Satellite remote sensing as a tool for monitoring vegetation seasonality

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ABSTRACT

An increase in average air temperature across the island of Ireland has resulted in a change in the seasonality of vegetation. Current ground-based methods of monitoring seasonality are species-specific and limited to a few point locations across the country. Medium resolution satellite data, e.g. MERIS, provide a means of acquiring multi-year time series of imagery that can be used to capture the spatio-temporal dynamics in vegetation seasonality over the whole island. For this study, a geophysical measure of vegetation growth, the Fraction of Absorbed Photosynthetically Active Radiation (FAPAR), derived from MERIS Global Vegetation Index (MGVI) data is being used to determine seasonality. Tiles, extracted from a rectangular global grid, covering the island of Ireland have been processed through the European Space Agency’s (ESA) Grid Processing on Demand (GPOD) service. Initial analysis of the imagery has consisted of defining an optimal time composite period in order to minimise cloud effects for daily MGVI values using ancillary cloud data from a meteorological observatory. Methods of in-situ observation of seasonality in mixed woodland have also been explored. Initial findings suggest that a 10-day composite period should be optimal for Ireland given the high occurrence of cloud cover.

Keywords: Vegetation, seasonality, phenology, composite period, Fraction of Absorbed Photosynthetically Active Radiation (FAPAR), Medium Resolution Imaging Spectrometer (MERIS).

1. INTRODUCTION

1.1 Vegetation Phenology

The pressing issue of climate change has prompted more focused research in the area of measurable climate change indicators. Phenology is the study of the interrelationship between biotic growth and environment and is one such useful indicator of climate change. Vegetation phenology refers specifically to seasonal trends in vegetative growth and decline [1]. Changes in the timing of seasonality can be considered as the response of actively growing vegetation to regional climate changes and in Europe it has been shown that the growing season has been extended [2]. These growing season trends are significant for the monitoring of the long term effect of climate changes on the biosphere. Analysis of data from four Irish Phenological Gardens has suggested that the length of the growing season for a 30-year period from 1970-2000 has increased, particularly in south-west Ireland [3]. Data were analysed for three species common across all four sites, with results showing an extension of the growing season by 9 days for *Betula pubescences*, 3 days for *Fagus sylvatica* ‘Har’ and 7 days for *Tilia cordata*, for every 1°C rise in annual temperature. Although these observations have proved useful as indicators of change at a few specific locations across the country, the need has arisen, in line with European [4] and global efforts for a broad-scale method of vegetation phenological monitoring across the whole island. Satellite data offers the potential to address this need in Ireland as wide swath imagery can provide full coverage of the whole island in one pass. Annual time-series can reveal seasonal trends in vegetation and comparison of interannual data may reveal annual to decadal phenological variability. Phenological observations on the ground can provide a method of verifying the accuracy of satellite-derived trends; therefore, the two data sources are complementary.

1.2 Satellite remote sensing of vegetation phenology

Satellite remote sensing has been used to monitor vegetation dynamics since the early 1980’s with, for example, the generation of a global Normalised Difference Vegetation Index (NDVI) dataset from the NOAA Advanced Very High Resolution Radiometer (AVHRR) [5].

