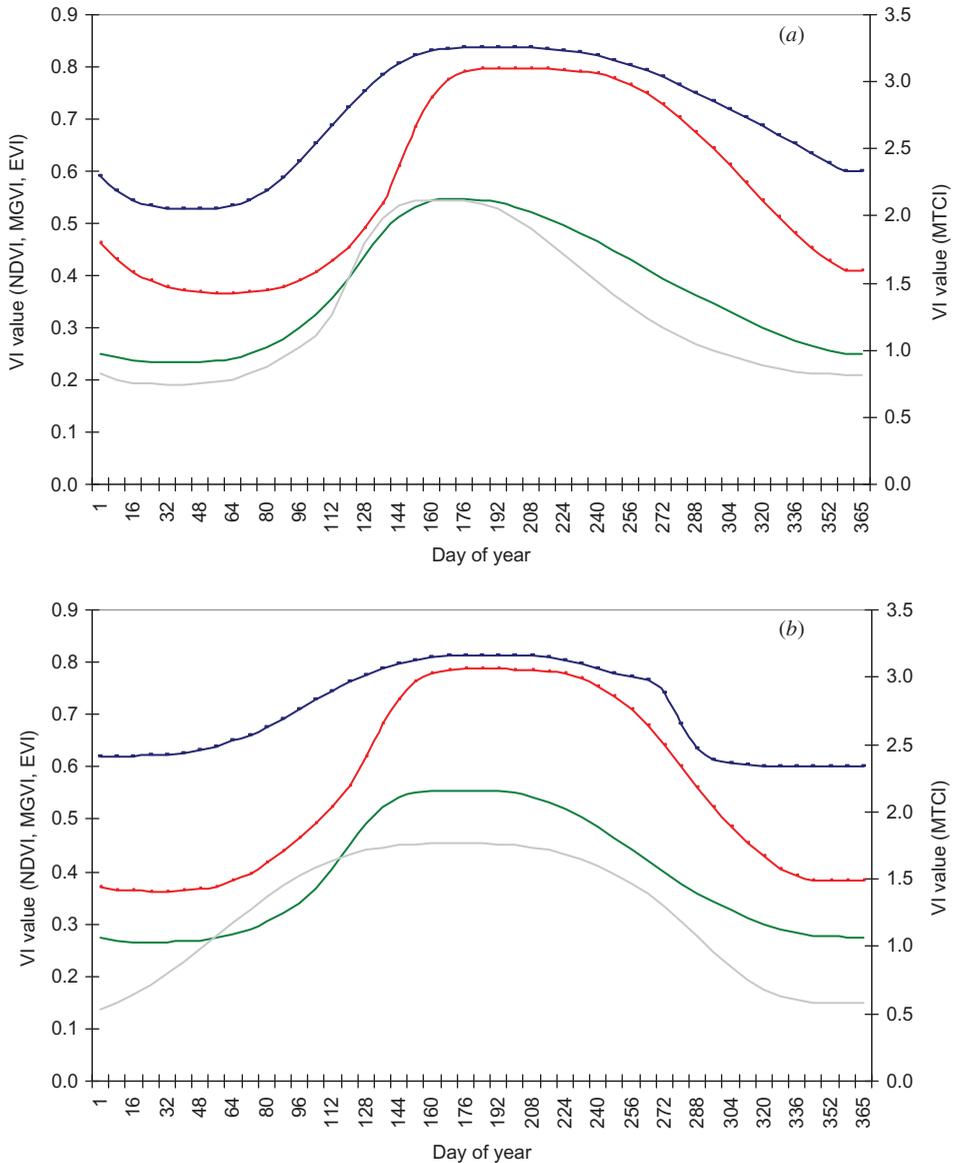
Figure 6. Phenological profiles for Envisat MERIS MTCI (red) and MGVI (silver) and MODIS EVI (green) and NDVI (blue) for (*a*) 2006 and (*b*) 2007.

the early green-up of 2007; however, it was only the MTCI that displayed the delayed autumn senescence of 2006. The derived dates for each phenological event differed between the indices in most cases, with the error in the total length of the growing season between the indices being 38 days for 2006 and 18 days for 2007 (figure 8).

The monitoring of forest phenology via satellite sensors requires a relationship between tree phenology and the VI employed (Jönsson *et al*. 2010). As the leaf phenological cycle progresses, leaves of deciduous forest canopy change in their biophysical (e.g. leaf structure and thickness), biochemical (e.g. chlorophyll and other pigments,

(*a*)

(*b*)

Figure 7. Computed phenological event dates for the woodland site for (*a*) 2006 and (*b*) 2007 as derived from Envisat MTCI, Envisat MGVI, MODIS EVI and MODIS NDVI phenological profiles.

nitrogen) and optical properties, which in turn influence albedo, latent and sensible heat flux and photosynthesis of the land surface (Xiao *et al*. 2004). Although, each of the four indices examined is a function of these changes in the cycle, the relative contribution of each differs, both spatially and temporally. Broadly, the MTCI is sensitive to variation in chlorophyll content, that is, biochemical activity, and relatively insensitive to vegetation configuration. The NDVI, EVI and MGVI, however, are primarily
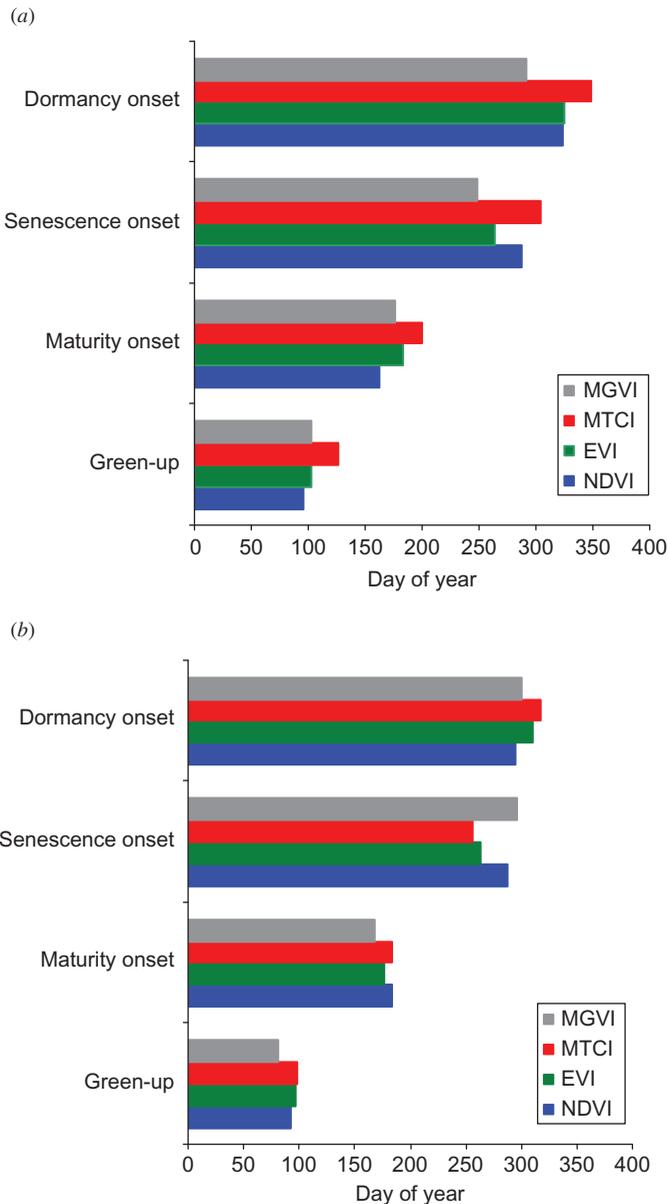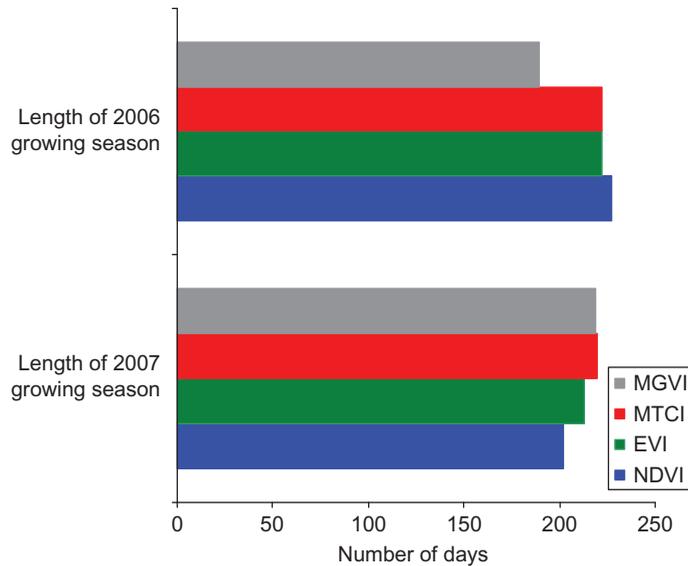
Figure 8. Computed length of growing season for the woodland site for 2006 and 2007 as derived from Envisat MTCI, Envisat MGVI, MODIS EVI and MODIS NDVI phenological profiles.