Due to the fact that healthy, living green vegetation strongly absorbs radiation in the red (R) portion of the visible spectrum and strongly scatters it in the near infrared (NIR), reflectance values in these two parts of the spectrum are used...
in the satellite detection of vegetated land surfaces \[6\]. Valuable data about the biophysical properties, state and health of living, green vegetation can be derived through mathematical operations on these values; such data are known as vegetation indices (VIs). Classical vegetation indices (VIs) such as the Simple Ratio (SR) and the Normalised Difference Vegetation Index (NDVI) exploit the differential reflectance in the red and near infrared to produce a single value which indicates the amount of vegetation within a pixel. However, in the absence of a blue channel, there is no automatic correction procedure applied to spectral measurements which can alter the NDVI erroneously due to differential depression of reflectance values by atmospheric aerosols and other interference. Further optimisation of these simple indices has resulted in more advanced spectral indices, such as the MERIS Global Vegetation Index (MGVI) with improved geometric error correction, atmospheric interference reduction and greater sensitivity to seasonal vegetation dynamics \[7\]. The inclusion of the blue band in atmospheric correction for the MGVI is a clear advantage over the classical VIs such as the NDVI derived from the NOAA-AVHRR sensor. The MGVI algorithm is designed to exhibit maximum sensitivity to the presence and changes in healthy live green vegetation \[7\]. It has been used as an estimate of the Fraction of Absorbed Photosynthetically Active Radiation (FAPAR). FAPAR is a bio-geophysical measure of a plant’s photosynthetic activity, recognised by the Global Climate Observing System (GCOS) as an essential climate variable \[8\]. It is a key indicator of the state and productivity of terrestrial vegetation. The optimisation of the MGVI algorithm to represent a geophysical variable such as FAPAR is achieved through the implementation of spectral models to simulate the external effects of changing geometry, atmospheric interference, bare soil surfaces and other background reflectance on vegetation canopy reflectance values in the red and near infrared bands.

Comparison of the performance of the MGVI against the NDVI, derived from SeaWiFS, was conducted for annual time series from 1998 to 2003 for a site near Chartres, France \[9\]. Though the NDVI time series did capture seasonal trends in vegetation growth, there was greater temporal variability in the trend than was the case in the MGVI trend. In 2003, a drought year, the NDVI trend remained indistinguishable from that of 2004, a year of normal growth, due to the presence of noise in the signal which may have masked any potential NDVI response to the drought. Therefore, in a concrete application, the optimised algorithm was found to outperform the simpler NDVI.

1.3 Reducing the effect of cloud cover on satellite imagery

Frequent, extensive cloud cover over mid-latitude, coastal regions of the Northern Hemisphere, such as Ireland, has presented a challenge to optical remote sensing of these areas. One of the most common approaches to minimising cloud interference in satellite-derived data is the averaging of consecutive satellite scenes over a time period of sufficient duration to achieve as much cloud-free imagery as possible. In this study, a time composite algorithm \[10\], is used to generate a time series of cloud free image composites of the derived FAPAR product.

1.4 Objectives

The objectives of this study are to develop a methodology using medium resolution satellite data to study the relationship between vegetation seasonality and climate in Ireland. The work is based on global scale work which suggests a greening trend for terrestrial vegetation in certain global regions \[11\] and will investigate this phenomenon for natural vegetation on a national scale. Once the timing of key phenological phases such as the onset of greenness have been extracted from multi-annual time series of FAPAR, an attempt will be made to characterise the spatio-temporal relationship between climate parameters, e.g. temperature and phenological events across the whole island.

This paper presents the preparatory stages of the work in deducing an optimal composite period for daily images of FAPAR values in order to generate as much spatially continuous, cloud-free imagery as possible. Initial findings from in-situ observations of vegetation phenology in an area of mixed woodland will also be compared with analysis of satellite data from the same area.

2. DATA

2.1 Satellite Data source (MERIS)

One of a class of regional scale sensors, the Medium Resolution Imaging Spectrometer (MERIS), launched in 2002, aboard the Envisat platform, is in a sun-synchronous, polar orbit with an acquisition time of 10 a.m. mean local solar time \[12\]. Regional scale coverage sensors gather higher resolution imagery than coarser resolution sensor systems such as NOAA-AVHRR and the NASA- Sea-viewing Wide Field-of-view Sensor (SeaWiFS).
MERIS data are acquired globally every three days in 15 spectral bands, of which bands 2, 5 and 8, corresponding to the blue, green and red part of the visible spectrum respectively and band 13, corresponding to the near infrared (NIR) part are the most useful for the monitoring of vegetation growth. The MGVI FAPAR product is obtained in a two step procedure. In an initial step, geometric and atmospheric corrections are applied to spectral measurements in the red (R) and NIR bands to produce the rectified R and NIR values. The next step is to input these rectified values into a mathematical formula which calculates numerical values of FAPAR.

MERIS data are operationally provided to the user in varying levels of processing, level 1 data, for example, are the least processed, whereas level 3 (L3) data are the processed, geophysical product. The L3 MGVI product was chosen for this study as the image preprocessing steps are complete and the MGVI values generated. The L3 product is supplied in hierarchal data format (hdf) containing 16 scientific data files, the data layers include spectral data in bands 2, 5, 8 and 13 along with the rectified red and near infrared reflectance values, the angles of illumination and observation and the MGVI values.

2.2 FAPAR/MGVI product from the Joint Research Centre (JRC)

The Institute for Environment and Sustainability within the JRC of the European Commission, in Italy, has generated an FAPAR product for Western Europe since 1997, using a range of sensors (MERIS, SeaWiFS, MODIS and MISR). The 1.5 km resolution SeaWiFS FAPAR product is available from 1997 onwards, the 1.1 km resolution MODIS product from 1999 and the 1.2 km MGVI FAPAR product has been completely processed from May 2002 onwards. The MGVI FAPAR data are supplied at the full spatial resolution of 300 m or at the reduced resolution (RR) of 1.2 km. As the higher resolution geophysical product has not been processed for MERIS, the reduced resolution MGVI product was chosen for this study. There is a ready availability of time series data for the RR product going back to May, 2002. The MODIS product was not considered further due to missing data in the time series and the SeaWiFS product as it was at a coarser spatial resolution.

2.3 ESA-GPOD processing

The GPOD (Grid Processing on Demand) processing engine of the European Space Agency (ESA) applies a time-compositing algorithm to daily MGVI data with the output accessible through an online web portal. Tasks are submitted, processed and completed on the GPOD from where the results are published. Scheduled services allow for long time series of the product to be generated for different months and years; requests for these services can be submitted directly to the GPOD administrator.

2.4 Cloud Data

The Armagh Observatory Meteorological Station contains a significant amount of meteorological data dating back over 200 years which is available to download for general use and it was chosen as a point source of cloud data for this study. Meteorological readings, including visual cloud estimates are taken daily at 9 a.m. Cloud cover is estimated on a scale from zero to eight okta where eight okta represents a fully clouded sky. The same observer records these readings to ensure consistency in the observations. The current observer has been recording observations since 1998.

3. METHODOLOGY

3.1 Criteria for an optimal composite period

As there is no standard approach, a set of criteria was devised in order to determine the minimum number of days per compositing period needed to monitor seasonality within Ireland. The aim of the compositing process is to combine consecutive satellite images over a number of days in order to generate as much cloud-free imagery as possible. For this study, the challenge was to retain a period short enough to be concurrent with phenological change in vegetation, while accounting for the almost daily occurrence of cloud in some or all parts of the island. Therefore, these criteria were established to maximise sensitivity to seasonality dynamics while minimising cloud interference. The criteria state that:

a) The period is of a sufficient length to include at least one cloud-free day for each image pixel.

1 http://gpod.eo.esa.int/
b) The period is short enough to remain sensitive to seasonality change.

c) The period takes into account the spatial distribution of cloud across the island.

In order to achieve this, ancillary cloud data from the Armagh Observatory data were analysed with a view to establishing the annual trends in cloud cover. This analysis consisted of averaging daily cloud cover estimates over a period of days corresponding to the duration of the composite periods under investigation. By altering the number of days in the averaging period and examining the effect on the mean value, it was hoped to gain an idea of the number of days needed in the composite period to minimise the presence of cloud. Interannual comparisons of the mean cloud values were also conducted in order to verify the extent of change in cloud cover between years.

3.2 Processing of satellite data

A publishing server was set up to automatically download the generated MGVI dataset for further processing. Since the processing generates a large number of files, it was more suitable to set up a publishing server where the requested files could be automatically uploaded by the GPOD administrator.