structurally driven spectral indices that quantify the biophysical activity of vegetation. Furthermore, the mathematical and scientific value of the VI is critically dependent on the form of the data used to calculate it in that a wide range of factors determine the final value of the index (Steven *et al*. 2003). The impact of solar, illumination, sensor sequence and waveband placement on a time series of vegetation indices is well established (e.g. Sexias *et al*. 2009). All these uncertainties can be 'corrected' for and so minimized. Temporal compositing time periods (Zhang *et al*. 2009) and method (White *et al*. 2009) are also factors to consider, as are methods for curve smoothing and extraction of phenological event dates.

Due to mixed species stands found in the New Forest, pixels will contain coniferous and deciduous species. Therefore, the small seasonal variation in photosynthetic biomass demonstrated by coniferous species results in a small change in LAI throughout the growing season (Kimball *et al*. 2004) when compared with deciduous areas. Compared to the NDVI, the MTCI is more suited to determine phenological event change in mixed tree pixels as total chlorophyll content will change more between seasons than LAI. The NDVI is more sensitive to green biomass and will respond to the aggregated change in seasonal LAI between coniferous and deciduous species. The effect of soil background will be a function of vegetation phenology and directly linked the foliar development of deciduous species. Therefore, during the period late autumn to early spring, which coincides with 'leaf-off' of deciduous tree species, the relatively higher NDVI values are due to the effect of soils background as well as the presence of coniferous species within the study sites. The NDVI phenological profile exhibits small amplitude, with limited variation between summer maxima and winter minima. The NDVI has a weak relationship with green biomass when vegetation cover is appreciably greater than 100%. Saturation in high biomass ecosystems and peak periods of growing season (Zarco-Tejada *et al.* 2001) may limit the use of the NDVI as a tool

for phenological monitoring. The MTCI is based on the relationship between chlorophyll content and red-edge position, which has a strong correlation with biomass (Eitel *et al*. 2007). MERIS acquires reflectance measurements in narrow bands, which should overcome biomass saturation issues (Blackburn 1999). The associated decrease in MTCI from late August 2007 is considerably earlier than the observed senescence observed by the MODIS NDVI time series. This supports the earlier decline in chlorophyll concentration as compared with decrease of other physiological or structural changes, namely leaf area, during autumnal senescence (Miller *et al*. 1991).

Whereas the NDVI is chlorophyll sensitive and responds to red band variations, the EVI is more sensitive to variation in near-infrared reflectance and is therefore very responsive to canopy structural variations, including LAI, canopy type and canopy architecture (Gao *et al*. 2000, Harris and Dash 2010). However, the EVI remains sensitive to a wide range of variation in canopy density (Xiao *et al*. 2004, Zhang *et al*. 2005). Previous studies have concluded that the EVI provides more information on the seasonal dynamics of deciduous broadleaf forest at leaf and canopy levels than NDVI and *f*APAR, which is closely correlated to the MGVI (Xiao *et al*. 2004). Previous comparisons between the NDVI and MGVI have concluded that the MGVI appears to reveal more information on the status of terrestrial surfaces than does the NDVI and note that this is due to a gain in the spatial contrast associated with a much lower noise on the computed index values (Gobron *et al*. 1999). The detection of *f*APAR through the MGVI index is useful since this acts at once as an integrated indicator of the status and seasonal evolution of the plant canopy in a range of vegetated environments (Verstraete *et al*. 2008, O'Connor *et al*. 2009). The magnitude of the MGVI has a near-linear and positive relationship with *f*APAR, which, in turn, is related positively to LAI and reflects its photosynthetic activity and, although related to the chlorophyll content of a canopy, this is a different variable to that measured by the MTCI. The ratio of the MTCI/MGVI is approximately equal to the chlorophyll concentration, and the temporal variation in chlorophyll concentration of vegetation may provide a valuable discriminating variable for mapping land cover (Dash *et al*. 2007).