The GPOD preprocessing consists of combining multiple MERIS scenes into a remapped global product, using an interpolation technique, in the form of a rectangular grid of lines of latitude and longitude, presented in the Plate Carrée projection [16]. Tiles corresponding to regions of interest can be extracted from this global grid. Overlaying of tiles from multiple dates can produce a long time series of vegetation index data for a particular region.

Initially, multiple files from different composite periods were stacked and a water mask was applied to exclude as many non-terrestrial pixels as possible. The number of cloud-covered pixels per image composite was calculated and a temporal profile of cloud amounts was generated.

In order to generate values of FAPAR, the MERIS Global Vegetation Index (MGVI) was scaled, resulting in numerical values, between zero and one which correspond to the FAPAR of vegetation over land surfaces.

The analysis of MERIS data has been carried out using ENVI 4.0 and ERDAS IMAGINE 9.1 software.

3.3 Fieldwork

The approach to in-situ phenological monitoring in a forest, as described in [17], was modified and implemented on a smaller scale in mixed woodland near Cork Harbour. The main tree species types in the woodland were identified as Oak, Ash, Horse Chestnut, Sycamore, Beech and Birch. In total, thirty trees were marked for observation. Of these, between four and six trees were chosen per species type as representative of the phenological behavior of the species as a whole.

Initially, the approximate age, orientation, height, health and location of each tree was noted. On a once-weekly basis, phenological observations were taken which consisted of subjectively estimating the percentage of the tree canopy which had undergone budburst as well as the percentage leaf cover. Photographs of individual trees were taken to document the progression of these stages and were used to support the qualitative estimates of budburst and leafout.

Weekly phenological observations were recorded for a 12-week period from the beginning of March to the beginning of June, 2008, when all the trees were recorded to have 100% leaf cover.

4. RESULTS

4.1 Armagh cloud data

In order to investigate the effect of altering the number of days in the composite period on average cloud values and by their comparison, understand interannual cloud characteristics, daily cloud readings from Armagh Observatory were initially averaged over a 10-day period and were compared with cloud amounts in MERIS 10-day image composites over the same time period: the beginning of February to the end of October, 2007, Figure 1 illustrates the results of this comparison exercise. It is evident that cloud observations at Armagh are in reasonably good qualitative agreement with cloud amounts detected by MERIS over the whole island. There are anomalies however, in particular for the early spring period (March – April), where island-wide cloud trends, as detected by MERIS, were extremely low (between 0 and 10% for March, April and May) in contrast to reasonably large amounts of cloud cover observed at Armagh (between 4 and 7 Okta).
4.2 Optimal compositing period

Based on previous studies, ten day, monthly \(^{[6]}\) or twice-monthly image composites \(^{[18]}\) are standard. Analysis of the field results suggested that monthly or twice monthly composites would not be of sufficient temporal resolution to detect seasonality change but that either a 7-day or 10-day period would be more appropriate to characterise spring greening. Daily cloud observations at Armagh were averaged over 10-day intervals from February to October (i.e. the growing season) from 2005 to 2007 in order to select the most appropriate year on which to base the analysis for a suitable composite period, with the results shown in Figure 2.

According to monthly weather summaries compiled by Met Éireann, anomalously low cloud amounts were present across the country from the beginning of April to the beginning of June, 2007 \(^{[19]}\). Therefore, data from 2006 were chosen for further analysis as it was a year of more representative cloud trends. Both 7-day and 10-day MERIS composites from 2006 were compared to investigate the effect of the different composite periods on data loss due to cloud cover. Figure 3 illustrates the percentage of pixels recorded as being cloud covered for a 7-day and 10-day composite period between the beginning of March and end of June. The large number of peaks of high cloud cover in the 7-day data suggest that compositing over such a period could result in significant data gaps due to cloud interference. For optimal monitoring of vegetation seasonality across the whole island, it was decided that fewer than 10% of pixels should be cloud covered within the composite; this was achieved on 77% of the 10-day composites, compared with 50% of the 7-day composites. However, even a 10-day period did not satisfy the initial criterion as mentioned in section 3.1 (a) as not every image pixel had at least one cloud-free day.