Differences in the phenological profiles between the indices will also be a function of the temporal compositing method. EVI and NDVI data from MODIS utilize Maximum Value Composite (MVC) data. The MVC filter (Holben 1986) is designed to find the highest VI value (and therefore lowest noise) within a fixed time increment. 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). The MERIS MTCI and MGVI data sets use the arithmetic mean compositing technique, which is less sensitive to temporal biases compared with the widely used maximum value compositing technique. With an optimized cloud mask it can produce outputs with a greater spectral and spatial consistency than otherwise (Dash *et al*. 2010).

These results do not lend themselves to a recommendation of one particular VI over another. However, it has been demonstrated that there is significant variability in phenological event metrics obtained from different vegetation indices and that the desire for remote sensing products with ease of use and wide applicability and without the requirement for expert knowledge or operator intervention (Verstraete *et al*. 2008) could lead to unintentional errors. The implications of these differences in phenological event dates between different indices are of importance to studies of climate change and related impacts on the terrestrial biosphere. Inter-annual variation in the timing of phenological events is large (Badeck *et al*. 2004) as a result of circulation patterns, solar cycles, and oscillations such as the El Niño Southern Oscillation (ENSO) and

the North Atlantic Oscillation (NAO), thus uncertainties relating to measurements of change and choice of satellite sensor data further complicate an already challenging task.

The MTCI captured the key phenological events in a similar fashion to the more commonly used NDVI and EVI and the less prevalent MGVI. Further research at finer temporal resolutions, employing other methods to derive the phenological event dates, would be advantageous. In addition, it is critical to establish a robust methodology to validate this satellite sensor-derived phenological event information. Since it is predicted that the magnitude and frequency of extreme, such as drought, cold and hot, periods will increase (Jentsch *et al*. 2009), it is imperative that a robust system for studying the impacts of these is developed. Further application of the MTCI in other environments, such as tropical and dryland ecosystems (e.g. Zhang *et al*. 2010), is also required. Once the boundaries of use of the MTCI are established, a system that is future-proof is desirable; the planned launch of ESA's Sentinel-2 polar-orbiting satellites will provide systematic global acquisitions of high spatial resolution multi-spectral imagery with a high revisit frequency. This mission is tailored towards the needs of operational land monitoring and will provide estimates of leaf chlorophyll content via a MTCI-like index.

4. Conclusions

We used Envisat MTCI data to construct a phenological profile of and extract key phenological event dates from vegetation in Southern England during a period of known climatic anomalies. Overall, the research findings support the use of the Envisat MTCI for this purpose, principally due to its sensitivity to canopy chlorophyll content, a vegetation property that is a proxy for the canopy physical and chemical alterations associated with change to phenological event timing. Specific findings include:

1. A close correspondence between MTCI and canopy phenology, as indicated by ground observations and climatic proxy.
2. A significant difference between MTCI-derived phenological profiles and key phenological event dates and those from other vegetation indices, namely the MERIS MGVI, MODIS NDVI and MODIS EVI. Uncertainties arising from these differences are as large as those arising from climatic perturbations.
3. Further research is needed across a range of vegetation cover types and climatic conditions with full spatial resolution MTCI data (300 m) and employing other methods to derive the phenological event dates.

The use of satellite sensor data in phenological studies is increasingly recognized as a key component for the understanding of the response of vegetation systems to climatic change. Repeat observations from satellite-borne multispectral sensors provide a mechanism to move from plant-specific to regional scale studies of phenology. Here, it is advocated that the readily available MTCI data set should be considered for use along with understanding of the physical processes and computational approaches that determine the index values and how these may vary from those obtained using other vegetation indices.

University for a PhD studentship awarded to S. Almond. The authors are also extremely grateful for the valuable comments of two anonymous referees and to the authors of the TIMESAT software.

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