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Fig. 1: A comparison of subjective cloud estimates at Armagh with the percentage of cloud-flagged pixels per MERIS 10-day composite for the growing season, beginning 1st of February and ending, 31st of October, 2007.

Fig. 2: Daily cloud observations from Armagh Observatory averaged over 10-day periods during the growing seasons of 2005-7 (note that 8 okta represents total cloud cover)
4.3 Fieldwork

The mixed woodland consists of a multitude of tree species as well as a dense understorey of scrub, flowering plants and other herbaceous vegetation. According to field observations, the most abundant tree species, Oak and Sycamore as well as the less extensive Horse Chestnut tree exhibited rapid greening throughout April and early May while the Beech and Birch tree exhibited a later and more steady and gradual greening up until the end of observations on May 30th; when the Ash tree was last to green up. Such results compare favourably to in situ findings over woodland in Europe [17] where the date of onset of greenup of Beech was found to be 7 to 12 days later than for Oak. Field notes also point to a strong greening trend in the woodland, associated with a noticeable rise in air temperature, during the first week in May.

Early spring greening in a Horse Chestnut tree during the month of March can be seen in Figure 4; such photographic data provided a visual estimate of the percentage of canopy cover of an individual tree which supported estimates in the field. However, in undertaking the fieldwork it was evident that even within a very small sample of trees of the same species, there could be considerable variation in the timing and rate of green-up. Given the very mixed nature of Irish vegetation, it is therefore anticipated that at the 1.2km scale of the MERIS imagery there will be considerable variability that is averaged to produce a single pixel value that may in effect not be a true record of change for any single plant within that pixel. Nevertheless it would still be expected to be able to generate an overview record of spatial and temporal change that is representative of the country as a whole from such imagery.

Fig. 4: Spring greening in a Horse chestnut tree over a three week period, 13/3/08-27/3/08
4.4 Growth of vegetation in an area of mixed woodland, spring 2006

Figure 5 illustrates the MGVI values for a pixel corresponding to the site of fieldwork from the beginning of March to the end of June, 2006. The increasing productivity of vegetation is evident in the rise in MGVI values from the beginning of March to early May with a stabilisation of values in mid May and a decline in values in late May and into June. Data gaps due to cloud appear in March and May. These results exhibit the ability of the MGVI values to depict typical growth patterns in an area of mixed woodland while also showing the effect of cloud on 10-day composite values. These results compare favourably with other investigations of mixed natural vegetation in New England [20], North America, which indicate that vegetation begins spring greenup in early April and reaches maturity in early June.

5. DISCUSSION

Meteorological observations throughout the spring period of 2007 revealed anomalously high sunshine amounts for the months of March, April, May and the beginning of June with record sunshine amounts recorded at various points throughout the country [16]. This explains the low cloud amounts detected across the island by MERIS during this period. Larger amounts of cloud observed at Armagh in some periods over these months show the limitations of using one point-source of cloud data to display island-wide cloud trends. However, combining data from a number of point sources may be a more reliable means of understanding island-wide cloud characteristics. Obtaining and analysing cloud data from point locations is useful in decreasing the number of compositing options for medium-resolution satellite data which reduces the processing requirements.

The criteria for a composite period were set out with the aim of finding an optimum between shortening of the period for capturing seasonality dynamics and lengthening the period to minimise the effects of cloud contamination on satellite data. In order to test these criteria, the satellite data that were used for analysis were coincident with the same time of year as the fieldwork (beginning of March to the end of June). Weekly field observations suggested that a 7-day period would be ideal for the compositing of satellite data; however, this had to be lengthened to a 10-day period as significant data gaps appeared in the 7-day composites due to cloud contamination. The first criterion of having at least one cloud free pixel for each image pixel was unattainable without extending the composite period to a length which is of no value for following the seasonality signal.

Results of the 2006 MGVI pixel value analysis for the mixed woodland would appear to be supported by the 2008 field observations. The stabilisation of MGVI values from early May onwards following an initial rise in values from the beginning of March is most likely due to the most abundant tree species such as Oak and Sycamore reaching maximum growth by this time. The reduction in values from late May to the end of June may be due to the presence of a dense leaf canopy, which may inhibit further photosynthetic activity due to competition for light. Though the analysis of the 2006 data points are qualitative and the fieldwork not concurrent with the year of imagery, this exercised has demonstrated how the field observations support the analysis of satellite data.
Further to this analysis, it is intended to extract a set of seasonality measures from the MGVI pixel data; however, the measures may represent the phenological response of a whole ecosystem, e.g. mixed woodland, rather than the phenology of a specific tree species. This is due partly to the 1.2 km resolution of the MERIS pixel as well as the heterogeneity of tree species within that pixel. The presence of three missing data points in Figure 4 from a total of thirteen points represents a sizeable loss of data due to cloud cover in this part of the country. Therefore, even a 10-day composite cannot account for the extensive cloud cover present in some parts of the island, emphasising the challenge that is inherent in optical remote sensing in Ireland.

Although not an extensive survey, the methodological approach to ground-based phenological monitoring showed the necessity of having observations to support analysis of the imagery and will be implemented on a larger scale for the 2009 growing season. However there are a number of issues related to the difficulty of validating the satellite derived phenology measures. Firstly, a 1.2 by 1.2 km image pixel represents reflectance from a multitude of vegetation types while observations in the field represent an individual tree. Secondly, the timing of observations needs to be coincident with the satellite image composite so that analysis of the imagery can be supported by field observations. Thirdly, the phenology of a pure stand of trees, of common species type, should be observed so that an average of phenological estimates from a number of trees can be taken.

Some of the difficulties in the field work included visually estimating the percentage of buds emerged in the tree canopy and the percentage of leaf cover present. In addition, using the same tree for weekly observations proved difficult due to interference from the public with the tags used to mark trees. Further modifications of the method for the next survey include a more rigorous approach to the tagging of trees to ensure consistent observations of the same tree on a weekly basis, assistance from an expert on in-situ phenological monitoring and using an established standard for qualitatively estimating the extent of the green canopy cover.

In order to deduce the timing of key phenological phases, an appropriate set of phenology metrics must be derived from the satellite data. The initial measures correspond to the start of growing season (SOS) and the end of growing season (EOS) while other intermediate metrics such as the growing season maximum and the annual ecosystem productivity can also be derived on a pixel-by-pixel basis using a variety of methods [21]. For example, in order to establish the beginning of a particular phenophase, the threshold method seeks to define a threshold VI value at which the phase begins. Direct measurements of the change of curvature include identifying inflection points, the point of maximum and minimum curvature and employing a delayed moving average to smooth out variation in the time curve. In this study a suitable threshold could be difficult to find due to the heterogeneity of vegetation on the island. Therefore, one or a combination of the direct measurements may be employed in the next stage of this study.

6. CONCLUSIONS

Ireland demonstrates some specific characteristics which provide a challenge to defining phenological change from satellite imagery. The island experiences frequent, extensive cloud cover which limits the use of daily imagery to record change but 10-day composites of daily images provide a good compromise to allow rapid changes to be monitored, without excessive data loss due to cloud-contaminated pixels. Vegetation cover is very heterogeneous which favours the use of higher spatial resolution imagery; if the methodology used for the extraction of seasonality measures is successful, the use of higher spatial resolution products will be considered. This work is ongoing and will provide a supplementary phenological dataset to national efforts to augment the phenology network in Ireland. Outputs from this work will include a set of metrics for the determination of phenological phases from satellite data as well as maps showing spatio-temporal trends in phenology across the island.

Acknowledgements –The Environmental Protection Agency has provided funding for this project under the STRIVE initiative, 2007. The authors are also grateful to the staff at the Institute for Environment and Sustainability, JRC, Ispra, Italy as well as the G-POD technical team at the European Space Agency’s ESRIN facility for their input.
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